国际工程科技发展战略高端论坛
International Top-level Forum on Engineering Science and Technology Development Strategy

中国工程院
CHINESE ACADEMY OF ENGINEERING

重大地下工程安全建设与风险管理

ZHONGDA DIXIA GONGCHENG ANQUAN JIANSHE YU FENGXIAN GUANLI

SAFE CONSTRUCTION AND RISK MANAGEMENT OF MAJOR UNDERGROUND ENGINEERING

高等教育出版社·北京
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内容提要

随着世界经济的持续发展，未来20年，地下工程建设与地下空间开发和利用是世界工程建设的重点之一。 由中国工程院主办，中国工程院工程管理学部，土木、水利与建筑工程学部，中国岩石力学与工程学会，中国科学院武汉岩土力学研究所/岩土力学与工程国家重点实验室共同承办的“重大地下工程安全建设与风险管理——国际工程科技发展战略高端论坛”于2012年5月18～19日在武汉举行。 论坛设置了大会特邀报告和主题圆桌高端研讨会，广邀国内外岩土工程、铁道、水利工程、防震减灾工程界的知名专家，围绕复杂地质与环境条件下的重大地下工程安全建设与风险管理，开展多方位、多角度的战略性与前瞻性主题研讨，通过多学科的交叉与融合探求复杂地质环境下地下工程与地下空间灾害机理研究与预测预警的攻关方略，推动我国乃至世界地下工程灾害（岩爆、大变形、塌方等）预测预报、灾害防治与风险管理的新发展，牵引新理论、新方法、新技术的自主创新与突破。 本次高端论坛取得的成果，分析、确定了未来10到20年地下工程安全建设领域发展的重点方向，凝练了未来一段时间地下工程建设领域需要重点组织研究的若干重大科学技术问题。

本书为中国工程院国际工程科技发展战略高端论坛系列丛书之一，配套的PPT文件请在中国工程院网站下载（www.cae.cn）。 本书适宜于科研院所从事地下工程风险评估的研究人员、设计和施工单位从事现场风险管理的高级工程师阅读，也可作为研究生开展研究的参考书使用。

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第一部分

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综　　述

一、论坛背景

随着世界经济的持续发展，未来 20 年，地下工程建设与地下空间开发与利用是世界工程建设的重点之一。一系列大型水电地下洞室群和深埋长隧道、大量的跨江越海公（铁）路隧道以及城市地铁将陆续在世界范围兴建。与此同时，为满足经济建设发展对资源的需求，煤矿、金属矿等资源的深部开采已成为世界的发展趋势。在这些地下工程建设中，由于建设规模巨大、地质条件复杂，岩爆、大变形与大面积塌方、突水、地表沉陷等地质与工程灾害事故频发，导致人员伤亡、设备损坏、工期延误和工程失效等重大损失。地下工程灾害孕育演化规律与成灾机理、风险评价与管理、控制理论与技术等已成为地下工程建设面临的具有挑战性的关键科学与技术难题。

论坛广邀国内外岩土工程、铁道、水利工程、防震减灾工程界的知名专家，围绕复杂地质与环境条件下的重大地下工程安全建设与风险管理，开展多方位、多角度的战略性与前瞻性主题研讨，通过多学科的交叉与融合探求复杂地质环境下地下工程与地下空间灾害机理研究与预测预警的攻关方略，推动我国乃至世界地下工程灾害（岩爆、大变形、塌方等）预测预报、灾害防治与风险管理的新发展，牵引新理论、新方法、新技术的自主创新与突破。

二、整体情况

在论坛各方的共同努力下，“重大地下工程安全建设与风险管理——国际工程科技发展战略高端论坛”于 2012 年 5 月 18 日 ~19 日在武汉洪山宾馆举行。论坛由中国工程院主办，中国工程院工程管理学部、中国工程院土木、水利与建筑工程学部、中国岩石力学与工程学会、中国科学院武汉岩土力学研究所/岩土力学与工程国家重点实验室共同承办，并得到湖北省委、湖北省人民政府、国家自然科学基金委员会、中国科学院武汉分院的大力支持。

会议面向未来 20 年世界重大地下工程安全建设与风险管理方面的重大科技问题开展高端性、宏观性、综合性、战略性研讨，具体围绕三个主题：复杂地质与环境条件下重大地下工程灾变机理与调控机制、设计理论与方法、安全风险评价理

论与管理体系。论坛设置了大会特邀报告和一场主题圆桌高端研讨会。

出席会议、做特邀报告和参加研讨的有18位院士:中国工程院院长周济院士、钱七虎院士、陆佑楣院士、孙永福院士、葛修润院士、马洪琪院士、王景全院士、孙伟院士、张祖勋院士、周丰峻院士、郑守仁院士、郑颖人院士、钟登华院士、秦顺全院士、崔俊芝院士、龚晓南院士、李建成院士,中国科学院宋振骐院士,8位外国著名院士专家:英国皇家工程院院士、国际岩石力学学会前任主席 John A. Hudson 教授,英国皇家工程院院士、澳大利亚技术科学与工程院院士、国际岩石力学学会最高奖(Muller 奖)获得者 E. T. Brown 教授,美国国家工程院院士、瑞典皇家工程科学院院士 Charles Fairhurst 教授,加拿大国家工程院院士、国际岩石力学学会前任副主席 Peter Kaiser 教授,国际岩石力学学会最高荣誉 Muller 奖获得者 Nick Barton 博士,南非矿震专家 Kevin Riemer 博士,以色列岩石力学学会主席 Yossef Hatzor 教授,国际岩石力学学会前任副主席葡萄牙 Luis R. Sousa 教授,以及罗绍基院士代表、施仲衡院士代表、国际岩石力学学会主席冯夏庭研究员,丁烈云教授、唐春安教授、何满潮教授、李术才教授、国家自然科学基金委员会工程与材料科学部水利学科主任李万红教授等。钱七虎院士和 John A. Hudson 院士担任大会主席,孙永福院士、陆佑楣院士和葛修润院士担任大会副主席。

冯夏庭研究员主持了开幕式,中国工程院周济院长致开幕辞,论坛主席钱七虎院士、论坛主席 John Hudson 院士、湖北省副省长郭生练分别代表论坛组委会和有关政府部门致辞表示祝贺。

会议历时两天。5月18日~5月19日上午,与会专家学者围绕地下工程安全建设与风险管理作了精彩的特邀报告。其中,大会主席钱七虎院士作了《地下工程建设安全面临的挑战与对策》的主题报告,分析了我国目前地下工程建设的现状以及安全管理面临的挑战与对策,并着重分析了地下工程建设中突水突泥和岩爆两个最主要工程灾害的对策措施。国际岩石力学学会前主席 Ted Brown 对地下工程建设安全管理中的风险评估和风险管理进行了综述,详细阐述了地下工程风险评估和管理的理论、方法和实际工程应用。英国皇家工程院院士 J. A. Hudson 针对岩石力学参数获取和不明地质条件下的工程设计问题进行了详细的阐述。郑颖人院士在报告中介绍了有限元极限分析法在隧道工程设计和稳定性分析中的应用,提出了预知和控制工程安全的先进设计方法。马洪琪院士详细介绍了我国水利水电地下工程安全建设技术、国家需求及科技前沿问题;国际岩石力学学会罗哈奖得主 Nick Barton 介绍了 TBM 和钻爆法的混合解决方案在深埋长大隧道中降低风险中的应用。Yossef H. Hatzor 教授介绍了非连续变形分析(DDA)方法在浅埋隧道坍塌风险评估中的应用情况,详细阐述了该方法在 Ayalon

隧道、Zedekiah 采石场和 Beersheba 地下蓄水系统中的具体应用。中科院武汉岩土所冯夏庭研究员、东北大学丁烈云教授、山东大学李术才教授、大连理工大学唐春安教授、中国矿业大学何满潮教授等也就地下工程建设安全中的突出问题做了精彩的报告。

5 月 19 日下午,论坛主席钱七虎院士和 John Hudson 院士共同主持了重大地下工程安全建设与风险管理主题圆桌高端研讨会。研讨会集中对地下工程安全建设和风险管理未来 20 年的科技发展战略,从国际视野进行了研讨,探讨未来的研究、合作。与会的中外院士和专家进行了精心准备,积极发言,并达成了一系列共识。周济院长在会上发表总结讲话。

三、会议主要观点和结论

会议经过两天的报告和研讨,形成了如下主要观点和结论:

1. 重大地下工程的安全建设与风险管理是当前国际岩土力学工程界最为关注的前沿问题,也是我国未来需要重点研究的关键问题。目前我国正处于地下工程建设的高潮期,水利水电、交通、城市、矿山、国防等领域正出现越来越多的隧道(洞)、洞室群和地下空间。这些工程的建设规模及其所遇到的复杂地质条件很多都是世界少有的,工程建设过程中岩爆、突泥突水、塌方等地质灾害时有发生。地下工程安全形势虽有所好转,但事故发生率仍居高不下。

2. 在地下工程安全建设与风险管理方面,取得的代表性进展主要有:

1)有限元极限分析方法技术及其隧道稳定性分析;

2)光纤光栅传感技术、地下工程施工过程当中的安全状态实时感知技术、施工便携式智能预警终端技术,部分技术已经在实际工程中成功运用;

3)水利水电地下工程建设技术(包括大型地下厂房安全建设技术、复杂地质条件下大断面、长隧洞安全建设技术、无钢衬高压钢混凝土叉桩管设计及施工技术、高压长斜井安全建设技术、地下工程的混凝土模板建设);

4)岩爆孕育过程的现场和室内试验方法、特征、规律、机制、分析、预警方法、“三步走”和基于微震信息动态演化规律的动态调控方法、控制岩爆的大变形锚杆。该成果在锦屏二级水电站引水隧洞和排水洞群进行了成功实践,表明了岩爆是可以预测的,在高强岩爆洞段,钻爆法比 TBM 有更好的适应性,TBM 与钻爆法联合可降低岩爆风险;

5)建立了一套集陆地声纳、瞬变电磁和复合式激发激化技术为一体的含水构造超前预报技术体系,研制了动水注浆新材料,形成了集地质预报和科学服务为一体的信息化综合治理的决策系统研究。该成术在沪蓉西、青岛的海底隧道中

得到成功应用；

6）在地铁建设领域，完善了安全风险管理的法规体系建设和制度建设，对工程建设安全风险管理体系进行了积极探索，主要包括：建立了业主、勘察、监理方、施工方和第三方监测单位的管理职责明确的组织管理体系；建立了涵盖工程建设的全过程，包括勘察阶段、方案设计阶段、初步设计阶段、施工图设计阶段、施工阶段及工后阶段的安全风险技术管理体系；建立和规范了涵盖风险识别、分类、评估和控制的安全风险管理流程体系；建立了包括监控量测与安全巡视的安全风险管理预测预警制度及监控预警模型；建立了针对施工现场活动的安全风险管理指南；建立了安全风险管理的远程监控平台和完善的第三方监控体系，并针对常见施工突发工程及环境风险事件提出了预防及应急措施。

在研究和实践过程中总结出的以上成果应加大力度在地下工程领域进行全面推广。

3. 查明复杂地质环境的风险并进行及时有效防范是地下工程建设面临的巨大挑战和安全建设的关键所在，应加强地下工程全生命周期（也就是地下工程规划、勘察、设计、施工和运行的全过程）工作的协调和统筹，加强地质勘查、地应力测试和岩体的非确定性和非均质性研究，加强与 7 个关键因素 GTHMCBE（即地质、温度、水力、应力、化学、生物和工程因素）相关的重大事故预测预报和防治的基础理论、新技术和新材料的研究，建立基于现代化、信息化技术的地下工程安全风险管理信息系统，通过国家项目如 973 项目等的立项攻克相关理论和技术难题，提高地下工程安全建设与风险管理水平。

4. 目前地下工程建设中突出存在管理体制不健全、招标不规范、赶工期、工程造价低造成安全措施投入缺少、用工制度造成人员技术水平低等问题。提高地下工程安全建设与风险管理水平的关键是：加强针对地下工程安全风险管理的法规建设；完善各行业的地下工程勘察、设计与施工技术规范；推广建立地下工程安全风险管理体系和安全监控中心，完善第三方监测监理制度；加强工程安全文化建设，促进树立企业的社会责任理念；建立和推广地下工程安全风险管理指南。

5. 鉴于地下工程在抗震、抗风等方面以及利用水库可以提供大量的冷却水的优势，在水电站地下厂房建设地下核电站是一种可能的选择。

四、论坛意义

本次高端论坛目的明确，针对性强，出席会议的有较多国内外世界顶级专家，具有很强的代表性，研讨问题重点突出。本次高端论坛取得的成果分析、确定了未来 10 到 20 年地下工程安全建设领域发展的重点方向以及凝练了未来一段时

间地下工程建设领域需要重点组织研究的若干重大科学技术问题。正如周济院长在总结讲话中指出:“这次会议开得很成功,体现了国际工程科技发展战略高端研讨会的目标和宗旨,参加本次论坛的有中国工程院工程管理学部,土木、水利与建筑工程学部两个学部的院士以及来自世界各地的顶级专家,大家从各个方面以一种开放的心态互相学习,共同研究,强调综合,强调集成,从更高层面上进行了研讨,突出了战略研究的主题,体现了协同创新和国际合作,是一次成功的论坛,为加强中国与世界工程技术的交流,进一步促进我国乃至世界重大地下工程建设发展和科学管理发挥了积极的作用。”

第二部分

参会人员名单

参会人员名单

序号	姓名	单位	职务/职称
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*4	Nick Barton	挪威尼克·巴顿国际顾问事务所	博士
*5	Kevin Riemer	南非金田公司	博士
*6	Yossef Hatzor	以色列本·古里安内盖夫大学	博士/教授
*7	钱七虎	总参科技委	院士
*8	郑颖人	后勤工程学院	院士
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26	刘洪波	郑州航空工业管理学院	副教授
27	陈　健	中国科学院武汉岩土所	研究员
28	钮新强	长江水利委员会长江勘测规划设计研究院	教授级高工/院长
29	杨启贵	长江水利委员会长江勘测规划设计研究院	教授级高工/总工程师
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58	王继敏	二滩水电开发有限责任公司	局长/教授级高工
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“*”为论坛报告人

第三部分

特邀报告及报告人简介

地下工程建设安全面临的挑战与对策

钱七虎

解放军理工大学

一、地下工程建设的现状和分析

地下工程建设安全的现状,可以从表 1 看出来,这是我国最近几年重特大事故的统计。

表 1　2008 – 2011 年我国重特大事故统计

年份	事故性质	发生次数	死亡人数
2008	重大事故	86	1304
	特大事故	11	667
2009	重特大事故	67	1128
2010	重特大事故	74	1438
2011	重特大事故	59	897

由此可见,我们的安全形势虽然在 2011 年稍有好转,但是事故的发生率仍居高不下。

土木工程领域里的事故、伤亡人数在所有事故类型中排在什么位置呢?位于全国安全事故的第三位,第一位是道路交通事故,第二位是煤矿事故,第三位就是土木工程领域的伤亡事故。在特大工程领域事故中,土木工程领域事故约占 10%,图 1、图 2 是土木工程领域和地下工程领域里的安全事故数和伤亡数。

可见,土木工程领域和地下工程领域的安全事故、伤亡人数近 4 年来没有明显的下降,2008 年地下工程与其他三年相比存在大的波动,2008 年为什么特别高?大家可能记忆犹新,那一年发生的杭州地铁事故一次死亡 20 多人,因此,总体上可以说地下工程的安全形势并没有明显的改善。下面是对于事故的分析,我们统计了 50 多起矿山地下工程发生的事故案例,20 多起浅埋暗挖浅工程事故案

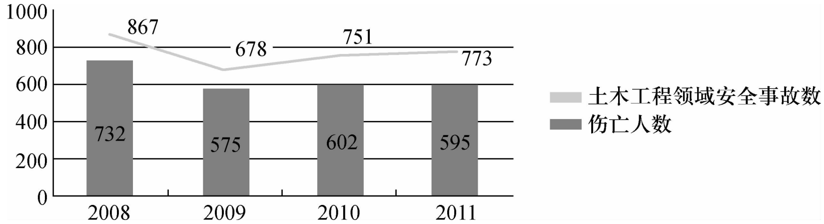


图 1　土木工程领域安全事故数及伤亡人数

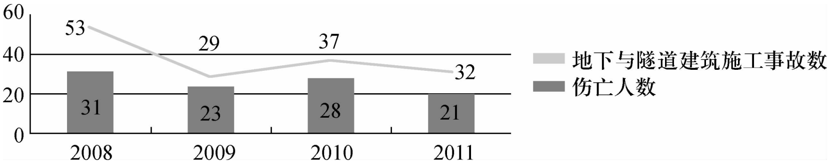


图 2　2008 - 2011 年地下工程安全事故及伤亡人数

例,从图 3 ~7 里可以看出,事故类型主要是垮塌、突水突泥和岩爆,这些是主要的事故类型。

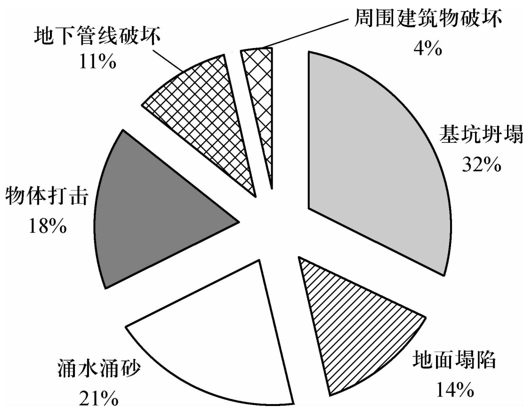


图 3　明挖法地下工程施工安全事故案例事故类型

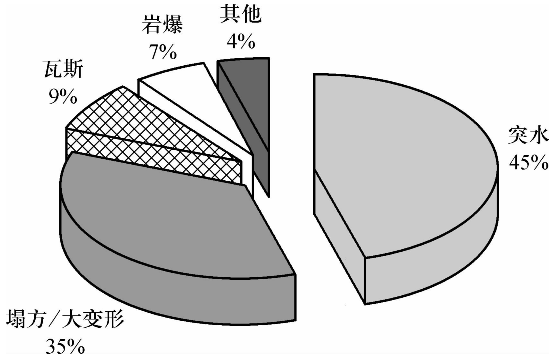


图 4　矿山法地下工程安全事故类型

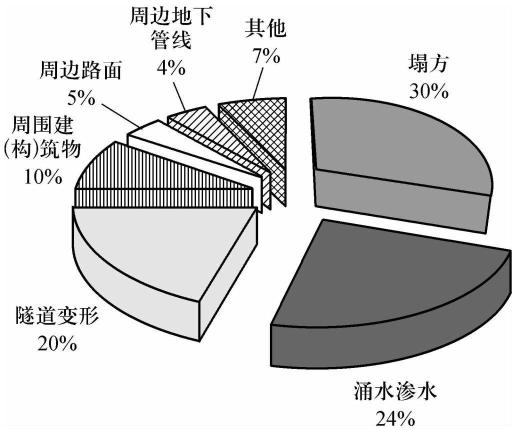


图 5　浅埋暗挖法地下工程安全事故类型

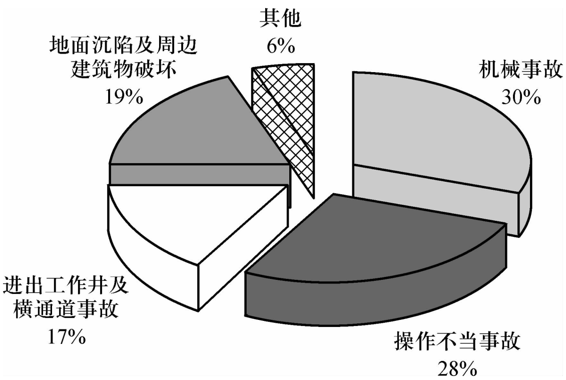


图 6　盾构法地下工程安全事故类型

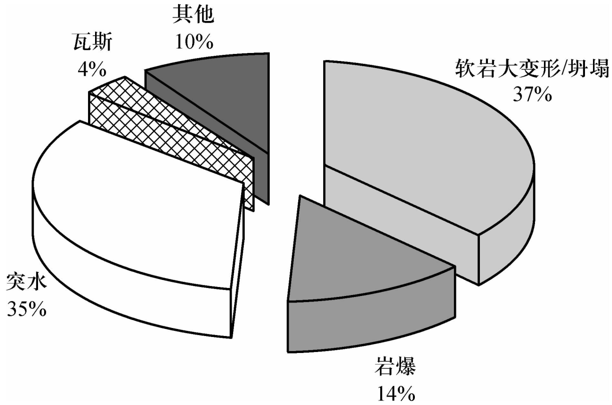


图 7　TBM 法地下工程安全事故类型

事故原因分析,总体上,1/4(占22%)完全是客观原因,1/3多(37%)完全是主观原因,1/3多既有客观原因,又有主观原因,两个方面的主观原因都可以归为责任事故和人的因素,其中有政府监管部门监管责任缺失、以罚代管、以包代管,施工方安全管理人员未能履行好安全管理职责,施工指挥人员违规指挥,施工人员违规操作,施工方案不完善。监理不严,责任心缺失,业主方招标时违规发包、转包、抢工期,设计方案存在缺陷、勘测资料不全等等。

在主观原因背后的深层次原因归纳为以下方面:

1. 赶工期。一个重要因素就是政府、业主干预,工程完工日期要限定。

2. 工程造价低,因此影响了安全措施的投入。

3. 我国用工制度存在着一定的问题,地下工程领域、土木建设领域有大量的农民工,他们技术水平低,安全意识差,无证上岗人员多。

4. 工程招投标过程中存在违规现象,存在违规发包,层层转包,以包代管,以罚代管的现象。

上面提到的这些客观原因,绝大多数的事故都是环境和气象引起的,而其中工程地质环境、水文地质环境的复杂是其第一主因,特别是在地下工程中突水突泥和岩爆地质灾害的难度最大,挑战最强。

二、地下工程安全管理面临的挑战和对策

根据上面的现状和分析提出在管理方面和科技方面的挑战和对策

(一)首先是管理的,中国地下工程安全管理面临的挑战

我国是世界上城市地下空间开发利用大国,开发规模已经位居世界前列。城市的轨道交通建设速度在世界上是最快的,工程量是最大的。现在很多城市已经开始了地下快速道路的建设。因此,形成了国家地下工程的建设规模大、发展快这么一个客观形势。由于这样一个形势导致的地下工程技术和管理力量难以保证,而且工期又偏紧,因此产生下列的问题和挑战。

1. 前期工作不充分,包括地质勘察和工程可行性研究不充分。

2. 设计人员、施工管理人员青黄不接。很多工程师,甚至助理工程师在主管工程建设项目,岗位编配不合理。

3. 工程人员对于地下工程的高风险特点认识不足。

4. 管理体制比较混乱,安全管理、多头管理相互既有重复又有缺陷。

5. 工程招投标制度不规范,存在着转包和违规招标等现象,项目管理水平参差不齐。

6. 工程低价中标机制造成了工程造价偏低，安全措施投入和安全风险管理投入不到位。

（二）面对这样的挑战，我们应从管理科学的角度来寻找对策；管理科学告诉我们：工程事故的预防是可行的

我简单讲几点工程安全科学研究的结论。

图 8 显示的是工程事故发展示意图，事故的发展是从萌芽发展到险情的，从缓慢发展到快速发展的阶段一般是两到三天。另外根据海恩安全金字塔原则（图 9），一件事故是由下面 300 个先兆造成的。

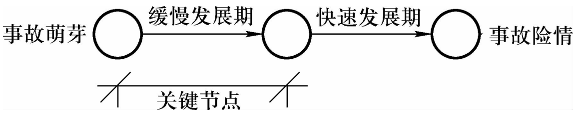


图 8　工程事故发展示意图

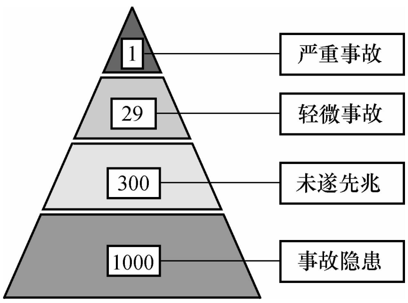


图 9　海恩安全金字塔理论模型

刚才讲到的海恩安全法则是根据大量安全事故统计产生的法则。通过 55 万件事故统计分析，发现发生的事故里 88% 是由于人的不安全行为，10% 是因为物的不安全状况，只有 2% 是不可抗力的因素。因此，如果我们预先发现人的不安全行为和物的不安全状态就可以预防和消除事故。

约翰逊的工程变化和事故模型（图 10）认为，事故的发生是由一系列的失误和变化引发的，包括领导者、计划者、监督者、操作者一系列的变化。如果我们切断了事故的链条，就可以把事故制止。因此，上述这些安全科学的研究理论揭示了一个法则理论模型，揭示了一个十分重要的事故预防原理，就是：要预防死亡的重伤害事故，必须预防轻伤害事故；要预防轻伤害事故，必须预防无伤害虚惊事故；要预防无伤害虚惊事故，必须消除日常不安全行为和不安全状态。能否消除日常不安全行为和不安全状态，取决于日常的安全管理是否到位，也就是说安全

风险的细节管理。这是作为预防重大事故最重要的基础工作。所以安全管理的重点不是事后的管理，而是在事先的安全风险管理。我们往往是出了事故后，来检查、处理人等等。就好像医疗卫生一样，它的重点不是在医疗，而是在预防。

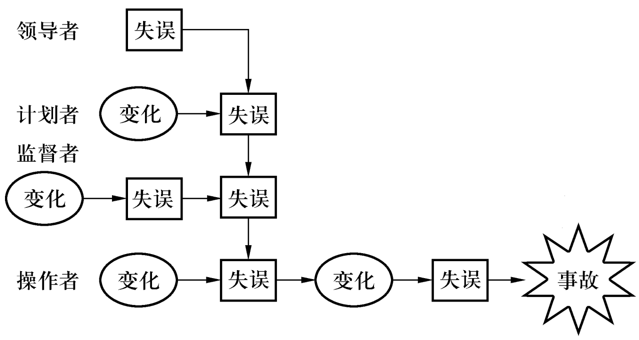


图 10　变化－失误模型示意图

基于上述的挑战和分析，我们提出了地下工程建设安全管理应该实施的对策。

1．加强法规建设

安全风险管理不单单是安全管理，首先是重在安全风险管理的法规建设。

（1）需要政府有关部门以及相关的行业协会制订有力的法规来规范。

（2）明确各个方面的安全法规责任，这个责任要建立在一个体系里面，因此要建立一个安全风险的管理体系。

（3）通过法规来强制实行重大工程立项前的安全风险分析、评估研究，凡是安全风险评估为严重等级的工程方案要实行一票否决制，必须进行工程方案修改。下面我再介绍一些地下工程安全事故，譬如说宜昌到万县的铁路线路发生了多次事故，三次重大的突水突泥事故，死亡 20 多人，因为通过岩溶地带，这样一条线路的方案定位在重大立项前要进行风险评估，要考虑线路的埋深是否合理，能不能有风险降低的措施。同时要强制实行重大工程的设计和施工方案的审核制度。我们现在的重大工程是一个设计单位设计了，没有另外一个设计单位来审核，包括刚才我们提到的设计方案不完善、施工方案不完善，没有严格的审核。比如说杭州地铁事故的主要原因是野蛮施工、野蛮开挖，施工方案没有审核把关。

（4）通过法规规定，按照风险管理的相关规定来确定风险管理费用，而且这个费用要确定其在建设费用里的合理比例，像国外一样，安全管理的费用应该占到百分之几，而且专项经费非常清楚，不列入商业的投标，不管是哪个标都应该保证此项经费。

2. 实施地下工程安全风险管理重在预防

（1）全面推广地下工程安全风险管理制度，把安全风险管理作为地下工程建设管理的必要组成部分。

（2）安全风险管理包括风险因素辨别和分析，安全风险管理还应贯穿施工建设的全过程，而不仅仅是施工阶段，因为很多隐患和问题存在于勘察阶段、存在于设计阶段。

3. 地下工程建设安全管理中心的建立

（1）我们怎样发现事故的前兆呢？这就需要监控，安全风险管理里面最重要的组成部分就是监测和控制，要建立相应的机构和制度。

（2）安全监控中心是地下工程安全风险管理的信息枢纽，负责各个部分、各个阶段的安全风险监控，对于从事监控的这些单位的资质应该有严格的管理，现在我们也有监理，但是资质管理不够。

4. 建立基于现代化信息技术的地下工程建设安全风险管理信息系统

从出现苗头到发生险情一般是两到三天，有的时间更短，根据记录，如果层层书面报告，肯定来不及事故的预防。所以要用现代化的风险管理信息系统，同时这个事故的链条能否切断呢？只要是有一方不负责，马上就有其他方来承担。这个信息应该是畅通的、透明的、共享的。信息应当由基础的支持部门提供，包括地理、地质、工程和环境信息等。

5. 加强地下工程风险管理理论研究以及重大事故预防预报的防治技术研究

我们刚才讲，有2%的事故源于不可抗力因素，也就是说，有的险情还达不到100%能够预测预报和预防，这是需要我们研究的。最典型的例子就是宜万线马鹿箐隧道的险情，2007年11月20日发生事故，死了11个人，当时就停工了，专家决定建一个排水洞。2008年3月21日，这个排水洞成功地泄洪，溶洞成功泄洪，2008年4月19日铁道部机关领导和专家现场考察和评定，认为这个水道实现了打通的目标；水利部的专家也认为该水道的成功泄洪标志着解决了大范围、高水位、多淤泥这一世界级难题，取得了突破性进展。但是，就在宣告成功三天以后马鹿箐隧道又发生了严重的突水，死了4个人。这个例子告诉我们，目前的技术水平还没有完全解决重大的地质灾害预报和预防问题。因此需要我们加强防治的研究。

三、突水突泥地质灾害的挑战和对策

突水的问题是地下工程风险最大的环节，由于我国是世界上岩溶分布最广的国家，岩溶分布面积占国土面积的1/3，这个问题很突出。表2显示的是部分岩溶

灾害,其集中涌水量都达到每天上万立方米、十几万立方米这样一个水平。这里有很多事例,有很多重大的突水突泥事故,比如野三关的事故(图 11),因为时间关系,就不详细介绍灾情了。

表 2　我国部分长大隧道突水突泥灾害详情表

隧道名称	地质灾害描述
大瑶山铁路隧道	施工期涌水量:4000～15000 m^3/d,平导 1994 + 213 涌水造成竖井被淹、洞内机具被淹没达数月;正洞 DK1994 + 600 涌水淹没隧道 200 余米,水深 1.4 m,隧底淤积泥沙厚 1 m,中断施工长达 1 年之久;DK1994 + 636～637 处发生涌泥、涌沙 80 m^3,淹没轨道,造成短时中断行车;地表斑古坳地区生产生活用水枯竭;地表坍塌约 413 个次
圆梁山铁路隧道	施工期涌水量:110000 m^3/d(出口 DK361 + 764);DK354 + 450～510 溶洞发生涌水为 9.6×10^4～1.656×10^5 m^3/d,伴随涌沙涌泥,淤积长度 130 m,高度 2.5 m,涌沙量约 1300 m^3;DK354 + 879 溶洞发生涌水,伴有涌泥涌沙(总量约 6000 m^3),最大涌水量达 7.2×10^4 m^3/d,造成人员伤亡事故,被迫采用迂回导坑通过;DK360 + 873 涌沙,淹没导洞近 200 m;DK361 + 764 处发生涌水伴随涌沙涌泥,涌水量为 240000 m^3,涌泥沙覆盖整个掌子面,淤积量约 15000 m^3
歌乐山铁路隧道	DK2 + 619.6 发生涌水,涌水量 14400 m^3/d,涌水泥沙含量达 20%～30%
宜万马鹿箐隧道	2006 年 1 月位于湖北省恩施市屯堡乡的宜万铁路马鹿箐隧道发生涌水,死亡 11 人
宜万野三关隧道	2007 年 8 月 5 日发生突水突泥事故,在 30 min 内,突出 15104 m^3 水、泥、石等,导致大量机械被冲出,并造成人员伤亡,治理时间至少半年,淹没正洞 500 余米,掌子面附近 200 m 全被大块孤石充满


(a)　(b)

图 11　宜万线野三关隧道突水

（一）突水突泥地质灾害对地下工程建设安全的挑战

在国内外隧道特大事故中，突水事故在死亡人数和伤亡人数上均居于前列，还有其对工期的影响很大。据我国施工的统计，突水突泥事故影响总工期达30%。而且由于基础设施建设，特别是西部大建设、大开发，隧道的埋深增加了，所以突水突泥的经济损失、人员伤亡呈现增长的趋势。

（二）突水突泥地质灾害的发生是有科学规律可循的

突水突泥的发生条件是含水构造的能量储存，含水的动力性能和能量释放以及围岩的稳定性，围岩不稳定了，含水就可以突破围岩到隧道里面。而且它的影响因素包括客观因素和客观的地质因素等等，这也是可以在科学上弄清楚的，因此，确定突水突泥地质灾害发生前的预兆，这类事故一般是可以预报预测的。

（1）突水突泥地质灾害的地质调查前兆特征

通过观测钻孔出水情况以及对开挖揭露的围岩变化情况进行预测。

（2）突水突泥地质灾害在地球物理勘探中的前兆特征

一是地下工程开挖的时候，包括地质雷达波通过地下水、含水溶洞及富水介质等含水体后，高频成分被吸收，反射强烈，雷达波遇含水层的反射波相位，相对于入射波，相位差180度。

（3）突水突泥地质灾害临突水前的前兆信息

应对突水突泥地质灾害的对策是什么？一个是实行超前的地质预报预警机制，是可以避免的。地质预报主要包括长距离、短距离预报，即长距离50米~200米超前预报和短距离50米以内的超前地质预报。宏观的超前地质预报方法包括红外探水、瞬变电磁、超前钻探等。根据超前预报结果制定一些预警措施。

（三）应对突水突泥地质灾害的对策

首先，评估有没有重大的风险；其次，要把整个工程根据调查的情况进行风险等级评价并发布。不同风险等级采取不同的预报方案，风险等级比较低的工程项目不可能也实施很严格的地质方案，这样成本太大，工期太慢。在这方面介绍山东大学在突水突泥预报预警工程上的成功经验，他们成功率已经达到90%。当然这是少数单位，还没有全面地形成制度，但是这个成绩给了我们很大的鼓舞。

四、岩爆地质灾害的挑战和对策

(一)岩爆地质灾害对地下工程建设安全的挑战

由于我们矿井埋深不断增加,岩爆的风险也不断地增加。图 12 为 1980 年以来岩爆呈指数的规律增长。金属矿的开采更深,所以岩爆灾害更为突出。

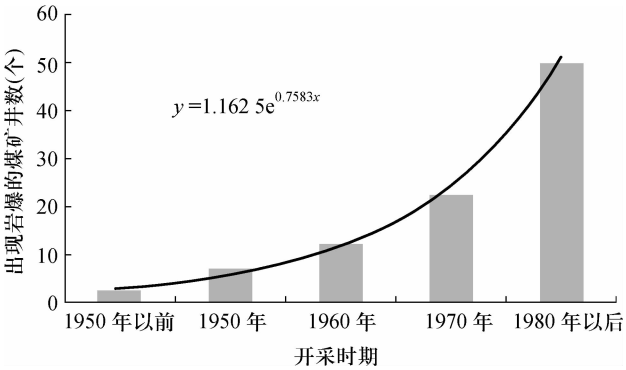


图 12　出现岩爆的煤矿井的数量

表 3 为我国发生岩爆的隧洞汇总,随着地下工程埋深增加,岩爆灾害发生的频次和等级明显增高,呈现岩爆等级向中级和强烈等级明显增加的趋势。

表 3　我国发生岩爆矿区及隧洞工程汇总(不完全统计)

工程名称	竣工年份	最大埋深(m)	岩爆等级及比例(%)			岩爆次数(次)	岩爆段长度(m)	备注
			轻微	中等	强烈及极强			
成昆铁路关村坝隧道	1966	1650	为主	少量	无			零星岩爆
二滩水电站左岸导流洞	1993	200	为主	少量	无		315	工程区位于深切河谷卸荷集中区域,最大主应力为 26 MPa,方位角 N34°E,倾角 23°,因而以水平应力为主
岷江太平驿水电站引水隧洞	1993	600	为主	少量	少量	>400		
天生桥二级水电站引水隧洞	1996	800	70	29. 5	0. 5	30		比例依据岩爆次数统计

续表

工程名称	竣工年份	最大埋深（m）	岩爆等级及比例（%）			岩爆次数（次）	岩爆段长度(m)	备注
			轻微	中等	强烈及极强			
秦岭铁路隧道	1998	1615	59.3	34.3	6.4		1894	比例依据岩爆段长度统计
川藏公路二郎山隧道	2001	760	为主	少量	无	＞200	1252	
重庆通渝隧道	2002	1050	91	7.8	1.2		655	比例依据岩爆段长度统计
重庆陆家岭隧道	2004	600	55.8	39.7	4.5	93		比例依据岩爆次数统计
瀑布沟水电站进厂交通洞	2005	420				183		工程区位于深切河谷卸荷高应力集中区内，地应力方向沿着河谷边坡向与隧洞呈大角度相交
秦岭终南山特长公路隧道	2007	1600	61.7	25.6	12.7		2664	比例依据岩爆段长度统计
锦屏二级水电站引水隧洞	2011	2525	44.9	46.3	8.8	＞750		比例依据岩爆次数统计出现数次极强岩爆
江边电站引水隧洞	2012	1678	46.4	50.4	3.2	＞300		比例依据岩爆次数统计

锦屏二级水电站引水隧洞工程多次发生历史上罕见的极强岩爆。2010 年 11 月 28 日，锦屏电站引水隧洞发生了严重的岩爆（图 13），把出渣装载机都抛掉了，当时死了 7 人。

（二）岩爆是可以预测的

因为岩爆地质灾害发生的主要机理目前已大致清晰，因此我们可以对岩爆进行安全风险分析意义上的预测，当然这个还在不断的研究过程中。也有专家认为岩爆预测预报是不可能的，只能预警．但是我的观点是，根据理论和实践，岩爆的预测预报在我国是可以进行的，虽然结果不是很准确，但如果岩爆没有预测预报，那么岩爆预警是盲目的，而且也是事倍功半的。

（1）为了要讲一下预测预报，我们把岩爆的定义和分类简单说一说。将岩爆定义为高地应力地区由于地下工程开挖卸荷引起的围岩弹射性破裂的现象。分

(a) 岩爆概况示意图　(b) 岩爆导致锚杆脱落

(c) 岩爆导致的爆坑　(d) 岩爆推翻的出渣装载车

(e) 技术人员察看事故现场　(f) 台阶底板的巨大裂缝

图 13　锦屏二级水电站岩爆现场

为应变型岩爆、地质构造型岩爆以及应变与构造杂交型岩爆。这样的定义和分类有利于我们进行预警预报预测。

（2）预测的原理是什么？应变型的岩爆，由于岩石存在着微缺陷、微裂纹，由于工程开挖，高地应力卸荷，工程所在地区的初始高地应力开挖卸荷所引起的。我们可以从应力曲线分析（图 14）。

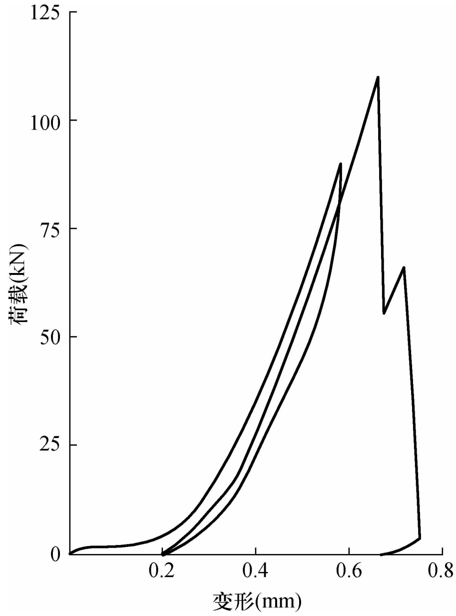


图 14　粉砂岩的峰值前加载曲线和荷载变形全图

如果岩爆要进行预测,需要有四个条件:一是对工程围岩岩石的加卸载过程的全应力曲线。二是计算出高地应力地区洞室开挖卸荷应力重分布后,非连续非协调变形岩体中的应力(应变)场,这种理论在计算中是可以实现的。三是计算出相应峰值强度前塑性变形能的微缺陷扩展以及次生裂纹稳定扩展所消耗的能量,所以,与无宏观裂隙的围岩相比,含单条裂隙的围岩洞室更加明显。

在工程设计里,发现结构面对岩爆有重大的影响。我们初步计算发现,如果结构面存在应力集中区,就会存在岩爆发生的可能性;如果在集中区以外,影响就不是很大。

(三)岩爆的监测预报在理论上是可行的

岩爆的宏观破裂是由大量的微破裂产生的,微破裂的集群导致失稳破裂,这是岩爆的前兆。因此,这些微破裂可以被微震监测器所接收。我们把破裂的规律掌握了,这就是岩爆监测预报的可行性理论基础,这个监测系统应具有自动化、信息化、智能化和远程化的特点。因为在锦屏发生了严重的岩爆,中科院岩土所和大连理工大学分别研究了一个案例,成功率均在85%以上,证明岩爆预报是可行的。

(四)综合以上的岩爆预测,提出应对岩爆地质灾害的下列对策

(1)在高地应力地区建设重大地下工程时,必须在原位实测和反演分析的基础上,掌握该地区初始地应力的分布资料,同时要掌握全过程的应力应变曲线。

(2)进行工程开挖前结构面的超前地质预报。

（3）进行岩爆的数值研究分析。

（4）选择有经验的科研队伍，进行连续有效的微震监测，保证监测的连续有效。

（5）在地震预报的结构面信息、微震监测信息、岩爆预测数据的基础上，提出岩爆监测风险预报报告。

（6）根据锦屏工程的经验，不能只有预报，一定要在预报的基础上建立会商制度，要有领导和专家参加的岩爆风险预报报告的会商制度。我们当时建议每天、每三天进行会商，根据岩爆等级提出风险等级的防护措施以及施工调整方案，包括增设超前钻孔爆破的应力释放孔以及若干的措施。所以，在增设岩爆的预报预警制度以后，锦屏没有发生岩爆的伤亡事故。

钱七虎，1937年出生，江苏昆山人，中国工程院院士，解放军理工大学教授、博士生导师，技术一级、文职特级。总参科技委常委，总装科技委顾问，军委空军、海军、军委二炮科技顾问，国际岩石力学学会原副主席，全国政协八、九、十届委员，现任国际城市地下空间联合研究中心亚洲区主任，中国岩石力学与工程学会理事长，中国土木工程学会防护工程分会理事长。担任江西东华理工大学名誉校长、山东科技大学土木工程学院名誉院长；《地下空间与工程学报》、《防护工程》、英文版《岩石力学与工程学报》等学报的主编。

长期致力于防护工程、地下工程的教学与科研工作，在防护工程计算理论及防护系统工程理论方面有突出成就；1992年曾主持实施了世界最大药量的珠海炮台山大爆破；主持和参加了国内多条地铁工程、城市水下隧道和海底隧道等重大工程的设计方案审查工作和评标工作，作为专家委员会主任和委员协助完成了南京长江隧道、上海长江隧道和武汉长江隧道建设；在深部岩石力学及深地下防护工程的关键技术以及地下空间开发利用方面进行了开拓性的研究，研究成果获国家科技进步一等奖。

主持完成了《21世纪中国城市地下空间发展战略及对策》、《我国重要经济目标防护措施及对策》等多项国家咨询课题；编写了《高等防护结构计算理论》、《岩土中的冲击爆炸效应》等15本著作；发表了学术论文300多篇，10项科技成果获得国家和军队科技进步奖励。

满足地下岩石工程安全的设计方法

John A. Hudson

英国帝国学院

非常高兴能有这样一个机会参加此次论坛,刚才钱七虎教授讲了关于地下工程出现的问题的原因,在这个基础上我再提供一些背景资料,因为今天和明天的讲座都要遇到这些问题。钱七虎教授提出了两个问题,岩土的参数,提出了一些条件。另外我还想讲一下所谓的集体记忆这样一个机制,最后我会讲所谓的集体记忆,就是所有的到目前为止收集起来各式各样的资料,这是一个集体的记忆,也是一个数据库。

要预测这个施工最终的目标是非常关键的,如果不这么去做就不行,如果我们要把一个隧洞挖在一定的深度有一定的方向会发生什么问题呢?应该是朝着这个方向还是应该朝着那个方向呢?所以我们需要有一个选择,我们应该知道后果会如何?

首先要考虑到安全生产和灾难的控制调控,所以要考虑到各式各样所谓的条件,有所有的正常条件就没有什么问题了。但是我们主要关心的特殊条件,有的特殊条件可能是高的、可能是低的、可能是有风险的,像锦屏那样的。但是有各式各样的特殊条件,像熔岩的具体问题,这里面有环境上不太好的情况,也有可能有断层、裂缝,非常严重,也有可能有很大的断裂层,也有可能有应力,还有可能有碎石,中间这一条也有可能出现混合的土岩,要离地面不太远的地方进行钻孔,如果是一半一半,上面是土,下面是石头,这样去钻孔是很困难的。

另外一个问题是水压高或者是水流很急、温度高,比如说废放射性燃料的存储可能会释放出大量的温度,温度很高。也有可能是温度很低,有些国家的温度很低,比方说在韩国有一些岩洞主要是放食品,想用低温来储藏一些食品就会出现这个问题。温度太低,岩石会发生什么样的变化?可能会有不利的化学条件,比如:甲烷比较多;在已有的建筑附近开挖,比方在伦敦,在议会大楼附近的主要建筑物下面开挖隧道,就要非常的小心。有的时候,我们项目的目标是比较不寻

常的，比方说处理放射性的废料，因为这里是高危险的材料，放到土和地里面就不能发生任何的事情。但是，民用工程、火车隧道，移开岩石，这里面不会有什么后果。但是，如果是废燃料和放射性燃料可能会有很严重的后果。地质条件也是非常非常复杂的，当然我这里列出很多东西不完整，但是已经列出了一些，可能这些东西会给我们造成很多的不利条件，并且会引起各种各样的困难和事故。

比如说英国和法国之间的大隧道开凿开挖的时候，有非常大的灾害可能性，这里是在海底进行的，我们的钻孔机到底能不能钻，因为这个地质是白灰石，这个是很柔软的，但是有时候又有碎石，碎石很硬，白灰石里面有很多的小石头可能会把钻孔机器弄坏了，最关键的是海水会不会从隧道上边流到隧道里面去，这是非常糟糕的。有的时候别的地方的水是从隧道里流过去的，但是这里是无限的水，如果有缝隙的话，会通过白灰石渗到隧道里面去。但是，我很高兴地说，这个项目还是完成得非常的成功。有的人可能也坐过这个海底隧道火车，遗憾的是什么都看不见，因为是漆黑一团的。

煤炭的矿山开矿有很多的事故，岩石内部的结构无法展示出来，如果这些岩层是断层，那么开矿就没有什么问题。有的时候地质条件可能比较复杂就会造成这些问题，就是离地面不远处看到这些断裂，斜着下来，由于是地摩擦力的，我们从事这种岩体力学有一点非常重要的是对地质有一定的了解，或者是要请一些地质方面的专家跟我们共同开展工作，应该和他们保持密切的联系。在很多我从事的项目过程中这个是非常关键的，要了解地质条件。给大家举几个例子，尤其是讲应力的问题，我在芬兰从事的一个项目，放射性废料的处置，所以在地下要挖很多很多隧洞，算起来有好几公里的隧洞，准备把这些废料处理在这些隧洞里面，这里有些井，有一个螺旋楼梯，下面的隧道深 420 米。在设计的过程中，为确保不发生任何事故，任何结构方面的事故，我们必须很好地去了解周围岩体的应力和地质，尤其是断缝情况。

考虑到这些有可能危害我们的建设的特殊条件，我们也是看客观方面的因素。还有很多很多特殊的情况，当然这个图可以画得更大，可以加上更多的。考虑一下我们具体项目具体情况的要求，比如说放射性燃料，也就是要挖很多的隧道来处置这些放射性燃料。我们这个项目是有这么一个轮廓，如果可以画出这种图，我们就可以更好地关注我们应该研究的课题。但是问题马上就出现了，我们要改变设计，到底有多少灵活性呢？普通工程、矿工工程、石油工程是不一样的，因为民用工程主要是想创造地下的空间，形状主要是靠工程的功能，比如说火车从一个地方跑到一个地方，需要把水从一个地方引到另外一个地方去，而我们隧道的方向和处置基本上已经定下来了。所以，我们在设计方面没有多少灵活性，

没有多少的余地。但是矿山工程是要开采矿石,这里面有很多不同的方法,这么一来我们的设计途径、设计方法也可以很多。石油方面的工程目标就是传输石油,所以我们要有钻孔,钻孔的方向可以有很多不同方法,钻孔机本身很有限,但是,变动性很大。但是,我们知道最大的两个困难是岩石的应力和岩缝隙。应力在不同的范畴,比如说在地球的范畴是地球板块,板块的移动也会造成一些地球的应力,但是我们可能在项目周围就地来做,在锦屏项目中所出现的碎石是在隧道范围内,但是我们在测试这些应力的时候,就需要把这个机制应用到钻孔里,在钻孔这个范畴内进行测试。可能要在钻孔壁上增加一些涂层,这个就是微观的应力,这个是从唐教授那里取出来的图案,通过应力可以看到岩石是怎么碎裂的,所以我们的应力可以分不同的范畴。

回头来看放射性废料的时候,首先一定要了解应力,所以要造一些模型,我们就用这个测试方案来造模型。问题是在岩体中有大量巨大的断层裂缝,这些裂缝就会影响到应力,所以我们不能说听天由命吧,我们必须要做一些模型来看看应力会造成什么样的后果。岩石应力一般是往这个方向来走,这些裂缝都是脆性的,在裂缝的地方应力的强度变化很大,到这个地方来挖,你也不知道到底是高应力还是低应力。所以各种应力的情况很不一样,各处的地方不一样。如果不很好地去了解这些应力,从而来计算一下应力的强度,问题可能出现在这里,也有可能出现在那里。当测量这些应力的时候有一组是量出应力,这个是应力。另外一个小组到另外一个地方去测量,就会说应力的数据不一样,然后就开始辩论哪个方法是最好的。实际上跟方法没有关系,一点都不奇怪,应力在不同的地方测量,答案就不一样,这个也没有什么奇怪。我们的目标是要很好地了解这些应力的分布情况。如果再深一点,刚才这个是 150 米,现在如果到 420 米,存储地是 420 米深,发现应力比较均衡了,为什么呢?这是因为裂缝已经由于这些应力压到一起了,所以没有起到那么大的作用。

我希望所有的项目,凡是应力很重要的时候,应该进行这种模拟,因为包括了自然的应力、自然的裂缝。但是,这里就需要一个专业精通的地质学家来告诉我们,到底在这个模型里应该放上什么东西。这个应力可以受到很多因素的影响,比方说岩体的不均匀,可能是非均质现象,尤其是受到裂缝的影响,工程师做什么呢?他们在建立一个自由面,马上就改变了这个应力的作用。如果这个是我们的开挖壁,这个自由面就没有什么应力了,那么这个就是一个主要的应力平面。在进行开挖的时候就肯定改变了原来的应力。所以这个就改变了应力,变成了 1 或者 2,这里还有一个 0、Σ,我们必须模拟模型开挖发生了什么样的变化,这个裂缝怎么样影响岩体的应力?在裂缝的里面实际上没有传过去,一般都是 0,当然要

看裂缝有多大,这个本身可能就会造成大的应力,也可能会看到碎石的破坏。

我刚才讲了地质学是非常重要的,再过两周在瑞典有一个很重要的会议,我安排了一个专题讨论,特别是把结构地质资料放到我们的地质岩体研究当中。我们作为工程师,不能说我是工程师,我不管地质,不能这样。我觉得所有地下开挖的人应该尽量多地了解地质方面的知识,如果我们要到一个地方去,一定要把地质学家带过去,不要回来还对地质情况很糊涂。实际上,裂缝的地质学基础也不是非常艰深的,要么是一个没有变形的完整岩体,或者像第二个在这里,由于开口造成的裂缝,再后面是一个裂缝,这里面有一些脆性的剪切,这些都是由于时间所造成的,还有一些易变形的剪切,还有一些岩体的变形。看到横线就可以考虑到岩体是怎么会变成这样的。最后对特性我们应该很好地考虑一下。如果这个岩体没有什么破坏,当然是显而易见的。当然这边如果全是岩体,岩体也都是有一种情况,那也比较直截了当。但是中间这里就比较麻烦了,特性就不一定是这么明确的,这里就需要一个地质学家来帮助我们。我每次到一个地方去做咨询,我都是带着一个地质学家跟着我一起去考察这个地点。岩体缝裂有很多的特性,这个是很多年前画出来的图,但是实际上要来确定应力就需要六个数据三个原则,有横向的、还有纵向的。一般就可以计算出应力,但是如果要看一个断缝情况就不一样了,这个就比较复杂了,这里面有很多的参数,这个是 Q 系统,但主要要集中于对我们至关重要的项目,不可能所有的都进行测试,有的是无法去测试的,这个图像有的是可以在地表测的,但是用钻孔就没有办法测试了。

这个岩石要做模型怎么做呢? 怎么样把这些裂缝放到我们的模型中去呢? 不能就简简单单的拍个照然后就弄个模型,因为这个是三维的。还有一个比较大的问题,这些不是随意断裂的,这些是由应力而造成的,所以是有一定的规律,我们也不知道到底哪一个是先裂,哪一个是后裂的。乍一看是看不清楚的,如果了解一下后,是可以的。我们应该按照它们形成裂缝的顺序放到我们的模型中去,我们根据它们的地质时间来列到我们的模型中。这里就看出了形成裂缝的顺序,主要是看结尾的终点,这个裂缝是一直串到头,第二个到第三个就停了,第四个到第三个就停了,如果要想裂缝的模型准确,不能随随便便地扔进一大堆的数据输到电脑里面,我们应该把这些终点选好。开发我们的软件有很多很多工作要做,但是这个是非常重要的,只有这样我们才能很好地了解应力和断裂的影响。

现在我们利用电脑又做了很多的事情,从一个现场的情况可以到虚拟的模型,用一个虚拟的空间来模拟隧道。这里有许多因素,有 GTHMCBE 因素,地质特性、水测试、力测试、化学测试、生物测试、工程测试,这些因素都要考虑进去。不同的地方有不同的模拟,应该说这些模拟不是综合的,每一个不同的人在处理一

个项目的时候有他自己的模型，我们希望可以有一个大家综合起来的，把所有的这些方面都加到里面去，电脑的模型是真正代表着实际情况的。要测试这个，我们需要地下实验室，这样就可以做一个虚拟的地下研究和真正的情况进行比较。遗憾的是菲赫斯教授（Fairhurst）没能出席，明天我会帮他介绍。

在国际岩体力学的学会里面有一个小组，专门开展岩体工程和设计方法研究。我们和另外一位教授共同出版了一本书，在今后三年我们还准备把风险写到里面去。这次的会议对我们来说很重要，因为我们知道应该把什么样的内容放到里面去。我认为一个很关键的问题就是发展一种系统，可以把资料拿到手。如果没有这个信息、没有这个资料我们就没有办法去进行设计和评价它的风险，所以首先需要信息资料。目前我们的这些信息实际上不是连贯性的，换句话说，你不能很快地就可以调出你想要的东西。我们需要一个岩体力学学会水平的存储系统，这样可以把整个行业里的各种方法整合起来，而目前，没有这样一个系统。

网上现在有大量的资料，你想看到的东西，很多都可以查得到。在不到一秒钟，你可以找到你要的信息，简直是奇迹，但仍存在一个问题。在 Science Direct 输入“岩石开挖”这样的关键词，一下子就可以出来很多的报告，收集起来以后要总结和概括，这个是很花费时间的。如果两个不同的人开展同样的工作，可能得出的结论是不一样的，所以我们需要一个行业协会。我们一边需要岩石性能的资料，同时需要模型的案例，同时还要有实践的应验。我们的大脑是非常了不起的，好像也不需要多少的能量，早上吃一点早饭就可以开工了。瑞士有一种软件对人的大脑进行模拟，不知道会不会成功，反正是要造一个模型。这个好像离我们太遥远了。问题在于如果你设计一个电脑的项目，你有一个三维，但是它不会回想起我们大脑所记的东西，它所记的东西跟我们所记的东西不一样。我们现在需要各种各样的模型经验，需要一些施工模型的案例。在模型方面我们有一般性的模型，不一定是具体的专题，但是我们需要专题的模型，同时我们还需要大量的建设案例。有的时候这种建设案例由于法律的问题你拿不到数据，公司不愿意把资料发放出去，尤其是出现事故的时候就不要告诉你，但是至少我们应该可以拿到最理想的设计案例和建设案例。

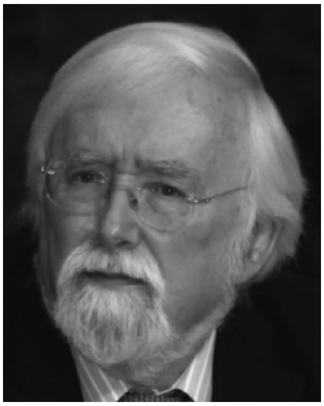
拿到这些六个主题的数据之后怎么办呢？我们需要一种连贯处理的方法，一种组织资料的方法，这样就可以很快地查询和获取。但是没有案例还有模拟的解决方案，还有设计的案例，以及建设的案例，尤其是牵涉一些风险或者灾难的情况。不像因特网，你可以查询资料，而这些资料是零零碎碎的，可以去查询了，马上就可以把资料调出来；但是我们的资料是零零碎碎的，我们应该有这样一个系统，至少你提出问题，得出答案，帮助你设计。这就是所要求的行业存储要换成行

业的记忆要花很长的时间,但是头两条是很重要的。钱教授刚才让我讲一下岩体的特性,我觉得现在很多人都在开展这方面的工作了,但是这种模拟的模型解决方案,还有设计案例、生产范例好像还没有,前面这些东西已经有了,后面的没有,我们的岩体力学国际协会准备想开展这方面的工作。

现在举一个例子,这是我从事的一个隧道的项目。有些事情是没法预测的,在钻孔的时候主要是考虑到可能会遇到一些没有预想到的事情,这个就发生了,是在英国,第二层是沙子,下头是砂石作为基石,因为上头是沙子,所以我们用一个软底的凿孔的机器,因为是沙子,所以很可能掉到前头,在机器的前方,后来就用一个方式进行挖孔,定下头是用泥压着沙子,让它不要掉下来妨碍机器,问题是前面是看不见的,机器在那里凿,一切非常好,好像挺快的,但是突然之间就遇见了花岗岩,怎么回事呢?是因为这里原来是一个很古老的地面,在某个冰期的时候,有冰川掩盖,冰层往下走把花岗岩带过来,冰川融化时,把花岗岩的石头留在那里,原来是在地面,后来在后面一个地质时期,沙子又沉淀下去,谁都不知道沙子下面有花岗岩,我们的机器就遇到了花岗岩,不知道是怎么回事,把机器也砸坏了,到底有多少花岗岩?我们都不知道,所以说我们真是无法预测。但是如果我们可以从这个行业的数据库里,有各种各样的建设案例,这些数据可能在数据库里面,而不是当我们需要的时候,藏在某一个报告中找不出来,可以通过系统把信息调出来,我们也可以有所预感。所以如果我们有行业的数据库,可以大大减少我们的风险,而且帮助我们的地下建设项目。

有人说电脑越来越聪明就不需要人了,我们大家都认为还是需要人。所以我想总结一下什么叫知识,什么叫智慧。尽管这个系统会给我们大量的知识、信息和数据,但是我们还是需要人做出判断,而且有足够的智慧、能力来判断和决定应该做什么样的建设,所以我们还需要人的因素,还需要人的大脑,我看至少还要100 年,需要人的大脑。

18 世纪英国有一个诗人特别强调知识和智慧之间的区别,那个诗词是用比较古老的英文写出来的,现在把它翻译成中文,就是知识和智慧是有区别的,知识本身是不能协调的,在变成智慧之前知识是需要组织的。我们没有知识,我们就没有智慧。



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有限元极限分析法在隧道稳定分析和设计中应用

郑颖人

解放军后勤工程学院

今天我要向大家讲的题目是《有限元极限分析法在隧道稳定分析和设计中应用》,从这个题目一看就知道是两个方法结合起来的,一个是有限元,第二个是极限分析法。

极限分析法已经用了一百多年,它是研究材料从塑性到破坏过程中的方法,可以求岩土工程的安全系数,在实际工程设计中非常有用,所以被广泛的采用。但是这个方法也有一个缺点,适用性不广泛,复杂的问题不能用,只能求解简单的问题。像隧道这样复杂的问题是不能用传统的方法去算安全系数的。

第二个方法是大家比较熟悉的近代的有限元数值分析法,这类方法的优点是适用面很广,各种复杂问题都可以求解,但是它唯独无法求解安全系数,如果不能计算安全系数,工程上就难以应用。如果把这两个方法结合起来取它们两者之间的优点,一个是适用性很广,什么都可以用,另外一个是可以求安全系数,直接用于工程设计,这样有限元极限分析法就应运而生。

现在我们来解释一下有限元极限分析法的原理是什么。这个原理是和传统极限分析方法本质上是一样的,没有什么不同,只是它的手段不一样。传统的方法要先知道破坏面并通过计算得到安全系数;而它可以通过数值分析手段求出来,用计算机和软件求得安全系数。

传统的方法(极限分析法)以一个滑坡或边坡为例,安全系数就是抗滑力/下滑力,如果这个滑动面事前就知道,那么可以在破坏面上求出它由于重量引起的下滑力;分子上面的是抗滑力,因为岩土有强度。如果岩土的强度很高,抗滑力比下滑力大,肯定就不会滑下来;如果抗滑力和下滑力相等就是破坏状态;安全系数小于 1 就会出现滑坡。

现在讲有限元极限分析法如何来求安全系数。1975 年英国的力学家辛克维

奇提出了一种叫有限元强度折减法,这是有限元极限分析法中的一种主要方法,这种方法非常有用。安全系数公式上面是抗滑力,下面是下滑力,只要把抗滑力不断的降低直到与下滑力相同,这时候岩土就破坏了。所以这个手段很好,计算机会自动显示出破坏状态。从稳定时的强度降低到破坏强度,这一强度折减系数就是安全系数。这个安全系数是与传统极限分析法的安全系数完全一样。到了破坏的时候,计算机会自动的形成破坏面,传统方法一定是要找到破坏面后才能算出安全系数,但是实际上复杂的问题都很难找到。现在这个方法是自动生成的,不要你去找就自然生成了,并会显示岩土整体破坏的信息,由此就可求出极限荷载或稳定安全系数。从实际情况到破坏情况,岩土体强度降低的倍数或者载荷增大的倍数就是岩土工程的稳定安全系数。前者称为有限元强度折减法,后者称为超载法,它们都是有限元极限分析法之一。现在我们又做了进一步的工作,不仅可以求安全系数,还可以求出破坏面的形态,这个破坏面出现在哪里?什么样的形态都可以求出来。

先看看传统的破坏机理,我们知道隧洞有深埋和浅埋,深埋的时候采用的是普氏压力拱理论,这个理论在国内是广泛应用的,它认为地下工程里面会形成一个拱,结构是承受拱下岩土的重量。第二种是浅埋,如果地下工程上面的埋深很小,岩土的坍塌一定会延伸到地面,这个理论比较著名的就是太沙基理论。

再来看现代的隧道破坏机理,现代的理论比早期的普氏压力拱理论和太沙基理论有很大不同,如拉布希维兹破坏理论,他提出了一个观点,即隧道上的压力不是从隧道顶上掉下来的岩土,而是隧道两侧挤进来的岩土,把里面的衬体剪断。他是根据实际工程的观测得到的。在我国这种理论很少被采用。这种理论以前只能做试验验证,不能计算,现在有了新方法我们就可以计算了。传统的方法无法求安全系数,现在我们用有限元极限分析法,用数值的方法来算,计算机只要算到破坏的时候就可以了,不仅能算出安全系数,还能找出破坏面。这里面最核心的就是破坏面,但目前国际上的通用软件都无法直接找出这一破坏面。

有限元极限分析法能不能用到隧洞计算中,不像边坡滑坡可以通过传统极限平衡法来验证,必须要做一个模拟试验,如果试验与计算是一样的,就可以证明这一方法可行。我们用水泥、沙子和滑石粉作试验材料,模型尺寸一般是 50 cm 左右,模型中开挖跨度 8 cm 左右的隧道,做了五组试验,挖了五个洞,跨度一样,但拱高都不一样。我们对模型试验与数值模拟的结果进行了分析,计算机不是模拟实际工程,而是模拟这个模型试验。我们用刚才的方法就可以把破坏面求出来、安全系数求出来。下面对比试验与计算的结果,做模型试验的时候,达到多大荷载会产生破坏,计算机模拟达到多大荷载会产生破坏。除了看加到多少荷载时隧

道发生破坏外,还要看计算出来的破坏面和实际模型的破坏面是否一样?已经看到破坏面的位置与形态是一样的,还要看破坏范围的大小是不是一样,从洞边到破坏面的最大距离,做试验的时候可以量出来,计算机可以算出来,两者的结果是不是一样,如果一样,就证明这一方法是可行的。

图上记下的是模拟试验与数值模拟的结果,可以看到两者是相近的。其中第四组方案得到的极限荷载两者差异比较小,模拟试验是61 kN,计算机做出来的就是60 kN,总体来讲它们基本是一样。再看隧道左右侧破坏面的最大水平距离是不是一样,试验得到的是13.4 cm,用计算机算出来的是13.1 cm,基本上两者也是一样。五组试验基本上都相近,这就说明刚才采用有限元极限分析法,可以用到隧道上,其计算结果跟模拟试验是一样的。

再看如何确定破坏面,目前国外的技术做不出来,我们可以做出来,道理很简单,隧道破坏面里面的岩土要破坏,有很大的位移,而外面的岩土没有破坏,位移不大,所以破坏面上位移或应变要发生突变,把突变的地方找出来连成一条线就是破坏面。我们在这上面画了五个水平截面,每个截面上的应变大小计算机都可以算出来,看第一条应变线,最大的应变点在隧道边上,就是在洞边;第二条应变线上有一个凸起的地方,它就是极大值,这个点肯定不在洞边,而是距洞边有一定距离的地方;第三条就是破坏面中间这条线,距洞边最远,把五个面上的应变最大点都连起来形成一个面,这就是我们要求的破裂面,它跟模拟试验的破裂面是一样的。

均质隧洞的破坏状态,只有等到塑性应变发展,塑性应变逐渐连成了一条线才可能发生破坏。动画中看到,应变从隧道下面墙角开始向上发展,另一方面从墙顶向下发展,最后连成一条线,实际上塑性区连通的时候还没有破坏,真正到破坏的时候还要过一会儿,因为破坏还要应变达到一定的值,图上颜色越深表示是应变越大。可见对深埋隧洞来讲,它的破坏范围不在拱顶,而在两侧。如果对这个理论还不相信,那么我们再看一个实际的工程,跨度13 m的黄土隧洞,现场实际测试了5根锚杆的拉力,按照以前的理论来说,拱顶锚杆受力最大,而测试结果两侧锚杆的拉力要比拱顶锚杆拉力大9倍,这表明隧道受力主要是在两侧。现在有些工程人员在实际工作中都已经这样做了,在某些情况下适当减少拱顶的锚杆。从收敛位移看,隧道垂直方向的收敛位移小,只有9.8 mm,而两侧有19 mm,也说明了两侧是主要受力部位。上面讲的是深埋隧洞,再讲浅埋隧洞,模型试验上面覆盖层厚度为3 cm。同样我们用计算机数值模拟,从图上看出两者的破坏部位与形态是一样的。试验中加荷达到28 kN,发生破坏;计算机加荷到26 kN发生破坏,所以基本相近。

再看节理隧洞的破坏机制。裂缝的倾角是45度,裂缝的强度比岩石低8倍。由动画可见,此时在拱角的地方最容易塌方。说明这种方法确实可以解决隧道究竟是如何破坏的问题。我们认为随埋深不同,隧道破坏机理也不同,如果埋深比较浅,洞顶上的土体一定要塌到地面,现在看这个矩形的洞室,埋深到了9 m时,上面就形成一个完整的拱,这个拱保证土体不会塌到地面,这个拱的形成是与埋深有关的,我们把它叫做浅埋压力拱。10 m以后的情况就不同了,上面的拱虽说还有,但是颜色变浅,比较深的颜色是新形成的压力拱。这个拱就是我们以前通常所说的普氏压力拱,叫做深埋压力拱。虽然不会坍塌到地面,但矩形洞室上面普氏压力拱下面的土体会坍塌。这也就是为什么我们要把隧道做成拱顶的道理。随着埋深增加,深埋压力拱形成,当埋深18 m,隧洞顶上有拱形,两侧也出现塑性拱;到了18 m以后,两侧的塑性应变更大,破坏首先出现在两侧;到埋深30、50 m的时候更明显,而且安全系数逐渐降低;可见破坏与埋深有关。

总之,矩形洞室的破坏机理是:埋深0~9 m是浅埋压力拱破坏阶段,10~18 m是深埋压力拱破坏阶段,18 m以后是两侧破坏阶段。

拱形隧道也是一样,只是分两个破坏阶段。第一个阶段是9 m以前,到9 m就没有普氏压力拱,直接形成两侧破坏阶段。为什么大家感觉都是洞顶上塌下来,因为真正破坏的时候首先是两侧破坏,造成拱脚失稳,最终导致洞顶土体大规模坍塌,这就出现了所谓片帮冒顶的大事故。

以前的隧洞不能计算安全系数,对围岩稳定没有一个定量要求,现在可以求安全系数,也就可以有定量的指标。已经知道,按松散压力与荷载-结构法计算不符合实际受力情况,衬砌主要是承受变形压力,国内70年代起就叫形变压力。数值方法可以计算压力,但不能确定什么时候隧洞破坏,因为没有安全系数,所以设计的时候要用一些经验法,一种是看塑性区大小,另一种是看周边位移大小,然后按人们的经验来确定塑性区或洞周位移多大时就发生破坏,这两种经验方法现在经常应用,但它们没有严格的力学依据,而且还会受到各种因素的影响,很难算准。如用洞周位移判定的方法,弹性模量对位移影响很大,而岩石的弹性模量可以测试,岩体的弹性模量没有办法测试。看表中变形模量是20兆帕,洞周位移就是9.4 mm,如果是60兆帕,洞周位移是3.6 mm,模量增加3倍,位移也是减少3倍,对计算结果影响很大。如果采用安全系数作为隧洞围岩稳定指标,从表中看出,不管模量是多少,安全系数都是一样的值,它不受变形模量的影响,因而可以准确确定安全系数。

总的来讲,采用安全系数作为隧洞围岩稳定指标有如下几个好处:

1. 计算有严格的力学依据。

2. 稳定有统一的标准。

3. 不受岩体变形参数的影响。

下面以老百姓住的黄土窑洞为例,洞跨 3 m,有了新方法,我们可以知道安全系数,如果用 ANSYS 程序来计算,算出来老黄土中的窑洞安全系数是 1.69,如果用 FLAC 算出来的安全系数是 1.71,两种软件算出来的基本一样,误差只有 1%。安全系数都在 1.5 以上,表明老黄土中的窑洞是安全的,人们可以安心睡觉。

认识了隧洞破坏机理,提出了计算理论,就可以进行设计,我们提出如下五点设计理念:

理念一:计算模型一定要考虑到岩土与结构的共同作用,这种模型才符合实际情况。

理念二:按照新奥法观点,围岩也是承载体,应充分发挥围岩自承作用,也就是说对隧洞要采用极限设计。在设计的时候要使隧洞周边的围岩有一定的位移,只要在破坏范围以内,位移越大,越能发挥围岩的自承作用。当然塑性不能太大,如果塑性太大了,就会发生破坏。

理念三:按照新奥法观点和根据实际的工程情况,我们认为不仅围岩进入塑性,而且初衬也会进入塑性。从实际的工程中看到,初衬变形是相当大的,即使初衬做好了以后,还要留出 10 cm 让初衬继续变形。有的时候初衬还会出现一些细微裂缝,说明初衬已经进入塑性,当前按弹性设计是不符合实际的。初衬一定要控制得好,既要有一定的强度,不让它破坏,同时又要有一定的柔性和塑性,让它可以承受更大的变形,充分发挥衬砌与围岩的自承能力。这也对初衬的材料提出新的要求,既要有足够高的强度,又要求较低的弹性模量。

理念四:初衬应当承受围岩的主要荷载,确保工程施工的安全,而二衬作为安全储备或承受少量的荷载,二衬可以按弹性计算。按当前的理念,初衬只承受少量荷载,有的甚至作为临时支护,不能确保施工的安全。当前隧道的风险都是在施工时段。以前建的隧洞跨度小,单线隧洞跨度是 5 m,现在三线隧洞跨度 17 m,在软弱松散地层中修建,就会造成很大的风险。以往初衬只有 20 几厘米,最多 30 cm,现在就不够了。前两天在青岛地铁开会,有人提出了这样的问题,初衬的厚度够不够、强度够不够,要不要采用双初衬,初衬强了才能确保工程安全。因而建议应对初衬后的围岩提出安全系数的要求,例如大于 1.15 ~1.2。

理论五;隧道设计计算要尽量科学,做到安全可靠、经济合理,这就需要计算方法正确,计算参数也要准确。计算方法可以采用提出来的有限元极限分析法。计算参数有多个:一是释放荷载量要准确,初衬之前一般认为释放 50%,二衬之前一般认为释放 90%,这样就能达到初衬承受主体荷载,而二衬承受少量荷载的

目的;二是岩土强度参数要准确,土体参数可以通过测试确定,而岩体强度是测不出来的,应当依据最新的围岩分级,将强度控制在一定的范围内,或者采用位移反分析法确定岩体参数;三是初衬混凝土进入塑性,因而需要各级标号的混凝土的强度参数,应通过大量测试,逐渐解决这一问题。

下面是一个黄土中的隧洞,高度为 9.8 m,跨度 11.6 m。初衬厚选用 30 cm,二衬厚 40 cm,初衬后围岩安全系数达到 1.38,满足施工要求。二衬只承受 10% 的荷载,按弹性杆件计算,二衬上的内力、弯矩和轴力都可由计算机直接求出。按钢筋混凝土规范可以得到杆件的安全系数。经计算都能满足要求。隧道二衬后,要求围岩安全系数达到 1.35 以上,二衬安全系数要求达到 1.4 以上,总安全系数大约在 1.9 左右。上述衬砌尺寸与目前实际采用的尺寸一致。

最后还要说一句,目前国内隧洞设计还存在一定混乱,各种规范都说按以往设计经验,采用工程类比法确定衬砌尺寸,但实际上各部门、各种规范采用的衬砌尺寸相差甚大。例如对Ⅲ级围岩跨度 10 ~ 15 m 的隧洞,按国标锚喷支护规范,采用的锚喷支护,衬砌总厚度 10 cm;而按公路与铁路隧洞设计规范,同样的情况下衬砌总厚度 43 cm,两者差距很大,表明设计还不成熟。殷切期望今后的隧洞设计,能做到理论和经验相匹配,切实做到科学合理。

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先后在军事地下工程、边坡工程、地下工程围岩力学、岩土塑性力学、岩土极限分析方法、区域性土等理论研究与应用领域取得了丰硕的成果,发表论文 400 余篇,其中论文《有限元强度折减法在土质与岩质边坡中的应用》被评为全国首届(2007 年)最有影响的百篇论文;《极限分析有限元法讲座—Ⅱ有限元强度折减法中边坡失稳的判据探讨》获 2009 年中国百篇最具影响国内学术论文;2009 年论文被引用数列全国作者排名第 12 位;2008、2009 年在全国力学学科排名第 1

位;2005、2006 年在全国建筑行业排名第 1 位。出版专著 12 部,《边坡与滑坡工程治理》专著 2008 年获全国三个一百原创科技图书奖,2011 年获中国政府出版奖提名奖。主编国标、军标 5 部。培养博士、硕士研究生百余名。

其研究成果先后获得国家科技进步二等奖、三等奖各 1 项,军队、部委级科技进步二等奖以上奖励 9 项,全国科学大会奖与国土资源部全国地质灾害防治科技进步特别贡献奖各 1 项。先后获总后勤部“一代名师”,“重庆直辖十年建设功臣”,“新中国成立 60 周年重庆杰出贡献英模”等荣誉称号。

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我跟大家介绍隧道挖掘方法这个方面的情况,我会尽量地讲得简单,我的翻译能够更多地参照幻灯片来翻译。关于怎么样在复杂长隧道风险控制方面联合应用 TBM 联合钻爆法,我很荣幸参与了一些项目,这些项目在刚开始的时候是错误的,有几个月的时间工期耽误掉了,因为只用了 TBM 法,TBM 的机器就被永久地埋到山体里。我想在座的各位很多都有类似的经验、经历,跟大家介绍几个极端的例子。

我想可能说起来极端,但是事实上大家都见过这样极端的例子,我的发言分成几个内容:首先有一个介绍;第二,关于 TBM 的反向逻辑;第三,我们知道对于 TBM 来说,有一个非常重要的减速法则,我想每一个人都知道,在 10 ~ 12 年前谈到这个的时候大家都不知道,但是现在大家知道了;第四,介绍什么造成 TBM 的延误,在断层区的挑战案例,会谈到台湾的案例的一些项目,还会跟大家谈到突水的问题。最后跟大家介绍在深部,有点跟地震相关,断层的速度会给我们造成什么样的假象。另外,是选择双护盾,还是开放式支撑 TBM,这是一个挑战。再其次,我们长久的挑战是什么,我们是使用 TBM 还是使用钻爆法? 接着,跟大家简单地介绍一下单钝的钻爆,我们把它称之为 NMT,它是根据 Q 系统来做出的一个钻爆方法。最后,做一个总结。

我会给大家读出少量的事实和假设。我们知道关于 TBM 的隧道,有很多的例子,最后都失败了,机器都被抛弃了,因为前期勘察的力量不够或者不充分。当然有一些不确定性,包括地质、水文地质的不确定性,还有地应力和岩石强度,深埋隧道和超深埋隧道都面临的问题,还有一些挑战是相对于钻爆法而言的,对 TBM 项目造成更大的影响,这时,我们选择联合应用,而不是使用其中的一个。

TBM 性能的急剧降低,我想很多人都已经看到了,也就是说掘进率和时间的

关系。我会跟大家讲一下，有的长隧道，TBM 机会挖得很快，但是有很多的长隧道用 TBM 会碰到一些问题，使用了新的 TBM 设计可能会减少或者延迟，采取连续的探钻或者预灌浆的方法，大家意识到可以通过新的 TBM 设计减少工期延误。关于钻爆法，它有很多的钻探孔，在每次掘进之前有很多的钻探孔，尤其在勘探的一些信息特别有限的时候，用钻爆法比 TBM 法更好一些，因为我认为：选择 TBM 仅仅是因为长度，你就选择 TBM，我不认为这样的做法是正确的，可能这会是你做的最错误的决策。

我们是选择钻爆法还是选择 TBM？我想有很多的因素影响我们的选择，这个选择非常重要，特别是在引水隧洞里面。在南美有一些案例，我首先给大家介绍一些，介绍一下 Q 系统与 TBM 之间的反向逻辑。大家可以看这个表格，上面是 Q 系统的分类，它这个分类适合于岩石支护，但不适用于 TBM，有一些元素，因为这个区域 PR 非常非常低，PR 值，就是掘进速度非常非常低的时候，大家可以看一下，这个隧道的稳定性，这个岩石的质量很高，质量高这样就会出现 TBM 掘进速度慢的情况。我们知道，从这个图上大家可以看到几个等式，就是使用 Q 值来反映岩体性能的变化，就是一个数值的变化。对于 TBM 来说，Q 值太高或者太低都不是一个好的条件。

日本有一个案例告诉我们，TBM 掘进机随着岩石的质量的增强会降低，会放缓放慢，但这并不是全部的情况，PR 减慢了，但是这个时候它的 AR 值还能够保持一个好的速度。但是随着时间的推移，它的 AR 值会减少，就是递减法则。所以它的速度以及 PR 值之间有一定的关系，对于用 TBM 来进行挖掘，遇到这样的问题。

现在跟大家介绍一个非常重要的法则，就是减速法则。我把它称之为法则，因为我认为所有使用 TBM 的人员都必须要遵循这样一个法则。这是一个调查，大家对 1000 公里长的 TBM 的隧道进行了一个调查，它是非常具有代表性的，对于这个岩性进行了很好的描述。它使用的是开放式支撑 TBM，这个图上有很多的数字，左边的轴是关于 PR 值，就是推进速度（米/小时），横轴是时间，一天、一周、一个月，这里就是它的 AR 值，也就是它的尺度，尽管世界级速度，大家可以看到还是有一个减速度的。即便是世界纪录，在工程结束之前达到 2 米/小时，这意味 16 公里/年的进度，也仍然是递减的。工程区域的岩性非常差，可能会建得更多，特别是碰到这些与低 Q 值强相关的非预期事件时。稍后跟大家介绍，并且评论这两个等式是什么关系。

大家可以看到上面的角是 T，就是时间（小时），M 指的 T 递减的米数。我在这里要强调的是，使用率是完全取决于时间的，所以说在选取 TBM 的时候，不仅

仅要考虑到速度,也要考虑到时间,因为它确实是对时间有依赖度的。而且它有掘进度的递减的现象,所以T是整体时间,160个小时,也就是7天,每天24小时全天候运转的话,要完成整个隧道的挖掘需要的时间。红色的是最好的,绿色是平均值,但是蓝色的就是很遗憾,比较糟糕的情况,Q值比较低,待会儿跟大家提供一些图表。我想有些人在这方面有更多的经验,比我了解的更多,因为中国有很多超长的隧道在开挖。对于一些未遇见的事件,出现了断层的现象,极端水的现象,还有蠕变的情况出现,另外就是自稳时间的普遍缺乏,这些都会让机器闲置好几个月,工程进度受到影响,最后合同方不得不使用钻爆法的方式作为弥补。

对于道路和隧道来说,我们必须通过阻塞区域,要开挖的区域可能比这个房子还要大,必须要解决这个问题,这是一个非常大的挑战。为什么这个断层区对于TBM来说会造成极大的延误呢? 首先这是世界上最著名的一个TBM的合同方,就是经验原因,他们刚开始不认为这样的原因是真正的原因。事实上有三个基本的等式,非常简单的三个等式,我称之为半理论半经验(Theo-Emperical),之所以是半理论半经验,因为如果你不相信它们,你就得付出代价。第一个对于TBM是最基本的,$AR = PR \times U$,但它是依赖于时间的;所以就出现了第二个等式,$U = T^{m}$,T就是时间,时间和掘进米之间的关系;第三个大家可以看一下,就是$T = L/AR$,时间和长度有一定的比例关系,如果把三个等式加在一起,我们就会得到下面这个等式。这个等式很简单,但是,这个m是负值,它跟Q值有非常重要的关系,尤其是在断层区,所以这个因素很大,因为m是负值,-0.5、-0.6、-0.7,几乎需要无限的时间,所以就会出现延期。大家可以看到左边的指数,-0.1,是针对双护盾,还有梯度不断地往上走,随着Q值不断地降低,所以提前灌浆是非常重要的,可以帮助我们避免问题的出现。

没有探钻和预灌浆就会过于乐观了。这些图是从Robbins早前的文章中摘出来的,当时他们正在创造世界纪录,他们没有进行探钻,破纪录的时候他们尝试着不探钻,然后他们在这个区域耽误了许多个月。如果他们有探钻,那可能会是在TBM机的上方,也可能会在下方。在大多数情况下,必须真的要有四个探孔,以保证没有丢失重要的信息。对于这个断层区来说,对于双护盾TBM来说,也会造成很大的问题。这是TBM设备,问题是这个区域没有进行预处理,合同方、承包方放弃TBM设备也是个错误。瞧这个链条2241,这是他的机器,如果他们没有放弃TBM,那么他们遇到的问题就会少一些。现在我们可以做一个比较,时间的延迟,低速、PR值是这样,因为缺乏支护,所以在这种断层区,对于TBM一定要有提前的支护,否则就会出现坍塌等问题。这个图又是最有经验的TBM开挖承包商碰到的,这是他们完全没有预见到的断层岩体,有四、五甚至六个不同方向的结

构面，在 TBM 的前方发生了塌方，因此造成了工期延误。在 Q 系统的术语中，我们这里还有一些不利的参数，比如低摩擦力、小块体尺寸等。

推进率从每天 15 米、20 米、25 米迅速跌落到数周推进 2 米或 3 米，仅仅因为出现了像这样一些非预期的事件。没有事先预见，没有探钻，也没有预处理。还有一些具体的问题，比如一个项目，和大家介绍它跟水之间的关系，就是出现水的问题怎么办？Werth 是世界知名的设备制造厂商，Werth，Herrenknecht，Robbins，Mashimatsu，大家都知道这些名字。这两台机器是用来挖掘坪林隧道的。这些 TBM 机需要从台湾北部东海岸穿过台北，掘进 14 千米。打头的 TBM 已经先掘进了 5 米，但它被卡住了许多许多次。至少十二三次不得不绕过这个导洞，所以导洞不能用作地面预处理，导洞有一点下潜到这个山里，这是承包方的草图，这里的变质砂岩给他们带来了很多问题，石英类岩体，节理中含黏土，有些地方还有大量的水。再看一下这张图，顶板这个地方存在非常不良的地质条件。他们穿过了其中一个不良地质体，结果导致了更大范围的坍塌，TBM 被摧毁，不能再用。再看这个大的 TBM，他们抓住机会换了一个盾，因为在这一带高磨蚀性岩层中每隔几千米就会磨损掉一个。这张图是回顾第十次或者第十一次绕过导流洞的情形。我去过台湾数次，讲了几次课。有两三次是访问这个工程。

我想我看见的是第 10、12、13 次的绕行，在几年之内。现在我们转到断层含水的情况，前两张图仍然是同一个工程，就在 TBM 损坏的地方，他们还需要采用新奥法（NATM）处理顶板和边墙。这可能是个经常性的难题，他们不得不在许多公里进度里面不断地加以处理，因为他们在头一公里半里面损失了 TBM。这张图是掌子面的特写，实际上我们是在真正的掌子面以外 100 米的地方，7000 立方米的土、岩石和水涌进了隧道。非常不幸，有人员伤亡，我想仅仅在这个工程接近 15 年的工期里面，每年有两人死亡，这是非常非常严重的伤亡问题。

现在来看看意大利的水和断层案例，这是我第一次访问现场所得到的草图，那个时候还不能用，这个勘察还不是地质专家做的。他们做了 200 ~ 300 米的深钻孔勘察，以及地震波反射剖面图。不幸的是，他们漏掉了一个平行于峡谷的断层群。这是在意大利北部一个叫 Pont Ventoux 的地方。是隧道太深不适合于工程勘察吗？这是非常重要的问题。首先它有地应力的问题，还有水的问题，你们可以看到水位线在这儿。最特别的是，当他们钻到这个平行于这些小断层非常近的地方，出现了 1 ~ 1.5 米厚的黏土岩芯。但是非常非常不讨喜的是，在第二张图里他们叠加了地质专家的草图，每周他都进一次洞子，描出进尺，可能隧道已经往前挖了，TBM 也向前进了几米，我已经把这些草图一张张叠起来放给大家看。这里的问题是岩块混杂着水、泥、沙不断地从竖井落下来，阻碍着刀具。这还不是唯

一的问题,另外还有泥沙三角洲的问题,那儿水是非常静态的。每次火车、卡车或者泥头车进来,往往会造成脱轨。瞧这里的空洞,追随着指盾,延伸到另一边的空洞里面大概 10 ~ 15 米,可能往上还走了 200 多米,因为你在很远的地方还能听到块体落下的声音。现在,这个是来自克什米尔的水和断层的例子,这个是地质专家绘制的草图,大概有 4000 立方米的突水突泥,令人吃惊的是围岩中有一些石英砾岩,尽管我们是在 900 米深的地下,地面水还是流到了这儿,而且是持续的流入,大概有每分钟 60 立方英尺的量。这让工程延误了 280 天,不得不建一条单独的隧洞以处理流入的水。

以上跟大家描述的三个案例,他们没有一个先期计划好的钻爆法与 TBM 联合掘进的解决方案。他们刚开始使用 TBM,但是后来他们不得不使用钻爆法,从另外一端来进行拯救和弥补。比如说锦屏二期,最后也是不得已采取了联合的方式来最终完成了这个项目。跟大家介绍一下关于深隧道的声波速度误导问题。图表这里的深度可达 1000 米,P 波的速度可达 6 千米/秒,这些线是连续的岩体质量,还有连续的 Q 值。问题是,当你在深部隧洞前方碰到断层,会出现一个错误的高波速。但事实上围岩应该有更高的波速。问题在于,当你挖到断层的时候,你释放了应力,改变了应力场,就像应力场一直是这样,然后它的特性得到了揭示。表面上波速 2 千米每秒可能是个错误。这还是那个分析,已经释放了应力,低的 P 波速度,这种材料更差,有黏土填充,这是波速,这个轴上是 Q 值,深度随着这条线增加,我的观点是,在深部,在几百米的深部,Q 值很低的断层可能会有高的波速。关键在于,如果是相对于围岩而言,围岩应该更高的波速,比如这儿应该有高得多的 Q 值。这是日本一个隧洞地震波测试图,在平行于隧洞方向是 4.2 千米每秒,不是很好,岩石的速度预计会降低到 3.7 千米每秒,但即便是那时,也只降低了 0.1 千米每秒,尽管他们有所准备,仍然出现了掌子面垮塌的现象。

再简单地介绍一下是选择双护盾 TBM 还是选择开放式支撑 TBM。对于断层区来说,有些时候开放式支撑 TBM 是不能使用的,因为它的推力是由 PC 元素的最后一环的推力来实现的。这是关于开放式支撑 TBM,有两个结果,双护盾的两个结果。这些是头三四个月双护盾机在块状岩体里奋战的曲线,Q 值是 500 或者 1000,RMR 几乎高于 95,如果你信的话,这是双护盾机,对于开放式支撑机也是一样。这个还是双护盾机,这个效率就非常高了,在 14 千米结尾的地方,达到了令人尊敬的 2 米/小时的速度。这个是 Guarddarrama 隧道,这是 4 个 TBM,在这些原则的指导下,他们在 30 ~ 33 个月里开挖了 14 千米。这张图来自于其中一条隧道内部,当然,这是针对双护盾工作量巨大的调查,把所有这些因素都考虑进去的话。很明显效果很好,但这意味着价格的增加,更何况这些隧道岩体质量很差,需

要支护。如果岩体中存在水压力的话,所有的 TBM 选择都有问题,不幸的是此种情况并不鲜见。

这个草图显示的是四种情况,来自石油行业,只有一个对于 TBM 来说是有利的。第一个,这个跟理想的 TBM 快速掘进非常吻合,能达到每月 1.5 千米的进度,如果能够持续的,一年能掘进 10 千米。第二个是代表着高磨蚀块状岩体,掘进率大概每小时 1 ~2 米,每隔 2 ~3 米就得换刀具,由于更换太频繁,会占去大量的时间,因此总的掘进率实际上是缩减了。第三个,你们可以想象,这里可能会由于挤压而卡住 TBM,我们再次看到,这里有个梯度很陡的效率降低。第四个代表着由于断层存在而导致的掉块,可能是岩爆的预兆,或者由于应力而引起的破裂。

大家如果看到这些岩芯柱状图,中间没有节理,所有的岩体参数都在我 Q 系统的右边,非常高的 RQD 指标,几乎没有节理、不连续体,可能会掘进得非常慢。尽管岩石质量非常好,对于 TBM 而言却并非如此。如果数据充足可以用预测的方法,如果没有那么多的数据,我们可以采用工程判断的方法对输入参数加以评估。从这个图上大家可以看到它减速的情况,以及双护盾机模拟的情况,用 * 表示,开放式支撑机用方块儿表示。我选择了两种稍微不同的切削力,26 和 28 吨,这里的梯度的陡峭程度约是双护盾机的两倍。一般来说,有一些变量。在这个破碎区域的模拟过程当中,可以看一下,由于对断层区域没有进行预处理,如果我们模拟的情况是真实发生的,那么这台 TBM 将永久地埋入山里。输入参数,最后 50 米的输入参数,大量的花岗片麻岩,一级岩体,但这可能是我们最不想看到的最坏的岩体,它的 RQD 值很高,仅有一个节理组,所需的切削力也更高,大概 32 吨左右,这对 TBM 而言是个坏消息。把开放式支撑 TBM 和双护盾 TBM 做一个比较,可以看出开放式支撑 TBM 的预测结果不如这条线,因为这里的花岗岩具有高磨蚀性。这里存在大量的节理,所以掘进得很快,如果我们使用双护盾,那么会更有效率,掘进得更快。QTBM 实际上是 Q 指标中添加了额外的机器 - 岩石相互作用参数。最近在巴西的这个区域有一条隧道,50% 的岩体 Q 值大于 500,RMR 值大于 95 的岩体占了 50% ,很多公里都是这样。掘进得非常非常慢,尽管岩体是我们概念中所认为的那种非常好的岩体。近年来高地应力的挑战、深埋隧道的挑战,一般来说很多都是埋深超过 1000 米的 TBM 掘进的隧道,有少量的超过 2000 米埋深。我知道有两个案例局部超过了 2500 米埋深,其中一个就是锦屏二级水电站,另一个是秘鲁的 Olmos,两个都由于岩爆而遭受了严重的损失。今天上午我听说了锦屏二级事故的死亡,Olmos 隧道也许没有出现过伤亡,但是近 20 年来这类深埋隧道已经出现了很多伤亡,而且直至最近仍在持续。

这儿我给大家展示一张 TBM 所遇到的理论挑战,看这个螺旋破坏面,这是地

应力高达40、50、60 MPa时的破裂模拟,如果这里多一些节理会是什么情形?有一些解释可能是你们选择更深的地方突围以避开节理和岩爆问题。这是物理模型,这是砂岩中沿三个主应力方向的钻孔,还有一个层状模型。这是个小块体的甲板模型,可以用来强调为何断层带在节理发育岩体中是个大问题。如果岩体够硬,剪胀特性够明显,比如花岗岩,可能破坏模式是拉破坏而不是剪破坏为主,但我在块状片麻岩、大理岩和砂岩中看到剪破坏模式。在Q系统中,我们有一个参数叫做应力折减系数SRF,在这个区域,应力强度比0.4、0.5、0.6,SRF值会急剧上升而Q值会降低。这是1993年发表的记录1990年以前的案例,大多数是挪威的深埋隧道,其中一个埋深1400米。这里是马丁教授发表的一篇文章中的一组数据,他是独立统计的,他可能是在这篇参考文献很多年前发表的,这个上面显示着应力强度比达到0.4、0.5,应力开始引起岩石破裂,这是一些显示岩石破裂的图。

这是锦屏二级导流洞的钻爆法开挖,这是TBM开挖方案被放弃前的TBM隧道。这里是巴西一个浅埋隧道坚硬的玄武岩由于应力导致的破裂。这个可能是锦屏二级轻微岩爆的结果。巴西的这个浅埋工程尽管埋深只有60~70米,应力强度比却非常高,因为这里的水平地应力出奇的高,水平应力与竖向应力比高达20或者25,破坏深度多达3米。不管是TBM还是钻爆法,所有的隧道都会受到地质环境的影响,比如极脆弱或者极坚硬的岩石、大断层、高压水、高地应力。然而采用TBM开挖对于每种地质情况都会增加风险。轻微的表征对决定是否采用TBM可能是更加重要的。我们来对比一下钻爆法和TBM,如果要使TBM比钻爆法更快,那么节理岩体的质量必须适中,因为TBM可能掘进得很快,也可能掘进得很慢,那么我们的问题可以表述为:“使用TBM掘进长隧洞真能更快么?”这里我把钻爆法开挖隧道的数据放上来,瞧这条曲线是整个周期的Q值,我要创建一个简单的TBM案例,每周每月每年的进展速度合理。我们需要岩体质量,大多是在这个区域,如果TBM快于钻爆法的话。这儿,仅仅为了有趣,世界纪录,我想钻爆法的掘进速率是每周104或者105米,钻爆法最快的掘进速率是每周164米。非常明显,没有哪个岩体或者承包方能掘进得那么快。这里确实指出了如果岩体过于块裂,钻爆法能比TBM掘进得更快,钻爆法还比TBM更能有准备地解决断层问题。如果岩体的质量非常好并且无需支护,钻爆法还能将循环周期降低至4~5个小时,我们要知道岩体质量的分布,对于深埋隧道特别重要的一个问题是,块状岩体伴随着高单轴抗压强度、低刀具寿命、高石英含量、高山覆盖。

从统计的角度讲,长的隧道和短的隧道哪个更好呢?这是5千米长的隧道,这是它的Q值的分布,右边是25千米的隧道,这是它的Q值分布,这里有一些极

端值在尾部,有很多大型的岩壁或者是比较硬,HH,是双 H 值,而不是只有一个 H,还有一些比较严重的断层区的问题,FF,而不是 F。对于长隧道来说,最好的技术是什么呢? 是使用 TBM 还是使用混合的方法? 我想答案是明确的,就是使用混合法,当出现 FF、HH,FF 岩石的情况就得避免使用 TBM,同时硬度又非常高,顶盖又非常厚,所以我们的技术方案是,左边是使用 TBM,往右是使用钻爆法,钻爆法可以从这一端开始,提前一年,努力在这儿跟 TBM 接上头。TBM 可能会进展得非常快,但这一端得等钻爆法,钻爆法会更有效。

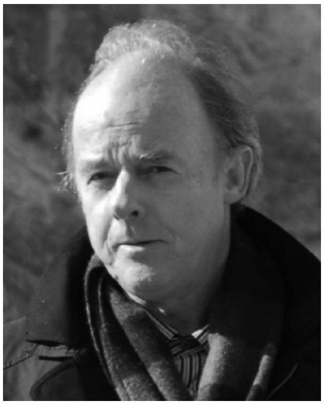
中间的部分有一些优势,如果从物理的角度来说是可行的话,大家可以看一下传统的采取联合方式的做法,这是马来西亚的一个水隧道。传统的选择就是在两端使用钻爆法,长的高山段使用了两台 TBM 机。时间会告诉我们,它是一个好的做法还是一个不好的做法,这是三年前的一个项目。

最后我们再来看一下钻爆法。大家已经知道,它能够达到最高的速度是 160 米,有的时候一周甚至达到 170 米。对于整个项目的平值来说,超过 100 米,显然有很少的岩体和承包商他们是希望有这样一个表现。每周 40 ~ 70 米的表现对钻爆法更常见。根据地质和水文地质的条件,各个国家的情况,承包商经验会有不同。对于一个新的项目来说,Q 值的分布是什么样的呢? 大家可以来看一下这张图,这应该是我们做决策的一个部分,是否使用混合方法。

在左下角的时候我们要做预喷灌,这样使用钻爆法可能更容易一些。如果是很多块状岩石,我们不能使用 TBM,预灌浆在 20 ~ 30 个小时内能完成,它所给出的结果更能预见,通过预灌浆可以降低风险,这对于 TBM 比对于钻爆法要容易。解决了水流入的问题,改善了岩体质量,如果能够预灌浆,那么这条表示开支的曲线就能降下来,根据 Q 值,这条表示相对时间和开支的曲线就能降下来,我们能够改善 Q 值,预灌浆伞可能已经避免了数月的工期延误,预灌浆能把非常低的岩石质量值改善到这个区域。

最后我做一个总结,是使用单护盾还是双护盾,必须进行探钻,如果主要断层的位置已知,也要能进行预处理。如果没有探测到或者没有进行处理的话,断层区对于 TBM 来说会是它最薄弱的环节,断层对于钻爆法而言不具有控制性,因为它们更容易进行预处理。但是这个预处理必须在到达断层之前完成,否则很难做这个预处理。所以在进行预处理的时候,地点的选择很重要。连续的预灌浆对于不良、多变的地面是最好的。还有预灌浆可以帮助我们改善 6 个与 Q 相关的参数,很明显 Q 值能有助于改善钻爆法隧道,因为这时所需的支护会更少。假设 TBM 对于长深隧道是最好的选择,这种想法是风险之源。TBM 对于长深隧道来说,看起来是唯一的选择,但并不是这样的。钻爆法如果可以使用真空的通风设

施，钻爆法的进度是可以提升的。它的横截面需要进行一些处理，比如锦屏二级的隧道就面临这样一个问题，因为没有及时地把污染的气体排出去，也造成了很多工期延误的情况，就讲这么多。



尼克·巴顿，1944 年生于英国。1966 年获国王学院土木工程专业理学学士学位，1971 年获伦敦帝国学院岩土力学博士学位。1971－1980 年供职于挪威岩土工程学院，1981－1984 年，任美国盐湖城斯伦贝谢公司力学部经理。1984－1999 年再次供职于挪威岩土工程学院，其间担任 5 年系主任，在大坝、岩石、隧道、山崩和水库部门担任 10 年技术顾问。2001 年以来，在奥斯陆和圣保罗创办尼克·巴顿国际顾问事务所。

1974 年，开发并广泛应用了 Q 系统，该系统可进行围岩分类，来选择岩石隧道和洞室支护的形式。1982 年，运用 Barton－Bandis 本构关系，构建了岩石节理模型。发表学术论文 270 篇。2000 年出版《节理断层破碎岩体的隧道钻掘机开挖》，2006 年撰写教材《岩体质量、震波速度、衰减和蛤异性》。

近 40 年来，在 35 个国家担任过咨询顾问，其课题涉及隧道、洞室项目、石油池沉降、岩石应力测定等。2004 年获阿根廷科尔多瓦大学荣誉博士学位。2011 年于北京举行的国际岩石力学学会大会第 6 届缪勒演讲会上发表演讲。

岩爆条件下的支护设计

Peter Kaiser

加拿大力拓地下矿井建设创新开采技术中心,加拿大

很高兴又回到武汉。大概 20 年前我曾在这里,我当时讲了岩爆的发生条件及其支护措施。从那以后,我们又学到了很多,(很荣幸)我再次被邀请回来讨论这个话题。

我想先介绍一下本篇文章的共同作者,蔡明(音译)博士,他与我一起正在进行支护设计指南的修编工作,主要是有关地下工程结构的安全施工和风险管理,其中涉及一些关键要素。从北美的角度来看,首当其冲的要素是企业的社会责任,它取决于企业对安全、风险管理的态度。我很高兴今天上午听到中国已经有了一些如何处理这方面问题的重要举措。在澳大利亚这被称为社会和环境公正,蕴含着法律含义。第二个要素是系统的风险评估和风险信息交流,在此基础上做出正确的决策,这一点在明天的讨论会上我会继续谈。

今天,我将关注以安全意识为核心的正确施工方面的问题,特别是想谈谈位于高地应力地区的深部隧道工程,(发生的)强破坏性的岩爆地质灾害及其支护系统设计。首先,我将简要介绍一下卓越开采创新中心,简单地展示我们在高地应力硬岩中的隧道掘进系统。然后,我来谈谈在深部开挖中的一些经验教训,重点讨论岩石支护方面的挑战和问题,这方面的很多内容都已经写在你们手头上的书面材料里了,我将重点用一些具体的实例来说明文字中的那些观点。这些例子包括土木界的阿尔卑斯山隧道工程,以及深达 2500 米的深部矿山开采。我所用的这些案例均来自于现实工程,(在这些工程中)工程师和设计师们并没有考虑可建造性,也就是安全隧道施工的能力问题,主要的原因在于(设计师们)对高应力引起的岩体破裂,即我们常说的岩体剥裂或深度压裂,以及(这种情况下)支护选择可能造成的后果缺乏(清晰的)认识。

刚才提过了,我是卓越开采创新中心(Center for Excellence in Mining lnnovation)的负责人,我们的使命是支持金属矿山安全开采方面 5 个领域的创新。

“for”这个介词很重要，因为我们的宗旨是追求卓越，推进创新。这不仅仅是从研究单个层面而言的，而是创新思想的整合以及这些理念的执行和实现。当我们谈论安全与风险的时候，我们更多谈的是实施层面上的，而不仅仅是学术研究方面。我们的一个部门，地下采矿施工中心，由当今世界上三大矿业公司之一的力拓资助。它的关注重点来自于这样一个事实，这家公司即将从露天开采转向地下开采，简而言之，需要实现阶段变革，因为时间就是金钱，矿山开采拖延一天就会造成百万美元量级的经济损失。为此，他们正在开发三种不同类型的凿岩掘进设备：一种是从德国沃斯引进的掘进系统，第二种从阿特拉斯－科普柯引进（PPT 左图所示），再有的一种就是海瑞克的竖井掘进系统，直径 12 米宽，竖井掘进速度可达每天 10 米。

同时，但完全不同的是，南非安格鲁－阿山蒂黄金矿业公司也正着力于机械化开采，只不过是因为他们不会将矿岩弄出来。他们把所有的注意力放在了黄金上面，他们有一个口号是“安全采矿”，也就是安全采出黄金，而且只是黄金，在任何时候。为此，他们启动的第一个付诸实施的方案将由 3 台隧道掘进机、4 套输送系统和 33 套反井掘进系统组成。

我完全理解并十分感谢那些有关机械化掘进困难方面的意见和评论，这将一直陪伴着我们，除非有朝一日这个动议被证明是错误的。那么，我们吸取的经验教训都是些什么呢？当我们谈论深部（掘进）时，第一个经验教训是（那里的）岩石可不是那么厚道。换句话讲，在浅部地层掘进时，我们可以犯错，我们也能够应付，但是到了超深（掘进），我们就不能犯错了，我们必须正确地施工。明天，但很不幸，菲尔赫斯－查尔斯先生不在，他的报告题目将是“我们现在有了工具”。这里的工具指的是模拟方法和手段，其中的关键在于如果不（使用这些工具）去设计，隧道也能够建造，能够被承包商以安全、低成本方式建造，那么这些工具就实在没有什么用处了。

当看到这些实例中的问题，比如隧道坍塌，或者（PPT）右边的岩爆，我们不得不扪心自问，我们的设计到底错在哪里？从专业术语方面来讲清楚，脆性岩石在拉应力作用下破坏形式表现为剥裂，如（PPT）左图所示，或者在高应力作用下破坏产生层叠褶曲现象，如（PPT）右图所示，这些图片拍摄于南非的一些超深矿山开采中。我也想谈谈导致岩体解体的过程，临近开挖面，这 2 张图片临近采区石门。（这张 PPT 的）左边，我们可以看到相对比较大块的岩石已经发生应力断裂型的剥裂破坏，产生较大的变形，在这种破坏机制里也会有剪切破坏。

在我们谈论支护设计之前，首要的挑战是我们必须完全理解硬脆性岩石在应力作用下的力学响应。关键之处在于，当岩石以脆性模式破坏时，我们必须在施

工时能够处理如上张幻灯片显示的那些破碎的岩块。我们必须去处理破碎岩块，必须去对付岩石破坏时产生的大变形，我们的支护系统必须能够承受这些变形——与这些变形相协调。这就是我今天演讲中的关键点——支护设计的重点在于变形协调。回顾很多地下工程案例，无论是采用钻爆法还是 TBM 掘进，你都会看到同样的景象，也就是产生应力断裂，在不同深度开挖边墙发生破坏，这个例子是深部岩爆情况。这种过程在相对比较弱的粘土页岩类地层中也会发生。我的观点很简单，这种（破裂）机理我们必须考虑和预判。我们广泛使用的弹塑性数值模型不能捕获这个过程。

第二点是我们需要预测破坏的深度。巴顿博士之前展示过这张图，他也阐明了当开挖面周边的应力，我们用水平轴来表示，这个应力水平在达到岩石 UCS 的 40% 之前，破坏就早已发生了。应力几乎呈线性增加，垂直轴上的破坏深度也几乎呈线性增加。理解了这种破坏机理，我们就能预测破坏的深度。巴顿博士也提到了应力比，很久以前他就讲过当应力比超过 0.6 时，就进入到应变岩爆状态。他那时还曾指出，当应力折减因子达到 10 到 50 时，也会进入这个阶段。当把这两张图表结合起来看，我们就可以得出一个非常简单的结论：当破坏深度超过隧道半径的 20% 或者 30% 时，破坏过程并不是缓慢的渐进的，而是能量（急剧）释放，产生强烈的应变岩爆。如果岩石沿着这么一个应力路径走，如这个例子所示，（完整）岩石相对比较大，因为突然水平收敛变形，产生拉张破裂，由于容积增大，岩块除了往临空面走没有其他地方可去，因此朝下变形，施加荷载于支护结构并使之产生变形。非常重要的是，岩石破裂成大块状。这幅图，对我而言，十分重要，它（清楚地）展示了（完整）岩石破裂成非常难处理的大岩块，我们称之为隆胀。这张幻灯片展示了应变（裂化）模型，可以看到单个的岩块并未破坏，但岩块交界面张开，因而伴随着破裂过程几何体积会增加。我不确定你们是不是都能看清楚这幅图，岩块沿着不连续面发生剪切破坏，但更重要的是在中间发生了拉张破裂。可以想象一下，如果继续变形，（岩体）体积将急剧增加。这幅图片再次告诉我们，当我们进行支护设计时，我们需要担心的不是支护结构将要承受多大的荷载，我们需要重点关注的是这个过程中产生的变形和位移。

我们曾经做过一些单轴试验，加压超过峰值强度，岩块破裂，结果汇在这张图表上，可以看出隆胀与围压大致呈线性关系。重要的是，当到了实际的地下工程，从南非测试得到的数据，展现了同样的线性规律，只是坡度有所不同。具有实际意义的是当围压小于 2 MPa 时，隆胀从 0 到 10%，这意味着 1 米就将变成 1.1 米长。在开挖面周边，（隆胀）只会朝一个方向发生，即朝向开挖临空面。这种行为取决于围压大小，（如 PPT 所示）我们展示了变形与围压的关系，没有围压、围压

从 1 到 5 MPa 的情况,可以看到开挖面周边径向应变大概是切向应变的 6 到 5 倍,最少也有 2 倍。实际上,这意味着朝向开挖临空面的应变要多出大概 4 到 5 倍。由于支护结构的典型承载能力小于 1,也许小于 0.5 MPa。请你设想一下,两条平行的隧道,中间有矿柱,当开挖这些隧道时,矿柱承受荷载,产生应变和变形,更重要的是,临近开挖面的岩块破裂产生侧向应变,我刚才已经阐述了,这在量级上会是 4 ~5 倍于矿柱之上的应变。在很多矿山开采中都发现了这种现象,这里是一个极端例子,金伯利岩矿,由于垂直方向的应变变形,发生很多隆胀导致原本可以通行 5 米宽设备的隧道产生了严重的收敛变形。更为有趣的是,在掘进这个隧道,或者相类似的隧道的时候,我们发现从始至终岩石大体上比较稳定,只是在开挖临空面附近有些鼓皮现象,也就是隆胀变形发生。讲到这里,我希望你们能够理解开挖面附近发生这个现象的机理其实就是岩体劣化的一种,它所带来的体积激增是我们必须处理的问题。

这对我们开挖隧道具有什么含义呢? 第一,是保持稳定的时间大大缩短,这会导致工期延误和成本增加。第二,这个过程的发生并不是那么美妙,具有突发性,也会导致工期延误和成本增加。现在我来演示一下我们是如何通过不同的方法来给围岩分类的,Earth、GSI 还有其他一些系统做的都是大致相同的事情,这根轴是岩块的大小,另外一轴表示节理裂隙状况。我们先来看看完整岩石,施加荷载后,出现不同形式的岩体劣化,在这种情况下可能出现半米或小于半米的剥裂。其他的一些例子,这是石英岩,它可能不会裂化到分米级别的岩块,而这一个会剥裂至厘米甚至毫米级。

应力(的变化)可以将勘探中看起来非常完好的岩体变成看上去如此糟糕的岩体,这表明应力是(使得)岩体劣化的重要组成因素。这张图表很好地建立了无支护跨度与保持(围岩)稳定的时间之间的关系,这个例子展示了对于比较好的岩体,比如其 GSI 或者 RMR 为 65,应力(扰动)的结果是使得这种岩体不再稳定,这时我们需要建造支护结构来增加(围岩)稳定的时间,当然,我们必须及时支护。对于空心钻进系统而言这非常现实,这个例子来自于哥特兰岛隧道工程,承包商估计日平均掘进速度在 25 米甚至更乐观一些,但是(实际中)使用了敞开式隧道掘进系统后只能达到预期速度的一半。问题不在于(如图所示的)断层区域的坍塌,问题是开挖面周边围岩破裂深度达到 1 米之多,这种破裂似乎看起来不是很严重,但是它的不良影响巨大,因为它将一个掘进循环割裂为二,这意味着要么只能进行机械开挖,要么只能进行支护,而一个好的 TBM 掘进系统应当是能够边开挖边支护的。在(如图所示的)这个实例中,就这么一丁点的岩石剥裂问题,没有得到很好的支护,竟然造成该项目拖延了一年的时间,而且,这个隧道根

本就看不出是由隧道掘进机施工完成的,因为随处可见围岩剥裂现象。在一些情况下,(剥裂)是由于节理裂隙的影响造成的,而更多的情况是由于应力效应引起的,支护设计必须考虑这一点。那么我们一般要怎样来设计支护呢?(如图)我们做弹塑性计算分析,结果显示每边都产生屈服区,也产生了拉裂破坏。但是,之前我展示过,当围压小于 2 MPa 时,出现严重的隆胀破裂。(如图)这里,显示了围压等值线,也就是到深蓝色线的地方,大概是 1.5 米(的破裂)深度。那么从实际意义来讲这意味着什么呢?在这条深蓝色线以外的岩石体积变化不大,但在所有蓝色线这么小范围区域内体积增加了 10%,出现了剥裂现象。这种剥裂是由于开挖卸荷引起隧道周边小范围内应力集中,这部分围岩力学性质弱化导致裂化,产生变形,而且这种变形是单一方向的,即朝向开挖临空面变形。

我们理解了硬岩在应力作用下的力学响应特性,那么岩爆是怎样产生的呢?有三种岩爆类型,其中一种叫断裂滑移型岩爆。如果有一个远程地震动或者矿震,亦或开挖面附近出现坍塌,都可能诱发岩爆。进行岩爆支护设计,需要预判可能出现的失稳破裂,预测可能破坏的深度以及变形,还要考虑应力的动态变化和时效问题。通过这些方程我们可以计算弹射速度,计算聚集能量,从而考虑支护应当如何来吸收或者消散这些岩体释放的能量。

我们做了一个模拟,这是一个断裂滑移,我们在三个地方布置了检波器,基本上距断裂相同的距离,来看看各个测点的反射情况。测试结果表明反射波比较杂乱,有 P 波和 S 波。沿着某条断层滑移产生的岩爆发生以后,向地表扩散,可能会导致剧烈的地震动,也可能顺着隧洞方向扩散,诱发远处发生应变岩爆。对于锦屏隧道,需要考虑断裂滑移型岩爆,我们需要对付应力岩爆问题。针对这种应力岩爆的支护设计,关键是能够承受突然产生的瞬时变形。随着岩体破裂,聚集的巨大能量瞬间迅速释放,产生突发位移和变形。如前面的照片所示,这种应力岩爆是在很短的时间里突然发生的,需要支护,但要处理这种突发变形是非常困难的,支护系统该如何应对这种突然的变形?这里有一个不幸的案例,但幸好我们把它拍了下来,这是发生在一个隧道的横断面上,是一个应力岩爆,我们的支护系统就需要能够对付它。对于一个工程师和设计师来说,我们应该能够预判这种应力岩爆,任何有不良地质结构、容易产生应力集中的地方,都有可能出现这种应力岩爆,能量急剧释放,产生瞬时大变形。钻爆法为什么会比较好?因为在钻和爆的过程中,应力充分释放了,也就不会产生这样的岩爆了。考虑时效问题,我们的支护系统必须是柔性的,钢锚需要是柔性的,才能承受这种突发变形。虽然我们可以预报岩爆,但从实际工程来讲,我们仍然必须做好支护工作,保护矿工的安全。

那么支护有什么功能呢？支护系统有三大功能，加固、支撑和悬吊作用。最基本的作用是加固岩体，增强其力学性能，控制隆胀发生；如果岩体出现破裂，那么支护结构的支撑作用将使得岩体不会解体崩塌，同时通过内栓构件悬吊固定作用来保持围岩的整体稳定。但重要的是，支护系统必须是柔性的，以这个隧道为例，支护结构用了很多钢锚，加固岩体，支撑岩体，可以使得隧洞收敛变形不会一下子剧增，可以有效控制变形过程。因此，我们的支护系统应当是既能够支撑岩体同时也具有很好的柔韧性。这个钢锚里面有一个锥形设施，可以来回伸缩，你们开发的另外一种钢锚，同样也能自由伸缩和拉长，这样可以允许岩体有所变形，但是仍然不会断，这种支护是非常必要的，尤其是针对岩爆现象。钢锚需要和铁板连接好，可以让碎岩能量有效地释放出去，否则就会出现另外一种情况，钢板或者铁丝网断裂，岩体碎块弹射到隧道里面，如右边这张图所示，钢锚断了，钢丝破了。因此，一定要保证钢丝网很好的重叠，铁板可以把能量转移到钢锚和锚杆上去，从而有效释放能量。

喷射混凝土和铁丝网以及钢锚需要联合使用，相互匹配，协调一致，才能发挥很好的支护效果。我们强调的是这种支护系统必须是柔性的，可以变形的，随着岩体的变形可以有所位移。另外，也可以事先钻应力释放孔，转移能量。但不管采取什么方法来防控岩爆，保证质量都是非常重要的一个环节，在很多事例中，我们发现出现支护系统失效的原因往往是安装质量不好、构件本身质量不过关或者喷射混凝土不到位等等。

针对岩爆的支护设计，我们加拿大正在开发一个新的工具 BurstSupport，这在你们手头上的那份书面材料里有详细的介绍。这个工具可以在支护设计过程中系统地考虑地质、岩土体、动力荷载等诸多信息。

彼得·凯撒，力拓地下矿井建设创新开采技术中心主任，开采技术创新中心副董事（研究）。此前，曾连续5年担任该中心第一任执行董事。劳伦森大学采矿工程教授，岩土工程和地面控制主席，地下智能监控和深度开采综合技术研究项目主要研究员。专长采矿和地下建筑的应用研究，也对下述领域感兴趣：地质力学、地下开采稳定性、矿井设计、机械开采及其他提

高采矿安全和效率的技术方法。在企业和学术界积累了广泛经验，任多家工程公司、矿井和公共机构顾问。撰写科技出版物300余部。供职于加拿大工程学院和加拿大工程师学院。

基于块体 – DDA 数值模拟的浅层硐室破坏风险估计:建议方法和实例研究

Yossef Hatzor

以色列本·古里安内盖夫大学

我在简短的讲话中主要想跟大家介绍一下,我们在地下工程方面的一些经验。我们最早进行研究的时候,实际是从煤矿下的溶洞群开始的,我们需要对这些溶洞进行勘探作业。当物探的方法不能实施时,我们必须进行钻探而且钻探之前必须确定井孔的深度和井孔之间的距离。非常重要的一点是,我们需要知道跨度和上覆盖层高度之间的临界关系,只有保证跨度和它的上覆盖层的高度的比例是合适的,才能在保证煤矿的拱顶是安全的前提下确定井深和井距。在这种情况下,我们进行了一些模拟,我们在这个模拟的过程中是怎么做的?

为了研究跨度和覆盖层高度之间的关系这一传统岩石力学问题,首先,我们模拟了在以色列中部的一种常见岩体,这种岩体水平成层且节理垂直。我们在分析的过程中用的是离散单元法,我们不是仅仅系统且综和地模拟了节理,而是生成了一个称作“机械层”的结构,在这个结构中节理被岩层厚度限制。我们可以看到节理没有穿透整个岩层而是停止了,它们被岩层厚度所控制。所以我们可以得到一个更真实的块状岩体结构,然后模拟穿过中线的节理。这里有一个块状岩体结构的例子,我们看到的参数是 B 和 H 的关系。我们的研究方法是采用一个特定的岩体结构,然后改变这些参数。虽然模拟结果可能和岩体结构有关,但是从我展示给大家的例子中可以看出这种节理模拟方法在不同的块状岩体结构中得到的结果都还不错。这里我们模拟了一个无限远的层状平原,而且模拟了两套近层向和两套近垂向的节理。在同一个模型的两个模拟中,考虑到机械层的作用的岩桥较大;而如果限制迹长不让节理穿透模型,则最后的作用是相同的。再接着上面已经介绍过的模型,我们开始做模拟。我们研究了重力作用下顶板偏转和拱区横向应力的情况。顶板中有 4 个不同的测量点:1 个在中部,其余 3 个接近地表。模型边界很远可以使集中应力消散。这是我们研究的几何模型。在这种研

究之后,我们就找到了三类不同的情况。

第一类就是稳定,也就是上部三个点没有位移,拱应力稳定。当我们丢失两个测量点时,应该在适当的位置加入两个。不稳定是3个测量点都丢失,或者断裂穿透地表。第二类情况就是一般的稳定、不太稳定,也就是说我们在两个测量点上,都表现出的是静态的稳定,但是还有一个测量点,或者是没有一个测量点就表示它有静态的稳定。现在我们把这三种不同的情况分别看一下,大家可以在这里面看到时间的DDA情况,它的时间是实时的记录,大家也可以看到纵轴上的情况,也可以看到我们测量的每一个点的情况如果都稳定,那么整个情况就是稳定的。

下面,大家可能看到我们所做的模拟,实际不仅仅是适合在煤矿当中,其实在其他的采矿过程中,其他的洞穴的情况也是合适的。大家也可以看到在内的横向应力的变化,应力的变化就会影响到它的稳定性,这是刚才第一类的情况。补充一点,在这个例子中,我们丢失了最下面的测量点,但当我们讨论采煤和土木工程上部问题时,如果丢失了顶板的中线,不是一个很大的问题。当我们丢失了顶板,其他的三个测量点还在,你仍可以看到除了顶板中的拱应力降为0,其他位置的孔应力,水平应力不变。

第二类情况属于基本的稳定结构,大家可以看到,在2~3个测量点数值的分布是稳定的,但是在有些敏感的地区和点上,情况可能就不稳定,所以整个的情况是处于一般稳定状态。这时我们失去了一半顶板,下面两个测量点丢失,其他的两个还在,这种情况在采矿中是可以的,但在城市中会更复杂。

第三类情况属于不稳定状态,是我们在四个测量点上都可以看到,从上边一直到最上面,不管是横向的应力,还是纵向的应力,都处于不稳定的状态,所以它就没有办法形成拱。

现在,我们再看一下我们从中得到的重要结论。四个测量点都丢失而断裂穿透地表。因为拱的发展,水平应力变为0。从这些图片中可以看到,在同一个20 m厚的盖层下,跨度增大则稳定性减小。同时,在深部开挖时,保持跨度一定而改变盖层厚度时,并不是像我们以前所想的可能是线性的。实际中更复杂,应该是一半率的关系。在图中可以看到,有的是5、18、14,有的是11,也就是说它的稳定性,也就是B和H的关系并不是线性的,如你所看到的,我们得到的是一个非线性的响应,这里已经达到稳定状态,而且盖层相对很薄,只有6~18 m。所以我们要是想进行模拟是非常非常困难的,不管怎么样,大家还是可以看到,在中间这块区域的风险是比较低的,今天上午有一位嘉宾提到,属于深埋的洞穴和浅埋的洞穴在进行钻洞的时候,稳定性的变化,而且他也谈到,如果深度达到30米以

下的情况，会怎么样。我们得到过一个急促的要求，要我们为了稳定性考虑增加盖层厚度。今天早上我们看到了危险区。结果是相同的，跨度增大时它变化迅速，后来当低于 30 m 时值又降下来。

以上结果我们从一个人工合成的岩体中得来。但是我们的结果实际上也在三个不同的岩体的不同案例当中都证明了我们研究的结论是正确的，一个是真实的采矿，两个是有历史意义的地下工程开挖。

这是 Ayalon，是在以色列中部的一个露天矿，开挖水泥所需的原料。在这里可以看到覆盖的深埋厚度是 30 米，它的跨度是 40 米，我们测量了节理长度，间距摩擦，然后进行模型建立。我们采用离散元 DDA 的方法，建立了 15,000 个块体，每个块体大约有 1 平方米，这么多的块体必须有相互作用。在这里我们用的检测方法跟我们在进行人工岩石研究的过程中的情况是一样的。我们对这种情况也进行了数值模拟，在模拟过程中也发现在到达一定点的时候就会坍塌，说明了在这个过程中稳定性的重要性。在这里有不同的岩块，相互之间可以作用，我们还要考虑重力的问题。通过研究我们得到 DDA 正向分析的结果，大家可以看到。大家可以看到第二个测量点的情况，是稳定的，但是在其他的测量点都是有一定的稳定性，并不像我们想象的那么稳定。根据我们刚才所做的定义，在其他两个点上都属于基本稳定，这个定义本身可能不是一个真正意义上的定义。但是不管怎么说，我们可以用刚才所说的标准把它划分到第二类，也就是基本稳定，不能算是太稳定。它运行了 36 个小时。第二个案例在耶路撒冷的旧城，这里的岩体和上个例子完全不同。这个旧城下有一个巨大的洞穴，是两千多年前古罗马时代开挖的，当时为了修建一个庙宇开采了这些岩石。这个地下采石场的跨度是 40 米，它上边的覆盖层是 25 米，你可以看到岩石的结构。我们也对它的顶部稳定性进行了研究，我们在研究的过程中，发现如果要是它的应力发生了变化，那么中间可能就会发生坍塌，而且如果把顶板看作连续梁，坍塌用普通的弹性理论是无法解释的，这是因为在最下方纤维中的拉应力有 10 MPa，然而我们得到的只有 2.8 MPa。

在这里，它有塑性点，还有它的重力，我们怎么来解释这个问题？我们借鉴了 Voussoir Beam Analog 博士论文（由 Brady and Brown 发表）和由加拿大学者发表的一些论文中关于拱石的研究。很多人对这个问题进行了研究，他的研究结果我们可以借鉴。也就是说它出现了裂缝，这样裂缝就会往上延伸，到了一定的程度之后，岩石的裂缝停止了，两块岩石依然还是联系在一起。所以人们一直试图想解释这种拱石的现象，人们也希望能够了解它的机制究竟是什么，在什么情况下使得两块石头在最上边把它们联系在一起。如果拉应力足够高，就会产生扩张裂

缝,然后这些拉张裂缝就有可能延伸到顶部,把梁分成两部分。这里存在的问题是它的不确定性,所以我们假设了受压区的宽度,还有它的几何尺寸,是或不是椭圆。在转折点有三种破坏机制,一种是在转折点的压缩破坏,一种是肩部的剪切破坏,另一种是由于屈曲而造成的折断。按照它的几何形态来说,应该已经折断了,但是它没有。所以 Voussoir 方法也不能真正解释顶板为什么稳定。所以必须采用和现实中一样的更多的节理。节理增多,块的长度就会减小,各块之间也会有更激烈的相互作用。

根据这个问题的解释来说,到了这个点上,应该有一个点依旧能够把它们联结在一起,不至于坍塌,但是实际上还是坍塌了,这种情况究竟怎么样解释?为什么在这种情况下它的顶部还能够保持稳定的状况,我们对这种状况用 DDA 进行了正向的模拟,大家可以看到我们研究的结果。在图上大家可以看到不同的岩石、岩块之间相互作用的力量非常大。大家可以看到初期的纵向的位移,但是在纵向位移一段时间之后就可以看到拱部的应力发生了变化,使得整个情况发生了变化。在这个情况下,位移就停止了。应力的情况也是一样的,在这点上,位移停止时应力仍在积聚,在适当的位置裂缝梁会被锁住。在顶板的确会有一些位移和开口,这足够发生剪切和压缩,这些作用会使梁停止下落。令人惊讶的是,节理使顶板稳定了。

我们做的第三个案例叫 Tel Beer-Sheva,这是 3000 年前的地下储水系统,公元前 1000 年,在考古学上称为以色列时期,即大卫国王和所罗门国王时期。我自己也去过,大家可以看到它的结构很有意思,可以看到一个井,一直伸到地下,在地下的地方就像水库一样。在这里大家可以看到它里面隧道的延伸情况,在某一个地方大家可以看到,隧道在建设的过程中出现了坍塌的情况。当时是古时候的工程师利用支护系统,把坍塌的位置又重新地支持起来了,它是如何做的呢?就是在一个点上做了支护的支柱,这些节理是跟地下的供水系统的墙和主节理平行的,开挖时借助这些节理可以省很多能量。大家可以看到有两组不同的节理,而且不同的节理相距只有 20 厘米,我们对它进行了进一步的分析,在分析的过程中,我们考虑到了它的剪应力和正应力情况,同时也发现了它的摩擦角是 35 度,在图上可以看到摩擦角的角度情况。

我们可以用 DDA 来对这些数据进行分析,我们发现 30 度的摩擦角是不能够支持住的。如果把摩擦角提高到 60 度,就可以支持住它的顶板了。大家可以看到,摩擦角对整个顶部的稳定是非常重要的。我们也需要能够对它的节理之间的距离以及摩擦角进行进一步的优化。我们可以在这里看到这条直线,实际上表现的是 DDA 在运行的过程中可能出现的一些局限性,一旦块体变大,需要的摩擦角

就会变小,DDA 中块体内部没有应力分布。不管怎么说,这是我们运行的结果,一个是摩擦角,一个是节理之间不同的距离,研究结果表明,这个摩擦角一定要大于 70 度才能保持稳定。我们可以看到三个案例的情况,研究结果已经发表了,最重要的是告诉大家跨度和覆盖层的高度之间(P 和 H)的关系并不是线性的,它对于采矿,以及对于浅埋的洞穴研究都是有用的。

下面,我要讲的一个问题就是进水口如果出现问题,它可能对民用的建筑形成巨大的风险。在这里我想再用最后的几分钟跟大家介绍一下,我们目前正在进行的一些研究。

现在,我们正在跟冯夏庭先生所带领的团队进行研究,我们也希望对岩爆形成的机理得到更多的结论,我们的研究主要是希望用 NMM 的方式,有限元网格在 DDA 网格之上,能够对岩爆的机理进行进一步的研究。我们在这里所碰到的第一个重要的问题就是如何施加高的原位地应力,到现在很多人不知道怎么用。我们是用 NMM 或者是 DDA 的方法,我们就可以对这个问题做出研究。研究最重要的就是我们如何能够用原位应变计的数据进行岩爆的机理形成的研究工作。我们现在已经得到了一些冯夏庭先生所带领的团队的关于应变计的数据,我们对这些数据进行了逆向的研究,这样我们就知道了原位地应力的情况是什么,还有怎么施加。我们研究的情况可能跟目前已经发表的有些结果有一些不同,我们需要了解究竟是为什么,这样的原位应力是什么,我们也希望在明年能够对这个问题有进一步的深入研究。我们同时也希望用冯夏庭教授所研究的结果,在明年能够做更多的模拟研究,以便能够知道这种动态的应力的承载,究竟会对爆破过程中的震动产生什么样的影响。

刚才,我也跟大家说过,我们要想得到这种原位地应力数据,尤其是在比较深的地方原位的应力数据,相对来说是比较困难的,所以我们现在就希望能够通过反演得到原位应力的数据。我们在以前没有这方面的研究,所以现在我们希望能够模拟挖掘过程中的每一个环节,以便能够产生这些应变计的数据,我们是怎么做呢? 我们怎么样能够得到初应力呢? 我们在边界上引用许多加载点,然后建立了一些方程进行计算,研究的区域必须是方形,而不应该是圆形,固定边界和点,避免位移和旋转。在这个星期李晓忠和冯夏庭先生,他们又有了一些新的数据,这些数据是来自不同的隧道中的钻孔。他们进入 A 隧道,这里有 4 个钻孔,在不同的钻孔中测量方法是不一样的,其中一个用的是应变仪。他们又对另外两个隧洞 A 和 F 里面的钻孔情况进行了进一步的分析,除了已有的应变仪,他们还用了超声波速测量设备和钻孔摄像技术等。所以他们在这种情况下,就可以知道在挖掘的过程中,岩石的反应究竟会是什么,这就是我们所用的 AF 两个不同隧道中

的数据。我们用这些数据来检查我们导入这些初始应力的方法？首先我们从他们提供的已有初应力的数据着手，这些数据是他们最好的解译结果，我们把这些初始应力放在边界上，把它作为一个常量，看在这种情况下，其他的数字会产生什么样的变化，付出了很多努力才得出了结论。

现在我们已经知道怎么做了，所以我们可以利用应变仪的数据，来进行下一步的研究。在应变仪中我们有 17 个测量点，每个点都可以看到不同时间下的位移情况。大家可以看到如果在这里，你要能成功地做到保持稳定，就说明在这个位置上应变仪测到的数据是弹性的，没有不连续和剪切破坏。也就说明你在挖掘的过程中，岩石反应的确切情况你了解到了。

所以我们为了进一步的研究，我们先把它分成了不同的阶段。在第一个阶段中没有挖掘任何隧道，我们在第二阶段开挖隧道 A，第三阶段开挖隧道 F 的上部岩层，第四阶段开挖隧道 F 的梯段。在第四阶段中，大家看到的是 F 隧道，这是我们在过去几个月中研究的不同阶段，在最早的 NMM 代码中是没有的，这是我们对其代码的扩展，所以我们能够进行开挖顺序的模拟。现在进行反演，我们有 17 个测量点的数据。

我们这里假设垂向应力是已知的常量，为什么？这是因为覆盖层的重力比我们感兴趣点深度的值偏高，但是这个数字我们在研究的过程中是一直把它作为常量。我们又做了一个循环，在一定的间隔下改变边界上的 $\sum X$ 和 $\sum Y$ 的值，我们这样做是为了找到最优解，这个最优解是在测量和数值结果中测量点的最小平方根。这就是我们现在得到的结果。在这里 RMS，大家可以看到它的最小值在这里，好像对于在剪切边界系统不敏感，但是对于 $\sum X$ 是非常敏感的。大家如果记得在前面我们所说的关于如何施加初应力和高的水平地应力，这是一个两维的过程分析。这里的应力有 30 MPa，所以最匹配的解是垂向应力采用 66.5 MPa。这个最匹配的解表明隧道中 X 方向的水平地应力约为 30 MPa。现在我们已经了解了应力场，我们就进一步研究岩爆的情况，这也是我们未来的计划。我来展示这个应力场，这里看到的是 17 个测量点最匹配的解，而且数值解与最匹配的解吻合。怎样得到如此吻合的结果呢？主要是应变仪的数据告诉我们，因为开挖而引起的岩石松动与岩爆没有任何关系，只是用来预测地应力。

现在我们到了一个非常关键的时刻，我们在这个阶段更多地是使用 DDA，因为我们用 DDA 的经验要比使用 NMM 的经验更多，所以我们决定继续使用 DDA 进行初应力的应用研究。第一步，把初始地应力导入到 DDA，之后我们还要用 DDA 进行各种不同的掘进过程中的环节模拟，其次我们还要用 DDA 进一步研究不同的节理情况。除此之外，我们还会研究侧壁的情况，还要看一看在应变松弛

模型中侧壁会发生什么样的变化。同时，我们也会研究在爆炸过程中，震动波在传播的过程中会对侧面的壁产生什么样的影响。然后，我们就会明白数值模拟岩爆是否可行。

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中国水利水电地下工程安全建设技术、国家需求及科技前沿问题

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我报告的题目是“中国水利水电地下工程安全建设技术、国家需求及科技前沿问题”，我主要是分两个方面向大家介绍：一方面是地下工程技术发展的现状，第二方面讲国家需求及科技前沿问题。

中国水利水电蓬勃发展，修建了一大批高坝大库、长距离输水隧洞和大型地下电站，为满足国民经济和社会发展的需求发挥了重要的作用。中国已经建成了120座地下电站，已经建成的水工隧洞总长度约1100 km，正在建设的金沙江溪洛渡水电站，左右岸地下厂房开挖尺度为长443 m，宽32 m，高79.6 m，各装9台770 MW的水轮发电机组，装机规模达1386 MW，是世界上规模最大的地下水电站。

锦屏二级水电站，装机容量480万kW，四条引水隧洞单线长度约16.7 km，开挖直径为12.4～13 m，最大埋深约2525 m，具有埋深大、洞线长、洞径大的特点，地应力高，地下水十分丰富，技术难度极具挑战性。

南水北调工程穿越黄河的输水隧洞，长2.6 km，地质条件复杂，这是在游荡性河流上建设的一条输水隧洞，采用盾构法施工和预应力环锚的混凝土衬砌技术。

一、地下工程建设技术发展的现状

20世纪80年代以前，中国地下工程施工以手风钻钻孔爆破开挖、人工出渣为主，围岩稳定性维护以架立支撑防止塌方的被动支护为主，施工速度慢，效率低，安全问题突出。改革开放以后，通过引进国外先进技术、先进设备和管理经验，并进行了消化、吸收、再创新，中国拥有了一批自主创新的地下工程建设技术。

水利水电地下工程技术的主要成就有以下五方面：

1. 大型地下厂房安全建设技术；

2. 复杂地质条件下大断面、长隧洞安全建设技术；

3. 无钢衬高压钢混凝土岔管设计及施工技术；

4. 高压长斜井安全建设技术；

5. 地下工程混凝土模板建设技术。

大型地下引水发电系统快速安全施工的主要经验。统筹规划引水系统、三大洞室、尾水系统的施工程序，对关键线路的主厂房采用了“平面多工序、立体多层次”的快速施工方法，首创地下厂房3层立体开挖。

这是3层立体示意图，因为涉及了母线洞开挖，尺寸大，支护要求高，所以这一层的施工进度比较慢。为了加快施工进度，我们从压力钢管道就进入了厂房第四层开挖，主要开挖厂房中轴线以上的上游部分，第三层主要进行厂房下游边墙支护及母线洞开挖，同时从尾水隧洞进入了厂房的底层开挖，这样的立体开挖工期大概可以缩短半年。

对于主厂房的顶拱开挖遵循“先中后边，先软后硬”的开挖支护原则。我解释一下，如果岩体比较完整坚硬，一般采用先挖中导洞再开挖两边，这是三峡地下厂房开挖的图片，就是采用了这样一种方法，可以看到三峡地下厂房顶拱开挖的效果；但是对于软硬相间的层状岩体，这些层状岩体倾角大概在60°左右，我们就采用“先边后中，先软后硬”的办法，首先开挖软的一边，而且是岩层的层状结构面是倾向于临空面，我们把这一块开挖支护完毕，中间保留一个支撑岩柱，再开挖硬的一边。再往下开挖高边墙，采用同样的办法，把软的一边开挖掉，完成支护，红水河的龙滩水电站和澜沧江上的功果桥地下厂房是典型例子。

我们国家从20世纪80年代后期起，普遍采用了岩壁吊车梁的技术，也就是说地下厂房的吊车梁不再采用传统的梁柱结构，而是把吊车梁通过锚杆锚在岩壁上，这应该是地下厂房吊车梁技术的一次重大的革新，这就要求岩台开挖成型非常好。所以，我们在建设过程中探索了采用“双向爆破，锁角锚杆”的岩台开挖技术，在岩台下面加了锚杆，使岩壁吊车梁能够安全运行的关键是岩台开挖。从照片看，岩台开挖的成型效果是非常好的，采用这种技术保证了岩壁吊车梁能够长期安全的运行。

另外，对于厂房的高边墙，最近几年又总结出了一套开挖稳定的施工技术，叫“施工分层，一次预裂，薄层开挖，随层支护”。大家知道，高大厂房是要分层开挖的，比如我们开挖到第三层的时候，这一层是一次预裂完成的，大概在8～10 m，但是开挖的时候是分两层的，上层开挖完毕之后，就对边墙进行及时的支护，所以“薄层开挖，随层支护”就是这样一个概念。再往下挖，第四层的时候也是一样，分层一次预裂，挖半层4～5 m，边墙支护完了再往下开挖，这样做是控制高边墙的有害变形。我们看到这是溪洛渡电站厂房高边墙开挖爆破后的成型效果，是非常好的。

最后一项技术，对于大挖空率的高边墙，遵循“先洞后墙，重点加固”的开挖支护原则。厂房底层由于水力机械布置的要求，布置有尾水肘管，开挖尺寸很大，大概洞与洞之间保留的岩体不到50%，最小的保留岩体只有40%，因此高边墙极容易失稳。我们对于这一部位的开挖程序和支护的原则是提出了明确的要求的，要求在两条尾水洞之间用对穿锚索，恢复它的三向应力状态，同时对于开挖的基坑可以看到，开挖的基坑中间留有岩墙，要求进行精细开挖，并进行重点的加固，这样保证厂房高边墙不产生大变形和有害的变形。

下面介绍一下复杂地质条件下大断面长隧洞安全建设技术。我这里主要介绍地质条件差的Ⅳ、Ⅴ类围岩。Ⅳ、Ⅴ类围岩在水电工程中主要是进出口，埋深很浅，风化很深，另外还有一些难免要穿过的较大的断层及破碎带。对这些部位，主要采取“超前勘探，预加固，分层分区开挖，短进尺，弱爆破，早封闭，强支护，勤量测”的围岩稳定技术，形成了“管棚双浆液预加固，中空自进式注浆锚杆预加固，格构梁或钢支撑与系统锚杆联合受力和分部开挖法、眼睛法、核心土法”等成套技术。这是一张典型的Ⅳ、Ⅴ类围岩的分区开挖的方法，这是一些预加固的措施，我们有的时候还采用从上部施工台阶上打锚杆把顶拱吊起来的方法。上午钱院士谈到地下工程的安全风险主要是一些不良的地质条件，我们在水利水电工程中，地下工程安全建设的一条最基本的原则是“防止塌方或者减少塌方”。这样在技术上，首先对地质条件要搞清楚，然后在施工技术上要采取一系列的方法防止塌方，要塌也不要塌得很高，如果塌得很高就不好收拾了。所以，在水利水电工程中，由于施工措施不当，地质条件不清楚造成事故伤亡的现象，是比较少的。

下面，我介绍一下锦屏二级水电站的案例。锦屏二级水电站总共四条引水隧洞，先施工了两条交通洞，叫 A、B 洞，在四条引水洞施工之前，我们又考虑到这里的涌水量非常大，所以用 TBM 打了一条 7 m 直径的排水洞。我们在施工规划中实际上采用了 TBM 和钻爆法优势互补的组合方式，这种组合方式就是1#、3#引水洞采用 TBM 法从东端往西端掘进，从西端相反的方向采用钻爆法迎接它；把 2#、4#引水洞两边全部采用钻爆法施工，而且通过 A、B 洞打了几条支洞进去，采用长洞短打的办法；如果碰到强烈岩爆，在 TBM 受阻的情况下我们就通过这些辅助洞去支援它。总的施工规划，我觉得现在实施的效果还是比较好的。上午钱七虎院士也谈到了，在施工 7 m 排水洞时，打到 2/3 多的时候，强烈岩爆把这台掘进机埋死掉了，之后通过从辅助洞打支洞，以及从尾巴用钻爆法，把整个排水洞挖完。现在锦屏二级水电站的四条引水隧洞已全部打通，今年首台机组要发电了。

总体来说，这样一种施工方案是非常成功的，就是充分利用了 TBM 和钻爆法各自的优缺点，来实现优势互补。锦屏二级水电站采用 TBM 法施工还是成功的，

月进尺一个月达到了600 m,最高一天达到了60 m。但是因为经常碰到岩爆,所以总体效率不算很高。锦屏二级水电站施工中主要地质问题是岩爆和大涌水,最大涌水量7.3 m^3/s,最大水压力10 MPa,围岩最大主应力70.1 MPa,岩爆倾向指数1.32~5.8。锦屏二级水电站对于前期的工程地质条件和水文地质条件是做了比较深入的工作的,我觉得这是很好的基础。尤其是我们在施工A、B两条辅助洞的时候,它是作为交通运输洞的,因此,把16.7 km沿线的强岩爆地区、地段,以及突涌水大的地段情况基本摸清,心里大概有一个数,在这样的情况下,在施工中对于岩爆专门成立了一个小组,采用地球物理法超前勘探,这是我们成功征服了强岩爆、大涌水难题的关键。

具体的处理办法:对于强烈岩爆,本次很多专家今天包括明天发言中都要讲岩爆,我觉得治理强烈岩爆,全世界还没有行之有效的对策和办法,那么锦屏采用了什么办法?基本上采用了修正掌子面形态法和超前导洞应力解除法。这是岩爆把多臂钻砸坏的照片,我们采用了超前导洞和应力解除爆破孔,把应力先解除一部分,我觉得这个办法锦屏用得是比较成功的。当我们用TBM法施工,碰到强烈岩爆的时候,实际上我们就从隔壁用钻爆法施工的洞子打一条支洞帮助它,TBM没有办法往后退,所以没有办法对付岩爆,用超前导洞把应力解除掉。另外,我们采用了两项技术:一项是纳米有机仿钢纤维喷混凝土封闭,这种喷混凝土不像传统的喷混凝土,一次喷5 cm,多了就掉了,这个不受限制,喷20 cm上去也不会掉;另外一项是,采用了水胀式锚杆和胀壳式预应力锚杆快速加固。有多位专家谈到锚杆不能完全刚性,需要适应变形的能力,表面还有尺寸较大的垫板,喷混凝土里面,因为纳米仿钢纤维喷混凝土比较贵,喷了6~10 cm之后就挂钢筋网,再往上喷纤维混凝土。这张照片是7 m直径的TBM机被砸坏压在里面的照片,我们可以看到强烈岩爆造成的变形体。我们的体会是,钻爆法对于岩爆的适应性强于TBM法。

在高地应力的地区,突水突泥比较大的地区,如果是有几条洞子的话,我觉得锦屏的施工规划是比较成功的。这张照片是突水,可以看到水已经淹了半个洞子了。突水处理的主要原则是"探、排、控、堵"。首先是探明情况,然后是排,另外还有控制和堵。前期我们在搞试验洞的时候,提出了"以堵为主,以排为辅"的原则,是失败了。压力这么高,流量这么大的地下水,要想采用灌浆封堵的办法是堵不住的;后来采取了"以排为主,以堵为辅"的原则,排的时候辅助洞打通了,主要往辅助洞和排水洞排。对于涌水较小的地段,采用了灌浆封堵,喷纳米仿钢纤维封闭,再打排水孔集中引流。所以,锦屏二级水电站的岩爆和大涌水的整个治理,实践证明基本是成功的。

下面，我讲一下第三项技术——无钢衬高压钢筋混凝土岔管设计及施工技术。我国已建成抽水蓄能电站18座，总装机20 000 MW，抽水蓄能电站都会碰到大直径高压岔管。如广州抽水蓄能电站主、支管分岔处内径由8 m变至3.5 m，岔管承受最大静水头610 m，最大动水头725 m，PD值达58 000 kN·m。如采用常规的钢岔管，需采用厚度60 mm左右的高强钢板，价格昂贵，运输困难。后与美国合作，成功采用无钢衬高压钢筋混凝土岔管新技术，混凝土衬砌厚度60 cm，28 d抗压强度为30 MPa，单层钢筋布置。我们的基本设计理念是内水压力由混凝土传递到围岩的应力应小于这个地区的最小主应力，围岩来承受绝大部分内水压力。隧洞放空时，外水压力由混凝土衬砌及一倍厚度的围岩联合承担，并且做好岔管顶部的排水系统。混凝土衬砌主要起到保护围岩、降低糙率的作用，并便于高压灌浆的施工。高、低压水道一般都是要进行固结灌浆的，这是水利水电工程跟公路铁路隧道的最根本的差别。进行高压固结灌浆，对于围岩进行加固，水荷载很快地传递到围岩上去。高压固结灌浆可以提高围岩特别是地质缺陷的抗渗性及变形模量，并对混凝土衬砌加一定的预压应力。衬砌混凝土根据有限元计算分析成果，按“限裂”的原则配置钢筋。我们对广州水电站进行基本的测试的时候，大概95%的内水压力全部由围岩承担，混凝土衬砌承担的水荷载非常小，三次放空隧洞检查的时候，衬砌产生的裂缝在限裂要求之内约0.2 mm。

第四部分，我想介绍一下高压长斜(竖)井的安全建设技术。以往斜井传统的开挖方法就是上部采用钻爆法，人工除渣，下面用阿力马克爬罐打反导井，这是80年代的方法；到了90年代中期，我们形成了一整套的开挖支护、混凝土衬砌等技术，这个比传统的方法安全得多。我图示的这张照片是在惠州抽水蓄能电站斜井，倾角是50度，301米长的斜井，这是反井钻机，不到一个月的时间，直径为240 mm的导孔贯通，在一个半月的时间完成直径为1400 mm的导井扩孔开挖，标志着我国长斜井反井施工技术的突破。到目前为止，反井钻机的开挖深度尚未突破300 m的极限。最近中国电建集团承接了厄瓜多尔的DELSI－TANISAGUA电站，引水隧道的深竖井达700 m，我们购买了一台最先进的反井钻机，可以开挖这个深度，当然现在还没有实施。

最后我想介绍一下地下工程的模板技术，难点是在斜井，斜井模板传统的立模方法施工进度慢，安全威胁很大。所以我们研发了具有自主知识产权的斜井滑模技术，填补了此项技术空白。主要技术创新是用前后液压千斤锁定在井壁的中梁为支承系统，由液压系统控制模板沿中梁滑升。而且开发了具有自锁功能的前后液压爬升器作为驱动，沿底部钢轨腹板爬升，实现了斜井混凝土衬砌的连续滑升，平均滑升速度是8 m/d，这个速度是非常惊人的。我们在三峡永久水船闸的

地下输水隧洞中，斜井是由小往上变大，我们在前面等直径的基础上又开发了能够变直径，而且两侧是直墙，下面还有反弧的滑模系统，我们对中梁进行了改造，并使模板具有收放系统，实现了三峡输水隧洞那么多条斜井连续的滑升。

至于说隧洞断面，方圆形断面，主要采用了钢模台车，在水利水电工程上，这个尺寸已经达到了跨度16米，高度23米。对于圆形断面直径小于9米的，采用针梁模板，对于直径20多米的圆形断面采用了先底拱，后边顶拱的钢模台车，这样实现了地下工程混凝土衬砌安全快速的施工技术。

二、国家需求及科技前沿问题

（一）为了应对气候的变化，中国政府承诺，到2020年，非化石能源占一次能源消费比重要达到15%，常规水电占9%

到目前为止，我国水电装机容量达2.2亿kW，占技术可开发量40%，而经济发达国家达到70%以上，因此，必须发挥水电在优化能源结构，减少二氧化碳排放中的主力作用。初步规划到2020年水电装机容量将达到3.8亿kW，其中抽水蓄能电站5000万kW，新一轮水电开发高潮即将来临。随着经济社会的进一步发展，城市化进程的加快，将面临资源短缺、环境恶化和土地衰退的严峻挑战。有识之士提出“Think Deep”的号召，把地下空间当成新型的国土资源加以开发利用，从地下油气库、地下变电站、地下仓库、采矿工程，发展到城市地下空间的开发与利用，地下工程需求潜力巨大。

（二）创新前沿研究

根据我长期工程的实践，对于我们应该进一步研究的一些问题提出一些思考。

1. 基础理论

三维非线性有限元分析成果与实际监测数据差别较大，数值模型很难概化复杂的地质构造，尚需根据反演分析成果改进数学模型，提高数值计算分析精度，使地下工程支护设计从经验为主向理论与实践相结合转变。如溪洛渡电站地下厂房为厚层玄武岩，地应力中等，实测松弛圈仅0.4~0.8 m，高边墙最大位移为46.2 mm；锦屏一级电站地下厂房为大理岩，地应力达35 MPa，围岩强度应力比小于2，实测松弛圈8 m，高边墙最大位移为238.3 mm，均与数值分析有较大差别。岩爆机理的试验研究，限于试验手段、试验设备和理论模型的局限性，尚处于探索阶段。现有的水工隧洞设计理念和规范，未充分利用围岩的承载能力，致使混凝

土衬砌厚度和钢筋用量偏大,需加以改进。

2. 技术创新

地应力测试技术:目前地应力测试技术误差较大,需进行深入研究。工程物探技术:目前主要采用地球物理法和电场类法,应开展相应的理论和分析方法研究,提高准确性。计算机仿真技术:依据地质勘探资料,采用仿真技术,构建三维地质模型及数字工程信息,可预测传统的地勘工作未发现的不良地质构造,提前研究相应的对策措施。地质灾害防治技术:主要是指岩爆防治技术、大流量高水压突水、突泥防治技术及不良地质体的塌方预警预报和治理技术。工程安全监测技术:现行的地下工程安全监测,都是在开挖过程中定期采集应力、变形、渗流、渗压等数据,评价地下结构工作性态,采取相应措施。小湾水电站地下厂房开挖中,采用计算机信息技术和数码摄像监测技术,可动态演示地下厂房岩壁变形情况。此项技术尚存缺陷,需继续深入研究。

3. 新材料研发,包括:喷混凝土材料以及锚固技术和爆破器材等都跟地下工程现状是不相符的

总体而言,中国的地下工程需求潜力巨大,但是面临众多的挑战,主要是重大的基础研究不够超前,技术创新能力不强,新技术的采用动力不足,新材料研发能力薄弱,科研成果快速转化困难。但是,随着中国技术创新体系的不断完善,满足地下工程发展的国家需求,经过各种复杂工程经验的积累,中国地下工程基础科学研究和关键技术攻关将取得新的突破。

马洪琪,1967 年毕业于清华大学,水利水电工程专家,我国水利水电地下工程及坝工建设领域技术带头人之一。他制定了地下厂房洞室群施工规划和安全建设的基本原则和关键技术,研制出我国第一台具有自主知识产权的高压长斜井滑升模板,解决了高拱坝、超高土石坝建设的多项重大技术难题。主持或参加了鲁布革、广州抽水蓄能、黄河小浪底、长江三峡、澜沧江小湾、糯扎渡等 20 余座大型水电工程建设。共获得省部级以上科技进步奖 12 项,其中 3 项获国家科技进步二等奖,发表学术论文 50 余篇,出版著作 2 部。

非耦合装药爆破和岩土动力学

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我这次报告的题目是“非耦合装药爆破和岩土动力学”。谈两个问题。

非耦合装药爆破,这个事情受到大家关注还是在 1992 年。1992 年我们国家搞了一个很大的爆破,在珠海为了修建机场,由钱七虎院士带领他的团队搞了一个万吨的大爆破,这个大爆破非常成功。为什么会取成功?是做了很多研究,我想其中很重要的一点就是非耦合装药爆破的成功应用,解决这个问题最重要的在什么地方?一是在实施大爆破的时候,我们首先遇到的问题是不可以采用过去的满装填的装药,因为它会使得爆炸开裂的过程当中,炸药直接作用在岩石上,不能保证岩石整体开裂的尺度得到控制,抛掷的距离也很难控制。由于这个问题,采用非耦合装药爆破和岩土动力学就被提出来了。过去有很多研究效果比较好,在大爆破中怎么用,很重要的就是把非耦合爆破的原理吃透,最主要的有三个物理过程必须搞清楚。

我们的装药。这次采用的是硝铵炸药,这个装药爆炸要通过周围的空气,通过空气传播了一段距离之后,再撞到岩石的洞壁上进行反射,靠着反射的压力,使得岩石造成破裂,然后分散,所以它要解决这个问题,三个物理过程中的三个问题都要解决。一是爆炸以后,炸药本身所产生的爆、轰、破,在爆轰破的面上要分解,向空气中传入一个击破,这个作用是怎么样,特别是有什么新的特征要搞清楚。二是这样一个冲击波撞到岩壁上要反射,用我们过去的压力计算是不是可行的,因为它离炸药非常近,这个问题过去的理论是否还正确,也要回答。三是我们抛掷的距离要得到控制,松散的爆炸能够抛掷一定的距离,同时还有市政府提的一个要求,离开三公里的地方,希望不至于抛掷到农村去,造成当地群众春节过不成。这些严格的要求,促使我们的团队对非耦合装药爆破进行了很仔细的计算,把这些理论做了进一步工作,现在进行汇报。

现在装药爆破和炮轰波冲击波存在的问题,主要是岩孔的尺度究竟如何确

定。这时候爆破根据我们实际做的就是1.5米的样子,里面的装药量要由总方案来确定,相对的关系是比较确定的。我们事后看到爆破的效果非常好,大概看到就半立方左右,非常均匀、非常好。

为了解决这个问题,我们要研究一下:

第一个是物理过程,装药爆破它产生的空气冲击波是怎样的,在强行过程中有没有什么新的特征,应该是做柱状装药的,又是直接装药进行的爆破,而我们实际做的工作还是用球装药。同样也可以摸索出在近期爆炸中的特点,有1000、300和125克,就可以提供整个实测的波形,也能得出沿着不同装药过程中不同距离上的实测结果,这是一种情况。

第二,我们要考虑空气真实的性质,因为在近区,空气不可以再看作是理想气体,那么我们必须用真实的空气状态,是怎样的?有什么样的特点?当冲击波是4兆帕,也就是40个大气压的时候,它的温度达到2000℃,冲击波后面的分子,包括氧、氮都要离解,到了8000多的时候就要电离,这样空气就变成了多组分的一种气体,这个状态完全不遵守理想气体的特点,这样我们就需要了解它的特点是什么。根据美国原来研究的情况,当理想气体的反射压力达到8倍的时候,最高能达到8倍,如果这时供气,反射压力很高,反射的特点如果不充分的估计,也会造成我们对整个理论工作出现一些新问题。

下面,我就把我们计算所考虑的真实空气,怎么简化它的计算,我们的做法是把入射的冲击波,一直爆炸进去产生的冲击波可能的压力,和它正反射之后产生的反射压力进行一下准确的计算。通过计算我们发现一个特点,入射冲击波,如果是0.5兆帕的时候,它的绝对指数和反射冲击波的绝对指数是相同的,和理想气体一样是0.4兆帕。但是到了5兆帕的时候,它的绝对指数就是1.34,反射波的压力很大,已经7倍多了,就是38兆帕,它的绝对指数是1.3。如果20倍以上的绝对指数还是继续变化,但是它们彼此的入射波和反射波的压力还是比较接近的,绝对指数都是1.26左右。根据这样一个特点,我们就可以计算它的,以真实空气的计算方程把它列进来。我们国内也做了许多公式,但是经过比较,我们认为还是美国Brode提供的公式比较好,也提得比较早,我们验证了他的公式,那么就使用了这个公式,因为从非常高的高压和理想气体非常低的低压,他都能完整地给出他的结果来。

根据理想气体对空气的流体动力学和爆炸所产生的情况,可以进行一些计算,用到连续性方程,也可能用到运动方程和能量方程,对能量方程就用真实空气所提供,同时我们也给出它的基波条件来,这样就可以完成整个计算。

下面,我讲一下装药爆炸的波形和场地。我们看到提供的是球形装药的波形

和自由场分布的情况，实测的波形我们给的是比较大，在自由场测到的17兆帕的压力，反射的时候可以达到48兆帕，这个压力都比较大。我们发现一个特点，在近区爆炸的时候，原来按照一般的计算，国内外提供的计算，它的冲击波随着超压的变化是这样一条曲线，但是在近区的3倍装药半径内，它在入射的冲击波后面还紧跟着一个更高的压力，这个压力远远超过冲击波的压力。在1995年的时候，美国学者也报道了这种情况，原来所给出的计算公式是不对的，没有考虑到冲击波后面还有更高的压力波存在，我们可以通过试验和理论计算发现它。我们在计算过程中发现它确实在第一个冲击波之后又紧跟着更高的压力波，这个更高的压力波实际上是爆轰产物的压力波，它的高度可能远远超过100兆帕，甚至达到几百兆帕。

流场也可以看到，有一个基波在前面，随后跟着一个更高的。第二个物理过程是强冲击波的反射，这个反射应该在岩壁上发生。这个反射的压力要考虑冲击波在撞击到岩壁时所产生的反射，因此这个反射过程也要同时把反射压力的特点考虑到。针对反射的过程，用了一个模型，这个模型就是用 Polachek 和 Korotkov（Russian）提供的一种方法，这个给出了入射冲击波和入射角这两个相对反射压力的关系，这个就可以计算反射压力究竟和入射压力是什么关系。在正常的条件下我们发现差别非常大。正常结果的压力范围，入射压力很低，是0.000235兆帕。按照这样一个结果，我们进行规则反射的计算，获得了一个很好的结果。

从这个图上我们可以看到，给了不同的入射冲击波的压力，反射的情况下都可以算出来，最大的不是现在8倍的冲击波，甚至可以到12～13倍这样的大压力，和美国做的结论是一致的。但是我们做的范围更宽，在高压方面入射高了两个量级，低压方面又向下延伸了一个量级，而且我们还同时给出了一个动压的结果，这个动压的结果在估算细长杆类的结构破坏的时候是非常有用的。

根据这样一个计算结果，我们对岩石问题就可以做一个回答。在一个洞壁，特别是在1.5米的直径直接装药、大爆破的情况下，由原来所使用的装药，在爆炸以后，在岩壁反射的压力会达到多少？可能要高于500兆帕，炸药本身的反射压力可能是上万兆帕。实际上由于我们采用的非耦合压力，它所能达到边界的压力只有500兆帕，非耦合装药爆破工程成功的很重要原因是正确地选择了装药的参数。

这个计算结论是这样的，真实空气的反射可以超过8倍，可以达到13倍。另外在计算规则反射的时候，不是理想气体所给出的39度，而是有可能达到46度。非耦合装药爆炸，我们一般选取了装药半径2～3倍，效果会比较好。现在的工程实用上，经常采用的也就是这个样子。将来进行大爆破的时候优化要很好地算，也要根据岩石性质的不同，把实际装药的直径和空墙的直径比要更好地计算和设

计一下。

岩石动力学的计算,我们认为有装药的爆炸,这是一种因素,还要通过空气。考虑空气的性质,还有岩石这样一个边界条件,整个是一个流体,弹射性的耦合过程,三个物理过程按理说应该统一地进行计算,这样使得将来的预报可能更为准确。

下面用一点时间讲两个工程上的进展。我们的一项工作就是竖井的开挖,我们的岩石动力学,最近在国内有很大的进展,这是其中的一项。岩石竖井的开挖有一些新的思想得到了应用,就是传统的开挖基本上是从上到下进行装药爆破,然后除渣就从上面出去。现在新产生的一种思想在实践过程中得到成功的运用,可以从上面开挖,从下面在施工隧道里面除渣,这些在工程施工中很好地使用了,它的效率可以达到 8 倍,为什么会达到这么高的效率?在原来的洞石很难实现,因为空间非常狭窄,危险性比较大,这种情况为什么会做到这一点?最主要的是我们采用的是一次爆破成型法。我们是怎么样做这个事情的?我们一次爆破在洞里面一般是做 5 米直径的一次爆破,5 米爆破我们在平面上垂直钻孔,一次爆破可以爆 30 米,直径是 5 米,在这个空间里面直接打孔打得比较准。一次爆成了以后,将来怎么样让石头下去,我们采取了分区爆破,最中间的区域,我们是粉碎爆破,很好地设计这些孔,它不可能像其他的八型孔一样向上分散,它是就地粉碎,中部比较有特色的,是破碎孔,所形成的岩石力度大概是 10 厘米左右,最外是破裂孔,破裂孔形成的砾石的块度达到 50 厘米左右,最外的一圈是边界孔,就是用的预裂爆破的方法。

当我们在施工的时候,需要在做完一次爆破成型之后,接下来怎么把实渣向外运出?在中间用高压水冲下去,冲了之后中间的粉碎的岩粉就被冲下去了,外圈的砾石体就掉落下去,大块落的就又掉下去。在施工的同时,上面也进行喷锚,喷射混凝土、注浆、加固,都要同时进行,所以这个进度可以配合得非常好。这样一个工程已经进行得很多了,看来整个施工的效率还是比较高的。

再说一个新的管棚法,这在国内已经得到了充分运用,这项技术特别适合于软土。这是在沈阳新乐地铁车站做的,这是中国中建总公司、市建工程公司做的,这个做得非常好,管棚技术常用,一个管棚的直径不是几十厘米,是几米,一般我们认为用二三十厘米就可以了,但是它做的是 2.3 米,大概国内外一般都没有做这么大的,为什么要这样做?因为当地的土非常软,而且在市中心,所以这时候想了很多方案都不好办,最后采用了管棚技术,它的做法就是打了许多的平行的管道,我们看打成的管道就形成了这样一个空间,每个管子的直径都是 2.3 米,最后形成整个空间净跨度达到 26 米,它能够很好地完成 26 米的跨度软土中的工程,而且整个成现量控制在 2 米内,它的南北两方向是采用顶管技术做的,中间衔接

的误差也只控制在1厘米，这个工程应该说是非常成功的。

做好了以后，我们看到结构是一个导式站台，分出两层，一层是地铁，一层是候车室，看看它做的顶管的技术，就是这样进行的。施工的时候，在一个竖井里面把管一个个放进去，进行顶推，最长的顶推是110米，方向控制得非常好，最重要的技术在什么地方？就是管和管之间不是放在那里不管，而是管和管之间有横向和环向的连接，这个连接是如何做的？挖了一些方孔，钢板在里面焊接，这样使得整个管棚形成了一个整体的钢结构，而且这个钢结构做完之后还要灌注混凝土，这样使它有一个很牢固的混凝土结构。在没有做好之前，下面的洞并不挖，做好之后再开挖下去，成现量为控制在1米，最主要的就是它的结构针对性非常好。

通过这种情况来看，现在国内一方面面临着岩土工程的大工程问题，前边几位国外的专家都进行了介绍，中国现在大规模建设还在继续，过去几年重点发展的是交通工程，特别是铁路工程，今后几年可能更重大的是水利工程，在安全和能源使用上可能更好，目前水利工程占整个国民经济能量的比例还不够，应该是急速发展的方向，这时候有很多大跨度的问题，岩石类的许多问题还等待着我们继续研究。

周丰峻，出生于山东省黄县，防护工程专家。1961年2月毕业于清华大学，获学士学位。现任总参工程兵第三研究所研究员，河南省力学学会理事长，防护工程学会名誉理事，中国空气动力学学会理事，中国岩石力学与工程学会常务理事。周丰峻研究员长期从事和主持防护工程领域的研究工作，对于爆炸效应试验、爆炸理论计算以及防护工程抗冲击爆炸作用模拟等方面进行了全面深入的、开创性的研究，对防护工程的发展起了重要的推动作用。已经完成的重点项目和课题中，先后获全国科技大会奖两项，国家科技进步二、三等奖各一项，军队科技进步二等奖四项，对我国效应试验和防护工程技术理论发展有突出贡献。1996年以来根据面向21世纪防护科技总要求，主持开展了防护工程发展目标研究和防护工程技术专著编著工作，为防护工程发展提供了理论依据。1992年被批准为国家级有突出贡献的中青年专家。

1999年当选为中国工程院院士。

岩爆孕育演化机制、规律、预测与动态调控

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我的汇报以岩爆孕育过程为主线,介绍岩爆孕育过程的特征、规律、机制、预警与如何调控方面的研究进展。岩爆是高应力和大埋深条件下,地下工程开挖诱发的动力灾害。岩爆有多种类型,有应变型的,破裂面非常完整的,还有应变与结构面滑移型。结构面控制岩爆爆裂形态的类型。从时间上,有开挖过程中很快发生的即时型岩爆,还有时滞型的岩爆。不同类型的岩爆孕育的演化规律和机制是不一样的,我们现场通过钻孔摄像观察的结果表明,在岩爆孕育的过程当中,它会产生新的裂隙,也就是图中红色部分所表示的。开挖一天之后,很多红色所示的裂隙产生,没有贯通的新生裂隙两天以后贯通,如图中蓝色区域所示的,直至岩爆的发生。我们从裂隙的宽度来看,无论是开挖之前的原生裂隙,还是开挖引起的新生裂隙,它的宽度都有可能增大,也有可能减小,这意味着在岩爆的孕育过程有张拉破坏、剪切破坏,甚至二者的混合型破坏。从微震信息的演化规律来看,大多数即时型岩爆,微震事件数持续增加,空间在不断地集中,而且它在发生之前没有明显的平静期,多是轻微岩爆、中等岩爆、强烈岩爆,表明岩爆越强烈,微破裂事件越多,而且能量越大,这是一般性的规律。在能量释放方面,能量释放持续在高位,有下降的趋势,在岩爆发生之前有增加的趋势。非弹性体积变形会持续增加,而且有突然增加的趋势。

岩爆孕育的机制是什么呢?通过我们提出的分析方法对监测到的整个孕育过程中微震事件进行分析,我们发现对于即时型、应变型岩爆主要是拉伸破裂事件引起的,从观看爆坑的形态,也能看到非常光滑完整的爆坑。我们可以给出每个微震事件产生的裂隙的长度及其产状,我们看到新生裂隙的产状的演化特征,如果投影在断面图上可以定性分析到爆坑如何形成,岩片不断弹射出来,形成爆坑。即时性应变结构面滑移型岩爆:多数微震事件是拉伸破坏引起的,除此之外还有剪切破裂事件,还有绿色所表示的混合破裂事件,爆坑的形态比应变型岩爆

的更为复杂。从破裂面的形态、长度来看，变化比较大，沿着隧道投影图来看，沿着原来的硬性结构面有剪切滑移作用，从隧道断面来看，也可以看到爆坑大致的形成过程。

这样的一个规律是否有自相似性？我们对它进行了时间分形行为的研究。从这两个图可以看出，这六个不同等级的岩爆，包括轻微、中等和强烈岩爆，在岩爆孕育过程中，时间分形维数都在不断增大，到发生的时候在减小。从微震的能量释放方面，随着能量释放的增加，分形维数也在增大。如果一个区域多次发生岩爆，其孕育过程同样存在着分形特征。在一个区域内，一天内发生的岩爆次数的增加，能量分形维数也在增加，而且随着平均能量释放的增加，能量分形维度也在增加，这表明即时型岩爆孕育过程有一定的自相似性，这为后面基于微震演化信息的演化规律所建立的岩爆预警提供了科学的依据。

时滞型岩爆：在开挖过程中，它的孕育规律和即时型岩爆大致相当，但其之后存在明显的一个平静期，很少或者没有微震事件发生，平静期可以有几天，甚至几十天，这样对岩爆的预警产生了更大的困难。从能量的演化规律和非弹性体积变形演化规律来看，同样存在这样一个平静期；从机制上，除了拉伸破裂事件以外，还有多个剪切事件，以及多个绿色所示的混合破裂事件。从微破裂事件的分布来看，时滞型岩爆比即时型岩爆要更加复杂，从爆坑的照片来看也是这样。

在这样一些规律和机制的认识基础上，如何进行合理的岩爆风险估计和预测预警。风险估计和预测预警，希望在开挖之前有一个估计，在开挖的过程当中如何根据实际的地质条件和微震实时监测的信息进行岩爆的即时预警。风险评估和预警力争能够做到定量化，包括岩爆可能发生的区域、等级及其概率。我们更关心岩爆发生断面的位置及其爆坑的深度，这样使岩爆防治具有更好的针对性。从这个图可以看出，岩爆可能会发生在顶板、左拱肩、右拱肩、左侧墙、右侧墙、左拱角、右拱角，甚至底板开裂。这样一来，我们需要给出断面具体位置上岩爆风险估计。岩爆等级的划分有很多方法，包括国家标准。我们在前人工作基础上，重点对支护破坏程度和工程影响程度给予了具体的划分方法，并且对声响特征、围岩破裂特征和破坏深度，以及支护破坏程度和工程影响程度等四个方面分别进行评分，根据总分的多少，给出岩爆的等级：轻微、中等、强烈、极强。利用微震能量指标，也建立了一个岩爆等级划分的方法。有了这样一个等级，对岩爆的预警就有了一个基础和可以参照的指标。首先在开挖之前要对岩爆的倾向性做估计，我们建立了 RVI 新的指标，它考虑到水平与垂直的应力比系数、开挖洞型、应力偏转以及矿物成分、含量、平均颗粒尺寸，起裂强度、损伤强度，还有开挖一起引起的包括单双向开挖、单多洞开挖，以及地质构造方面的褶皱、断层、硬性结构面等等，综

合对岩爆的倾向性给出 RVI 的评分,基于 RVI 评分我们可以通过大量分析,统计得出其与爆坑深度的关系。

第二个方面,我们关心隧洞洞室开挖以后,其断面位置上不同处围岩体的破坏程度。所以,我们提出了破坏接近度的新指标,可以给出不同位置上的围岩破坏程度。下台阶开挖以后会引起围岩损伤程度、破坏程度的增加。对岩爆来说,是有能量释放的问题,局部能量释放率可以给出围岩不同部位破坏时能量释放的大小。而且下台阶开挖以后,局部位置可以看到危险性在增加。在这基础上,再考虑到体积,可以得到该区域总的释放能量,有这样一个指标可以对岩爆断面上可能的风险给予估计。

第三个方面,是基于微震信息演化规律的岩爆预测预警。我们现场监测获得了微震事件随时间演化规律,包括微震事件及其每天的增长速率、能量及其速率、非弹性体积变形及其每天变化的速率。这六个指标,每个指标分别建立隶属度函数,包含岩爆四个等级:强烈、中等、轻微,甚至无岩爆的隶属度函数。一个实际数据输入后,可以得到这六个指标所隶属度的概率,将其相加起来,就可以得到每个等级岩爆可能发生的概率。这是基于微震信息的岩爆预警。如果有明显的前兆规律,岩爆预警能给出的比较好。但是有些情况下,尤其是时滞型的岩爆,前兆规律很不明显。我们考虑到既然有大量的工程实例在手,是不是可以基于工程实例学习的神经网络方法。比如说考虑到埋深、应力比、区域构造、强度应力比、岩体完整性、支护效果等等,建立其与爆坑深度和岩爆等级的关系。这里给出八个例子表明,在不同的深度、不同的地质条件下,神经网络可以给出好的结果。这样一来,在开挖前,用 RVI、神经网络和数值分析方法,可以预计爆坑的深度和岩爆等级,以及断面上哪个位置岩爆风险可能比较高。然后,在开挖过程中,根据现场实际揭示的地质信息,可以及时运用这三个方法,对预测结果进行及时的动态更新。在实际应用过程中,在这一区域得到的微震演化信息,用刚才介绍概率的方法,可以用前几天的数据来预测这个区域岩爆的等级和概率。

在岩爆预警之后,最关键是如何防止和避免岩爆的发生。针对岩爆孕育过程提出了相应的动态调控的方法,利用前面的方法可以对岩爆的区域和等级进行风险估计。我们考虑是不是可以有三步走的策略?第一步是减少能量释放,通过不断优化开挖断面的形状、尺寸、台阶的数量、开挖的速率、导洞形状、尺寸、超前距离等等,通过这样的优化,尽可能减少开挖过程中的能量聚集水平。如果需要考虑预释放和转移能量,通过优化应力释放孔位置、长度、间距,以及应力和能量集中转移优化,尽可能一定程度上预释放和转移一部分能量。如果还不行的话,就是走第三步:吸收能量,及时喷混凝土增加岩体的延性,通过锚杆等支护系统的参

数优化来尽可能地吸收一定的能量。当然可以通过一些实例的分析得到开挖与支护措施优化建议,在开挖之前进行设计。在开挖过程当中,根据新揭示的信息,可以做进一步开挖和支护的调整,以及基于微震信息的演化规律,进行开挖支护过程的动态修正,尽可能地降低和避免岩爆的发生。

对于同样的断面尺寸,圆形硐室有利于减少岩爆的风险。对于同样直径的深埋隧洞,在降低岩爆风险方面,台阶高度小的要比大的好一些。室内的实验结果表明,在一定应力范围内,随着卸荷速率的增加,岩石强度在增加。这意味着一旦岩体发生破坏,它释放的能量就会更大。随着卸荷速率的增加,剪胀角增加得很快,这表明可能产生更多的宏观裂纹。所以要适当控制开挖卸荷速率,来减少岩爆的发生风险。关于开挖步长的影响,从能量的角度来看,随着开挖步长的减少,能量在减少,但是塑性区域变化不大,这表明合适的开挖步长和速率有利于减少岩爆的发生。以局部能量释放率和 ERE 为指标,以粒子群和数值计算进行开挖参数的优化,可以获得满足工程施工可能和工程要求的开挖方案。

实验结果表明,在单轴压缩情况下,硬岩的脆性比较大,施加小的围压力,延性有一定的增加。这表明即时喷层可以提供一定的表面围压,来提高围岩的延性。如何设计锚杆的参数? 基于爆坑深度和超过破坏范围的有效锚杆长度,可以给出锚杆的长度设计。单位面积锚杆所吸收的能量与单个锚杆所吸收的能量、锚杆的间距、面积相关。对于一个支护系统来说,它到底能够吸收多少能量,包括锚杆、钢筋喷射混凝土、永久性锚杆等,给出相应的能量计算方法。只要永久性锚杆的长度达到围岩长期安全系数等于 1 的边界,即可。单位面积内支护系统的吸能要大于岩爆发生时单位面积释放的能量,这样的能量从一定角度可以基于局部能量释放计算。为了现场使用方便,针对四个不同岩爆的等级,分别对地质勘察、开挖和监测预警、支护给予了相应的对策,包括开挖的优化、支护设计的优化、性能的要求,是不是要形成微震监测等等给出了建议。

这样一套方法先后在锦屏二级水电站深埋隧洞和排水洞进行了成功的实践。锦屏二级水电站四条深埋引水隧洞,单洞长 16.7 公里左右,最大埋深是 2525 米。排水洞 7 米左右的直径,在 2009 年 11 月 28 日发生了极强岩爆,在这之后对岩爆的现场监测预警给予了高度的重视。我们的工作一个是在前面研究的基础上,建立一个强烈与极强岩爆的 TBM 开挖洞段上导洞开挖方案,通过对 TBM 全断面开挖、中导洞开挖、不同断面尺寸的上导洞开挖方案进行比选和优化,从降低能量聚集水平的角度,建议了上导洞开挖的方法。从现场微震监测结果来看,这一边是有导洞开挖方案,这一边是没有导洞开挖方案;从微震事件的演化,以及能量的演化来看,有导洞的明显得到改善;从岩爆事件发生的速率和大小也可以看到这一

点。从岩爆实际发生的情况也可以看到,有导洞的情况下,这一区域发生两次轻微岩爆;在没有导洞的情况下,这一区域发生了多次轻微岩爆、两次中等岩爆和一次强烈岩爆,从微震事件的大小也可以看出这样一个规律。这表明导洞取得了一定的效果。

强岩爆洞段应力释放孔的深度和位置确定。我们的计算结果表明,掌子面前方,应力释放孔长度可在 6 m 左右,断面位置上可以是 9 m 左右。对 3 号 TBM 2 -1 实验洞的现场观测结果表明,TBM 开挖诱发的声发射主要集中在断面的 9 m 区域和掌子面前方的 6 m 左右的范围内,这说明现场的结果和计算结果比较吻合。优化建议了不同等级岩爆洞段支护参数,分为轻微、中等、强烈、极强岩爆,包括初喷、锚杆、钢筋网以及护坑等分别进行了建议。支护系统的性能计算结果表明,仅仅靠支护很难解决锦屏大埋深情况下的岩爆风险控制问题,也就表明需要通过开挖优化策略来降低能量的聚集和释放。对强烈岩爆和极强岩爆,给出了不同类型的锚杆长度建议,基本上都被设计所采纳。在典型洞段进行了岩爆的微震监测和预测预警,我们开始工作的洞段埋深在 2150 ~ 2525 m,涉及 1、2、3、4 号引水隧洞和排水洞,在这个工作取得较好的效果之后,因施工单位的强烈要求,增加了对 3 号、4 号引水隧洞和排水隧洞 1600 ~ 2100 m 埋深的洞段进行了微震监测和岩爆预警,整个监测预警的总长是 12. 4 km。

总体的效果是,微震连续监测期间发生了 275 次岩爆,预测并发生岩爆有 243 次,占实际发生岩爆次数的 88% 左右,其中岩爆预测的区域与实际发生的区域相一致的占 85. 4% ,区域有点差别的占将近 3% 。这可能有几个原因:一是预测有偏差;二是预测这个区域有高等级的岩爆,加强支护后,岩爆转移到其相邻区域支护比较弱的区域发生;三是前兆规律不明显。基于微震信息的岩爆预警,前兆规律不明显而未预测到的岩爆有 32 次,占 11. 64% ,少数是强烈岩爆,多数是轻微岩爆,还有接近应力型塌方等等。这样预警之后,通过调整开挖速率和加强支护,来预防岩爆的发生,或者降低岩爆的等级。这里给出三个实例,第一个例子,我们预警是强烈岩爆,通过调控之后降为中等岩爆。随着开挖的进行,微震的事件数和能量在不断地聚集,我们在 9 月 8 日预警是强烈岩爆,开挖进尺由 9 月 8 日的 16. 25 m 降到 9. 55 m,而且局部增加了 6 m 长的系统锚杆,发生了中等强度岩爆。在 10 日掘进速率又降到 6. 25 m,发生了中等强度的岩爆,随后这个区域得到很好的控制。第二个例子,预警是中等岩爆,结果是没有发生岩爆。随着微震活动性不断增加,在 10 月 28 日预警是中等岩爆,建议补充系统锚杆,三天连续加强系统支护,微震活动性得到很好的控制,也避免了岩爆的发生。第三个例子,在隧洞贯通之前,两个掌子面相向掘进,何时改为单相掘进? 我们的数值计算结果表明,随

着两个掌子面不断掘进,应变能不断地集中,岩爆的风险不断增加。10 月 25 日,我们预警在 2 - 1 - E 掌子面附近,在两个掌子面贯通之前有发生中等岩爆的可能性,并建议停止这个掌子面的掘进,改为仅由 1 - 1 - W 掌子面单向掘进,并加强支护。一天之后果然发生了中等岩爆,我们强烈建议改为单掌子面掘进,然后微震活动性得到很好的控制。29 日,施工单位又恢复 2 - 1 - E 掌子面的掘进,它的微震活动性增加。30 日,仅仅 1 - 1 - W 掌子面掘进并加强支护,直至掌子面贯通,取得较好的效果。总体来说,对整个 241 个洞段累计洞长 7.6 公里进行了不同等级的岩爆预警,避免了 135 个强岩爆洞段,累计 4 公里不同等级岩爆的发生,降低了近 13 个洞段 400 多米长的不同等级岩爆的强度。在整个区域中,微震监测和岩爆预警对岩爆的防治、指导施工发挥了重要的作用,各监测洞段施工过程中,未发生岩爆造成的严重后果,确保了施工过程中人员与设备的安全和工期,2011 年 11 月 4 条引水隧洞和排水洞都贯通了。

总体来说,通过现场实时综合观测实验,揭示了两种不同类型的岩爆孕育过程中裂纹、变形、波速、微震信息和演化规律及其机制,在这个基础上提出了信息动态更新岩爆风险评估和预警方法,包括 RVI 方法、数值方法、工程实例类比神经网络方法,以及微震信息演化概率方法,在这个基础上考虑动态调控的方法,也就是三步走的策略,减少能量聚集,预释放和转移能量、吸能,再加上微震信息动态演化规律的动态调控方法。在这个过程中,得到相关单位和项目的大力支持,而且通过学术交流,也得到更多的鼓励,特别要感谢二滩公司、华东设计院、施工单位、矿山等一起合作,使这个项目进展非常的顺利。

冯夏庭,1964 年 9 月出生,籍贯安徽潜山县,汉族。现任中国科学院武汉岩土力学研究所研究员,博士生导师、岩土力学与工程国家重点实验室主任,国际岩石力学学会(ISRM)主席。1986 年 7 月毕业于东北工学院采矿工程专业,获学士学位,并免试推荐攻读东北大学岩石力学专业硕士学位;1992 年 4 月获东北大学岩石力学专业博士学位。1992 年 1 月在东北大学先后任讲师、副教授、教授。曾任南非金山大学 Senior Research Officer,日本资源环境综合研究所客座研究员,日本 ITIT 特别研究员。1998 年 2 月入选中国科学院"百人计划",受聘于中国科学院武汉岩土力学研究

所。2001 –2005 年曾任副所长、所长。

冯夏庭提出了智能岩石力学这一新的研究方向,并开展了系统而深入的研究。作为第一获奖人获国家科技进步二等奖 2 项,省、部自然科学奖一、二、三等奖分别 1、2、1 项,获得省、部级科技进步奖一等奖 1 项。出版专译著 8 部,参编教材和论文集 2 部。在国际权威学报、国内核心刊物和国外学术会议上发表学术论文百余篇,其中被 SCI 收录 70 余篇,EI 收录 200 余篇,应邀在国际、国内学术大会上分别作大会报告 20 次和 36 次,被国外作者的 SCI 收录的论文引用几十余次。

冯夏庭曾获得“光华工程科技奖”、“中国青年科技奖”、“沈阳十大杰出青年知识分子”、“辽宁省青年先进科技工作者”、“湖北省五一劳动奖章”、“湖北省十大杰出青年”、“湖北杰出专业技术人才”、“湖北省劳动模范”和“首批新世纪百千万人才工程国家人选”等,2002、2009 年被国家科技部聘为 973 项目首席科学家,2003 年获国家杰出青年科学基金资助,2004 年获中国科学院杰出青年称号。

长江地铁隧道之间的联络通道的施工监测预警

丁烈云

东北大学

我将课题组就长江地铁隧道之间的联络通道的施工监测预警工作，从工程管理的角度来谈谈我们的体会。

一、首先介绍项目的背景

（PPT 对照讲解）武汉地铁二号线越江隧道从汉口的江汉路到武昌的积玉桥，全程 3100 米。根据地铁设计规范，每隔 600 米，两个隧道之间应该要设联络通道，作为逃生通道。这样地铁越江段要设五个联络通道，其中两个联络通道正好处于长江的江底，因此它是处于高承压动水施工环境，风险非常大，稍有不慎，后果不堪设想。

一个典型的联络通道施工安全事故，是上海的穿越黄浦江的隧道联络通道的施工事故，由于冷冻失效，造成了隧道 270 米的塌陷，以及上部房屋和防洪大坝的严重破坏，总共直接经济损失达到了 6 亿元。据太平洋保险公司分析的结果，如果不计上海地铁四号线事故，保险公司的赔付率是 60%，如果算了这个事故保险公司的赔付率就达到了 1000%。

在涉及穿越长江的隧道联络通道的设计上，一般尽可能避免设联络通道。如正在运行的武汉长江隧道，这是一个公路隧道，设计时有设联络通道的方案，但上海四号线的事故使业主心有余悸，最后，反复论证，决定还是把联络通道取消，采取设置纵向逃生道的方案。因为隧道的直径比较大，在路面下面还有一些空间，将这个空间中作为纵向的逃生道。类似的设计还有南京长江隧道、日本东京湾的海底隧道也是采取这种设计方案。

武汉地铁二号线越江隧道内直径 5.5 米，避免不了设置联络通道。有二号、三号联络通道，三号联络通道下面还有一个水泵房，加大了施工的难度。联络通

道所处的地质条件为,洞身处于含砾中粗砂,下面是中风化泥质粉砂岩,上面是粉细砂。从江面到联络通道的距离,施工时达到 37 米。隧道管片厚度 350 毫米、两个隧道中心之间的距离 13 米,联络通道的净空尺寸长 5.5 米、高 2.1 米、宽 2.55 米,下面的水泵房的体积大概有 10 立方米。

联络通道采取冻结法施工。沿着联络通道的土体的周围打一圈冷冻管,把冷冻管通过排管接到冷冻设备,通过冷冻设备和排管向冷冻管里面输送冷冻液,也就是盐水,使得联络通道的土体冻结,从而形成强度高、防水好的冻结帷幕,这样就可以用矿山法进行联络通道的施工。冻结帷幕的设计厚度为 3.1 米,冻结帷幕的平均温度小于零下 10 度,冻结时间是 45 天。

联络通道的施工风险主要有三个:第一个风险,武汉的联络通道号称是目前长江最深的联络通道,因此施工经验的储备还不是太足,在高承压水以及动水条件下,砂层冻结效果直接关系到联络通道结构体的安全。第二个风险,由于施工前要进行冻胀,冻胀好后再进行开挖,再进行支护,联络通道施工完后解冻,在整个过程中,联络通道的土层、结构体,既有隧道等受力体系在不断地变化,因此风险也在不断地演化。也许在某一个阶段某个部位是薄弱环节,但是在另一个阶段,薄弱环节又转移到另一部位,风险具有迁移性特点。第三个风险,工人在江底下施工,一旦出现紧急情况,怎么样能够让这些施工人员紧急疏散,在第一时间逃生。

二、多场耦合实时感知系统的建立

控制上述风险的一个有效措施就是加强施工过程中的安全信息管理工作,包括信息获取或监测、传递、分析和使用。获取施工安全信息最好是在线监测,通过全面地、实时地和充分地掌握工程安全信息,使得工程的安全风险处在可控之下。另外,对于施工人员、管理人员,他们所在的位置也应该进行跟踪定位。通过监测冻土的安全信息,结构体的安全信息,并与施工人员共享信息,一旦出现紧急情况,马上通知管理人员和施工人员。

我们的监测系统实际上是一个实时的感知与预警系统。其基本思路是,通过对联络通道处的土体、联络通道结构体和既有的隧道结构体布置传感器,及时地感知施工安全信息;同时对施工人员也设置可移动的无线传感器,然后通过工业以太网,或者是 3G 网络,把感知到的信息及时地传递给信号解析仪器,以及安全分析仪,一旦出现风险马上通知管理人员和施工人员,这样就形成"感、传、知、控"的实时感知和预警网络。

施工安全信息感知主要是结构体的安全信息的感知,包括联络通道的土体冻

结效果安全感知。对联络通道的冻结监测,主要监测两方面数据,一是温度,另一个是应力或应变。目前,还是传统的监测手段,对于温度监测,采取电热耦传感器;对于土体的应变或者是应力,采取土压力盒进行冻胀面监测,或者用电阻应变片进行变形监测。这种监测存在一些问题,一个是监测温度的传感器所布置的点与监测应变压力所布置的点处于不同的位置,所以不能进行耦合监测;还有采取的是人工的监测,所以不能进行在线的、实时的监测;我们希望知道冻土深部的情况,这些传感器很难布置到冻土的深部。因此,我们选择另一方案,即采取光纤光栅传感器进行安全信息的感知。它有一些优点,一是能够进行在线监测,二是在同一个点可以同时监测不同属性的安全信息,可以进行耦合监测,三是防水性能也比较好。我们构建的实时感知系统主要包括三个方面:一是数据的实时采集,通过光纤光栅传感器采集信息,并传递给光纤光栅解析仪;二是数据存储分析系统,解析仪把所解析的位置和所测得的这些数据,传递给数据存储分析系统,由工控机进行分析;三是独立的供电系统,为了保证整个系统的安全运行,还有一个独立的供电系统,当断电的时候,独立的供电系统自动工作。

冻土的光纤光栅传感器的布置。光纤光栅传感器布置的难点是怎么置入到冻土的深部。这是光纤光栅传感器监测冻土时的布置图。传感器的布置更多是工艺过程,前面是一个钻头,传感器固定在无缝钢管的壁内,把钻头打进土体后,再把装有光纤光栅传感器的钢管接上去,然后是另一根带有传感器的钢管,中间通过光纤线缆来进行连接。这是现场制作的情况,这是整个钢管生产安装过程。

联络通道初期支护以后的传感器布置。主要布置在三个地方,一是拱顶,另外是联络通道两侧初支的结构体上。另外还需要监测现有的隧道结构安全状况,我们把隧道结构体监测布置到三个管片上,956、957 和 958 环,每个环布置 3 个或 4 个传感器。选择 SM130 解调仪,把传感器接到解调仪的四个通道上,调试后就可以进行监测了。

三、感知信息分析

冻结管的温度监测数据分析。积极冻结时间从 2012 年 1 月 18 日开始,到 3 月 6 日,一共 40 天。联络通道土体在积极冻结时间内,温度的变化有这么一个规律:一是在冻结的初期原始的温度在 12 ~ 16℃,基本上是稳定的。在初期阶段冻结温度变化速度很快,以后趋向缓慢,最后平均温度逐步稳定在 -8℃到 -10℃之间,达到了施工要求。只有一支传感器的温度稍微高一些,初始温度为 16℃,冷冻后也有 5℃。原因是这支传感器接近隧道体的管片,与外面空间的热交换比较大。从这里可以看到,在冻结施工过程当中,往往冻结体与隧道之间的连接处是

薄弱环节。二是同一点冻结管的应变情况,应变跟温度的变化有相似的规律,也就是说在冻结的初期,应变的变化比较大,以后逐渐缓慢,最后逐步稳定。从这里也可以看出来,冻结点的温度和它的应变具有一定的耦合效应,呈正比的关系。

这是冻结帷幕形成过程的动画。可以看出,冻结胶圈形成的时间大概是 20 天,在 40 天以后,冻结帷幕的冻结壁达到 3.5 米厚度,设计要求是 3.1 米,而且温度达到了 -8℃,符合施工要求。冻土的中心温度从左边向右边呈升高的趋势,它提醒我们在维护冻结的施工过程中,应该加强右线冻结工作。

从冻土位移分析图可以分析冻土位移规律:最大位移处于隧道的上方,隧道两侧的位移比较小。这是隧道起到的刚性约束作用,由于孔隙水向上迁移,引起上面地应力增加。

联络通道初期支护的情况。在喷射混凝土前,应变的变化是缓慢的,用高强混凝土喷射后产生了集中的应力变化。

这是既有隧道体的变形分析,表示第 957 环管片应变的三条线变化比较大,原因是该管片处在冻土帷幕与非冻土的交界处,形成应力集中情况。另外有两条表示 k 管片应变的曲线波动比较大,K 片是该环管片最后安装上去的管片,由于体积比较小,所以容易出现应力集中。

将设计的预警值也赋存系统,就可以预警了。

接下来的问题是,我们把结构体的预警信息怎么做到共享,即应该指导人的安全行为。为此,还要建立一个传感系统,也就是人的移动定位传感系统。这是人的移动定位传感系统布置图,下面是隧道,布置一个个阅读器,通过阅读器识别施工人员位置,通过风井传到地面,地面有一个无线 AP,把信号传达到控制中心,也就是项目部。每个人身上携带的识别卡,也就是移动的 RFID,它可以通话,可以报警,也可以进行定位。定位算法有两种,一是根据信号的强弱衰减来确定阅读器与定位器之间的距离;二是通过不同信号达到的时间差计算阅读器与定位器之间的距离,定位精度为 1 米。在中心控制室可以看到施工人员所处的位置,一旦由光纤光栅传感器感知到施工警情,同时通过无线传感器实时通知施工人员和管理人员及时应对。

这是地铁越江隧道联通道竣工后,中央电视台的报道。

后续研究:进一步优化深部冻土感知工艺方案;探讨水平冻结的冻胀融沉规律与灾害孕育机制,以及冻胀融沉作用下的隧道管片力学响应与损伤机理。

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主要研究方向为工程管理信息化、风险与安全管理。国家“十二五”支撑计划项目“地铁工程安全控制关键技术研究及应用示范”负责人。主持完成的“数字轨道交通工程集成建设关键技术及应用”获国家科技进步奖二等奖、“基于精益建造的建筑工程质量协同管理技术与应用”获湖北省科技进步一等奖，“地铁工程施工安全风险识别及预警技术研究”获教育部科技进步奖一等奖。

主要学术职务有：教育部科技委委员及管理学部副主任，中国建筑学会工程管理研究分会理事长，住建部工程管理专业评估委员会主任；《土木工程与管理学报》编委会主任，*Automation in Construction* 等国际学术期刊编委。

南非 Witwatersrand 盆地矿山开采和微震活动的监测、孕灾机制与减灾策略分析

Kevin Riemer

南非金田公司

我想利用这个机会,给诸位介绍一下我们在深部金矿开采过程中碰到的一些工程地质灾害问题。

我今天演讲的主题是南非矿山开采概况、开采技术及地震影响。我们已有120年的金矿开采历史,世界已开采的黄金有一半以上来自南非。在金矿开采过程中,我们遇到了许多地震事件。下面,我首先解释一下灾难和风险两个概念。那我们如何来定义灾难和风险呢? 灾难,通常是指那些具有潜在危险并造成破坏和损伤的事情;而风险是指灾害发生的概率。当我第一次来到中国,我就听到这样一句谚语'鲨鱼无论在哪里都会咬人'。以我们南非长达6米的大白鲨为例。如果你在水中,被白鲨咬住,你就没命了,这就是灾难。而风险,则是这种事情发生的概率,如果你在岸上,大白鲨怎么也不会咬到你,风险就是零;如果你在水中,风险就会增大。下面,我想介绍一下地震灾害的两种定义。刚才我所讲的是非洲国际风险控制委员会的定义,另外一种是联合国灾害救援组织的定义。后者主要和地震相关,他们主要关心建筑遗址的保护。因此,灾难被定义成地震或飓风发生的概率,而风险是指建筑遗址破坏的概率。对此,每个国家都有一些微小定义差异,不过,他们都会使用灾害和风险两个概念。

南非矿山开采的规模是我在这次论坛中听到的、已介绍的矿山工程中最为庞大的工程。我们部分矿山长达数公里,深达四千公里。我们不得不采用不同的矿井系统,需要沿着矿脉走向进行开采,而该走向通常绵延数公里。比如,在1970年,我们的黄金产量达到顶峰的时候,我们所开产的一千吨黄金,是从28平方公里矿脉中提炼出来的。这里,我们碰到了两大问题,一是高温,另外一个是地应力问题,后者通常表现为岩爆和地震。

南非的安全统计数据不怎么好,我想和诸位回顾一下历史。过去,南非的死

亡率相当高,其中每年有 800 多人死于矿难。这个数据现在有所降低,这也许是因为矿难数量减少,因为我们能够部分控制岩爆。如果我们仔细观察事故统计数据,今天,许多人会质疑‘每千人事故率或每百万工作小时事故率’,从历史数据表来看,事实并不总是这样。因为,我们会看到这些不同数据,有些是表示实际死亡率,有些是每千人死亡率。我们需要结合两个数据表来得到自己的灾害判断。为了评估灾害,我们需要了解事故发生数,及其所属类别,然后进行安全统计分析,进而进行风险评估,并采用一些防灾措施进行预防。

过去,我们面临的最大问题是岩体崩塌和岩爆。以 2010 的统计数据为例,其中 38% 的南非矿山事故是由于岩体崩塌和岩爆引起的。我的好朋友 Alex Mendecki 2001 年曾经尝试将技术、灾害机制理解程度、经验引入到一个数学公式中,使其反映灾害和风险研究的进展。基于这一设想,我想提及微震监测策略,这也许和中国的情况不太一样,因为我认为中国矿山灾害问题主要存在于隧道工程,但是对于我们来说,监测策略是不错的控制灾害的方法。通过监测,理解灾害机理,并采用相应的措施控制灾害风险。监测可以通过两种方法来实现,一种是利用我们自己肉眼观测,这种方法,具有较大的主观性,会带来较大的偏差,不同人可能会得到完全不同的看法。另外一种,是利用技术,记录数据来监测并分析。利用该方法,我们可以科学地分析并讨论同一问题。这也是过去几十年南非所采用的监测方法。技术的发展日新月异,我们必须时刻跟上技术发展的步伐。例如,我们现在碰到的另外一个困难就是无法找到 1910 年的数据和现代的数据进行对比,因为这样会产生兼容问题。因此,当你们在进行监测时,我希望你们尽量能够保存好你们的监测数据。如果你打算进行监测,一般需要设定三个不同阶段,行动、标准、条件,这三者的相互结合才能实现监测目标。比如,如果你准备矿震监测,你就要在行动前依据标准和实际条件,制定清晰的行动方案。如果你准备玩高尔夫,你需要打一手好球,执行标准就是美国公开赛的相应规则,而前提条件是需要有资金支持,拥有足够时间进行训练。因此,为了实现目标,我们不仅要有实现计划的动力,还需要有详尽的计划,并根据实际情况,进行方案讨论、细化。

现在我们回头看一下南非的情况,我发现我们最早的监测目标是由 Klokow 和 De Jongh 于 1982 年提出的短期、中期和长期的监测目标。短期目标是确定岩体坍塌位置以便进行营救和管理。这一目标在我们的科研项目 SIMRAC 中得到继续,不过,我们同时增加了预防、控制和预警系统。另外,我们也需要定义好监测范围。我认为我们使用的是一个非常大的监测系统,而在中国,人们通常使用微震系统,可能是每天监测 1000 到 10 000 个事件。在与 R. Durrheim 共著的关于南非的 Artlant 监测系统的论文中,我们区分了 7 种不同的阶段。如果你查看一

下南非的监测系统，其中50%是由一套拥有6个监测站构成的监测系统组成。现在，听上去这个系统不是很好，这主要是现代的技术发展太快。在南非，我们有一个著名的矿难分界线，我称它为Coalbrook线。这是我们南非一个特大矿难，其中435名矿工由于矿柱坍塌而死亡。自从那次特大矿难之后，南非加大了监测管理。从此，我们进入了一个监测系统时代，并和IMS以及XISS一起开发了可以定量分析的监测系统。

上面提及的SIMRAC研究项目主要目标是实现现场监测并解释数据，但从1970年之后，我们对系统目标进行了调整，我们更专注于岩体坍塌位置的确定和营救的管理方法，这也变成了我们一大特色。我们有3个监测参数，事故数、使用系统数量，A~D不同抽样及抽样比。大约从1960年起，随着技术的快速发展，我们可以记录更多的事件，并进行解释，这加深了我们对矿震的理解。这也和全球地震研究进展同步。我们同时注意到，上世纪60年代计算机的出现和发展，帮助我们更好地理解地震运动、地壳变化、震源机理。网络设计和敏感性是科学监测的两大主要问题。你需要设计并确定你所需要什么样的敏感度和地震测量精度，并将这些数据输入到监测系统进行维护。早期的系统，并没有这些功能，比如Artlant系统。图中的红色环表示地震张量示意图，它们分布在矿墙体的一侧，这些环和地震发生地非常接近，但是在矿墙体的另外一侧，则吻合不好。这就是位置精度问题。值得欣慰的是，现在，我们有非常强大的软件，并评估出P波波速测量误差。这样我们可以对我们的监测系统进行准确的精度和敏感度分析。在此，我给大家介绍一个在10到12公里范围内，安置了40到50个地震监测站的系统（如图示）。

我们现在用的技术可以进行地震事件处理，得到三维地震示意图，波传播时间曲线并以此确定矿震位置，并得到震源参数，通过地震波波形分析，努力探求灾害产生的机理，并确定灾害发生的时间。大家可以看到，在我们的表格中，每天下午都有一个高峰，这个实际上是我们爆破的高峰，很多爆破都是6点钟进行，因此仪表上也有这个形状。我把这个表格拿出来主要是让大家了解一下其中的机理。从1973年到1981年，南非有10次震级超过4级的地震，有86人死于其中8次地震。并不是所有的地震都造成人员伤亡。因此，这就提出了如何定义地震事件引起灾害的风险问题。早期的理论有时候引导人在错误的地方进行监测，自然，最后什么也没有发现。今天，我想介绍其中的两个理论。单一灾害理论伴随着地震监测误差发展起来的。Wiechert地震波图中的试样数增加非常缓慢，使得那些靠近开采区的灾害事件出现的非常慢。这些图不能够确定P波和S波的到达时间，这使得理论确定的时间和实际不符。第二个比较有意思的理论与机械振动有关。

早期捣桩机是垂直冲击岩石,这和我们今天的施工方法不一样。真正引起早期研究人员注意的是岩柱。他们认为岩柱内的应力集中导致了岩爆。昨天,我们已经听了岩隆理论,后者带来了许多研究,它是连续体和弹性理论的源头。其中Nicola Solomon 教授 1970 年代就第一次给出了矿脉面内应力和强度评估公式。随着技术的发展,今天,我们已经可以预测岩石线性、非线性和塑性变形。当然,技术的发展也帮助我们理解地震问题。我认为有三位学者对地震的聚焦机理和运动张量的发展起了重要作用。其中一位是 Bunjiiro Koto,他于 1893 年发现了地层断裂和地震相关,他否定了前人的封建思想,认为山崩地裂是神发怒的后果。第二位是 Theodor Reid,他于 1906 年研究洛杉矶地震时提出了弹性回弹理论。第三位是来自日本的 Honda 教授,他第一次发现了地震波的极化效应,并给出了确定断裂层、面的方法。当然,今天,我们有很多新的方法可以把张量法引入到地震测量中,将不同震源分区确定清楚,并对波形进行分析。具体这方面可以参考Alex Mendecki 撰写的书。

关于灾害事件分布。现在我们可以按能量和矩张量来画这些图,我们也可以将之分为两大类:回采面周围的弱破坏事件,远离开采区的破坏性事件。根据它们的频率、大小、分布等,我们可以将这些灾害事件分成两类事件 A 和 B。我们现在可以确定出一些矿震的时间,这样就可以指引我们何时爆破,并进行开采矿区。我们的采矿面周边的应力集中区主要是在矿脉的垂壁和垂壁以下,如图上的一些灰区,它们就是应力比较集中的地方,即是最大主应力 σ1 和最小主应力 σ2 之差,这些地方绝对不能建设隧道,因为这是岩爆和矿震时常发生的地方。

这里,我将简单地介绍从一张震波图得到的两个地震事件,它们发生在非常靠近的地方,可能只有十来米的距离,你可以从这张图中清楚地看到两个波形的区别。但是,有时候,在同一张震波图中,这些灾害事件非常接近,只有几秒之差,但是它们的发生地可能达 400 米之远,它们受控于不同的机理。它们是非常难于分析的。它们有时发生在不同的地质结构中或不同采矿区。如果采用同样的空间和时间表来分析,它们可以分别形成两组不同的群集。这让我想起了地震诱发激励,可能是由于 P 波,有可能是 S 波,也有可能和灾害事件产生的高应变率相关。那么,这种事件造成的后果是什么呢? 如果是两种不同的波互相地干扰,那会产生一个非常复杂的干涉模式。如果两个事件距离和时间都很远,就会出现这种情况。来自两个不同地震源的地震波相互交叉,会产生一条直线。交叉处可能是 P 波之间的相互干扰,也可以是 P 波和 S 波之间的相互干扰。这些波可能会沿着不同的方向振动。波之间的相互干扰,尤其是这些交叉区对支护有何要求呢? 当事件靠的比较近时,这将变得更加复杂。我们将先有第一个灾害事件发生,如

图中蓝色点所示的S波随时间的辐射图,然后我们会在一些较远的点获得第二个灾害事件,它是P波辐射线,因为P波速度较快,它将跟上S波。我们还将获得一个交叉区,这个交叉区不是圆的,若在一个确定的标准距离内,它会自行封闭。它非常像一幅极坐标图,如果你获得如下的方程式:r = a - a cos(theta)。但是,问题是,针对这些交叉区,我们能做什么呢?当然,我们有时也看到损伤破坏区也远离这些交叉区,尽管我们不能理解它。

我接着介绍针对灾害的减灾措施。根据南非矿区情况,我将之分为三个步骤:预防、保护、预报。我知道大家都想了解预报,因此,我将介绍一下我对预报的理解。Alex Mendecki教授已经指出了地震和矿震的区别,这让我们可以据此考虑地震控制的措施。尽管波形是一样的,但是地震的来源可能不一样,因此,应变速率也会根据不同地震而有所区别。在平面边界,应变率可能是每年几公分,而在开采矿区,这个速率通常是每天几公分,因此,在地震事件和矿区事件中,这是两个不同量级应变速率。这就有一个自我组织的问题,对于地震,它是一个非常大的区间内的自我组织、成核,从而产生大的事件。而在矿区内,会在一个相对小的区间产生应力集中,这和地震事件不太一样,其机理和涉及能量均不一样。对于地震,我们无法控制,只能当它来临时,采取相应措施应对。从这一点来看,我们可以进行预测,但是,实际上,我们从来没有能够做到这一点。矿山事件,我们可以控制,通过观测开采区、开采体积。但是与时间相关的分析告诉我们这好像也是一种无用功,因为实际情况每天变化很大。那么,针对矿山灾害,我们究竟能做些什么呢?我们的回答是‘研究’。首先,我们查看不同开采层、设计。这里我给大家展示的就是南非的一个超大金矿的三个阶段:图中A就是分散开采区,事实发现有太多的岩爆发生在这区间;到了20世纪70年代,我们转到了B区,采用连续长距离开采,而C区是在一个新的地层,那里有较深的矿柱,其方向与B区使用的稳定岩柱成一定角度。这里涉及多个参数研究,我在这里简单介绍其中几个参数。

首先,能量、应力、强度、岩墙条件。关于岩柱,我们经常谈论它们的宽高比,并进行适当设计。但是,下面的图显示应力集中区通常也是地震发生区。从图中可以看到在回采面的上部和下部发生地震,但是我们得到的地震信息只在C区开采面附近一个很小的区间,因此,这是一个非常关键的区间。我们针对一个时间段,根据矿柱倾角进行一个快速分析。图中矿震下轴是时间,事件活动以红色标注。开始采矿时间是1998年7月份,采矿一年之后,系统记录到矿震事件。图显示该矿区出现了两次大的灾害事件,每个月都有一个小的矿震,其地震等级相当于震级2。这对我们来说是一个大问题。我看了一下地震具体发生地,它们大多是矿柱跨度为100米的位置。这可能是设计的不对、不好,因为我们的柱子间距

原本设计是 140 米,而问题是出现在距离为 100 米处。因此,我们重新修改设计,尽量采取措施避免矿震发生。这一点和 Cook 教授 1966 年的发现一致。所以这些新的数据更细致地告诉我们灾害发生情况,尽管,40 年前人们就知道其规律,但是现在的最新详细数据,将帮助我们修订设计方案。

中心爆破。过去,我们称为'Stay - a - lite'法。该办法需要三个小时完成爆破,基本上没有办法调控,一天内随时可以引爆,这对矿震的产生有着直接的影响,因此,有必要采取措施控制中心爆破,阻止误炸。在南非,我们一般在 30 米长的一个面上,布置 120 个孔,每个孔引爆间隔时间是 200 微秒,这个爆破时间是 24 秒。我们每天可以实施 50 组的爆破。这将对岩体产生巨大的能量和应力集中。中心爆破的主要研究目的就是尽量控制矿震。从监测系统得到了地震事件是这些爆破所产生能量的综合反映,它们非常复杂难于分析。

关于保护。昨天 Kaiser 教授已经介绍了许多保护措施。我只想再次强调能量的吸收对控制灾害非常重要,其中能量吸收设计主要考虑控制速度。我通过这张图给大家展示两种支护的方法,右边是一些 POS,采矿的支护有 2 米高。

关于预防。我简单介绍一下,预报一直可以追溯到 1939 年第二次世界大战之前美国的矿务局(代表性学者有 Obert 和 Duvall)就开始增加了这方面的工作。他们觉得在岩爆之前有微震的现象,他们持续做这样的研究。在南非,1960 年发生的特大矿难导致 435 人死亡之后,我们的预报工作开始启动,我们 1983 年在 Brink 和 Mountford 两地开展了一系列微震监测,发现在地震事件之前的 3、4 个小时,看到能量的释放有所变化,这样的试验让我们相信可以预报有一个大的地震事件即将发生。但是,从那以后,再也没有什么成功的结果。我们的研究主要是想通过一到两个参数(能量参数、表体积)确定地震事件成核阶段,我们有时候看到有一个参数在增大,另外一个则下降,因此,这个方法也没有成功。我们现在有了应对风险的评估和灾难的评价系统,我们每天查看震形,尽量用一些数据的方法显示出来,每天发送给研究人员,以便我们更好地了解开矿的情况。

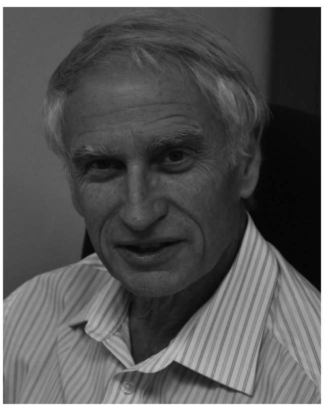
数值模拟是一个综合评价系统。尽管,我们没在这次论坛过多谈及,但它在过去 10 年成为灾害预测的有力工具。现在人们总在想用一些数学模型预测地震,这一领域得到快速发展,而且也是一个非常有价值的工作。

最后,我打算介绍一些美国在这方面的工作。美国许多学者说他们正考虑研究岩石内部电子、原子在应力条件下的运动,这将导致电场、磁场改变。他们观测到在地震之前动物有一些异常的现象,试图理解这些异常和电场、磁场的关系。我个人认为,这有一定的道理。大白鲨等动物大脑中有一些结构,对电磁场非常敏感。它们也就是利用这一特殊功能寻找猎物。尽管它们可能根本看不到猎物,

但可以通过意识确定猎物的位置。因此，这些非地震参数之间存在着某种联系，而这也是我们需要去探究的一种预测方法。我也是让我很受到鼓舞的工作，我个人认为这也许会成为以后预测的一个方向。

研究工作在这方面起了很重要的作用，你们应该很好地和你们的研究部门保持密切的联系，尤其是在进行隧道开挖工作时。以前南非矿山企业和研究部门保持着非常密切的联系，对我们这些企业获益非浅。

我知道，中国拥有许多非常美丽的景色，在此，我也给你们介绍一下位于南非瞭望角的世界自然遗址：开普敦桌山。这座山与众不同的地方在于其山头是宽阔的平顶，但是离这座山 20 公里处，这座群山和一断层山脉相交，其断层长达 15 到 20 公里，这也使得这座群山非常独特秀丽，当然，从地质学角度，这是另外一回事。我想表达的意思就是，如果我们想在地震方面有所进展，我们要把监测、机理和减灾方法结合起来，减灾对于我们来说首先是一个预防和保护，当然也可以把预报加进去。对于三重地震预测、预防法，我们可以将这一方法简单概括成如图所示的一个三角形，而我们应该融入这一方法，就如同置身于三角形图的中心。关于减灾，我们倾向预防和保护这一面。最后，我们需通过研究将数据变成知识，进而发展成为一种减灾智慧。关于这一点，我要感谢昨天 Peter 先生给我们谈到知识和智慧的区别给我的启发。



Kevin Riemer，1951 年生于南非夸祖鲁－纳塔尔省斯科特堡市，1977 年毕业于纳塔尔大学地质学专业，获理学学士（荣誉）学位。后加入比勒陀利亚地质勘测所，从事工程地质学研究，并于 1979 年获英国杜伦大学工程地质学理学硕士。

工作期间，在大坝和地下研究方面开展了多项可行性研究，其中包括瓦尔大坝修缮经费计划和西开普省 Theewaterskloof 蓄水计划。1980 年至今，就职于南非金田公司岩土工程部，协助设计、策划 Venterspost 和 West Driefontein 金矿的深层地下布局工作。1982 年，调入金田公司地震部，负责管理 West Driefontein 金矿集体地震台网。该网能对 5 个距离较远的矿井起监控作用，这 5 个矿井通过超高频无线电设备与 West Driefontein 总办事处的中央站相连。1996 年，该技术得到广泛应用，形成数字三位系统，由国际地震综合系统负责其销售和维护工作。

通过与约翰内斯堡办事处的各位矿山地震学家和岩土工程顾问展开紧密合作,研究了地震发生原因以及国际地震综合系统关联方法,特别是如何提高废品抽样过程的采样率。Kevin Riemer 是南非公民,也是南非国家岩土工程研究所成员。

岩爆的机理及其控制

何满朝

中国矿业大学

我汇报的题目是“岩爆的机理及其控制”。汇报分五方面的内容,首先汇报岩爆破坏的严重性。从几个方面搜集的照片和两个现场破坏的实例看一下岩爆破坏的现象和破坏的严重性:这张照片是煤矿发生岩爆的情况,在发生岩爆之前巷道还比较稳定,岩爆发生以后破坏非常严重;这是金属矿岩爆破坏,这是交通隧道和锦屏水电站导流洞破坏的情况。下面我们看两个岩爆的现场破坏情况,这是2009 年 Hudson 教授在一次会议上讲的在秘鲁发生的岩爆事故现场,这是锦屏发生的岩爆现场的情况。为什么我们把它再现一下,哲学上有一个基本的原理,就是要从现象看本质。我们有很多有识之士从破坏的现场看到了什么,看到了岩爆破坏是应变的岩爆和冲击的岩爆。我们实验室多年来一直致力于这两种岩爆的实验工作,我们把这两种岩爆细分为六种岩爆类型。这两种岩爆发生的时间,我们注意到它的应变式岩爆是在开挖过程当中,隧道没有形成,就有了这些应变岩爆的发生。冲击型岩爆,一般发生在巷道形成以后。隧道形成之后受到其他的动力学的冲击,然后产生的岩爆。这两种岩爆发生的时间是不一样的。应变岩爆根据工程的不同,还可以分为岩柱岩爆、采面岩爆,隧道或巷道发生的岩爆,要点是临空面不一样。没有开挖就不会有岩爆。我们现在用应变岩爆的实验系统来进行室内再现。冲击式岩爆,是在开挖以后能量不够,所以在开挖过程中不能够产生岩爆,很顺利进行开挖,把巷道做成了,但是在巷道工作期间会受到别的冲击,比如说爆炸的冲击、采矿顶板的破坏冲击、周期性来压冲击、断层错动冲击,然后就会产生岩爆。我们设计了一个刚性加载系统,再加上一个动荷载的冲击加载系统,成功地进行了冲击型岩爆实验。

再看一下两大类岩爆的实验情况,我们首先看应变岩爆。这是我们设计的应变岩爆的实验系统,这是应变岩爆的声发射收集系统,一秒钟可以有一千帧拍摄照片。应变岩爆有三个充分必要条件:首先是足够的深度(或足够高的应力水

平);其次是足够大的压缩能;满足上述条件不能产生岩爆,一定要开挖,开挖形成一个临空面,沿临空面能量突然释放,构成了应变岩爆的三个基本条件。按照这样三个基本条件,我们设计了应变岩爆实验系统并做了200多例的岩爆实验。现将实验结果给大家展示一下:第一个实验是加拿大的样品,这是一个花岗岩,取样深度2500 m。可以看到岩爆时出现非常猛烈的能量释放,而且大家会注意到,岩爆的碎片在空中进行旋转,还看到有攻角现象。和一般的破坏不一样,岩爆是一种特殊的破坏。第二个实验,是中国的花岗岩样品。突然的开挖使一个方向荷载卸掉,花岗岩产生了能量的释放。实验过程中出现的能量释放有三个阶段,第一个阶段是颗粒物向外弹射,第二个阶段是颗粒和片状颗粒综合弹射,到最后开始爆裂的时候有一个巨大的声响,这就是岩爆事件。我们看实验三的岩爆现象是锦屏二期的大理岩的岩爆过程。下面是砂岩岩爆,水平层理时,发生近顶板的岩爆;垂直层理时,发生岩样中间的岩爆;层理平行于自由面时,岩爆就是整个临空面。我们刚才看的是几例典型应变岩爆,给大家展示了三种岩类,沉积岩、花岗岩和变质岩,说明岩爆与岩石类型关系不大。

另一类岩爆是冲击型岩爆。当应变岩爆的条件不能满足,即能量不足以产生岩爆,巷道工程顺利完成后,在服务年限内有其他动力冲击。所以冲击型岩爆发生的时间是在巷道形成以后。深度不够时静力荷载不足以发生冲击岩爆,要获得足够的能量,从各种冲击源来获得更多的能量,这是冲击岩爆的特点。冲击岩爆实验系统具有16种基本波形,我们在现场测定一个复杂的波形,可以用16种基本波形的组合来实现。冲击岩爆实验一:为了测试实验的系统,我们在垂直方向,Fy方向上,在静力学基础上加载一个动力学荷载,不断地加载。我们看看整个扰动以后发生岩爆的过程,这时候到第二级的扰动,到C级的扰动,到D级要特别注意,岩爆首先是气体出来,煤矿叫做瓦斯突出。然后是气体和固体同时产生爆裂现象,气体和固体同时岩爆和突出。

下面是第二个实验,我们进行组合式的扰动。在Fy和Fz两个方向上,进行红色波形和黑色波形的横向扰动,这是时间轴,这时候岩爆还能发生吗?所以我们观察到了很多破坏的现象,开始是有了破坏,这种破坏是岩爆的前兆。但是有时候是只有前兆,而没有岩爆。这个有可能就是这样的。这实际上是一种破坏,我们做的这个实验就结束了。这个实验告诉我们,组合式的岩爆,双向进行扰动的时候,只能发生破坏。我们再看三个方向的组合扰动,在Fx、Fy、Fz三个方向同时扰动,对应的是绿色波形扰动、红色波形扰动和蓝色波形扰动,这时候看它还能不能发生岩爆。两个方向的组合扰动发生的破坏,三个方向能发生岩爆吗?实际上在三个方向上的组合冲击,组合冲击条件下也发生了破坏。在组合冲击的时

候，有很多扰动能量在抵消，所以最后发生了破坏。第四个实验，这是相邻的两个隧道，这个隧道已经打好了，另一个在施工的时候，对相邻隧道的扰动表现为水平的应力突然的降低，这种突然卸载会引起岩爆。下面再看一个实验，这个破坏是岩爆的前兆，这个前兆还是稍微长了一点，大家要看到后面的岩爆就要有足够的耐心，一直到这个时候应力水平，开挖使在中间应力降低，产生裂变后，迅速产生岩爆。岩爆发生在这个部位，实验当中我们可以非常清楚地看到整个的片帮的过程，非常细微的一些过程。我们看下面的这次岩爆，即第五次岩爆是持续地不断在 Fy 上加载，最后发生了一次岩爆。这个是有前兆的，开始应该是破坏。我们看第六次岩爆实验，第六次实验在 Fy 方向进行应力波的持续扰动，最后发生了岩爆。它也是一样，开始的应力水平比较低，是一种破坏，可以达到破坏的能量，但是不足以扰动到岩爆，岩爆需要更多的能量。

我们从这些实验的现象想到了什么？第一，岩爆不是普通的破坏，岩爆是一种特殊的破坏，岩爆和单轴实验的破坏有什么不同呢？我们选择了样品，持续地加载，我们刚才的岩爆是怎么做的呢？我们是加了围压，也加了荷载，按照现场的测试水平加上，然后围压卸掉，瞬时加上了横向纵向的荷载，这时候速率状态大体上差不多，这时候和它不同的地方，就是瞬时加载以后会获得很高的 όc，这个是缓慢的加载，这个是快速的加载，由于加载速率的不同会很高的强度指标。这个是静力学的，它的能量实际上是这样一个阴影，这些能量就足以使岩石产生很多裂缝，变成碎屑，多余的能量再把碎屑抛出去，这应该是岩爆的机理。岩爆必须有超出破坏的多余的能量，把破坏的物质抛出去，变成速度，而且碎屑在空间能够旋转，然后能够抛射一定的距离。$\Delta E > 0$ 可能是岩爆的条件。$\Delta E = 0$ 就是破坏，$\Delta E > 0$，有多余的能量把破坏的物质变成速度，岩爆这时候所得到的能量，分为两部分，一部分是可以破坏岩体，另外一部分把破坏的岩体抛出去，变成一种有能量的东西，把它的加速度变成速度，这就是目前的理解。对于瞬时岩爆、一开挖就有岩爆的，应力状态是 ό1、ό2、ό3，一开挖临空面就卸载，加载速率不一样，很深的隧道一卸载，就会有多余的能量产生。这是接近破坏的能量，径向方向突然卸载，切向方向应力升高两倍，就得到多余的能量；对于滞后型的冲击岩爆，本身的能量并不够，但是一冲击又获得了多余的能量，开挖再加上冲击，能量就够了。

我们通过实验研究，一共得到六种获得多余能量的途径。研究这些岩爆，不管是室内实验还是野外观察，我们的目标是怎么保护那些被岩爆伤害的人，怎么能够把岩爆的现场变得更为安全。如果人在这里是绝对不能生还的，岩爆之后空间变化了，这是非常危险的。这是因为目前的支护材料，在这样强大的能量面前显得软弱无力，锚索、锚杆都断了。我们现在能不能研究一种材料，让它不断，在

能量作用面前冲击荷载,在突然的加载面前能不能不断,这是我们聚焦的问题。国外已经做得很好了,Kaiser 教授在加拿大已经做了一个很好的产品。这个是 120 毫米的,最大可以达到 300 多毫米,这是澳大利亚的。我们一般的大概是 100 多毫米,这是最近几年我们做的,可以做到 20 ~ 35 吨的横阻,变形可以达到 1000 毫米,这是我们设计的横阻大变形锚杆的结构。

为了把这样一个锚杆的力学性能测试出来,我们专门设计了它的拉伸实验,看它拉伸到多长才断,可以拉伸到 1 米。在 13、14 吨条件下,我们可以实现 300、500,根据具体的情况进行选择。我们有 12 吨、20 吨的锚杆,35 吨的锚索,现在的煤矿需要用 20 吨和 35 吨的组合,来对抗岩爆的冲击荷载。特别强调的是,我们所有的岩爆和灾害的发生,都是与开挖有关系的,我们支护的目标是什么?就是把开挖的效应抵消,或者要用支护来替代原来岩体的作用。替代的最好方式就是预应力,预应力水平越高越好。问题是,现在的材料如果给足够高的应力,就会断,不能够适应很高的变形。应力越高,适应变形的能力越差,现在的 35 吨的横阻可以给你 35 吨的预应力,20 吨的变形产品可以给 20 吨的应力,在变形过程中可以吸收能量。

刚才只是对缓慢拉伸的,可以适应很大的变形,但是对于突然的荷载的出现,它能不能够适应呢?我们专门设计了 20 万焦耳和 15 000 焦耳荷载的实验系统进行冲击实验。这是第一次冲击、第二次冲击、第三次冲击、第四次冲击、第五次冲击,第六次冲击的时候断了,一个锚杆(锚索)能够忍受冲击五次,能够忍受五次冲击不断,证明它吸收能量的能力还是可以的。为什么能吸收能量了?产生了塑性滑移,达到一个很高的力之后自动降下来。我们用霍布金森杆达到更高速度的冲击,更高速度的冲击也是可以的,这是单个锚杆冲击实验,这是锚杆群的冲击实验;这是锚杆的能量本构关系,锚杆和岩石的相互作用平衡方程。值得注意的是,这种特殊锚杆和岩石相互作用的时候,平衡方程可以推出解来。过去是得不到解的,因为力和变形都在变。现在只要有了变形,力就是恒定不变的,所有锚杆的作用力就是常数,因此只剩下位移一个变量。这样问题带来极大的简化。

最后的结论,应变岩爆和冲击性的岩爆可以在室内做出来,再现出来这种岩爆现象可以帮助我们理解岩爆的机理;从实验当中提出了岩爆的准则,包含了静荷载和动荷载作用下能够创造出多余能量的过程;恒阻大变形锚杆(索)能够吸收能量,能够帮助我们控制岩爆的产生。

何满潮,1956年5月生,中共党员,博士,教授、博导,中国矿业大学(北京)深部岩土力学与地下工程国家重点实验室主任,中国岩石力学与工程学会副理事长、软岩工程与深部灾害控制分会理事长、《岩石力学与工程学报》副主编,国家自然科学基金重大项目(50490270)首席科学家,国家973项目(2006CB202200)首席科学家,国家有突出贡献中青年专家,国家杰出青年基金获得者。

何满潮是我国矿山工程岩体力学领域的青年学术带头人之一,在工程岩体大变形灾害控制理论和技术以及用于工程实践方面,取得了系统的、有创造性的成果。出版专著4部,发表了包括3篇国际学术期刊TOP25论文在内的论文126篇,收录引用3917篇次;获国家发明专利17项、国家技术发明二等奖1项、国家科技进步二等奖3项。

地下工程突涌水灾害源超前预报与治理技术新进展

李术才

山东大学

下面我将代表山东大学地下工程团队汇报一下这几年所做的工作，我汇报的题目是“地下工程突涌水灾害源超前预报与治理技术新进展”。

目前，我国是地下工程建设规模和速度最快的国家，地下工程建设过程中遇到的突水涌泥重大灾害堪称世界级工程难题，呈现出“大埋深、强岩溶、高水压、大流量”的特点。施工前方往往会遇到溶洞、断层等不良地质，这些溶洞有的是干溶洞，有的是含水溶洞，甚至与地下暗河相连。一旦发生突水灾害，将造成重大人员伤亡和财产损失。例如锦屏二级电站辅助洞水压超过 10 MPa，流量超过 7 m^3/s，工程难度国内外罕见。宜万铁路在建设过程中也多次出现过突水突泥灾害，还有破坏力更强的突石事故。例如野三关隧道，一次突水突泥导致 10 人死亡，马鹿箐隧道前后共出现 19 次大型突水突泥灾害，共造成 15 人死亡。

在湖北沪蓉西高速公路建设过程中也出现过许多突水突泥灾害，例如龙潭隧道，穿越一条 700 m 长的超长断层破碎带，涌泥总量达 9000 m^3，但提前一两天预报出来，没有造成人员伤亡。

为了避免突水突泥灾害的发生，必须做好不良地质超前预报和灾害的防治工作。在水电隧洞、公(铁)路隧道建设过程中，很难在施工前期全部查清隧道(洞)沿线不良地质情况。隧道往往建设在崇山峻岭中，有的隧道埋深达到 2000 多米，地形地质条件十分复杂，通过在地表打钻孔进行地质勘探的经济代价太大，而且在崇山峻岭地区难以实施，并且采用其他的物探手段又难以做到，使得在隧道建设过程中的不良地质情况无法提前预知，这就需要在施工过程中做好超前预报工作。为了避免上述工程灾害的发生，主要做好以下两方面的工作。第一，不良地质的超前预报与定量识别。不良地质主要包括岩溶含水体(如溶洞)和断裂控水构造(如断层)，其中不良地质体中充填水量的定量预报很关键，是世界性难题。

第二，如果预报了隧道前方存在突水涌水的灾害源，灾害的防控技术尤为关键，尤其是高压动水治理的相关理论、技术和材料等。围绕上述两个问题，我汇报一下近年来所做的工作和取得的进展。

首先汇报含水构造超前预报定位、定量识别理论和技术方面的新进展。通过几年的工作，建立了一整套技术进行隧道前方含水构造超前预报。首先利用极小偏移距地震波法，也就是陆地声纳法发现隧道前方溶洞断层，实现远距离的定位。这样可以有的放矢，提前做好准备，预报距离可以达到 100 米以上。山东大学与钟世航教授共同发展完善了陆地声纳技术，其优势是可在 100 米范围内识别隧道前方的断层和中小溶洞。第二是水体中距离识别定位，利用全空间瞬变电磁技术对隧道前方 80 米范围内的水体进行有效的识别和定位，但这种技术不能判断水量的大小问题。第三是隧道前方水体水量估算。能否估算隧道前方水量大小对隧道施工至关重要。山东大学团队自主研发了复合式激发极化技术，发现了激发极化信息与水量之间存在正相关的关系，在这个基础上建立了 40 m 范围内水体水量的估算方法。以上三个预报方法，由远到近、由水体的定位到水量的定量，是一种渐进式的全过程的超前预报技术，应用效果比较好。

下面具体介绍一下复合式激发极化方法，这是山东大学团队研发的核心创新技术。激发极化的原理，简单地说就是向隧道前方施加电场，水体中的离子在电场的激发作用下产生形变和位移，然后把电源断掉，水体中的离子就有恢复到原来位置的运动趋势，离子运动就产生了电场，叫做二次电场，也是极化电场。研究发现，如果水量大，二次电场的衰减时间就比较长；如果水量小，二次电场的衰减时间就相对较短。基于这样的原理，开发了激发激化技术，开展了系统的物理模型试验和工程应用。研究发现，激发激化信息和隧道前的水量呈现近似的线性相关关系，并在现场几十条隧道中做了现场实验研究，实验结果表明这种规律是存在的。同时，突破了含水体超前探测三维反演理论，可以实现掌子面前方 40 m 范围内水体的三维成像和定位。在上述激发极化定量定位预报水体的理论研究的基础上，发明了复合式激化极化仪，现在已经发展到第三代，性能稳定，在工程应用中效果良好。

全空间瞬变电磁法是山东大学团队研发的另一种超前探测水体的技术。瞬变电磁法的原理是，向隧道前方发射电磁场，电磁场关断后，如果掌子面前方存在水体，水体就会产生感应电磁场，通过对感应电磁场的分析和反演就可以识别含水体，并可以对 80 m 范围的含水体定位。通俗地说，通过瞬变电磁法可以知道隧道前方有没有水以及什么位置含水，但是对水量大小无法判断。针对地下工程中的瞬变电磁，人们大多都照搬了地面瞬变电磁的理论，但是地面瞬变电磁是三维

半空间探测理论,与地下工程中的三维全空间的理论完全不同,无法适用于隧道超前预报。因此,山东大学团队发展了全空间瞬变电磁的等效导电平面理论,建立了视纵向微分电导成像技术,这个方法可以克服传统方法明显存在的假异常、定位精度差等缺点。如果在掌子面的前方 30 米有水体,利用传统方法会误判在 40 m 位置有水,而且映射的范围比实际情况要宽得多,而利用等效导电平面方法和视纵向微分导电方法,定位精度和分辨效果就大大改善了。在上述理论的基础上发明了全空间瞬变电磁软件和整套的仪器设备,可以实现 80 m 范围内含水构造识别与准确定位。

山东大学团队与钟世航教授合作,经过十多年努力,发明了陆地声纳法,该方法在锦屏电站辅助洞经过测试证明是切实有效的。陆地声纳法是基于极小偏移距方法,通过地震波探测隧道前方的不良地质情况。国外也有公司根据类似原理发明了一种设备,叫做 TSP。TSP 可以预报与隧道轴线垂直相交或者大角度相交的断层,但是对于与隧道轴线成小角度相交的断层和中小规模的溶洞则是无能为力的。山东大学团队利用陆地声纳,在中小溶洞、斜交断层识别方面具有独特优势。由这幅图可以看出,陆地声纳法对双层溶洞和斜交断层识别和定位精度比较令人满意,在广州地铁、大连地铁的超前预报中都取得了较好的效果。

通过以上方法,建立了一套渐进式的含水构造综合超前预报技术体系。第一阶段是宏观预报,结合工程地质调查和工程地质分析,对地质灾害划分不同风险等级。这一环节十分重要,进行隧道不良地质超前预报工作,一定要与地质工作相结合,地质工作是地球物理勘探的基础。打一个简单的比喻,对于中国人而言,看到“马到成功”这四个字中的任何两个字或者三个字,都可以马上联想到“马到成功”这一成语,而对于不了解中国文化的外国人而言,则很难实现这一效果。对于超前预报,地质工作就是超前预报的“文化背景和底蕴”。因此,进行超前预报要有较好的地质底蕴才能做到全面判断前方不良地质情况。第二阶段是远距离预报,主要是将陆地声纳法与 TSP 方法结合起来进行预报,可对隧道前方 120 米范围以内的断层、溶洞进行准确定位和识别。第三阶段是中距离预报,可利用全空间瞬变电磁法对隧道前方 80 米范围内含水构造进行定性识别和定位。如果隧道前方只有断层或者干溶洞,则施工中不会产生很大的事故,但是如果前方存在含水体,则将对安全施工产生严重威胁。最后一个阶段是近距离预报,可将复合式激发极化方法与地质雷达法相结合,实现 40 米以内含水构造的定量识别与水量估算。另外还可以辅以少量钻孔,对隧道前方的含水体情况进行准确判断。

运用以上技术体系,基本可以保证隧道施工不会发生危险。近十年来,这一技术体系在湖北沪蓉西高速公路、湖北宜巴高速公路、三峡翻坝公路、青岛胶州湾

海底隧道等几十条高风险隧道中得到成功验证。当然,这一方法是经过一系列理论研究和工程实践逐渐形成的,不是一蹴而就的。在这一过程中,地质预报的准确率得以不断提高。这是超前预报技术体系在沪蓉西高速公路齐岳山隧道的应用实例,利用地质分析、陆地声纳、瞬变电磁和激发极化这种全过程的预报方法,较好地预报了大型含水构造的存在,对施工提供了很好的参考,得到沪蓉西高速公路指挥部的高度评价。另外,在锦屏二级水电站、翻坝高速公路的应用,均取得了较好的效果。

下面向大家汇报在注浆治理理论与技术方面的新进展。在探明隧道前方的含水体之后,若要有效控制突水突泥灾害的发生,就应该进行灾害防治。隧道围岩中的水一般都是流动的水,称之为动水,而且有的情况下水压很大,流速也很高。浆液在动水中如何扩散如何运移?其封堵动水的机理是什么?什么样的材料、设备和工艺适用于动水的封堵?在封堵过程中如何进行过程化的控制?这都是我们的研究要回答的问题。

山东大学团队研制了准三维平面裂隙动水注浆试验平台,并开展了一系列注浆试验。试验结果表明,注浆浆液和水量必须要达到一定的比例,才能把动水治理住,如果是小于或者高于这个比例都不能实现理想治理效果。对于动水治理而言,还要求注浆材料要具有出色的性能,例如速凝、抗动水冲刷能力强、可泵性好、价格相对低廉,适合大范围的推广运用。山东大学近年来研发的水泥基的注浆材料,具有初凝时间可调,动水抗分散好,早期强度高,环保无毒等优点,在现场经过应用之后取得了较好的治理效果。

山东大学近年来发展的治理技术的最大特色是建立起了信息化综合治理体系。“信息化”的主要内涵就是:一、以综合地质预报为基础,提前探明动水的运移路径,明确注浆和治理的核心目标区域;二、以科学堵、排方案为前提,结合预报结果和地质情况,事先制定治理方案;三、采用了全程有效监控为手段,监测围岩的变形、压力等信息,动态评价注浆和治理的效果;四、以材料研制与工艺改进为核心,把工程需求作为研究导向,建立了室内的材料研发实验室和现场材料实验室,不断提高材料的性能。

具备了准确的预报技术和性能良好的注浆材料,就可以对隧道突水突泥灾害进行科学的防治。在许多隧道突水灾害治理过程中,往往是前期把水控制住了,一段时间之后又会出现突水。用这张图可以形象地说明这个问题,反复出现突水的主要原因是出水点距离隧道临空面较近,注浆后防突结构厚度较小,承载力小,在压力作用下又将发生破坏。如果探明水的来源,打关键钻孔,在距离隧道较远处阻断水的补给通道,就会形成承载力较大的保护层。采用这样的治理方案,尽

管施工长钻孔费用较高,但注浆量较少,而且不会出现反复突水,治理效果明显。在地质条件较差的重庆中梁山隧道,采用这个方法治理取得了良好的效果,避免了附近水库的渗漏,重庆市政府给予了较高评价。另外,在年产1000万吨的山东龙固煤矿以及济南张马屯铁矿,都采用了这样的治理方法,取得了令人满意的治理效果。

李术才,1965年12月生,教授,博士,博士生导师,长江学者特聘教授,国家杰出青年科学基金获得者,国家863计划现代交通技术领域主题专家,新世纪百千万人才工程国家级人选,第九届中国青年科技奖获得者。现任山东大学土建与水利学院院长,山东大学岩土结构工程研究中心主任,大型地下洞室群教育部工程研究中心主任,中国岩石力学与工程学会地下工程分会理事长,山东省力学学会理事长,*Tunnelling and Underground Space Technology* 副主编,《岩石力学与工程学报》、《岩土力学》编委,所带领的团队入选教育部创新团队和山东省泰山学者攀登计划。主要从事地下工程灾害预报与控制、施工过程力学等方面的研究工作,在隧道不良地质超前预报和灾害控制方面取得了重要进展,研发了复合式激发极化方法含水体水量定量预报技术、全空间瞬变电磁法含水体定位识别技术,建立了隧道不良地质综合超前预报的理论方法和技术体系,其研究成果保证了湖北沪蓉西高速公路多条高风险岩溶隧道、青岛胶州湾海底隧道、三峡翻坝高速公路高风险隧道群等数十个重大工程的建设安全,在行业内产生了良好的学术影响。发展了地下工程施工过程力学,建立了我国钻爆法施工的海底隧道最小岩石覆盖层厚度分析方法,确定了国内第一条海底隧道(厦门翔安海底隧道)和第二条海底隧道(青岛胶州湾隧道)的最小岩石覆盖层厚度,在国内外处于领先水平。在地下工程岩体稳定性与安全控制、大型地质力学模型试验方法和设备研究方面取得突破和进展。近年来,主持国家973计划课题1项,国家863计划项目1项,国家自然科学基金重点项目2项,国家自然科学基金国际重大合作项目1项,国家重大重点工程科研课题30余项。出版专著3部,获发明专利20余项,发表论文被SCI、EI收录200余篇,获国家科技进步二等奖3项,国家技术发明二等奖1项,省部级科技进步一等奖3项。

第四部分

主题圆桌高端研讨

研讨主题:地下工程安全建设与风险管理未来 20 年科技发展战略,包括:

1. 如何加强工程安全建设与风险的管理
2. 科技创新发展:
   a) 地下工程灾害(岩爆、突涌水)的孕育机制、预测预警与防控理论
   b) 面向地下工程安全的设计理论
   c) 风险管理理论

我国煤矿开采技术发展现状及方向

宋振骐

山东科技大学

能源是人类生存和发展的基础,世界能源资源竞争日趋激烈。煤炭是我国化石能源的主体,我国煤炭储量在化石能源中的比重超过95%。截至2010年年底,全国煤炭已探明地质储量1.5万亿t,占化石能源资源总储量的97.9%。

目前,我国煤炭生产中存在的问题主要是顶板、瓦斯、冲击地压、透水等重大事故没有从根本上(即在依靠正确的理论指导和现代装备、管理手段的基础上)得到控制,严重影响我国煤炭安全生产形象。因此,实现煤炭安全高效开采,有效地控制环境灾害,最大限度地采出煤炭资源,实现中央"资源节约型、环境友好型、可持续发展"发展战略是我国能源安全和国民经济发展保障体系建设中的重中之重。

时至今日,国有大型重点煤矿赋存条件好的薄及中厚煤层在综采技术(包括装备水平和管理水平,以及技术经济指标)进入国际先进行列,厚煤层综放开采技术及经济指标处于国际领先地位。但是时至今日,由于缺少理论指导和在相应技术和管理模式方面的突破,采掘工作面推进引发的瓦斯、冲击地压、突水等重大事故时有发生。对于在相关矿井相应煤层条件下采用无煤柱充填开采技术控制重大事故和环境灾害的重要性还很不明确,缺乏推广应用的积极性和主动性。数以千计占全国85%的中小型矿井,特别是受构造运动破坏赋存条件较差的薄及中厚煤层,缺少拆装方便、搬家倒面容易的综采装备,导致综采工作面比例很低,开采技术和装备水平仍然比较落后;管理水平依然停留在依靠统计经验决策、传统条例管理模式的阶段。我国航天、航海等地表以上的空间技术成就和现代化矿井综采技术发展成就和管理水平,奠定了我国实现井下智能化开采的基础。通过煤矿实现智能化开采目标将进一步推进我国机械化制造业、信息化产业以及相关产业的发展,已经成为我国现阶段国家工业化和国民经济发展的客观需要。可以说,实现井下智能化开采已经成为我国现阶段工业化发展的火车头。

当前,实现井下采掘工作面智能化开采要求突破的技术重点包括以下三个方面:

(1) 在深化回采工作面顶板控制理论的基础上,成功地研制出具备发送支架所在工作地点安全工作环境信息、设备工况信息,以及与可能事故相关的顶板运动和煤层压缩(支承压力分布)动态信息,实现操作过程遥控的"支护机器人"(智能综采支架)和"挖底充填机器人"(智能挖底充填综掘机)装备薄及中厚煤层回采工作面,杜绝顶板事故和相关联的瓦斯、冲击地压、顶板透水、底板突水等重大事故。有效地解决数以千计的中小型煤矿采用传统综采难以承担的高额资金投入,以及因拆装搬家困难,不能适应多变的煤层地质条件造成的高成本、低效益的局面。

(2) 在深化巷道矿压控制理论的基础上,成功地研制出巷道"挖底充填机器人"(智能挖底充填综掘机),以及在具备发送工作地点顶板下沉、煤层压缩和瓦斯压出等动态信息,保证杜绝老塘(采空区)透风和有利于瓦斯抽放、注氮防火工艺实施,具备让压可缩功能的充填墙体结构方面取得突破的基础上,实现"无煤柱护巷开采"成套技术的智能化。

(3) 在深化实用矿山压力控制理论的基础上,建立随采场推进在回采巷道外侧,根据无线通讯和电液遥控操作距离的要求和方便工作人员及时进入工作地点视事的需要,聚事故预测、控制决策、实施监控,以及事故灾害发生时人身防护功能与一体的"智能化开采指挥中心"(井下前线指挥部),并完成相关信息采集系统和决策软件开发任务。

(4) 在实用矿山压力控制理论的指导下,完成重大事故预测和控制决策及其实施监控支持系统建设的实用性突破。融合事故预测和控制决策模型和相关信息基础建设于一体的决策支持系统,包括采前预测和控制决策,以及实施过程中,根据监测仪表手段采集的岩层运动和应力场应力分布等动态信息,判断事故控制效果,提出新的控制决策实施方案等两个部分。

管理学部很重要,工程管理过去主要就是统计经验决策,靠规范和条例管理这个模式,这个不行,管理问题需要创造性东西,特别是要不断地发展,现在煤矿存在的最大的一个问题就是管理。统计经验决策,规范管理,条例管理的模式思想,始终影响我们真正的科技的发展。煤矿灾害事故处理方式依然遵循出事抓人的方式,事故发生首先要抓原因和事故教训,而不能着重去抓人的责任。

中国工程院管理学部是非常重要的一个学部,从科学思想上研究管理问题。怎么把相对真理的追求和实际真理结合起来,这个问题是当前一个非常非常重大的课题。地下工程煤矿是最大的地下工程,涉及的问题非常复杂,希望我们专门

好好地研究一下，解决这个问题。

宋振骐，湖北武汉人，1935 年 3 月生，山东科技大学教授，中国科学院院士。宋振骐院士是我国“实用矿山压力理论”的学术带头人，在建立和完善“实用矿山压力理论”以及建立采场重大事故预测和决策控制结构力学模型、推进采矿方法和工艺技术创新、推进煤矿安全高效生产决策和实施管理的现代化方面做出了创造性的突出贡献。为煤矿高效安全，特别是重大事故灾害控制方面做了大量卓有成效的工作。宋振骐院士是我国高等教育发展改革、实施人才强国战略的积极支持者，坚持走教学（出人才）为主，科研带教学，产、学、研结合发展道路的教学改革方面做出了创造性的贡献。

抽水蓄能电站地下工程地质灾害风险控制

罗绍基

广东蓄能发电有限公司

一、背景

随着社会经济快速发展和对电网稳定要求不断提高,广东已建成了广州抽水蓄能电站一期、二期和惠州抽水蓄能电站 A 厂、B 厂,目前正在建设的有清远抽水蓄能电站和深圳抽水蓄能电站等,广东抽水蓄能电站分布见图 1。

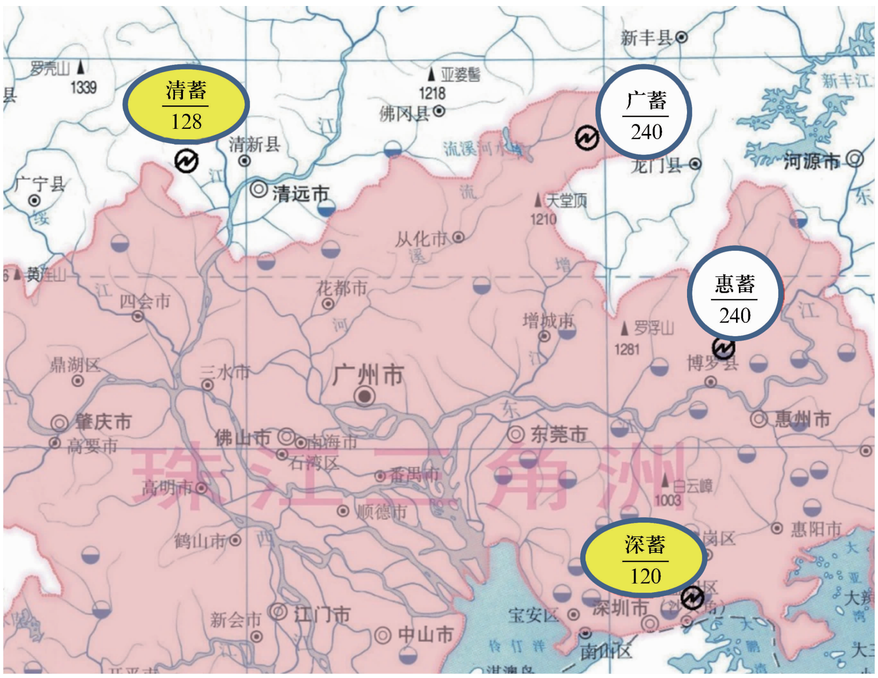


图 1　广东抽水蓄能电站分布图

抽水蓄能电站由上水库、下水库、引水及发电系统等组成,引水及发电系统由长隧洞和地下厂房洞室群组成,广东已建的抽水蓄能电站上下库水头差一般在 500 m 左右,地下厂房埋深一般在 300 ~ 400 m 左右,属于高水头埋藏深的地下电

站。抽水蓄能电站机组采用可逆式水泵水轮机组，考虑在抽水工况下机组吸出高度的要求，地下厂房机组安装高度比下水库死水位还要低水头的1/10以上。因此，抽水蓄能电站地下厂房洞室群上下游均处于水库高水位以下的复杂地质和地下环境条件下。

抽水蓄能电站地下工程中，引水系统主要为长隧洞，包括引水隧洞、高压岔管、引水支管、尾水支管、尾水岔管、尾水隧洞、调压井等。引水隧洞和尾水隧洞等长度一般在2000～5000 m之间，直径在8.5～9.5 m之间，一条引水隧洞和尾水隧洞控制四台机组。引水隧洞通过高压岔管和四条引水钢支管与地下厂房连接，为满足水力梯度要求，各洞室布置应尽量远离钢筋混凝土衬砌的高压岔管。尾水隧洞通过尾水岔管和四条尾水支管与地下厂房连接，尾水岔管与地下厂房间距约150 m左右。引水隧洞和尾水隧洞根据水力过渡要求，根据开发方式不同，一般设置上游调压井和尾水调压井，或仅设置上游调压井或尾水调压井，调压井高度在120～150 m之间，包括直径9 m左右的升管和直径20 m左右的大井。地下厂房洞室群包括地下厂房、主变洞、母线洞、尾闸室、交通洞、通风洞（排风井）、高压电缆洞、排水廊道和自流排水洞等。地下厂房跨度20多米、高50多米、长150～170 m，高压岔管与地下厂房间距在130～150 m之间。主变洞宽约20 m、高约20 m、长150 m左右，有四条母线洞连接地下厂房与主变洞。为满足围岩稳定要求，地下厂房和主变洞间距为40 m左右。鉴于深埋的输水隧洞和错综复杂的地下洞室关系，且处于地下复杂的工程地质和水文地质环境条件下，地下厂房位置选择、施工开挖支护控制和地下截排水控制体系至关重要。清远抽水蓄能电站输水系统纵剖面见图2。

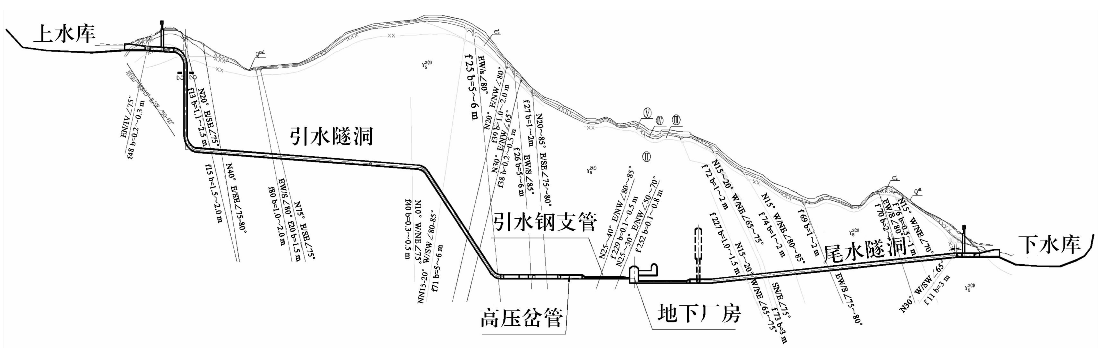


图2 清远抽水蓄能电站输水系统纵剖面图

二、地下工程位置选择

地下厂房洞室群深埋于地面以下 300 ~ 400 m 左右,高压岔管承受近 600 ~ 800 m 的动水头,且采用钢筋混凝土衬砌,所以地下厂房和高压岔管的位置选择十分重要,而对地下工程起控制作用的因素主要有断裂、蚀变、地应力和地下水等。为了将高压岔管及地下厂房系统布置在相对完整的岩体,在前期地质勘探和厂房位置选择设计工作中,根据设计阶段不同分步研究分析地下地质情况,逐步优化确定高压岔管及地下厂房的位置。

首先从地形条件研究确定电站的开发方式,拟定具备布置地下厂房的基本位置范围,根据地表查勘判断该区域范围的地质构造情况,判断断层的宽度、走向、倾角等,拟定地下厂房的位置。

根据初步拟定的位置,布置 400 m 以上的深勘探孔从地表钻孔深入厂房底高程以下,判断经过该区域的断层、裂隙及地下水等情况,进一步优化地下厂房的位置及轴线。

更关键的是,为进一步确定厂房的合理布置,我们针对基本确定的地下厂房位置,布置长 2000 m 以上的地下探洞。由于厂房埋藏较深,而探洞坡度很小,所以探洞位置只能在厂房顶拱高程以上数十米,因工程而异。同时在探洞内布置辅助的地质钻孔。通过探洞和辅助的地质钻孔,充分分析揭示该区域各断层宽度、走向、倾角等,并长期观测该区域地下水变化情况,测试该区域地应力,最终分析研究确定高压岔管和地下厂房等地下工程重要部位布置位置和轴线方向,将高压岔管及地下厂房系统布置在相对完整的岩体,而且没有出现过地应力大、变形大和大塌方情况。

尽管如此,在广蓄一期排风洞和交通洞开挖过程中发现花岗岩蚀变现象,经过准确分析判断主要断裂的走向,将关键的地下洞室置于新鲜完整岩体中。如主厂房、调压井、高压岔管等,均是利用长探洞掘进到建筑物上方,再向下补充钻探工作,了解建筑物位置的地质条件后,修改洞室位置及体型。如地下厂房轴线方向从原来的 SN 向改为 NE80°,使之与主要断层、蚀变带的夹角大于 40°,整个厂房往西移了 40 m。蚀变岩被揭露后,遇地下水和潮湿的空气膨胀崩解,影响部分围岩的稳定。经过研究摸索,逐步形成了一套处理蚀变岩的工程措施。通过清理蚀变松散物,及时喷护并处理好地下水等措施稳定了围岩。

经过广蓄一期的地下厂房位置选择和蚀变岩带处理,积累了丰富的经验,广蓄二期、惠蓄 A 厂、B 厂和清蓄的地下厂房和高压岔管等关键洞室的位置,均很好地避开了较大规模的断层和裂隙密集带,特别是清远抽水蓄能电站厂房位置,有

效避开近EW向及近NE向断层带，将高压岔管和地下厂房全部布置在Ⅰ类和少量Ⅱ类围岩中。目前地下厂房已开挖完成，施工过程中未出现岩爆和塌方等现象，将复杂地质和环境条件下重大地下工程安全风险控制到最低，开挖质量受到业内知名专家好评，充分证实了地下厂房位置选定在了优越的地质条件范围内，同时，有效节省了支护工程量，为缩短工期和节约投资提供了良好的基础。

三、施工开挖支护控制

除了选择好地下厂房位置及轴线外，地下厂房开挖过程控制对地下工程安全也至关重要。厂房开挖过程中采用“分层开挖、及时支护”，并实时进行监控，及时对开挖爆破参数进行调整，有效地保证了开挖质量，在防止围岩破坏、控制厂房边墙变形方面，收到较好效果。

广东抽水蓄能电站地下厂房跨度20多米、高50余米、长150～170 m。在开挖过程中，根据相应的施工通道和施工方法，考虑上下分Ⅶ层或Ⅷ层开挖。为确保开挖质量，尽可能减少开挖对围岩的影响范围，根据每层的布置特点，考虑不同的施工开挖方案。广东抽水蓄能电站地下厂房第Ⅰ层开挖采用手风钻开挖中导洞超前，顶拱扩挖和上、下游侧扩挖错距跟进，周边孔光爆的综合开挖控制方式。第Ⅱ层采用中间预裂拉槽，两侧预留5.5 m的保护层，周边孔光爆开挖方式。其中岩壁吊车梁岩台采用垂直孔和斜孔光爆开挖。第Ⅲ层至基坑层，先对边墙进行预裂，上、下游开挖错距跟进或全断面开挖的方式进行。

在选择较好的地下工程位置和精细的施工开挖控制基础上，广东抽水蓄能电站地下厂房支护充分利用围岩自稳能力，采用喷砼+锚杆的柔性支护方案。根据围岩不同，顶拱挂网喷砼，或取消挂网喷钢纤维砼或掺聚丙烯纤维喷砼，设长3.5～3.7 m锚杆，拱脚设2～3排长5.3～6 m锚杆，锚杆间距1.5～1.8 m；边墙挂网喷砼，设长3.5～3.7 m和5.5～7 m间隔布置的锚杆，锚杆间距1.5～1.8 m。在岩壁吊车梁上两排下一排布置三排长9 m的锚杆，锚杆间距1.5～1.8 m。为保证厂房各部位开挖完成后及时支护和保证施工质量，锚杆钻孔均采用三臂台车钻孔，锚杆注浆采用麦斯特注浆机注浆，喷砼采用麦斯特喷车湿喷。

地下厂房的开挖质量直接影响围岩的变形，特别是岩壁吊车梁对围岩变形要求非常高。通过精细的施工开挖控制和及时支护，广东抽水蓄能电站厂房开挖有效地保证了开挖质量，未出现塌方等围岩破坏，厂房边墙变形控制在允许范围。广蓄开挖支护控制变形效果见图3。

四、防渗排水控制体系

抽水蓄能电站是高水头深埋的地下电站，高压引水隧洞和高压岔管承受500

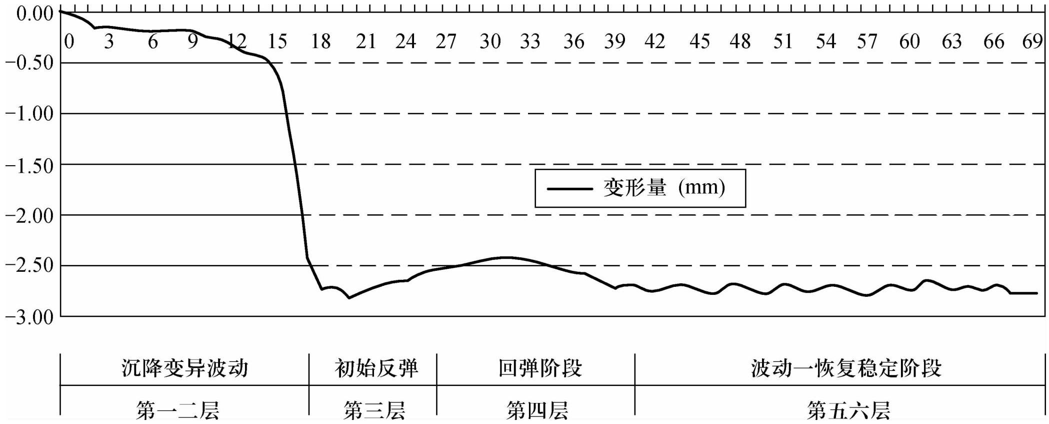


图 3　广蓄开挖支护控制变形效果图

注:1. 厂房顶拱最大沉降变形量:2.86 mm;2. 厂房边墙最大变形量:4.37 mm;3. 顶拱边墙变形规律与理论相符

m 以上的内水压力,高压隧洞和高压岔管均采用 40 ~ 60 cm 厚钢筋混凝土衬砌,按“高压透水衬砌”理论,限制裂缝张开宽度设计。因此,运行期间水道中的水由于水头压力高,将会产生内水外渗。

根据计算,高压钢筋混凝土岔管及引水高压钢支管等主要控制工况为外压情况,尤其在隧洞放空时,会有较高的水压作用在衬砌上,对钢衬支管安全很不利。同时,为了减少地下水和高压渗漏水渗进厂房和主变室,降低厂房边墙所承受的渗透压力,改善地下厂房的运行环境,根据水文地质条件,在高压岔管和地下厂房系统合理设置防渗排水系统,降低外水压力,对地下厂房、高压岔管及高压钢支管等具有十分重要的意义。

广州抽水蓄能电站通过五道安全防线,解决高压岔管和地下厂房的防渗排水,遵循先防渗后排水原则。第一道防线是高压岔管与厂房之间的引水支管采用钢板衬砌,保证该段范围不会产生高压内水外渗;第二道防线是在高压岔管与钢支管设置防渗帷幕,阻止高压内水在高压岔管外渗后,渗向高压钢支管及厂房区域;第三道防线是在钢支管表面设置排水系统,直接排放渗向钢管表面的水,直接降低钢管外表面所承受的外水压力;第四道防线是在高压岔管与厂房之间的 1# 排水洞布置排水孔,排除渗向厂房的渗水;第五道防线在厂房和主变洞周围布置两层排水廊道,并打排水孔形成排水帷幕,排去这一区域的地下水,以降低外水压力。高压岔管和地下厂房的防渗排水控制体系简图见图 4。

惠州抽水蓄能电站和清远抽水蓄能电站在上述五道防线的基础上,根据优越的地形条件,研究增设了自流排水系统,让地下厂房附属洞室和排水廊道内的排水通过地下厂房排水系统进入自流排水洞排出厂外,最大限度改善地下厂房的运行环境。

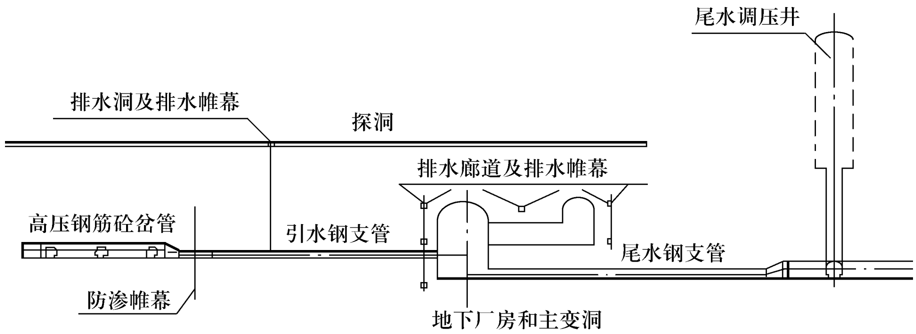


图 4 高压岔管和地下厂房防渗排水控制系统简图

抽水蓄能电站高压岔管和地下厂房区域地下水的渗漏能否得到有效的控制和有序的排放,能否为地下厂房创造适宜的运行环境,防渗排水控制系统的好坏是工程成败的关键。广东抽水蓄能电站高压岔管均采用钢筋混凝土衬砌,根据“高压透水衬砌”理论、限制裂缝张开宽度设计,通过五道安全防线解决高压岔管和地下厂房的防渗排水等,均取得了成功的经验,相对昂贵的钢板衬砌节省了投资。但在实施过程中也有值得借鉴的教训。

比如广蓄一期尾水支管钢衬渐变段,在初期充水时发生鼓包现象。其原因是尾水闸门槽外侧混凝土回填不密实,灌浆没有充分回填,尾水洞内水透过尾闸槽混凝土作用到上游钢衬渐变段外侧,形成与下库水位连通的外水压力作用,4 条尾水支管钢衬渐变段均出现不同程度的压屈变形鼓包。事后采取切割钢衬变形部分,焊补修复钢管,在钢衬缝隙内设置排水系统等措施,进行了有效的处理。

广蓄二期在上游水道首次充水时,因水力梯度太大(T = 17),位于上游水道系统的钢筋混凝土岔管上方的排水探洞出现了的喷射状高压渗水,最大渗水量达 31. 78 L/s。水道放空后进行全面检查发现:高岔混凝土衬体有 42 条裂缝、均有外水返渗。裂缝宽度一般为 0. 5 ~1 mm,个别裂缝宽达 2 mm,水道放空后大部分裂缝都呈张开状态。分析认为,高岔衬体开裂是南、东支洞大量渗水的主要原因,NW 向微张构造是高岔内水外渗的主要排泄通道。事后进行两方面的处理:一方面对高岔进行系统高压化学灌浆,在南支洞内对重点怀疑的地段和 P4 渗压计孔进行磨细水泥灌浆和化学灌浆;另一方面,对 1#排水廊道以南的地质探洞进行混凝土回填。处理工作结束后,上游水道已安全运行近 13 年,高岔区的总渗水量一直稳定在 2. 3 L/s,区内的渗压计读数也保持了良好的稳定状态。

惠州抽水蓄能电站 A 厂高压隧洞段地面高程为 425 ~ 435 m,平均埋深 260 m,A 厂高压岔管地面高程为 475 ~480 m,埋深约 340 m。在输水发电系统洞室围岩分布主要为花岗岩。高压隧洞及高压岔管洞周有数条断层穿过,其中

F304 断层带宽度达 10～15 m，破碎程度较为严重，为场区控制性断层。A 厂上游水道充水过程中探洞内 F304 断层大量涌水，1 号灌浆廊道内 F59 断层出露段大量喷水。实测探洞总渗漏量为 781.5 m^3/h，水道最大渗漏量为 811.4 m^3/h。A 厂上游水道充水试验在部分隧洞段的混凝土衬砌出现较密集的裂缝。根据充水试验的情况，在放空后对水道进行高压化学灌浆和加深加密固结灌浆加强处理，对断层等部位进行深孔水泥灌浆和回填封堵等处理。第二次充水试验完成充水后对探洞、A 厂厂房区各排水廊道、堵头等部位渗漏量进行测量统计，总渗漏量约为 19 m^3/h，长 3122 m 的 A 厂上游水道总渗漏量约为 80 m^3/h。A 厂上游水道经放空修复处理后，水道渗漏量大幅减少，渗漏量值在合理范围内。

五、结论

（1）高压岔管和地下厂房的位置选择对于控制工程风险、节约投资至关重要，前期工作中需要通过地表查勘、深孔勘探和地下探洞等多种综合手段，充分揭示地下洞室区域的工程地质条件和水文地质条件。

（2）地下厂房开挖过程中采用“分层开挖、及时支护”，并实时进行监控，及时对开挖爆破参数进行调整，通过精细的施工开挖控制和及时支护，有效地保证了开挖质量，未出现塌方等围岩破坏，控制厂房边墙变形等，收到较好效果。

（3）高压岔管和地下厂房等重大地下工程通过五道安全防线解决高压岔管和地下厂房的防渗排水，遵循“前堵后排”原则，每一道工序都至关重要，是工程成败的关键。

罗绍基，1933 年出生，籍贯广东省南海市，1955 年毕业于清华大学。历任水电部中南勘测设计院院长（期间曾任湖南省凤滩水电站设计总工程师），水电部华南电网办公室主任，广东省电力局副局长兼广东蓄能发电有限公司总经理，现任广东蓄能发电有限公司顾问。曾两次获得国家科技进步二等奖，1999 年当选中国工程院院士。

结合地铁工程建设做好大城市地下空间开发及其工程风险防范

施仲衡

北京城建设计研究总院

一、抓住地铁工程大规模建设时机做好大城市地下空间利用规划与实施

随着经济快速增长和城市化率的迅速提高,我国城市人口急剧增加,城市规模不断扩大,机动车数量迅猛增长、交通问题日益突出,城市土地资源紧张、建筑空间拥挤、绿化面积不断减少。为了解决交通问题,大城市采取了大规模修建地铁的办法;为了解决城市土地资源紧张的问题,开发利用地下空间资源的理念已逐渐被人们所接受。

城市中心区地铁一般以地下线为主,线路区间和地下车站占了城市地下空间。如果地铁工程建设时统筹考虑了城市地下空间的利用,那么就给将来城市地下空间开发留有了充分的余地,并且容易做到地上地下空间的综合、整体、优化利用;反之,地铁工程修建之初没有统筹规划城市地下空间的综合利用,势必给将来的地下空间开发带来不少障碍,甚至由于地铁工程的不可逆性而带来很多永久的遗憾。

国内外大城市的工程实践也证明了这一点。香港九龙综合交通枢纽结合地铁建设开发了地下街、地下商城等;加拿大蒙特利尔、多伦多,结合地铁建设了规模庞大、功能齐全、交通便利的地下步行道系统和地下城;美国纽约结合地铁系统建成了地下街、地下步行道、地下商场等地下综合体;巴黎拉德芳斯地铁车站,建成“双层城市”,轨道交通、道路和静态交通全部放在地下,地面只有绿地、公共活动空间、喷水池等景观设施;特别是日本,国土面积小,城市用地十分紧张,在地铁建设早期就做好了地下 30 米空间的分层规划:地下一层,深度为 3 米至 5 米,主

要规划布置干线、支线共同沟；地下二层，深度6米至10米，主要规划布置地下步行道、地下街、地下停车场、地铁车站等，或者干线和支线共同沟；地下三层，10至30米，主要规划布置地铁线路、或者地下停车场、地铁车站等。其地下空间开发利用效率、建设规模、成熟程度都居世界领先地位，现在日本已经开始地下100米空间的规划工作。

截止2011年底，我国已有13个城市开通了53条城市轨道交通线路，运营里程达1650多公里，目前已有36座城市完成了轨道交通规划，其中31个城市轨道交通规划通过了国务院审批，到2015年，全国28个城市将拥有地铁运营线路96条，运营总里程将达到4000多公里；到2020年，城市轨道交通运营里程将达到7200多公里。可见，我国目前，以及未来相当长的一个阶段，都将处于地铁的大规模建设时期。以地铁大规模建设为契机，做好城市地下空间开发利用，既是机遇又是挑战。

二、目前我国城市地下空间开发利用存在的主要问题

1. 地下空间规划没有专项立法，尤其是没有与地铁联合开发规划的相关法律法规，造成地下空间规划缺乏法律依据，这对城市的整体规划、城市轨道交通可持续发展和地下空间不可再生资源开发利用与保护产生很大影响。

2. 地下空间开发利用涉及部门多，并且部门之间条块分割，职能边界模糊，部分职能交叉，造成了多头管理与无人管理并存、不能形成合心合力的局面。地下空间的开发利用是一个系统工程，恰恰需要各部门之间的统一和配合，于是形成管理体制、机制与实际需求的不适应。

3. 地下空间利用规划滞后，缺乏前瞻性、整体性和协调性，造成地下空间开发各自为政、各行其是、零零碎碎、功能单一、缺乏衔接和连通的局面，综合效益十分低下，并导致后期综合开发利用难度大、风险高。

三、降低地下空间利用开发风险应采取的对策

1. 尽快出台城市地下空间利用的法律法规和规范标准体系。对城市地下空间的管理体制，以及城市地下的所有权、规划权、管理权、使用权等问题予以明确，使城市地下空间开发利用的规划、设计、管理都有章可循、有法可依。

2. 建立统一规划的机制。将城市地下空间利用纳入城市规划、城市综合交通规划、城市轨道交通规划中去，实现地下空间利用与城市交通、地铁枢纽和车站、人防工程、城市市政管线等的整体规划。同时，应该实现地铁与地下空间利用的同时规划、同时设计、同时施工和投入使用。重庆市几年前就开始倡导地铁规

划建设与地下空间开发采用“三同时”，取得很好的效果。

3. 做好前期勘查工作能够有效降低地下工程风险。结合地铁工程的建设，做好地铁车站及其周边开发区域的工程地质、水文地质、周边建筑、地下管线、地下构筑物、障碍物等勘察工作，将安全风险把控关口前移，可大大降低未来地下空间开发风险。

4. 推行地铁规划方案阶段进行地铁规划方案风险评估制度。使地下工程在未来建设、运营过程中的风险在规划方案阶段就予以避免和控制。

5. 研究大深度、大尺度、大空间的地下工程建设设计施工技术，从技术上解决未来大规模地下空间利用开发时的建设风险。

总之，城市地下空间是城市一种宝贵、重要的资源，同时，其工程风险也比较高。结合我国目前大规模的地铁建设，做好城市地下空间利用规划，无疑是防范和降低整个城市地下空间开发利用风险的一个根本途径。

施仲衡，1930 年生于上海，1953 年毕业于唐山铁道学院。随后参加空军抗美援朝工程队，1955 年赴苏联莫斯科铁道运输工程学院学习，1959 年 8 月毕业回国，获副博士学位，1999 年当选为中国工程院院士。从上世纪 60 年代参加我国第一条地铁——北京地铁一号线的建设工作开始，一直工作在城市轨道交通领域，历任北京地下铁道工程局科研所所长，北京城建设计研究总院总工程师。

施仲衡院士现兼任中国城市轨道交通协会专家委员会主任，中国地铁工程咨询公司顾问，北京交通大学教授、博师生导师，西南交通大学名誉教授，建设部质量安全专家委员会主任，中国国际工程咨询公司专家顾问，北京市人民政府专家顾问，北京、重庆、南京等市城市轨道交通专家委员会主任。

曾经主持了上海、北京、广州等各大城市几乎所有轨道交通项目的可行性研究报告的评估，主编了我国第一本地铁设计国家规范《地铁设计规范》，主编了我国第一本地铁专著《地下铁道设计与施工》，主编《都市快轨交通》(原《地铁与轻轨》)杂志。主持了中国工程院“降低地铁造价及工程建设管理等若干问题的研究”、“中国智能城市建设与推进战略研究”中“智能城市的空间组织模式语战略研究”子课题；国务院“国家中长期科技和技术发展规划战略研究”中“大城市综

合交通战略及关键技术研究”;“十一五”国家科技支撑计划“新型城市轨道交通技术”;“重庆市轨道交通发展纲要”等国家级和省部级地铁重大科研项目,其中基于降低地铁造价科研成果向国务院呈送的《降低地铁造价保证城市地铁建设可持续发展》的报告得到温家宝总理的亲笔批示,为我国城市轨道交通建设做出了卓越贡献。

中国地下核电站工程

陆佑楣

中国大坝委员会

本来会议是要求我做主题为“中国水力发电的地下工程”的发言,昨天马洪琪院士已经做了很全面、深入的发言,所以今天我就不重复了。钱七虎主席要求我在这个会上提出地下核电站的概念,他和几位工程院院士共同提出过这么一个建议,为此我做一个发言。

第一,大家都知道,日本福岛核电站的事故是因为地震引起的海啸,导致反应堆的备用电源——柴油发电机没有运作起来,出现失电现象,造成反应堆冷却水循环泵停运,致使堆心温度升高熔化,发生了核泄露。事故发生后,采用了很多非常危险的、非常困难的办法来处理。由这件事情我们想到了一个新办法:把核反应堆装置在地下,万一发生各种风险性事故,就可以将其封闭在地下,岩石是非常优良的抗辐射介质,这样就可以避免核泄露。这样人们就可以大胆地建设核电站,来解决人类的能源需求。地下工程施工技术日趋成熟,我举几个中国现在的水电站地下工程的例子。长江三峡水电站一共有 32 台机组,其中 6 台 70 万千瓦的机组是放在右岸的地下山体中。它的厂房跨度是 32. 6 米,长度是 311. 3 米,今年 6 月将全部投产。金沙江下游河段有 4 座巨型水电站,其中的溪洛渡水电站一共有 18 台 77 万千瓦的机组,总装机容量 1386 万千瓦,多年平均发电量达 571. 2 亿千瓦时,是一个非常巨大的电站,而它的机组全部安装在两岸的山体中。它的地下厂房跨度 31. 9 米,最大长度 444 米,开挖高度 75. 6 米。目前溪洛渡电站地下厂房土建工程已经全部完成,明年将陆续投产发电。

像溪洛渡电站这么大规模的地下工程,施工过程中没有遇到严重的岩爆,也没有遇到恶劣的地质环境,为什么?因为在选择厂址的过程中,预先做了大量的勘探工作,躲开了不良地质体,因此给施工过程创造了一个非常良好的条件。在整个工程的施工过程中,除触电、高空坠落等意外死亡的,没有一例因隧洞坍塌、渗水、岩爆等施工事故死亡。这都是一些成功的例子,说明在地下搞大规模的工

程是有条件的。但是在布置地下工程时,首先必须进行详细的工程地质、水文地质勘探,探明岩体等级、岩石强度、岩石构造等情况,确保厂址必须远离断层、远离可能产生地震的破裂带。这就是地下工程非常重要的前期过程。

大家会说如果要把核电站的反应堆装在地下,可能造价会增加,我也可以在这里举一些造价的例子。我们统计了一下,中国的地下水电站的造价水平大概是每一立方米石方开挖需要 100 美元左右。对于整个电站的造价来讲,它占的比重是很小的,在经济性上应该是可取的。

第二,岩体结构的安全性。核反应堆(像第三代美国 AP1000、或者是欧洲的 ERP)大概是 40 米左右直径的圆筒。从水电站的地下工程来看,完全能够做到 40 米直径的圆筒形的结构,圆筒形结构的周围岩石应力很低,所以水电站能够形成,核电站也一定能够形成,反应堆的安全性完全能够形成。核电站安全壳里面有一个反应堆叫压力壳,起重能力要求很高。水电站厂房能够起重 2000 吨以上的水轮发电机转子,因此,核电站压力壳的起重问题是可以解决的。

第三,抗震性能怎么样。大家也担心,装在地下的核电站的抗地震能力怎么样?大量的工程实践和监测研究工程师们都认为地下建筑物的抗地震能力,要比地面的建筑物可靠得多。

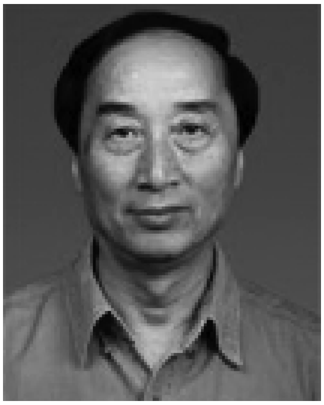
第四,地下水会不会污染。水电站的地下工程采取了很多厂房和地下水完全隔绝的工程措施,包括周围岩体的固结灌浆和排水、帷幕灌浆,使得地下厂房洞室和岩体的水系统完全隔绝。有人担心地下核电站可能有放射性物质会渗入到地下水,引起地下水污染。只要地下核电站做好防渗工程措施,这个问题是不需要担心的。

第五,地下厂房有很多通道和辅助厂房,我们可以在地下打另外的洞室用来储存低放射性的物质,即乏燃料的储存室。乏燃料经过再加工,可以在第四代核电站上使用。如果出现核泄露事故,所有的地下通道都可以通过特殊设计的、抗辐射的密封门封闭,防止核泄露。

第六,核电站需要大量的冷却水。一般的核电站都是建在海边,可以利用经过处理的海水,作为汽轮机的冷却用水。在内陆建核电站没有海水,就必须要有稳定的水源。如果和水电站的水库结合起来,完全可以稳定地解决地下核电站的冷却水供应问题。

进一步的设想,可以把核电站和水电站结合在一起,形成高效清洁的能源。中国的能源需求还有一个相当长的增长过程,目前全国人均占有电力只有 0.75 千瓦,而美国一个人是 3 千瓦,欧洲是 2 千瓦左右,所以中国还需要一定的增长。如果大量的烧煤,造成环境污染和二氧化碳的排放,都是很不利的。

地下核电站的构想并不是现在中国才想到的，其实俄罗斯和欧洲早就已经研究地下核电站的问题了。中国现在已经开始进行一定的实质性工作，由长江水利委员会的长江设计院和成都的核动力设计研究院进行合作，准备提出一个可行方案。在地下工程的安全建设风险管理会上，提出建设地下核电站这个课题，供大家参考。



陆佑楣，1934年生于上海，1956年毕业于华东水利学院，2003年当选为中国工程院院士。水利水电工程专家。曾任水电部副部长、能源部副部长、国务院三峡工程建设委员会副主任委员，现任中国大坝协会名誉理事长，清华大学、河海大学教授。

长期从事水利水电工程建设的技术和管理工作。先后参与、组织了刘家峡、盐锅峡、石泉、安康、龙羊峡等水电工程的建设。1993～2003年期间担任中国长江三峡工程开发总公司总经理，主持三峡工程建设，研究和决策了一系列重大工程技术和管理问题，2003年顺利实现了水库初期蓄水、首批机组发电和船闸通航的建设目标。主要论著有《三峡大坝混凝土施工》、《长江三峡工程建设管理的实践》和《在实践中认识三峡工程》等。

地下工程的设计和风险

郑颖人

解放军后勤工程学院

我感到这个会议开得很好,效率比较高,课题内容比较集中,参会人员大部分都是长期从事这方面研究工作的,我自己确实学习到不少新的东西,表示很赞赏。我对当前地下工程的设计和风险提一点意见。

第一,我觉得我们国家的地下工程设计还不尽如人意。与其他国家相比,风险也是比较大的。为什么设计不尽如人意呢? 因为我国应用最多的地下工程是铁路隧道、公路隧道和地铁。在隧道设计中,主要有两类规范,这两种规范隧道结构尺寸有很大的差距,比如说国家标准锚喷支护规范,这个规范对良好的围岩中,如Ⅰ、Ⅱ、Ⅲ级围岩,采用的衬砌厚度远远比公路、铁路、地铁采用的厚度薄,也不用二衬。比如说Ⅲ级围岩,跨度 10 ~ 15 m 的隧洞,没有二衬,衬砌总厚度大概是 10 ~ 12 cm,从 1985 年开始,这个规范也用了二三十年了,现在还是采用这个结构尺寸。如果采用铁路规范,同样的情况下,厚度大概是 40 多公分。这两类规范,都说是按照经验来确定的,为什么有这么大的差距,表明我们对这样一个问题还存在设计思想混乱,但没有引起相关政府部门的重视。我认为这种现状主要是工程计算界对隧道设计理念理解不一致造成的,目前这种状况是不合理的,应该引起政府部门的重视。

第二是关于风险,我认为这与工程设计人员设计理念有关。现在国内交通隧道设计中比较重视二衬,初衬很薄,主要由二衬承担荷载。这就导致施工中潜伏着较大的风险。现在跨度越来越大,遇到的围岩质量差、地应力大的情况越来越多,仍然用 20 ~ 30 公分初衬,不足以承受围岩变形压力。比如说黄土隧道,过去跨度只有 5 米,现在是 12、13 米,到 17、18 米。在黄土隧道中我碰到一个工程只掘进几百米,出了两次事故,地面上的房子一直塌到隧洞,第一次死了 3 人,第二次又是这样塌了,幸好没有发生亡人。这表明我们对初层没有足够重视,西方发达国家一般认为初衬应当承受主要荷载,二衬只是储备,我认为这个观点是对的,

我们应当重视初衬的修建，尽量减少施工风险，尤其应重视一些地质特殊、岩体破碎、跨度大的隧道，还有一些地应力高、水文条件复杂的隧道。多数情况下风险发生在岩体松散软弱的大跨度隧道。这种情况下容易引起隧洞两侧破坏，最终拱顶大塌方。所以，我认为我们的设计理念还不行，应该在初衬上下工夫。迫于形势，现在有些人搞了二次初衬，都是为了解决施工中的风险问题。我认为需要加强初衬，二衬厚度适当减薄，这样既可降低风险，也不会造成浪费。

第三，从我自己的研究工作经验来看，目前在科研方面发展的方向，应该：一是大量运用监测仪器，二是数值化，大量运用计算机。三是信息化，可视化。这三化是当前一个发展的方向。我们国家在这几个方面的差距比较大。一是要有先进的监测仪器，目前大部分都是引进国外的，我们国内还在起步状态。因为理论跟不上，一般都是工程在先，只有靠监控来调控，而且发展理论也需要监控的验证。二是数值化，国内国外做了很多数值技术，编制了很多软件，数值技术是一个方便、有用的工具，科研实验要花很长时间，而数值模拟就比较简单、速度快，只要采用的模型准确，肯定能与实验很好配合。当然，如果模型不准，参数不准肯定做不好。三是要使设计与施工做到信息化、动态化、可视化。希望今后我国在这方面有较快的进展。

第四，我们在工程领域要大力发展施工机械与工程设备，尽量做到产业化、标准化、规范化。跟国外相比，我们一些施工机械也与国外有差距，现在我们的大型机械也有了，但是人家还是走在我们的前面，我们生产的东西主要还是人家已经生产的东西。实际上只有在施工机具和设备上有大的改变，才会引起设计理论和安全风险防治的改变，所以发展大型设备是最重要的。谢谢大家！

地下隧道突水、突泥

周丰峻

总参工程兵第三研究所

我想只谈一个问题，就是地下隧道突水、突泥的问题。关于这个问题，挪威的Nick教授在讲述当中说了很多这方面的内容，我觉得非常珍贵。我们国家如果讲地下工程施工当中遇到的问题，最突出的问题就是隧道突水、突泥、突石问题。有几个突出的问题，就是元梁山突水突泥问题，钱院士已经讲过这个问题，它的特点是什么？地上的水位400米，在这个地方开挖铁路的隧道，这个铁路隧道有许多地下溶洞相互连接，溶洞率很高，但是当地老百姓说这个铁路一定从这儿过，我们太穷。本来铁路线不从这儿过，但是当地老百姓提了意见，铁路要从这里过，所以铁道部下决心从这儿过了。当然知道这里有风险，但还是去做了。这一点我觉得不能完全规避，但是，的确是为了解决当地经济的发展问题做了这样的工作。它遇到的问题是什么？一般的风险都经历过去了，但是有一次就过不去了。这一次的特点是什么？它所遇到的情况给人一个假象，掌子面土是风化的，岩石是风化的，好像还比较干燥，大家以为不会有大的突水的问题，因为没有看到任何迹象，但是再继续掘进的过程中突然就涌出来了，这个规模就是沿着9米直径的全洞室里面的风化土加上背后的高压水一起推出来了，推出来的土把前面装载运输的车向前推动了十几米，力量之大是可以想象的，发生了亡人事故。它的原因就是我们不能够查明在地质上这个土究竟多深，背后有多少水存在，对于水地质雷达也确实不好用。在土的后面其实就是非常大的水体在那里，这个水和400米以上的水的东西贯通性非常好，因此它的水压就保持了40个大气压，40个大气压的水这么大的压力，推着这一块土体，整个土体被高速推出来，灾难就是这样出现的。我们没有预料到会出现这么严重、这么突出的事故，但是确实出现了。第二个例子，就是我们的野三关。野三关不但突水突泥，还有突石，大概有一立方，而且从掌子面推出来的石头整个铺了300米长的路线，全部是推出来的石头。我下去亲自看了一下，我也不理解，开挖的桩号很明显，掌子面上都是，是什么原因？我不

搞地质,我完全不理解。后来请了地质专家来看,很明确的意见,和地下河打通了。我们回头来看,的确那里的石头不一样的,不是同类的石头,地下河的石头搬运到隧道里来了。所以大自然的威力之大是难以想像的,当然也造成了伤亡。马鹿箐,万县到宜昌这段铁路线上遇到的事,比这个礼堂还要大的水体贯通了,涌出来就是一条河,能够达到每秒钟 200 立方米,就是一条河喷出来的,当然还是造成伤亡。地下涌水给我们非常重要的教训,也有很重要的启示。我提三点建议:

第一,要非常重视地质调查问题。这个调查不仅是工程开工之前要搞好,在工程过程当中也要不断加强地质调查。因为我们不清楚,不清楚就更需要做。正是由于对地质不清楚,前面是不是有比较大的溶洞存在,有时候我们打得很进,但是前面有一个大的溶洞没有发现,地质勘察的办法,地质勘探必须在工程进行当中做,问题出现的时候要舍得花大的投资,我们往往认为交代给施工单位之后,就由施工单位全部承包,我们不管了,业主也不管了,设计单位也不管,这不行,这个应该是我们共同的责任,应该我们共同承担,地质调查要在施工前仔细做,不能简化,施工过程中也应该做。

第二,把施工当中的量测和危险预报做得更好一些。我们过去做了不少,但是经验还不够,我们有些事故就是施工单位抢进度,也不太注意,我们也讲了,我们应该做的探测没有达到施工掌子面附近,所以很多事件就这样出现了,因此监测尽量靠近开挖掌子面进行,这是必须的,量测的手段还要配得更多更好,除了雷达技术以外,一些新的技术,比如李术才教授提供的一些方法我觉得还是很有效的,在预报后来的整个公路隧道的时候,在预测突水问题很有效,成功率能够达到 80%、90%。

第三,在注浆技术上还要很好做工作。地道的涌水很多,20、30 米的喷出去,怎么在一个孔口有喷水情况之下,能够制止它,很难,但是应该不是没有办法。最近这些年搞出的有双液注浆技术,有注浆体把口迅速堵塞住,采用发射手段,把口发射出,通过一个管子继续向高压注浆,这个浆要超过整个水的高程,注射的压力要 400 米就要注到 40 大气压以上,目前可以达到 100 个大气压,使得注浆的压力更高,我们必须成功的是高聚物注浆,把整个水完全顶上去了。这种类似的技术,靠注浆止水的技术还要不断完善,这样使得我们多一些手段,把可能产生的灾害能够解决。谢谢大家!

煤矿安全管理

Kevin Riemer

南非金田公司

我主要是讲关于我们国家的变化的情况。我们这个国家自从政府发生变化之后,就一直在考虑如何在安全问题上能够有进一步的改进,我们在这个方面所做的一件重要的事情就是我们有了新的环境和安全以及医疗卫生法案,这使得煤矿的安全问题得到了很大的改进。对于这些矿主来说,必须要能够担负起他们的责任。Peter 在他的讲话中也提到,现在我还是进一步强调一下,工人要求安全的权利是必须要得到保护的。如果人们工作的环境,每天在那里工作,他们必须要知道工作的条件是什么,在接下来的工作时间当中,是不是安全;如果他们觉得不安全,他们有权力从不安全的界面尽快撤出来。根据我们的健康安全法案,所有的管理,如果觉得在某一个地方会发生岩爆,岩石的下坠,那么他们就必须要能够立刻作出决定。不管是岩爆还是岩石的坠落,他们在出现的时候都会产生很大的灾难,所以必须能够对此采取积极措施。在 Peter 在讲话中提到,我们必须加强在南非的安全生产文化,这一点已经得到人们很多的回应。在很多地方人们都认为,如果我们不能够安全采矿,我们就不应该采矿。在任何一个机构当中,规划都是非常重要的,如果你不能够很好地规划,那么你是注定要失败的。在今天下午的时候,有学者讲话中也提到规划的重要性,我觉得规划中非常重要的一个方面就是你制定了计划、有了规划之后就必须要遵守你的这个规划,如果要变化也必须要有足够的理由,你才能改变它。

今天上午我们谈到关于研究的问题,我们目前所面临的一个问题是对安全的管理,有的时候有点过紧了,政府现在也在做这方面的工作。但是就我来说,我觉得对于矿山的管理来说,安全的管理是永远都不会太过的,我们必须要能够遵守我们所制定的关于安全的这些规定。

Part I

Review

Review

1. Forum Background

With continuous development of the world economy, construction of underground engineering and development & utilization of underground space will be one of keys for the world engineering construction in the following 20 years. A great deal of large hydroelectric power underground excavation clusters and deep-long tunnels, many river-crossing and sea-crossing highway/railway tunnels and urban railways will be constructed worldwide continually. Meanwhile, deep mining of resources through coal mines and metal mines and so on has become the development trend in the world in order to meet the resource demands of economic building and development. For the construction of these underground engineering projects, their size is often huge and geologic conditions can be complicated, involving geologic and engineering hazards and accidents caused by rock bursts, large deformations, large-area landslides, water bursting, ground surface subsidence. They can cause such significant losses such as personal injury and death, equipment damage, delayed construction period, engineering failure and so on. Hazard development, hazard mechanisms, risk evaluation and management, control theory and techniques for underground engineering control have become key and challenging scientific and technologically difficult problems faced during construction in underground engineering.

The Forum invited many well-known experts in geotechnical engineering, railway, hydraulic engineering, earthquake protection and disaster mitigation engineering fields from home and abroad, and conducted overall, multi-perspective, strategic and forward-looking theme discussions on the safe construction and risk management of significant underground engineering under complicated geologic and environmental conditions. With this interdisciplinary combination, the Forum was aimed at developing and exploiting a resolution plan for hazard mechanism research, prediction and pre-warning in underground engineering and underground space for complicated geologic conditions, thus promoting the new development of a prediction and forecast capability of hazards (rock bursts, large deformations, landslides and so on) in underground engineering. This leads to hazard prevention and control and risk management in China, even in the world, driving independent innovation and breakthrough through new theory, new method and new technology.

2. Profile

With the joint efforts of the different parties, the Forum, "*Safe Construction and Risk Management of Significant Underground Engineering—International Top-level Forum on Engineering Science and Technology Development Strategy*" was held in the Hongshan Hotel in Wuhan during 18th –19th May, 2012. The Forum was organized by the Chinese Academy of Engineering, and was jointly sponsored by the Engineering Management Academic Division of the Chinese Academy of Engineering (CAE), the Civil, Hydraulic and Architectural Engineering Academic Division of the CAE, the Chinese Society for Rock Mechanics and Engineering (CSRME), Wuhan Institute of Rock and Soil Mechanics (IRSM) of the Chinese Academy of Sciences (CAS) and the State Key Laboratory of Geomechanics and Geotechnial Engineering. In addition, Hubei Provincial Party Committee, Hubei Provincial People's Government, the National Natural Science Foundation of China, and the Wuhan Branch of the CAS also provided great support.

The Conference faced the key scientific and technological issues on the safe construction and risk management of significant underground engineering in the world over the next 20 years, and conducted high-end, macroscopic, comprehensive and strategic discussions. Three key themes were discussed: cataclysm mechanisms and regulating systems, design theory and methods, safety risk evaluation theory and a management system for significant underground engineering under complicated geologic and environmental conditions. There were conference special reports and a one-theme-involved round-table high-end discussion.

There were 18 academicians who attended the Conference, gave special reports and participated in the discussion: Academician Ji Zhou—President of CAE, Academician Qihu Qian, Academician Youmei Lu, Academician Yongfu Sun, Academician Xiurun Ge, Academician Hongqi Ma, Academician Jingquan Wang, Academician Wei Sun, Academician Zuxun Zhang, Academician Fengjun Zhou, Academician Shouren Zheng, Academician Yingren Zheng, Academician Denghua

Zhong, Academician Shunquan Qin, Academician Junzhi Cui, Academician Xiaonan Gong, Academician Jiancheng Li, Academician Zhenqi Song from CAS. There were eight foreign famous academicians and experts: Professor John A. Hudson—Academician of the UK Royal Academy of Engineering and former President of the International Society for Rock Mechanics (ISRM); Professor E. T. Brown—Academician of the UK Royal Academy of Engineering, Academician of the Australian Academy of Technology, Science and Engineering, winner of the top prize (Muller Prize) of the ISRM; Professor Charles Fairhurst—Academician of US National Academy of Engineering and Academician of the Royal Swedish Academy of Engineering Sciences (ⅣA); Professor Peter Kaiser—Academician of the Canadian Academy of Engineering and former Vice-President of the ISRM; Doctor Nick Barton—winner of the top honor (Muller Prize) of the ISRM; Doctor Kevin Riemer—an expert in mine earthquakes from South Africa; Professor Yossef Hatzor—President of the Israel Society for Rock Mechanics; Professor Luis R. Sousa from Portugal—former Vice-President of the ISRM. Also prefect were Academician representative Shaoji Luo, Academician representative Zhongheng Shi, Researcher Xiating Feng—President of ISRM, Professor Lieyun Ding, Professor Chun'an Tang, Professor Manchao He, Professor Shucai Li, Professor Wanhong Li—Director of the Hydraulic Discipline of Engineering and Material Science Division of the National Natural Science Foundation of China.

Academician Qihu Qian and Academician John A. Hudson acted as the Conference Presidents; Academician Yongfu Sun, Academician Youmei Lu and Academician Xiurun Ge acted as the Vice Conference Presidents.

Researcher Xiating Feng presided over the opening ceremony. Ji Zhou—President of the CAE gave the opening speech. Forum co-Presidents Academician Qihu Qian and Academician John A. Hudson, Shenglian Guo—Vice Governor of Hubei Province made speeches and expressed congratulations on behalf of the Forum organizing committee and relevant government departments.

The Conference was held over two days. From 18th May to the morning of 19th May, 2012, the experts and scholars attending the Conference made excellent special reports on safe construction and risk management as related to underground engineering. Out of these reports, Conference President, Academician Qihu Qian made the theme report titled "*Challenges Faced by Construction Safety of Underground Engineering and Its Strategies.*" Existing conditions of current underground engineering construction in

China, challenges for safe management and countermeasures were analyzed, and the report focused on analysis of countermeasures for most major engineering hazards such as water and mud bursting and rock burst in underground engineering construction. Ted Brown—former President of ISRM made a review of risk evaluation and risk management in safe management in underground engineering construction, and elaborated the theory, methods and actual engineering applications for risk evaluation and management of underground engineering in details. John A. Hudson—Academician of UK Royal Academy of Engineering made a detailed elaboration on the acquisition of rock mechanics parameters and engineering design under unknown geologic conditions. Academician Yingren Zheng introduced the application of finite element limit analysis method in tunnel engineering design and stability analysis in his report, and put forward the advanced design method for foreseeing and controlling engineering safety. Academician Hongqi Ma made a detailed introduction of hydraulic and hydropower underground safe construction techniques, national demands and frontier scientific and technological issues in China; Nick Barton—winner of the Muller Medal of the ISRM, introduced the analysis of TBMs and drilling-blasting methods in deep-long tunnel for reducing risk. Professor Yossef H. Hatzor introduced the application of the DDA block interaction numerical simulation method in risk evaluation of shallow-tunnel collapse, and conducted a detailed elaboration on specific applications of such a method in the Ayalon Tunnel, Zedekiah quarry and Beersheba underground water storage system in Israel. Researcher Xiating Feng from Wuhan Institute of Rock and Soil Mechanics (IRSM) of the CAS, Professor Lieyun Ding from Northeastern University, Professor Shucai Li from Shandong University, Professor Chun'an Tang from Dalian University of Technology, Professor Manchao He from China University of Mining and Technology and others also gave stimulating reports on major problems in the construction safety of underground engineering.

On the afternoon of 19th May, Forum Presidents Academician Qihu Qian and Academician John Hudson jointly presided over the high-end round-table discussion on the theme of safe construction and risk management in significant underground engineering. Focusing on the scientific and technological development strategy over the following 20 years, the Symposium conducted this discussion from an international perspective and discussed research and cooperation in the future. Chinese and foreign academicians and experts attending the symposium had made good preparations and presentations, and so some common understandings were achieved. President Ji Zhou gave a summary speech at the end of the Symposium.

3. Major Viewpoints and Conclusions of the Conference

After the reports and discussion covering the two days of the Conference, the following major viewpoints and conclusions were formed.

(1) Safe construction and risk management of significant underground engineering is a frontier issue that currently attracts the greatest concern by the international circle of rock mechanics personnel, and is also the key problem that will be given key research priority by China in the future. Presently, China is experiencing a major period for underground engineering construction. More and more tunnels, excavation clusters and underground space requirements appear in such fields as hydraulic and hydropower, transportation, city, mine, national defense and so on. Complicated geologic conditions encountered by these engineering projects and their construction size are rare in the world. Such geologic hazards as rock burst, mud and water bursting, landslides and so on frequently occur in the engineering construction process. Although the safety situation of underground engineering is becoming better to a certain degree, the accident rate remains high.

(2) For safe construction and risk management of underground engineering, the representative progresses obtained mainly include:

- Finite element limit analysis method technique and the tunnel stability analysis;
- Fiber grating sensing technology, real sensing technology of safe status in underground engineering construction and construction portable and intelligent pre-warning terminal technology. Some of the technologies have been successfully applied in actual engineering;
- Hydraulic and hydropower underground engineering construction technology (including large underground powerhouse safe construction technology, large cross-section and long tunnel safe construction technology under complicated geologic conditions, design and construction technology for high-pressure steel reinforced concrete brace piles without steel lining, safe construction technology of high-pressure and long inclined shaft, concrete formwork construction of underground engineering);
- Field and indoor test methods, characteristics, laws, mechanisms, analysis and pre-warning methods for rock burst reduction processes, pre-stepsmethods,

dynamic regulating method based on the dynamic evolution law of micro-earthquake information and large-deformation anchorage bar for controlling rock bursts. The results have been successfully practiced in the Jinping second-cascade diversion tunnel and drainage tunnel clusters, showing that rock bursts can be predicted, and the drilling-blasting method has better adaptability than that of the TBM in high-strength rock burst tunnel sections. A combination of TMB and the drilling-blasting method can reduce the risk of rock bursts;

- The water-bearing structure advanced forecast technology and system integrating land sonar, hydrospace identification, transient electromagnetic and complex type excitation and activation technology, new material for dynamic water grouting, research on the information comprehensive treatment decision-making system integrating geologic forecast and scientific service. The result has been successfully applied in Hurongxi express highway and submarine tunnel in Qingdao;
- For the subway construction field, development of laws and regulations system on safety risk management and system building were improved, and active exploring of safety risk management system of engineering construction was made, mainly including: the organization and management system which defines the clear management duties of the Employer, Investigator, Supervisor, Constructor and the third party monitor has been established; the safety risk technology management system that covers the entire process of engineering construction (including investigation stage, schematic design stage, preliminary design stage, construction drawing design stage, construction stage and post-construction stage) has been established; the safety risk management flow system covering risk identification, classification, evaluation and control has been established and normalized; the safety risk management forecast and pre-warning system (including monitoring and measurement and safety inspection tour) and monitoring and pre-warning model have been established; safety risk management guide for construction site activities has been established; remote monitoring platform for safety risk management and sound third party monitoring system have been established, and prevention and emergency measures for ordinary construction emergency engineering and environmental risk events have been given; these results obtained in research and practice shall be further comprehensively generalized in underground engineering field.

(3) Determining the risk in a complicated geologic environment and conducting timely and effective prevention are great challenges and keys for safe construction of underground engineering construction, and it shall strengthen coordination and the overall arrangement of all-life-cycle (namely entire process consisting of plan, investigation, design, construction and operation of underground engineering) of underground engineering, shall strengthen research on geologic investigation, ground stress testing and uncertainty and inhomogeneity of the rock mass, strengthen research on the fundamental theory, new technology and new materials about significant accident prediction and forecast and prevention and control related to seven coupled key factors GTHMCBE (namely, geology, temperature, hydrogeolosy power, stress, chemical, biological and engineering factors), establish underground engineering safety risk management information system based on modernization and information. It shall solve relevant difficult theoretical and technological problems through project initialization in such State projects as the 973 project and improve safe construction and risk management level of underground engineering.

(4) Presently, there exist such major problems as unsound management system, non-standard tendering, pressure to hurry up during the construction period, less investment for safety measures because of low engineering cost, low personnel technical capacity caused by employment system, and so on in the underground engineering construction field. The keys for improved safe construction and risk management level of underground engineering include: strengthen the establishment of laws and regulations on safety risk management for underground engineering; improve the investigation, design and construction technology specifications of underground engineering in different industries; establish and promote an underground engineering safety risk management system and safety monitoring center, improve the third party monitoring and supervision system; strengthen the engineering safety culture, promote the setting up of the social responsibility concept for the enterprises; establish and apply safety risk management guideline of underground engineering.

(5) In view of the facts that underground engineering has the advantages of earthquake resistance, wind resistance and a reservoir can provide a great deal of cooling water, one possible option is for constructing underground nuclear power plants in the underground powerhouse of the hydroelectric power plant.

4. Forum Significance

The Top-level Forum had a clear purpose and great pertinence. There were many world top-grade experts attending the Conference. It had great representativeness and the discussed issues were focused. The resulting analysis obtained through the Top-level Forum determined the key orientations in the development of safe construction in underground engineering over the following 10–20 years and condensed several key scientific and technological issues that will be given key organization and research emphasis in the underground engineering construction field in the future. As pointed out by President Ji Zhou in his summary speech: "The Conference has been held very successfully. And the goals and ideas have been achieved by the International Top-level Forum on Engineering Science and Technology Development Strategy. Academicians from such academic divisions as the Engineering Management Academic Division and Civil, Hydraulic and Architectural Engineering Academic Division of the CAE and top-grade experts from worldwide range have attended the Forum. All of us have leart from each other with one open mind and from different aspects and have conducted joint research, emphasized combination, as well as integration, conducted discussion at a high level, focused on the theme for strategic research, shown coordinated innovation and international cooperation. It has been a successful forum, and it has played a positive role in strengthening communication in engineering technology between China and the world, further promoting construction development and the scientific management of significant underground engineering in China, and in the world."

Part II

Keynote Lectures and Speaker Introduction

Challenges Faced by Construction Safety of Underground Engineering and Its Strategies

Qihu Qian

PLA University of Science and Technology, Nanjing, China

1. The status quo of construction safety in underground engineering can be figured from the following charts

This is a statistical chart of China's major and extremely serious accidents in recent years (Table 1).

Table 1　China's major and extremely serious accidents from 2008 to 2011

Year	Severity	Number	Death toll
2008	Major	86	1304
	Extremely serious	11	667
2009	Major and extremely serious	67	1128
2010	Major and extremely serious	74	1438
2011	Major and extremely serious	59	897

We can see that although the safety situation took a turn for the better in 2011, accident frequency kept high.

What is the ranking of the accidents and casualties of civil engineering in all kinds of accidents? It ranks in the third place. Road traffic accidents rank in the first place and coal mine accidents in the second. It is the civil engineering accidents that rank in the third place. In the extremely serious engineering accidents, civil engineering accidents account for about 10%. The following charts show the number of accidents and casualties caused by civil engineering accidents and underground engineering accidents(Fig. 1,2).

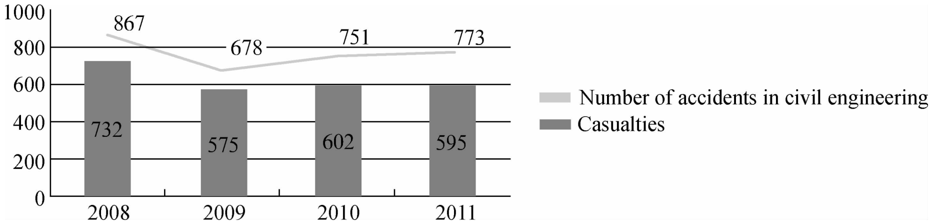


Fig. 1 Number of accidents and casualties in civil engineering

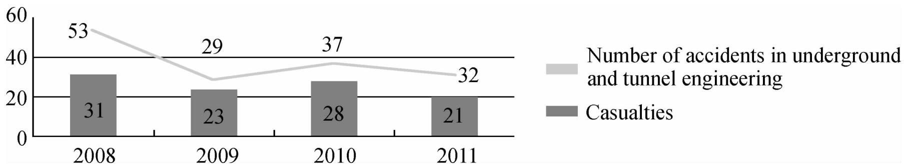


Fig. 2 Number of accidents and casualties in underground engineering

From these tables we can see that numbers of accidents and casualties in civil engineering and underground engineering haven' t declined obviously from 2008 to 2011. In underground engineering, there is a great fluctuation between 2008 and the other three years. Why is the number of 2008 so high? You may clearly remember that in 2008, the Hangzhou Subway Accident happened, causing the death of 20 persons. Therefore, we can say that there is no obvious improvement in the safety situation of underground engineering. The following is an analysis of the accidents. We collected more than 50 accident cases of underground mining and more than 20 accident cases of engineering adopting boring under shallow cover method. From the Fig. 3–7 we can see that the major types of accidents include collapse, water inrush, mud surging and rock burst.

Analysis of accident causes: in general, about 1/4 (accounting for 22%) of the causes are objective, more than 1/3 (37%) are subjective, and more than 1/3 are both objective and subjective. There are basically two kinds of subjective causes, that attributing to responsibilities and that attributing to human factors. Firstly, there is a responsibility defect in the supervising of government, fining and contracting taking the place of administrating. Secondly, the safety managing personnel of the Constructor hasn' t fulfilled the responsibilities of safety managing; the constructing directors

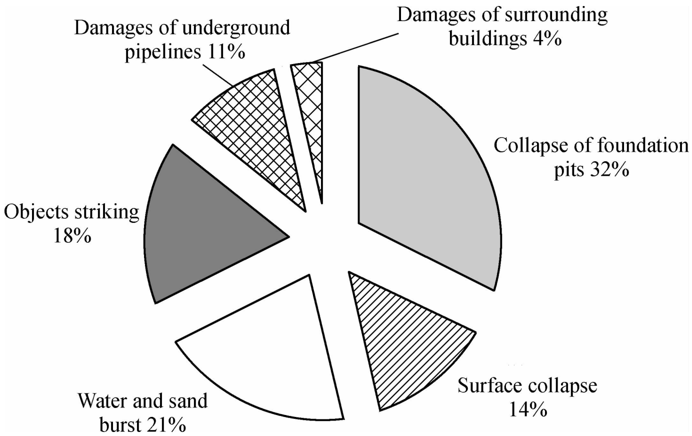


Fig. 3 Types of accidents in underground engineering adopting open-cut method

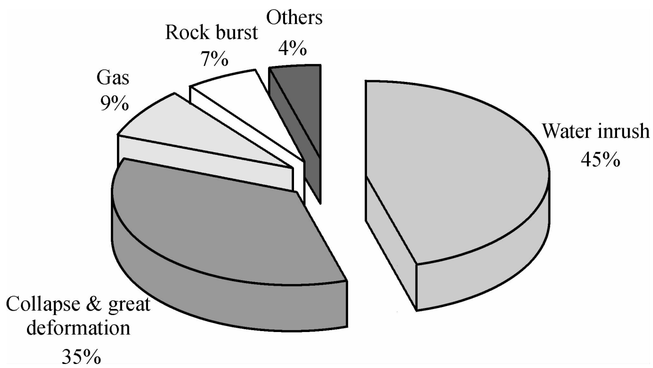


Fig. 4 Types of accidents in underground engineering adopting mining method

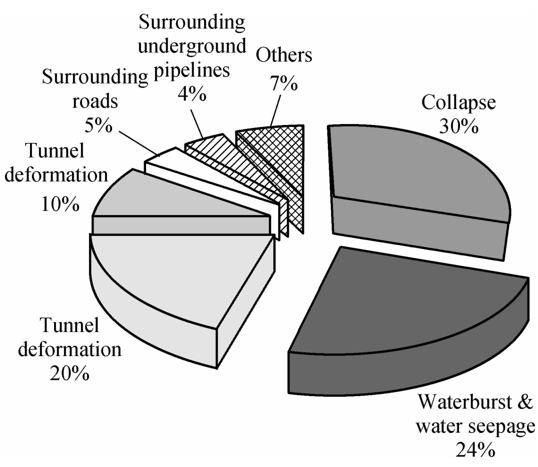


Fig. 5 Types of accidents in underground engineering adopting boring under shallow cover method

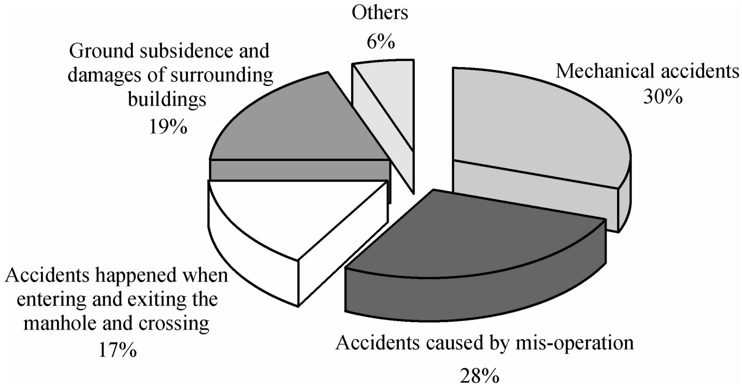


Fig. 6 Types of accidents in underground engineering adopting shield method

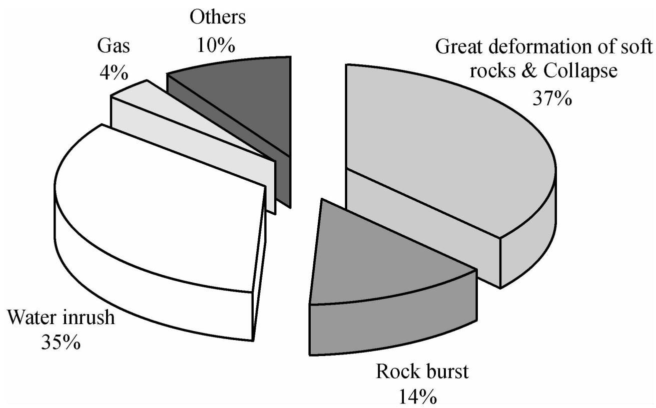


Fig. 7 Types of accidents in underground engineering adopting TBM

misdirect; the constructors mis-operate; and the construction planning is not complete. The supervision is not strict; there is a lack of the sense of responsibility; the Owner contracts and subcontracts illegally, and tries hard to meet the tight construction deadline; defects exist in the design proposal; the exploration data is not complete, etc. All of these are subjective causes of the accidents.

The underlying reasons behind these subjective causes can be concluded as the following:

1) Meeting the tight construction deadline. One of the important factors is the intervention of the government and Owner, making the construction deadline tight.

2) Low construction cost reduces the input of safety measures.

3) Problems exist in China's employment system. In underground and civil engineering, there are a lot of migrant workers, who possess little technique and poor sense of safety. What's more, there are a lot of migrant workers who are working

without licenses.

4) In the process of engineering bidding, there are phenomenon violating the regulations, such as illegal contracting, multi-level subcontracting, contracting taking the place of administrating, and fining taking the place of administrating.

As to the objective causes we mentioned above, most of the accidents are caused by environment and weather, among which the engineering geological environment and hydro-geological environment are the major ones. Especially in underground engineering, geological disasters like water inrush, mud surging and rock burst are the most challenging ones and the most difficult ones to deal with.

2. Challenges faced by safety management of underground engineering and its strategies. According to the above status quo and analysis, we put forward the challenges and strategies from the aspects of management and technology

Firstly, let's talk about the management—the challenges faced by China's safety management of underground engineering.

China is a great power in the world to develop and exploit urban underground space. The exploitation scale is ranking among the highest in the world. China's construction of urban rail transit enjoys the highest rate and largest quantity in the world. Many cities have undertaken the construction of underground expressway. Therefore, the objective situation of large construction scale and high development rate of China's underground engineering is brought about. But the underground engineering technology and management strength under such a situation cannot be guaranteed; what's more the construction deadline is a little bit tight; therefore, a lot of problems and challenges are generated:

① The preliminary work is not sufficient, including the insufficiency of geological exploration and engineering feasibility study.

② Temporary shortage of designers and constructors. Many engineers and assistant engineers are undertaking the construction project; the job-matching is not reasonable.

③ The high-risk character of underground engineering is not fully realized.

④ The management system is not in perfect order. Both overlap and defects exist in safety management and multi-head management.

⑤ The engineering bidding system is not standard, phenomena like subcontracting and bidding violating the regulations exist; and the project administrating standards are on different levels.

⑥ The system of winning the bidding at a low price makes the construction cost low, the input of safety measures and safety risk management is not sufficient.

To deal with these challenges, we need to find strategies from the aspect of administrative science. Administrative science tells us that the prevention of engineering accidents is feasible.

Now, I' m going to talk briefly about some of the research results of engineering safety science.

Fig. 8 is a general view of the development process of the engineering accidents; every accident develops from the beginning stage to the actual accident; and it usually takes two or three days from the slowly developing stage to the rapidly developing stage. In addition, according to Heinrich' s Safety Pyramid, an accident is caused by the 300 incidents below(Fig. 9).

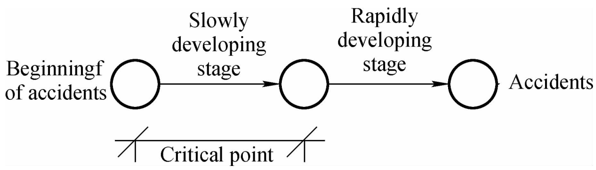


Fig. 8 An illustration of the development process of the engineering accidents

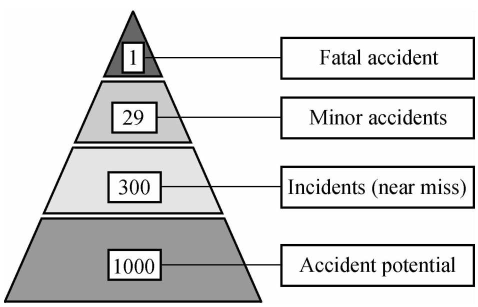


Fig. 9 Safety Pyramid developed by H. W. Heinrich

The Heinrich' s Safety Pyramid we just mentioned is a principle generated from the statistics collected according to large amount of accidents. Through the statistical analysis of 550,000 accidents, it is found that 88% of the accidents are caused by human's unsafe behavior, 10% are caused by objects' unsafe status, and only 2% is caused by force majeure. Therefore, if we can pre-discover human's unsafe behavior and objects' unsafe status, we can prevent and avoid the accidents.

According to the Change-fault Model proposed by Johnson (Fig. 10), the occurrence of an accident is caused by a series of faults and changes, including the changes of the leader, planner, supervisor and operator. If we cut off the chain of the accident, we will be able to prevent it. Therefore, the above research theories of safety science have revealed a theoretical model—an important principle of preventing accidents. The principle is: in order to prevent a fatal accident that involves death, you must prevent minor accidents; and in order to prevent minor accidents, you must prevent near-miss accidents; in order to prevent near-miss accidents, you must eliminate daily unsafe behavior and status. And the elimination of daily unsafe behavior and status depends on the daily safety management, or the details management of safety risk. This is the most important foundation of preventing fatal accident. Therefore, the emphasis of safety management does not lie on the post-accident management, but the safety risk management before the accident. Just like the medical treatment and public health, the emphasis is not on medical treatment, but on prevention. But we usually check the project and punish people after the accidents.

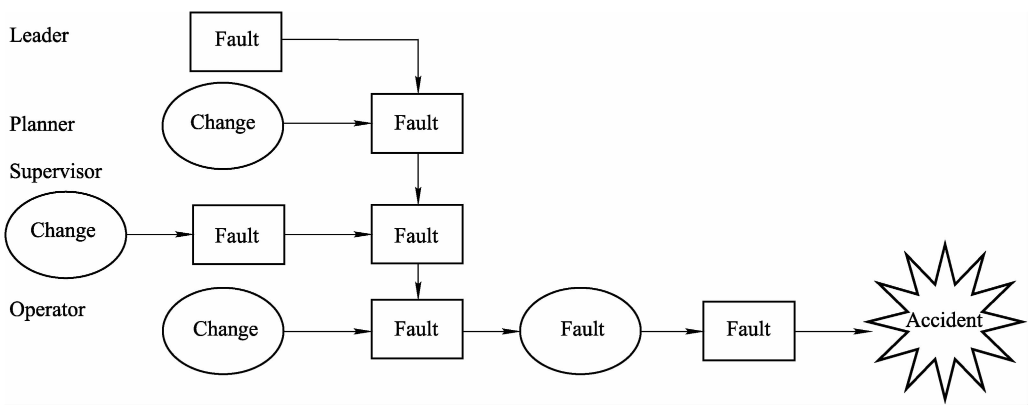


Fig. 10 An illustration of the Change-fault Model

Based on these challenges and analyses, we put forward the strategies that the safety management of underground engineering should carry out.

1) Strengthen the legislation

Safety risk management is not only safety management. The first thing we should do is to strength the legislation about safety risk management

① Related departments of the government and related guilds should make strict laws and regulations.

② The legal responsibilities of each party should be clarified in a system. Therefore, a managerial system of safety risk should be established.

③ We should enforce the safety risk analysis and evaluation research by laws and regulations before the approval of significant projects. For all the engineering projects that are evaluated as severe through the safety risk evaluation, we should adhere to "one-vote-down system", and must revise the engineering projects. Next, I would like to introduce some safety accidents of underground engineering. Take the railway from Yichang to Wanhsien as an example. There were three great accidents of water inrush and mud surging, causing the death of more than 20 persons. Because the railway is running across karst zones, risk evaluation should be carried out before the significant approval of the project—whether the burial depth of the line is reasonable, whether there are measures to reduce the risks. At the same time, checking system for the design and construction plan of significant projects should be enforced. But at present, one significant project is designed by one unit; and there is no other unit to check the design. There is no strict check for the insufficiency of design and construction plan that we just mentioned. For example, the main reason of Hangzhou Subway Accident was that the construction wasn't going through strict check, together with brutal construction and excavation.

④ Through the regulations and laws, the expenses of risk management should be determined according to the related rules of risk management. And the reasonable proportion of the risk management expenses in the construction expense should be determined. Just like foreign countries, safety management expenses should account for certain percent; and the special fund should be clear and out of the business bidding. This fund should be guaranteed no matter who wins the bidding.

2) The emphasis of carrying out safety risk management of underground engineering lies in prevention

① We should promote widely the system of safety risk management for underground engineering, taking the safety risk management as a necessary part of the construction management for underground engineering.

② Safety risk management includes the identification and analysis of risk factors. Because many hidden dangers and problems lie in the exploration period and design period, the safety risk management should be operating throughout the whole process of project, not only the construction period.

3) The establishment of safety management center of underground engineering

① How could we find the omens of accidents? The answer is monitoring and control. The most important part of safety risk management is monitoring and control. And correspondent agency and system should be set up.

② Safety monitoring and control center is the information hub of the safety risk management for underground engineering. The center is responsible for the safety risk monitoring and control in each part and on each stage. There should be strict management for the qualifications of the units that can undertake the monitoring and control. At present, we have supervisors; but the management of qualification is not sufficient.

4) A system for safety risk management of underground engineering should be established based on modernized information and technology

It only takes two to three days, or even less than that, for an accident to develop from the beginning to the actual occurrence. There is no time to send written report from the bottom level to the top level. Or the prevention will be too late. Therefore, we should use the modernized information system for risk management. And can the accident chain be cut off at the same time? If one party is not responsible, another party will stand out immediately and take the responsibility. The information should be unobstructed, apparent and shared. The information, including the information of geography, geology, engineering and environment, should be provided by elementary supporting departments.

5) To strengthen the theories about the safety management of underground engineering and the technologies of preventing and forecasting significant accidents

We have just mentioned that there are 2% of the accidents caused by force majeure. That is to say, some accidents cannot be perfectly forecasted and prevented. Therefore, we need to research on this problem. The most typical example is the accidents happened to Malujing Tunnel of Yichang-Wanzhou Railway. On November 20th, 2007, an accident happened, causing the death of 11 people. The construction was suspended immediately. Experts suggested the construction of a drainage tunnel. On March 21st, 2008, the drainage discharged the flood successfully, and the karst cave was drained. On April 19th, 2008, leaders of the Ministry of Railways and experts carried out on-spot inspection and evaluation, concluding that the target of making the tunnel through has been achieved. Experts from the Ministry of Water Resources also thought that the successful flood discharge of the tunnel stood for the solving the world-level problem of large scale, high water level and thick sludge, and that a breakthrough has been achieved. But only three days after the announcement of success, another severe water inrush happened to Malujing Tunnel, causing the death of 4 people. This example told us that our current technologies haven't solved the forecast and prevention of severe geological disasters. Therefore, we should strengthen the research on prevention and control.

3. Challenges and strategies of water inrush and mud surging

Water inrush is the most risky link in underground engineering. Because China has the largest scale of karst distribution, accounting for 1/3 of the national territory, the problem of water inrush is extremely prominent. The following is a chart of part of the karst disasters (Table 2). The concentrated water inflow reached a daily yield of more than ten thousand or hundred of thousand cubic meters. Here, we have a lot of examples of severe accidents of water inrush and mud surging. The Accident of Yesanguan is one of them (Fig. 11). Due to the time limitation, we cannot introduce the disaster in detail.

Table 2 List of water inrush and mud surging in parts of China's long and large tunnels

Tunnel name	Description of the geological disaster
Dayaoshan Railway Tunnel	Water inflow during the construction: 4000 ~ 15000 m^3/d, the water inrush in Parallel Adit 1994 +213 caused the submersion of the vertical shaft and machines and tool in the tunnel for several months. The water inrush of Main Tunnel DK1994 +600 caused the submersion of 200 meters of the tunnel; the water was 1.4 meters deep and the sludge was 1 meter thick; therefore, the construction was suspended for a year. Mud and sand surging of 80 m^3 happened in DK1994 +636 ~ 637, submerging the track and causing temporal traffic interruption. The production water and domestic water supply of Bangu'ao was running out. And there were about 413 surface collapses.

Continued

Tunnel name	Description of the geological disaster
Yuanliangshan Railway Tunnel	Water inflow during the construction: 110000 m^3/d (outlet DK361 +764); the water inflow of the water inrush in karst caves DK354 +450 ~510 was $9.6\times10^4 \sim 1.656\times10^5 m^3/d$, together with mud and sand surging which was 130 meters long, 2.5 meters high and had a sand surging volume of 1300 m^3. Water inrush, together with mud and sand surging (a total volume of 6000 m^3), also happened to karst caves DK354 +879; the largest water inflow was $7.2\times10^4 m^3/d$, causing casualties of the constructors who were compelled to get out through the pilot tunnel. Sand surging in DK360 +873 caused the submersion of nearly 200 meters. Water inrush together with mud and sand surging happened to DK361 +764; the water inflow was 240000 m^3; the surged mud and sand covered the whole tunnel face with a surging volume of 15000 m^3.
Geleshan Railway Tunnel	Water inrush happened to DK2 +619.6, with a water inflow of 14400 m^3/d; and the mud contained in the water inrush accounted for 20%–30%.
Maluqing Tunnel of Yichang-Wanzhou Railway	In Jan 2006, water inrush happened to Yichang-Wanzhou Railway's Maluqing Tunnel, which is located at Tunbao, Enshi, Hubei province, causing the death of 11 persons.
Yesanguan Tunnel of Yichang-Wanzhou Tunnel	On August 5th, 2007, an accident of water inrush and mud surging happened to Yesanguan Tunnel. Within 30 min, 15104 m^3 of water, mud, rocks etc. surged out, washing away a lot of machines and tools and causing casualties. It took at least half a year to deal with this accident. The main tunnel was submerged for 500 meters; and the space 200 meters within the tunnel surface was filled with boulders.

(a) (b)

Fig. 11 Water inrush of Yesanguan Tunnel, Yichang-Wanzhou Railway

1) Challenges caused by water inrush and mud surging to underground engineering safety

In the extraordinarily serious tunnel accidents both inside and outside China, water inrush is ranking among the highest in the number of casualties. Besides, it has a great influence on the construction period. According to the statistics, 30% of the construction periods have been influenced by water inrush and/or mud surging. What's more, due to the construction of China's infrastructures, especially the construction and development of the West, the burial depth of the tunnels has increased. Therefore, the economic losses and casualties caused by water inrush and mud surging are increasing.

2) Scientific principles exist in the occurrence of water inrush and mud surging

The occurrence condition of the water inrush and mud surging is the energy storage of the water-bearing structures, the dynamic property of the contained-water, energy release and stability of the surrounding rocks. If the surround rocks are not stable any longer, the contained water will be able to break through the surrounding rocks and burst into the tunnel. The influencing factors include objective factors and objective geological factors, etc., which can be figured out from the aspect of science. Therefore, as long as the omens of water inrush and mud surging are figured out, this kind of accidents can usually be forecasted.

① Omens of water inrush and mud surging in geological survey

Forecast should be carried out according to the observation of borehole leakage and the information of the surrounding rocks revealed by the excavation.

② Omens of water inrush and mud surging in geophysical exploration

During the excavation of underground engineering, if the geological radar wave goes through water-bearing structures, such as underwater, water-bearing karst caves and watery medium, the radio-frequency components will be absorbed, causing strong reflection. The phase of reflected waves after the radar wave going through the water-bearing structures is 180° different from that of the injection wave.

③ Omens of just before the water inrush and mud surging

What are the strategies dealing with water inrush and mud surging? One of them is to carry out advanced geological forecast and warning system. In this way, the disasters may be avoided. The geological forecast mainly includes long-distance and short-distance forecast. The long-distance forecast refers to the advanced forecast from 50 meters to 200 meters. And short-distance forecast refers to advanced geological forecast within 50 meters. The macro advanced geological forecast includes detecting the water through infrared rays, transient electromagnetic method, advanced boreholes. Certain warning measure should be taken according to the advanced forecast results.

3) Strategies dealing with water inrush and mud surging

Firstly, we should figure out whether there are great risks. Secondly, we should rank the risk grade of the whole project according to the survey, and release the grading the result. Risks of different grades should adopt different forecast programs. Projects of low risk grade shouldn't carry out very strict geological programs. Or the cost will be high, and construction will be slow. Shandong University has set a good example in the forecast and warning engineering of water inrush and mud surging. Their success rate has reached 90%. Of course, this is just an example; few units can obtain such an achievement; and no comprehensive system has been established. But this achievement is a great encouragement for us.

4. Challenges and strategies of rock bursts

1) The challenge caused by rock bursts to underground engineering safety

As the burial depth of our mines is increasing, the risk of rock bursts is also increasing. Figure 12 shows that rock bursts have increased exponentially since 1980. The excavation of mines is becoming deeper; therefore rock bursts become more prominent.

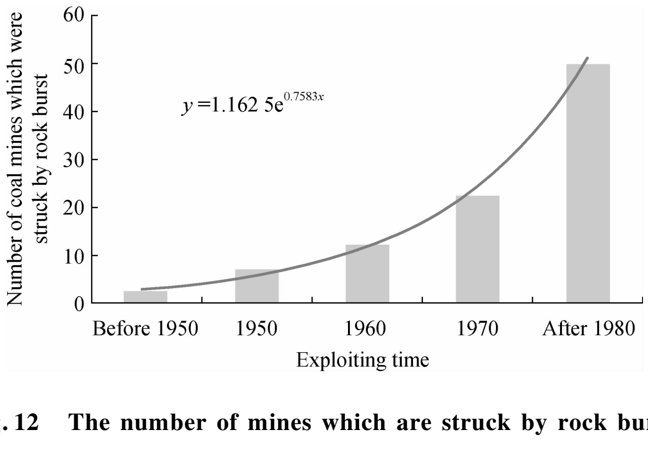


Fig. 12 The number of mines which are struck by rock bursts

The following Table 3 is a gathering of the tunnels which is struck by rock bursts. As the burial depth of underground engineering is increased, the frequency and degree of rock bursts is obviously elevated. For the degree of rock bursts, there is a tendency of approaching to medium and strong.

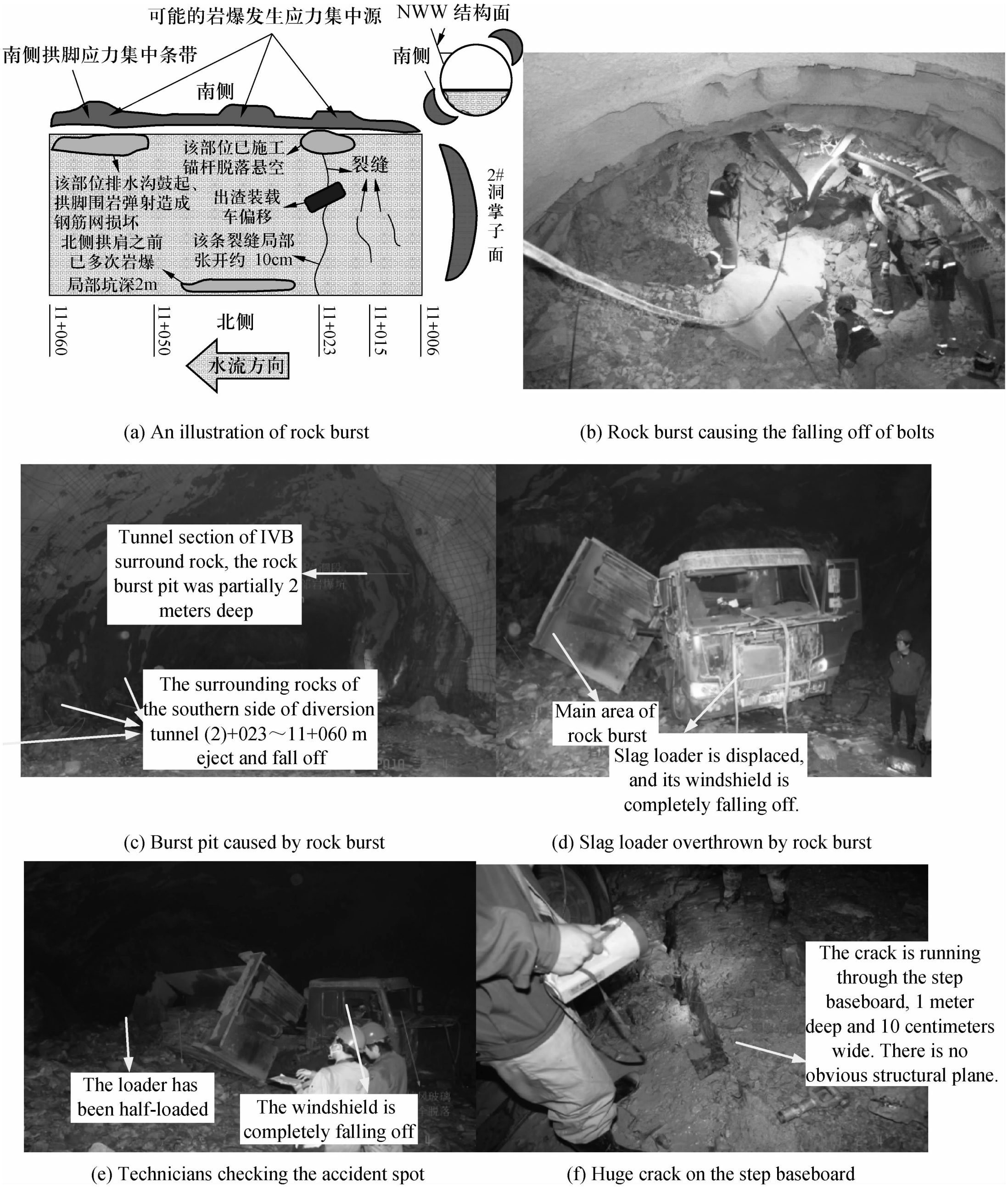
Table 3 A gathering of mines and tunnels that are struck by rock bursts in China (incomplete)

Name	Completion year	Largest burial depth (m)	Degree and proportion (%)			Number of rock bursts	Length of rock burst (m)	Others
			Slight	Medium	Strong and extremely strong			
Guancunbai Tunnel of Chengdu-Kunming Railway	1966	1650	Most	Little	None			Sporadic rock bursts
Pilot tunnel on the left bank of Ertan Hydropower Station	1993	200	Most	Little	None		315	The work area is located at the concentrated unloading area in a deeply incised valley. The largest principal stress is 26 MPa; the azimuth angle is N34°E, the inclination angle is 23°. Therefore, the stress is mainly horizontal.
Diversion tunnel of Taipingyi Hydropower Station on Minjiang River	1993	600	Most	Little	Little	>400		
Diversion tunnel of Tianshengqiao-ii Hydropower Station	1996	800	70	29.5	0.5	30		The proportion is calculated according to the number of rock bursts
Tunnel of Qinling Railway	1998	1615	59.3	34.3	6.4		1894	The proportion is calculated according to the length of rock bursts.
Erlangshan Tunnel of Sichuan-Tibet Highway	2001	760	Most	Little	None	>200	1252	

Continued

Name	Completion year	Largest burial depth (m)	Degree and proportion (%)			Number of rock bursts	Length of rock burst (m)	Others
			Slight	Medium	Strong and extremely strong			
Tongyu Tunnel in Chongqing	2002	1050	91	7.8	1.2		655	The proportion is calculated according to the length of rock bursts.
Lujialing Tunnel in Chongqing	2004	600	55.8	39.7	4.5	93		The proportion is calculated according to the number of rock bursts
Entering access tunnel of Pubugou Hydropower Station	2005	420				183		The work area is located at the concentrated unloading area of high stress in a deeply incised valley. The orientation of the ground stress is intersecting with the tunnel in a wide angle alongside the side slope of the valley.
The ultra long highway tunnel of Zhongnan Mountain, Qinling	2007	1600	61.7	25.6	12.7		2664	The proportion is calculated according to the length of rock bursts.
Diversion tunnel of Jinping-ii Hydropower Station	2011	2525	44.9	46.3	8.8	>750		The proportion is calculated according to the number of rock bursts. And several extraordinarily strong rockbursts.
Diversion tunnel of Jiangbian Hydropower Station	2012	1678	46.4	50.4	3.2	>300		The proportion is calculated according to the number of rock bursts.

Several unusual extraordinarily strong rock bursts happened to Jinping – Ⅱ Hydropower Station(Fig. 13). On November 28th, 2010, a severe rock burst happened to the diversion tunnel of Jinping Power Station, throwing away the slag loader and causing the death of 7 people.



(a) An illustration of rock burst (b) Rock burst causing the falling off of bolts

(c) Burst pit caused by rock burst (d) Slag loader overthrown by rock burst

(e) Technicians checking the accident spot (f) Huge crack on the step baseboard

Fig. 13 The scene of the rock burst of Jinping – Ⅱ Hydropower Station

2) Rock burst can be forecasted

Because the main mechanism of rock burst has been generally clear, we can forecast the rock burst from the aspect of safety risk analysis. Of course, we still need doing continuous research. Some experts say that rock burst cannot be forecasted, and that warning is the only thing that we can do. But in my opinion, according to theories and practice, rock burst can not only be warned, but also be forecasted in China. Although the results are not always accurate, rock burst warning will be aimless and inefficient without forecast.

① Before we talk about the forecast and warning of rock bursts, we need to introduce briefly the definition and classification of rock bursts. The rock burst is defined as ejective fracture of surrounding rocks that are caused by the unloading after the underground engineering excavation in high-ground-stress areas. It can be divided into strain bursts, geological structural bursts, and strain-geological structural bursts. The definition and classification is good for our forecast and warning.

② What are the principles of forecasting? The strain bursts are caused by the unloading after the excavation of the original high-ground-stress areas. There are slight defects and fractures on the rocks, therefore excavation will cause the unloading of high ground stress. We can analyze it from the stress curve(Fig. 14).

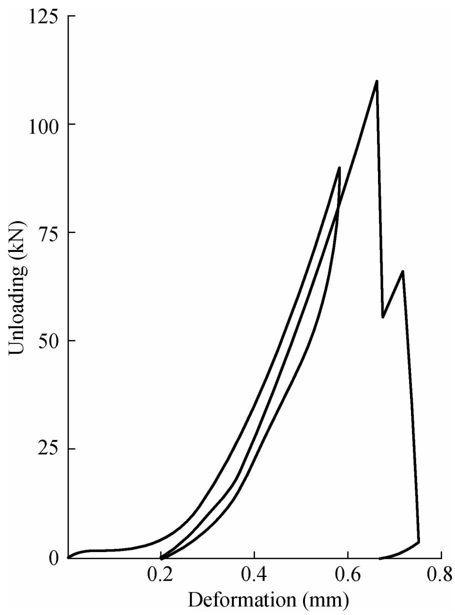


Fig. 14 Loading curve before the peak value and loading deformation of siltstone

There are four conditions to carry out rock burst forecast. The first one is the complete stress curve of the loading-unloading stress of the surrounding rocks. The second one is to calculate the stress (strain) field in the inconsecutive and incompatible deformed rocks after the redistribution of unloading stress of tunnel excavation in high-ground-stress areas; this theory can be achieved in calculation. The third one is to calculate the energy consumed by micro-defect expansion of plastic deformation energy and stable expansion of secondary fractures before the peak value; therefore, compared to surrounding rocks without macro-fractures, tunnels with a single fracture on the surrounding rock is easier to be observed.

In the engineering design, we have found that the structural plane has great influence on rock bursts. According to our preliminary calculation, it is found that if the structural plane is inside the stress-concentrated area, there will be possibility of rock burst, and that if the structural plane is outside the stress-concentrated area, the influence will not be obvious.

3) The monitoring and forecast of rock bursts is theoretically feasible

The macro fractures of rock burst are caused by large amount of micro fractures. The concentration of micro fractures will lead to unstable fracture, which is an omen of rock burst. And these micro fractures can be monitored by a micro-seismic monitor. Therefore, as long as we obtain the principles of these fractures, we will obtain the theoretical basis of the feasibility of rock burst monitoring and forecast. This monitoring system should be automotive, informationized, intellectual, and remote. Due to the severe rock burst of Jinping, the Institute of Rock and Soil Mechanics of Chinese Academy of Sciences and Dalian University of Technology jointly carried out case experiments; the average success rate is above 85%, proving that forecasting of rock bursts is feasible.

According to the rock burst forecast mentioned above, we can put forward the following strategies dealing with rock bursts:

① When the construction of significant underground engineering is located at high-ground-stress areas, we must get the distribution information of the original ground stress in that area and the complete stress-strain curve based on *in situ* test and inverse analysis.

② We should carry out advanced geological forecast of the structural plane before the excavation.

③ We should carry out numerical research analysis of rock bursts.

④ Experienced scientific research team should be chosen to carry out consecutive and effective micro-seismic monitoring, making sure that the monitoring is consecutive and effective.

⑤ Based on the structural plane information forecasted by the earthquake, the information of micro-seismic monitoring and the forecasting data of rock burst, a risk forecast report of rock burst monitoring should be put forward.

⑥ According to the experience of Jinping engineering, only forecast is not enough. A consultation system must be established based on the forecast. It is in this consultation system that leaders and experts should take part in to report on the risk forecast of rock burst. We suggest that the consultation conference should be held every day or every three days. The prevention measures of the risk and construction adjusting program should be put forward on the basis of the grade of the rock burst. The measures include adding more releasing holes of stress caused by advanced borehole blasting, etc. Therefore, after the establishment of the forecast and warning system of rock bursts, no casualties caused by rock burst happened in Jinping.

Qihu Qian, born in 1937 from Kunshan, Jiangsu Province, has been elected to the Chinese Academy of Engineering. He is a professor and doctoral advisor of the PLA University of Science and Technology. He is also a technician of first grade and a civilian cadre of grand grade. He is a member of the Standing Committee on Science and Technology of the Headquarters of the General Staff, a consultant of the Committee on Science and Technology of the General Armament Department, and a technological consultant to the Air-force, Navy and the Second Artillery Corps of the Military Commission. He was vice president of the International Society for Rock Mechanics. He also served as a member of the 8^{th}, 9^{th} and 10^{th} CPPCC. He now is the Director of the Associated Research Centers for Urban Underground Space for Asia and the President of Chinese Society for Rock Mechanics and Engineering. He is the Honorary President of Jiangxi East China Institute of Technology and Honorary Dean of School of Engineer of Shandong University of Science and Technology. He also serves as the editor-in-chief of several academic journals, such as the *Chinese Journal of Underground Space and Engineering*, *the Protective Engineering and the Chinese Journal of Rock Mechanics and Engineering* (English version).

Devoted himself to protective engineering and the teaching and research of underground engineering, Mr. Qian has made outstanding achievements in theories of protective engineering calculation and protective systemic engineering. In 1992, he directed the great blasting of Paotai Mountain in Zhuhai, which used the largest amount of explosives in the world. He also took lead or took part in the check and bidding evaluation of the design proposal of many significant projects, such as subway engineering, urban underwater tunnels and submarine tunnels. As the director and committee member of the experts committee, he assisted the construction of the Nanjing Yangtze River Tunnel, Shanghai Yangtze River Tunnel and Wuhan Yangtze River Tunnel. He carried out pioneering research in the key technologies of deep rock mechanics and deep underground protective engineering and the utilization of underground space; and his research results have been awarded with the first prize of National Science and Technology Progress Award.

He took head in several national consultative subjects, such as the "Development strategies and measures of China's urban underground space in 21st century," "Protecting strategies and measures of China's important economic targets." He published 15 books, such as *Calculation Theory for Advanced Protective Structures*, *Impact and Explosion Effects in Rock and Soil*. He has more than 300 published papers; and ten of his technical achievements have been awarded the National or Military Science and Technological Progress Award.

Design Methodology for the Safety of Underground Rock Engineering

John A. Hudson

Imperial College, London, UK

So, I was very pleased to listen to Prof. Qihu Qian's talk with such a clear exposé of the reasons for the problems for underground engineering. So, I would like to follow some of the things he said and to provide some background for the talks that are going to come for the rest of today and tomorrow.

I particularly liked Prof. Qian's division of the risks and the problems into the objective and the subjective. So, I am going to talk about the objective reasons. But of course the two are related; because the safer the objective conditions the less chance there is subjective problem. And as I mentioned in my opening ceremony small speech I was especially pleased to be giving this talk because it's Chinese Academy of Engineering. And we have these strong bonds now between the Chinese Academy of Engineering and the UK Royal Academy of Engineering. And thank you, Prof. Ji Zhou for attending personally. I am very grateful for that.

And Prof. Qian asked me to consider how to assess mechanical rock mass's parameters and how to design when the geological conditions cannot be known beforehand. So, I got to focus on the key rock properties and the conditions that affect the risk of underground construction, and the need for a rock mechanics "corporate memory". So, I will be explaining towards the end of my talk what I mean by the "corporate memory." But it is basically memory of rock mechanics and rock engineering that are already passed. So, the key, the ability to predict the consequences of construction is the key: we must be able to predict what's going to happen. Otherwise, we are not actually designing. So, if we are going to put a tunnel at a certain depth in the ground at a certain orientation, what is going to happen? Should we put it in this orientation, or should we put it in that orientation, assuming that we have the choice? So, when we are concerned with safe construction and risk management, we need to know how to deal with special conditions. So, if we have these normal conditions in the middle—assuming there is not a problem with normal conditions, then we are concerned with special conditions, which either is too low or too high, like the stress at the "Jinping."

But there are in fact many special conditions. And the first one, Karst, and again Prof. Qian mentioned about this specific problem with Karst. That could be some kind of problematic environmental conditions; we could have a high-density of fracturing/ or large faults; and we could have a high stress and stress spalling. And in the middle line, there could be mixed soil and rock. It's very difficult in the near surface tunnel to tunnel when the top half of the tunnel is soil and the bottom half of the tunnel is rock. That could often be major problems. And we have the high water pressure and flow. We could have high temperatures. And I will give an example in radioactive waste risk disposal of high temperatures. Because canisters that are put in the ground can be just below boiling point. There could be low temperatures in countries where the temperatures are very low. And also, for example in Korea, there are caverns where the refrigerated food is kept. So there is a problem of what happens to the rock when the temperature is lower. Then on the bottom line, we could have adverse chemical conditions. So, for example "Methane." Then excavation adjacent to existing structures. We have some tunneling excavation in London where we are underneath the major buildings near the House of Parliament. We have to be very careful about how that was done. There could be an unusual project objective. And I mentioned disposal of radioactive waste, that's actually a very unusual project objective to put. There is some dangerous material and you put it in the ground. And absolutely nothing should happen. So in the civil engineering project, there is some activity, some kind, maybe a train is going through a tunnel, the mining way, removing the rock. But when we disposing the radioactive waste, we put the material in the ground and we say nothing should happen. And finally in this list, we could have complex geology. So, this is not an exhaustive list. But it indicates that we have a wide variety of conditions that can cause risks and can cause difficulty and accidents. So, for example, when the channel tunnel from England to France was considered, there is a major possibility of disaster here, because the tunnel is going under the sea. So the first thing is can the tunnel boring machine cut the chalk. Because the chalk is a soft material, like soft lime stone, but sometimes it contains flints, which are very very hard rock. So, if there are a lot of those very hard small boulders inside the chalk, maybe this breaks the tunnel boring machine. But most important of all, will the water flow into the tunnel from the sea above? So, this is much worse than other conditions where water can flow in, because you have almost unlimited supply of water that can come down into the tunnel, if there are fractures through the chalk. However, I am pleased to say that project was completed successfully. Maybe some of you have traveled on a train through this tunnel. Unfortunately, it's not interesting. You can't see anything. It's completely dark.

I've been involved in the coal mining. And again, Prof. Qian emphasized about this sort of accidents that can occur. Now, I can't show you the geological structure inside the rock because we can't see in a rock. So, I am showing some pictures from an open pit mine where I was consulting. So, when the strata are undisturbed, the mining can proceed with no problem, whether we are on the surface or underground. But the geological conditions could cause some of the problems. And even here near the surface, perhaps you can see these faults, known as Listric Faults. Can you see these coming down here? And the reason why the shape? It is because the coal seam has a very low friction. So, the fault tends to axe them toward down to the coal seam.

So, one of the things I feel is very important is for all of us who are involved in rock engineering to understand geology, or at least to have access to a geologist, or to have a group where there is very good communication with geology. I have found in the projects that I have been involved with this is the key to many of the things that happened as to understand the geology.

And I want to show you some examples particularly about the stress. Another project I am working on in Finland, which is the disposal of radioactive waste. And so there is a very large number of tunnels of many many kilometers in total length, where this waste material is going to be deposited. So there are some shafts going down. There is a spiral ramp here. And the disposal tunnels are at four hundred and twenty meters. And in designing this, and to make sure that we don't have any accidents, structure accidents of any kind, we have to understand the stresses in this rock and the geology, and particularly the fractures.

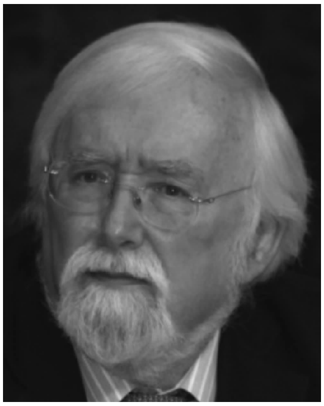
So when we look at these special conditions that can endanger construction we are looking on the objective side of things. We have these a variety of special conditions that can occur. As I say, we can make a bigger diagram with more of these. We can think about the profile of the particular project we had. So in the one that I just showed you, here, we are going to make a lot of tunnels in disposal of radioactive waste. We have a profile of the particular project. And this kind of diagram will help us (and extension of this help us) to think about what we should be studying. Then the question arises is what flexibility do we have in changing the design. And this is different in civil engineering, mining engineering and petroleum engineering. Because in civil engineering, our objective is to create an underground space. And the geometry will be specified by the engineering function. So if we need a train to go from one place to another, or, we need water to go in the Jinping Project from one part of the Yellow River to another, the position and the orientation of the tunnel is pretty well specified. So there is a limited scope for design in civil engineering. But in mining engineering, the objective is to obtain the excavated rock. And there is much more flexibility in how you do that. In fact, mining is a very creative engineering subject. And many mining methods are possible on use. And in petroleum engineering, again the objective is transporting oil through the boreholes. And although that is limited we have to use boreholes, there is a lot of variability in the wing, which we can put the boreholes into the ground and how we extract petroleum. But we know that two of the main factors (two of the main risk factors): the rock stress and rock fractures. So, I want to go briefly through these two subjects. And rock stress is a problem because it occurs on different scales. So, the top we have the world with the Tectonic plates and they are moving and creating a lot of stresses. But actually we want to know the stress around the project. This is very large mine in the United States, Bingham Canyon mine. And then we go down, so the next picture is some of this boring occurred in the Jinping Project here. So now we are at the tunnel scale. But when we are measuring the stresses, one of the methods is to put the device like this into a borehole and to pressurize the borehole with water until the rock crack. So we are actually measuring the stress on the borehole scale. And another method is to glue small electric items onto the wall of the borehole, so then we are interested in the microscopic scale. And this is picture from Prof. Tang's RFPA curve, we can actually look at the when the rock breaks through the stress. But of course, that program can work on many scales.

So, when we came to design this repository in Finland, we thought, in order to know what the stresses are we have to model the stresses. And so in a test program which was used to model the stresses, and the problem is, in this ground, in this rock mass, there are these major faults crossing the rock mass. And these affect the stresses. So rather than just saying well we hope the best, we are going to model these and see how much the stresses are affected. And so here is a picture of the model of the stresses. There is a general tendency for the stresses to go in this direction. But you see that where these faults, these BFZs where the brittle faults are, where the faults present, the magnitude of the stresses change considerably.

So, when this research was chosen here, you don't know beforehand if you are going to be a high stress rock or low stress rock. Because these faults significantly affect the rock. So, you can see in this region which is all at the same depth. This is a horizontal section at a hundred and fifty meters deep. There is wide variation in the magnitude of stresses. If you don't attempt to understand the stresses and to calculate the magnitudes, you could be anywhere in this rock mass. So, you could be down here; and you could be out here. And often when people measure the stresses one group measures the stresses and says this is the value of the stresses in the rock; another group measures the stresses and then they finally get different stresses. And then they start arguing which is the best stress method. But in fact, when you see a picture like this, it is not surprising if you measure the stresses in different places and you get different answers. Our objective is to understand distribution of stresses. If we go down from, this is at a hundred and fifty meters here, if we go down to the actual level where the repository is, minus four hundred and twenty meters, we found now the stresses are much more even there. This is because the fractures have been pushed together by the stresses, so they are less effective in diverting the stresses. But this is the type of analysis I would like to see for projects where the stresses are important, which incorporates the natural stress and natural fractures. But of course, as I say, we need a good geologist to tell us what to put into this model. So the stresses can be affected by many things. They can be affected by the rock inhomogeneity, by the rock anisotropy, particularly by the fractures, and also what the engineer does. Because, when the engineer makes a free surface, you immediately change the stress distribution. So, on a free surface like this, here, if this is a side of an excavation, there can be no normal stress here because this is a free surface, and there is no shear stress on here, so that means this is a principal stress plane. So when the engineer makes any excavation, you locally alter the stresses from what they were to the specific ( ) (part 2) of making this principal stress plane. So, we have the, that changes the stress tense to e1 or e2—the two principal stresses, and then a zero here. So, we also need to model the process of excavation. And you can see here how fractures affect the rock stress. Because if there is a fracture like this, in a very open fracture, on the side of the fracture, the stress is not transmitted across, the normal stress is, tends to be zero depending on how open the fracture is. So, the engineer locally alters this here. So, this in itself can creat high stress, sporing, and damage. I mentioned, I think geology is very important. And we' ll have a conference very soon, next, the week after next in Sweden. And I have arranged for a special session where we will discuss how you incorporate structure geology information into rock mechanics analyses. And I don' t think it is, I don' t think we, speaking as an engineer, I don' t think we should say I am an engineer I am not doing geology. I think we should all try to, all of us who are involved with underground excavation should try to understand as much geology as we can. And if we are going on-site, we should take a geologist with us, not just come back confused about the geology. And actually, the basis of geology, of this slide shows on the fracturing, is actually not that difficult. We either have an intact rock on the left, or the next one, here, we have fractures that were formed by the opening, or the next one, fractures that were formed by shear. And then, shear zones and ductile shear zones going out here, which occur over geologic time. And we can look at the lines underneath, and think about how the rock came to be the way it is. Then right at the bottom, how difficult is the rock mass characterization. So, we get the properties to put in the computer models. So, obviously, if the rock is undamaged, it' s straight-forward. But it' s also straightforward on this side, if we have a particular fabric in the rock. But in the middle of here, it' s not so easy to characterize the rock. That' s where we particularly need a good geologist. Whenever I am consulting a project, I always take a geologist with me. Literally, I take a person standing next to me. Because I think the subject is so important. But the fractures have many properties. And this is a diagram from Professor Barton from many years ago. But is very good for illustrating the fact: in stress, you only need six values to specify the stress at a particular point. Usually, the three principles of the stresses in the direction of those perpendicular stresses. But, when you are dealing with rock fracture, there are so many things that we could look at, we could look at the frequency of the fractures, and various parameters that going to Professor Barton' s Q system. But we need to concentrate on those that are important for the particular project in hand. We can't measure all of these; and some of them are not measurable anyway. So, if you look at the Persistence here, that is not usually measurable. You can measure that on the surface as a two-dimensional cut. But you can't measure it from a borehole. So, if we have a rock fracture array like this we want to make a computer model. How do we do that? How do we get those fractures into the model? And we can't just photography it and make a model, because this is a three-dimensional situation. And also there is a particular problem that these fractures are not random. These occurred because of rock stresses and so they have occurred in a particular way. And I don't know if looking at these, you can tell which fractures occurred first, and which occurred second, and which occurred third. But with a bit practice you can. And then when we are making the computer model, we should put the fractures in, in the same way they have been formed. So, we've not just got some random array of fractures; we've got a proper correct geological array. So, here you can see the sequence of the fractures and you get that by the terminations. This fracture is going right through; and the second fracture, this one is stopping here. And number three is stopping on number two; and then number four is stopping on number three. So, if we want to model the rock fracture system accurately, we don't just put random through random array of statistic array into the computer. It ought to have these terminations correctly implemented. So, that is lot of work for us to do in the development of the computer programs. But they are very important for understanding the stresses and the influence of fractures. And of course a lot of development with computing, and we are moving now from the real situation where we can model the total rock mass in the virtual world. And this is the sort of work that Professor Kaiser involved with of the modeling of the rock mass in the virtual space. But we have a lot of developments here. Where we have GTHMCBE, this is geology thermal properties, hydro properties, mechanical properties, chemistry, sometimes biology, and engineering. So, the different parts of our subject area have different models, so this is another problem that the models are not integrated. Each group people concerned with certain thing have particular models. Hopefully, we are moving towards a fully capable model which can in geo course include all these aspects. So the computer model is in fact accurate and does represent the real situation. And to check that we need underground research laboratories so that we can make a virtual world, underground world, and then we can compare it with what we actually happens. Professor Fairhurst is not able to come to this meeting but I am going to presenting his paper tomorrow and here are some examples of his work. And also, we have a commission, an international society for rock mechanics, and rock engineering design methodology. And this occurred over the last four years or so. We produced a book, Professor Feng and myself, on rock engineering design about what we have developed. Over the next three years, we are going to be concentrating on risk. So, this forum is particularly helpful to us to consider exactly what we should be doing. Now, I will try to finish very soon. I believe one of the keys is to develop a system where we have the information. If we don't have the information, we can't do the work. We can't do the design work; we can't evaluate the risk. We need information. At the moment, the information that we have is not coherent in a sense that you can easily find something that you want. So, I, this will cooperate means of the whole organization, so need the organizational memory system for rock mechanics, which doesn't exist at the moment. Now there is a huge amount of information on the internet. It's absolutely fantastic what's happened to the internet over the last ten years. You can just look out whatever you like. But even though this is wonderful, it's like a miracle being able to find out in a fraction of a second access to information, there is still a problem. So, if you look out, for example for rock engineering on the Science Direct website, which is the Elsevier publisher's website. You get a list of papers. So, that is very helpful. You get a list of papers you could read it. But you still have to do a lot of work. You have to collect the papers, you have to open the papers, you have to read the papers, then you have to make a summary of the information. So, this is quite difficult, if two people did the same job, they might come out with completely different information. So, what we need is a corporate memory system. On the left, we need rock property information, then we need modeling exercises, and then we need construction experience. We as humans, we have very clever brains. And they don't require much energy. You just have to have breakfast and your brain works. There is program in Switzerland at the moment for modeling the whole human brain. I am not sure if it is going to be successful. But there is an attempt to model it. That's too far in the future. The problem is that if you do a computer program like you use 3 data counter computer. The computer doesn't remember what it did. It has a computer memory. But it doesn't remember what we remember. We did this. Oh, we put the wrong parameters in. Let's do it again. We will do another one. It doesn't remember what we remember. So we need a list of modeling exercises and experience. Similarly, we need construction experience. Now conveniently devise on the bottom line and to laboratory testing, *in situ* testing. And for modeling, we have the generic model, where we are studying not necessarily with respect to any particular project. And then specific modeling for a particular project, and then construction experience. And sometimes you can't get this construction experience because of legal problem so company doesn't want to give the information out, particularly about accidents. But as far as we can, we should get the design case examples, and construction case examples. Then once we got that, if we were able to get that, we need some kind of coherency conditioning, which means organizing the material so that we can access it and use it. And that reduces them to these tables at the bottom here, the tables of intact rock properties, rock mass properties. And this is fairly easy for us to do at the moment. With some work, we can actually generate these. And there are many and various books have been published recently. But what we don't have is a library of the standard modeling solutions and a library of case examples, and also a library of design case examples, and construction case examples. Particularly, where these risk elements have been introduced. And then of course, unlike the internet, where you can interrogate the internet you can get information but this information is not coordinated. We need some system whereby you can ask questions at the bottom and get answers that are helpful to you in the design. And so this is the required corporate memory system. So, this will take a long time to develop. But certainly the first two of these are the key. And Professor Qian asked to talk about the properties of the rock mass. I believe this is something that we should be doing, and is in fact been done by various people that will be fairly easy to start better. But the library of standard model solutions and case examples is going to take longer. But our commission of the international society of rock mechanics is going to try and develop a system for doing this.

Now I'd like to just tell you one example of tunnel I was working on. And so you can't predict everything. So in tunneling, you should expect the unexpected. And this certainly happened here. This was in England. So the ground surface is here. There is sand here. And there is a sandstone rock at the bottom. Because there was sand here, a soft ground tunneling machine was going in this direction here. Because it is in sand, the tunneling machine is going round, the sand can come into the front of the tunneling boring machine. So there was the development at that time of a bentonite tunneling machine where there is pressurized bentonite here, mud, if you like, at the front of the tunnel boring machine which is putting a pressure on there to stop the sand coming in. So, the point about that is you can't see ahead of the tunnel boring machine. So we are in sand, we are in the tunnel boring machine, everything is going nicely going quite fast. And then, we hit granite, which is supposed, there is nobody has even thought there could be any granite here. What happened was: this was an old land surface here. And long time ago, when there was an ice age, so ice was covering the country. The ice had come down from the north of England and had carried these boulders down and had dropped the boulders when the ice had melted. So the granite boulders are on the surface here. Then the sand was deposited in a later age. And the boulders are hidden. And nobody knew that these boulders are here. Nobody even thought that could be any boulders there. And when the tunnel boring machine hit the granite, they couldn't believe it. There is granite here and has broken the tunnel boring machine. And how much granite is there? So this is just an example that we can't predict everything. But if we have been able to access the data base if we have had a library of construction case examples, so instead of this, if somebody had experience before instead of being hidden in the paper somewhere, which we didn't find, they should jump out when we asked the questions of this system. Maybe the warning would have been there. So I think this type of system will significantly help in the risk (management), will help in the whole design of structures underground.

Now some people say that the computers are going to be very clever so we don't need people anymore. But I guess most of us would agree that we do need people. And I finish with this distinction between knowledge and wisdom. So although this system will give us knowledge, the required knowledge that we need, we still need human beings to make the judgment and to have the wisdom, which is the ability to discern or judge what is the best approach to construction, given all this information. So we still need the human brain, at least for a hundred years or so. This has been said before there was an eighteen century English poet, William Cowper, who highlighted the difference between "knowledge" and "wisdom" long time ago. So this particular poem was written in old English style. But I asked Professor Feng to translate this into Chinese. I hope this Chinese says the same thing roughly. But we using our judgment we must have the knowledge; we can't make any judgment unless we have the knowledge.



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Application of FEM Limit Analysis Method in the Stability Analysis and Design of Tunnels

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My topic is "the application of FEM Limit Analysis Method in the stability analysis and design of tunnels." From the topic you can see that what I am going to talk about is the combination of two methods—finite element method and Limit Analysis Method.

Limit Analysis Method has been adopted for more than 100 years. It is a method that researches on materials in the process from plasticity to failure. It can be used to figure out the safety factor of the geotechnical engineering. Due to its usefulness, Limit Analysis Method is widely adopted. However, there is a shortcoming in this method—its applicability is narrow. It can be only used to solve easy questions, and is not applicable to the complex ones. Complex questions, like the safety factor of a tunnel, cannot be figured out through this traditional method.

The second method is the Finite Element Numerical Analysis Method, which has been familiar to us since modern times. The advantage of this method lies in its wide applicability. It can be used to solve all complex questions except one—safety factor. If the safety factor cannot be figured out, it will be difficult for this method to be applied in engineering.

If these two methods are combined, their advantages can be put together—one is widely applicable, another can be used to figure out safety factor. When used in engineering design, a new method called FEM Limit Analysis Method is born.

Now, please allow me to explain the principles of FEM Limit Analysis Method. This theory is essentially the same to traditional Limit Analysis Method. The only difference lies in the approaches to get the safety factor. Using Limit Analysis Method, you should know the failure surface first, and then get the safety factor through calculation. But using FEM Limit Analysis Method, you can get the safety factor through numerical analysis (using computers and softwares).

Take the landslide or slope as an example, according to traditional method (Limit Analysis Method), safety factor is anti-slide force/slide force. If the sliding surface is available to us in advance, the slide force which is caused by weight on the failure surface can be calculated. The numerator is anti-slide force which is caused by geotechnical strength. When the geotechnical strength is high enough, anti-slide force will be greater than slide force. Therefore it will not slide. When anti-slide force is equal to slide force, state of failure will appear. When safety factor is less than 1, sliding will happen.

Now, let's see how to calculate safety factor through FEM Limit Analysis Method. In 1975, Sinkewitz, an English dynamicist, put forward the theory of Strength Reduction Finite Element Method. This method is very useful and has been an important method of FEM Limit Analysis Method. Numerator in the algebraic fraction of safety factor is anti-slide force; the denominator is slide force. If you continually lower anti-slide force until it is equal to slide force, you will get the state of failure. The advantage of this method lies in that computer will automatically show the state of failure. The strength is reducing from the strength of stability to failure strength; this strength reduction factor is the safety factor. This safety factor is totally the same to the safety factor calculated through Limit Analysis Method. When the failure appears, computer will automatically show the failure surface. But using the traditional method, you can only calculate the safety factor after you find the failure surface which is very difficult to find. In the present method, failure surface is automatically generated, saving your time to find it. Besides, information of overall geotechnical failure will also be shown. Therefore, ultimate load or buckling safety factor can be calculated. From the actual situation to the failure situation, the reduction multiple of geotechnical strength or the enlargement multiple of load is the buckling safety factor. The former is called Strength Reduction Finite Element Method; the latter is called Overload Method. Both of them belong to FEM Limit Analysis Method. Now, we have done further work. We can not only calculate the safety factor, but also the form of the failure surface—where is the failure surface, no matter what its form is.

Now, let's look at the traditional failure mechanism. As we all know, tunnels can be divided into deep-buried tunnels and shallow-buried tunnels. When buried deeply, we adopt the Theory of Pressure Arch of ·M·Протодьяконов which is widely used in

China. According to this theory, an arch will be formed in underground projects, which will carry the weight of rock and soil. As to shallow bury, if the underground project is buried shallowly, the soil above the tunnel collapses and stress transfer exists. One of the representative theories is Shallow-buried Theory of Terzaghi.

Let's turn our attention to modern failure mechanism of tunnels. Modern theories are very different from Theory of Pressure Arch of ·M·Протодьяконов and Shallow-buried Theory of Terzaghi. For example, according to Rabcewicz, the pressure to the tunnel does not come from the rock and soil above it, but the rock and soil beside it. The rock and soil on the two side-walls of the tunnel will squeeze in, cutting off the lining. He got his findings from the observation of practical projects. But this theory is seldom adopted in China, because this theory can only be used to do experiments at the beginning, it cannot be used to calculate. However, this theory can be used to calculate now. Safety factor cannot be obtained through traditional method, but we can calculate it through FEM Limit Analysis Method. When the computer calculates the state of failure, both safety factor and failure surface can be obtained. The core of this method is the failure surface. But international common softwares cannot find it directly.

Whether FEM Limit Analysis Method can be applied to the calculation of tunnels depends on an experiment. Unlike slope and landslide, which can be tested through traditional Limit Analysis Method, we need an experiment to test FEM Limit Analysis Method. If the experiment result is the same to calculation, this method will be workable. We should use cement, sand and talcum powder as experimental material. The size of model should be about 50 centimeters. A tunnel with a span of 8 cm should be excavated on the model. We should have five comparing experiments. And five tunnels of the same span but different arch height should be excavated. We need to analyze the results of the experiment model and numerical simulation. Computer is not used to simulate practical projects, but the experiment model. Using this method, we can calculate the failure surface and safety factor. Then, we need to compare the results of experiment and calculation. When failure appears, what is the value of loading during experiment model and numerical simulation? Besides, is the calculated failure surface the same to the failure surface of practical model? If the position and form of failure face are the same, we should further examine the size of failure—whether they are the same size or not? The maximum distance from tunnel edge to failure can be measured in the experiment and can be calculated in the simulation. If the results are the same, FEM Limit Analysis Method is workable.

The results of experiment model and numerical simulation are very similar. In the fourth experiment, there is little difference in the ultimate load obtained from the two methods. Result of experiment model is 61 kn; result calculated by computer is 60 kn. Generally speaking, there is little deviation. Now, let's examine the maximum horizontal distance of the failure surfaces on both sides of the tunnel. Result of experiment model is 13.4 cm; result calculated by computer is 13.1 cm. They are also very similar. Actually, results of all the experiments are nearly the same, demonstrating that FEM Limit Analysis Method can be applied to tunnels. The result of FEM Limit Analysis Method is nearly the same to the result of simulation.

Now, let's look at how to determine the location of failure surface. Presently foreign technique cannot do that, but we can. Actually it is pretty easy. The soil and rock inside the tunnel will be broken, which will result in large displacement. The soil and rock outside the tunnel will not be broken, which only brings small displacement. Therefore, displacement or strain on the failure surface will saltate. Find out the saltations and link them together with a line, you will get the failure surface. We draw five horizontal sections on this picture. Strain on each of the section can be calculated by computer. Look at the first strain line, the largest strain is right beside the tunnel; the second line has a protuberance, and this is the maximum value. This point is certainly not beside the tunnel. Actually it is pretty far from the tunnel. The third line, which is in the middle of the failure surface, is farthest from the tunnel. Link the five maximum-value points, you will get a surface. This surface is the failure surface that we want. It is the same to the surface obtained from experiment model.

Failure state of homogeneous tunnels can only be reached when plastic strain develops into a line. From the flash, we can see that strain develops from two sides—one develops from the tunnel bottom upward, another from the top downward. At last the strain develops into a single line. Actually, failure state has not been reached when the line appears. Failure comes when the strain reaches a certain value. Please look at the picture. The darker the color is, the larger the strain will be. To deeply buried tunnels, the failure is not above the arch, but on the two sides of the tunnel. If you still don't believe in this theory, please look at another practical project. There is a loess tunnel, 13 meters wide. And we test the pulling force of five rock bolts. According to the previous theory, the bolt on the arch top bears the largest force. But the test shows that pulling force of the bolts on the tunnel sides is 9 times larger than the one on the arch top. Therefore, we can say that the main force bearer is the two sides of the tunnel. Some of the engineers are doing this in their actual work. Under certain circumstance, they will reduce the rock bolts above the arch. After examining the convergence displacement, we can see that vertical convergence displacement is the smallest, only 9.8 mm. However, the convergence displacement on the two tunnel sides is as large as 19 mm. This phenomenon also shows that the main force carrier is the two sides. To the present, we are talking about deep-buried tunnels; now let's turn our attention to shallow-buried tunnels. The burying soil of the experiment model is 3 cm deep. Similarly, we carry on the numerical simulation through computers. From the picture we can see that the location and form of the failure are the same. In the experiment, failure appears when loading reaches 28 kN; in the computer simulation, failure appears when loading reaches 26 kN. They are nearly the same.

Now, let's look at the failure mechanism of jointed tunnels. Dip angle of the fissure is 45°; Strength of the fissure is 8 times lower than that of rock. From the flash, we can see that the easiest place to collapse is the angular arch. This shows that this method can be used to figure out how the tunnel reaches the state of failure. In our opinion, with different buried depth, failure mechanism will be different. If shallow bury is adopted, rock and soil above the tunnel will collapse to the ground. Now, look at the rectangular tunnel. When it is buried 9 meters underground, a complete arch will be formed above it. This arch will guarantee that it will not collapse to the ground. The formation of the arch is related to the buried depth. This arch is called pressure arch of shallow-bury. When the tunnel is buried more than 10 meters underground, the situation will be different. The upper arch is still there, but its color becomes lighter. The darker color is the newly-formed pressure arch. This new arch is what we called Theory of Pressure Arch of ·M·Протодьяконов, or arch of deep-bury. Although it will not collapse to the ground, the rock and soil above the rectangular tunnel and under the pressured arch will collapse. This is why we make an arch above the tunnel. With increase of buried depth, arch of deep-bury will be formed. When the depth reaches 18 meters, arch will appear above the tunnel and plastic arch will also appear on the two sides of the tunnel. When the depth reaches more than 18 meters, plastic strain on the two sides of the tunnel will grow larger. As a result, failure will firstly appear on the two sides. It will become more obvious when the buried depth reaches 30 or 50 meters. And safety factor will decrease with the depth growing. Therefore, failure is related to buried depth.

In general, failure mechanism of rectangular tunnel can be divided into three stages: Shallow-buried pressure arch forms gradually and the maximum height of arch is 9–10 m; When the buried depth is between 10 m and 18 m, pressure arch of shallow-bury disappears and safety factor keeps constant. So 10 m can be regarded as the *dividing line* between deep- and shallow-bury; if the buried depth is over 18 m, failure moves from the arch to the two sides and safety factor reduces with the increase of buried depth.

Failure mechanism of arched tunnels is similar. It is divided into two stages: the first stage is when the buried depth is less than 9 m; when it reaches 9 m, it will skip the pressure arch of ·М·Протодьяконов and goes directly to the failure of two sides. But why do we feel that it is the tunnel ceil that collapses. The reason is that when failure appears, two sides of the tunnel firstly reach failure, resulting in instability of arch spring and large-scale collapse of tunnel ceil. This is what called spalling and roof falling.

In the previous time, safety factor cannot be calculated. Therefore, there were no quantitative requirements. But now quantitative requirements appear as safety factor can be obtained. As we all know, loose pressure and load-structure methods are not in accordance with practice. The lining mainly bears the deformation pressure. Deformation pressure is adopted since 1970s in China. Numerical method can be used to calculate pressure, but it cannot determine the exact time of tunnel failure. Due to the lack of safety factor, experiential methods can be adopted in the design. One of the methods is to take the size of plastic zone as failure criteria; another method is to take displacement of tunnel surrounding as criteria. These two methods are very commonly used in practice, but there is no failure standard. And both of the two methods are influenced by different factors. It is difficult to get accurate calculation. In the criteria of tunnel surrounding displacement, elastic modulus has great influence on the displacement. Although elasticity of rock and soil can be tested, elastic modulus of rock and soil is hard to test, so the calculation results would be influenced seriously. From this table, we can see that when elastic modulus is 20 MPa, maximum vertical displacement on the arch top is 9.4 mm; when the elastic modulus becomes 60 MPa, maximum vertical displacement on the arch top becomes 3.6 mm. Therefore, elastic modulus has a great influence on calculation results. But when adopting the safety factor of surrounding rock as criteria, it is always the same no matter what is the value of elastic modulus.

In general, adopting the safety factor of surrounding rock as criteria have the following advantages:

(1) It has strict mechanic basis.

(2) Stability has unified standards.

(3) It would not be affected by deformation parameters of rock and soil.

Let's take the dwelling carven as an example. The carven is 3 meters wide. Using certain methods, we can calculate the safety factor. If we use the ANSYS, the safety factor is 1.69; if we use FLAC, the safety factor is 1.71. Results of the two methods are nearly the same, with an error less than 1%. Both of the safety factors are above 1.5, which means that the dwelling carven is safe enough for people to live in.

After learning the failure mechanism of tunnels and the calculation theories, we can carry out the design. Now we put forward five design ideas.

Idea 1: Calculation model will be in accordance with practical situations only when the interrelationship between rock and structure is taken into consideration.

Idea 2: According to New Austrian Tunneling Method, surrounding rocks are supporting bodies. We should give full play to their self-supporting function. That is to say, limit design should be adopted in the design of tunnels. When designing, there should be certain displacement in the surrounding rocks. As long as the failure is within the limitation, self-supporting function will grow larger as the displacement grows. Of course, plastic strain shouldn't be too large. If it is too large, failure will happen.

Idea 3: According to New Austrian Tunneling Method and practical situations, surrounding rock is not the only one that enters into plasticity. Preliminary lining will also enter into plasticity. From practical experience, we can see that deformation of preliminary lining can be great. Therefore, 10 cm should be left for preliminary lining to complete this deformation. Sometimes, there will be cracks on preliminary lining, which means that preliminary lining has entered into plasticity. Under this situation, design should not be done according to elasticity. Preliminary lining must be well controlled, with certain strength to ensure that failure will not happen, and with certain flexibility and plasticity to ensure that it can bear larger deformation to fully display the self-supporting functions of preliminary lining and surrounding rocks. As a result, requirements for the materials of preliminary lining will be higher.

Idea 4: In order to ensure safety, preliminary lining should bear the most loading of surrounding rocks. The secondary lining should be treated as safety reservation and bear less loading. So the secondary lining can be designed according to elasticity. But according to the current ideas, preliminary lining only bears little loading. Sometimes, it even works as a temporary supporting, which cannot ensure the construction safety. All of the current tunnel risks lie in the period of construction. Previous tunnels are narrow. Single track tunnel is only 5 meters wide. Therefore, the risk is small. But the current tri-line tunnels are as wide as 17 meters. Constructed in the soft loose stratum, great risks will be formed. Previous first linings, which are only 20-30 cm, are not sufficient now. Several days ago, there was a conference about Qingdao subway. During the conference, some people put forward questions like: is preliminary lining thick enough, is it strong enough, shall we adopt double first lining? Safety can be ensured only if preliminary lining is strong enough. Therefore, we suggest that safety factor of the surrounding rocks with first lining should be larger than 1.15-1.2.

Idea 5: Tunnel design should be as scientific as possible. The design should be safe, reliable, economic and reasonable. So we need accurate calculation method and calculation parameters. Calculation method can be FEM Limit Analysis Method. There are more than one parameter. Firstly, releasing load should be accurate. Percent of releasing load after preliminary lining is usually 50%, and percent of releasing load after secondary lining is usually 10%. This will make preliminary lining bear most load and secondary lining bear less load. Secondly, rock and soil strength must be accurate. Soil parameters can be determined through test. But rock parameters cannot be tested. We should control rock strength into certain scope in accordance with latest grading of surrounding rocks. Or we can determine rock strength through back analysis of displacement. Thirdly, concrete of preliminary lining will enter into plasticity. Therefore, strength parameters of different kinds of concrete should be determined through large amounts of test.

Now let's look at an engineering calculation example. Tunnel model is a loess tunnel, 9.8 m high and 11.6 m wide. Preliminary lining is 30 cm thick; secondary lining is 40 cm thick. Safety factor of surrounding rock after preliminary lining is 1.38, which meets the construction requirements. Secondary lining only bears 10% of the total load. Treating secondary lining as elastic members, we can directly calculate its inner force, bending moment and axial force. Safety factor of elastic member can be calculated according to the standard of reinforce concrete. After calculation, we can see that all the requirements have been met. Safety factor of surrounding rock after secondary lining should be over 1.35; safety factor of secondary lining should be over 1.4; total safety factor should be about 1.9. The above lining size is in conformity with the current adopted size.

At last, I want to say that disorder exists in China's current tunnel design. All the standards are said to adopt engineering analog method to determine lining size. In fact, lining size adopted by different departments and standards differs greatly. For a tunnel of 10-15 m wide with surrounding rocks of grade Ⅲ, total lining thickness should be 10 cm according to national standards of shotcrete rock bolt support. However, total lining thickness becomes 43 cm in accordance with tunnel design standards of highways and railways. Therefore, current design is not mature. We hope that future tunnel design can be scientific and reasonable, combining theories with experience.

Yingren Zheng, born in Zhenhai, Zhejiang in 1933, is an academician of Chinese Academy of Engineering and renowned specialist in geotechnical engineering. He obtained his bachelor degree from Beijing University of Petroleum and is currently a first-grade professor of the Department of Military Architectural Engineering at Logistical Engineering University, Emeritus Director of Chongqing Research Center of Geological Disaster Prevention. He has served as consultant of Air Force engineering technology, Chinese Academy of Rock Mechanics and Engineering Society, Tunnel and Underground Engineering Branch of China Civil Engineering Society. In addition, he has been a Deputy Director of Special Committee of the Chinese Society of Theoretical and Applied Mechanics of Rock and Soil Mechanics, as well as Vice-Chairman of Chongqing Association for Science and Technology.

He has spent his professional career mainly in Military Underground Engineering, Slope Engineering, Underground Engineering Surrounding Rock Mechanics, Geotechnics, Geotechnical Limit Analysis Method and Zonal Soil. Among his more than 400 papers, "The Application of Finite Element Strength Reduction in the Soil and Rock Slope" was listed as one of the most influential Chinese papers in 2007; "Lecture on Limit Analysis of the Finite Element Method—

Criteria of Ⅱ Finite Element Strength Subtraction of Slope Instability" was listed the top 100 Chinese papers in 2009. He is the author of 12 books, in which Slope and Landslide Engineering won Chinese original Technology Book Award in 2008 and nomination of Chinese Government Publishing Award in 2011. Besides, he has been the supervisor of well over 100 graduate and PhD students.

Prof. Zheng has been the winner of one second-prize and one third-prize of National Scientific and Technological Progress Award, winner of 9 first and second Ministerial Scientific and Technological Progress Award, one National Science Special Award and 1 Special Contribution Award for Scientific and Technological Progress of the Ministry of Land and Prevention of Geological Disasters. In 2009, He was honored as an "Outstanding Contributor to Chongqing Municipality".

Reducing Risk in Tunnelling by Using Hybrid TBM and Drill-and-blast for Long and Difficult Tunnels

Nick Barton

Nick Barton & Associates, Norway

Thank you to Professor Qian and Professor Feng for inviting me to this forum. Let us hope we can give some good advice about tunnel boring machines. I will make it easier for the translators and read the slides, and not speak too much. Reducing risks in long deep tunnels by using TBM (as well as) drill and blast methods in the same project—the hybrid solution. I've been lucky to have been involved in some projects that have gone very wrong, and have called in the last months, let us say, of projects lives and TBM have stayed in the mountain forever and obviously it has been the wrong choice. I think I have learned quite a lot from some of these projects.

Obviously, in the audience here, you have many such experiences, so some of the fairly extreme things I show will not seem so extreme to many of you. The content of the lecture: the introduction and apparent reverse logic for TBM, and something that's very important—the law of deceleration for TBM. I think it's ignored by almost everybody; at least I've not seen it referred to by anybody since I suggested this about ten or twelve years ago. Why fault zones may delay TBM so much; there are special reasons for that. We can even put them in the form of a very simple equation. I'll show you quite a lot of examples of fault zone challenges from just one project in Taiwan, and then specific challenges of projects where faults, combined with the problem of water, are the main challenge and three projects I have personally experienced. Also, a little bit about seismic, the deceiving velocity of faults when they are discovered at depth, or let's say, before they are discovered at depth —this is part of the problem, I think. And, the choice between double shield and open gripper TBM, the challenge of high rock stress. Shall we choose TBM, or drill and blast; that is part of this hybrid question. The other part is should it be double shield or open gripper. Finally, to end with some words about single shell drill and blast, what we call NMT (Norwegian Method of Tunneling) based on the Q System, and of course, conclusions.

I'm going to read out a very few facts, and some assumptions. There are many examples of TBM tunnels in mountainous terrain which have suffered the ultimate fate of abandonment, due to insufficient pre-investigation, and the logic of hydro-geologic problems. Uncertainties about the geology, the hydro-geology, rock stresses and strengths go hand in hand with deep or ultra-deep tunnels. Unexpected conditions tend to have a much bigger impact on TBM projects than on drill and blast projects, and I'll show you very simple reasons for that if anyone is in doubt. Should it be TBM or drill and blast?

Unfortunately, one may witness dramatic reductions in utilization meaning very, very steep deceleration gradients of the TBM performance, when this is expressed on a log-log plot of advanced rate versus time in long tunnels that are showing problems. Some long tunnels can go quite fast with TBM, but we're concerned with the long tunnels that have the problems. Certainly some delays can be avoided or reduced with the new TBM designs, where belief in the need for continuous probe drilling, and sometimes also pre-injection —perhaps it should be continuous and on some projects it needs to be. When that is fully appreciated, perhaps delays can be avoided. Drill and blast tunneling, by its nature, has numerous sort of probe holes, even though they're only four or five meters long. Prior to each advance, one should use drill and blast instead, I think, if investigations have been too limited to justify investment in a TBM. I do not believe it's a correct argument to choose TBM because the tunnel is long, it may be the worst decision you could make.

The choice—shall we have drill and blast, or TBM. This is an important choice, especially in a headrace tunnel, as we are seeing here; (Ref. PPT) one which was empted for inspection in South America. First, the apparent reverse logic for TBM (and) the Q System adjectives. You see the numbers of the Q System along the bottom of this graph, and you see the adjectives at the top. They're actually misleading for TBM. They're suitable for rock support, but not TBM because as the PR gets much lower in this area here, there's a lack of rock joints, the rock quality is too high and the TBM goes much more slowly. Part of the reason is that both these extremes of rock mass quality, the Sugar Loaf Mountain on the left, with a Q value of say 1000, and the double fault zone, also in Brazil, in a tunnel in Brazil. At the other extreme, they are both unfavorable for TBM progress for very different reasons.

These are some interesting and important results from two tunnels, quite an old case record from Japan which shows that the penetration rates get slower as the rock quality improves. This is not the whole story because one can tolerate the PR getting slower, as long as the advance rate remains good. In general, if you have to change the cutters a lot, the advance rate goes down as well. The improved rock mass quality associated with high velocity and high productivity with drill and blast tunneling has exactly the opposite effect on TBM tunneling, especially where the penetration rate is concerned. Now we come to a very important subject, the "Law of Deceleration" for TBM.

I call it a law, because I think all TBM in principle have to follow this trend that you will see. This is a result of a survey of about 145, up to several kilometer sections of TBM representing a thousand kilometer of TBM tunneling where rock conditions were well described, because the majority were open gripper TBM. This is a synthesis of the figure, which I'll show in a moment, it's not quite so neat (Ref. PPT) and it shows on the left axis the penetration rate defined as the advance in one hour, and the rest of the chart is logarithmic scale—one day, one week, one month, and all this area in here is the advance rate according to the scale (Ref. PPT). Even the world record speed, you see the decline—it's a deceleration. Even the world record with 2 meters and hour, at the end of the project, that's 16 kilometers in one year—that is also decelerating. The project is in very poor rock and could decelerate even more, especially with these unexpected events which we find strongly related with low Q values. In a moment I'm going to show, I'm going to comment (on) these two equations here (Ref. PPT).

I've already placed one of them in the top corner here. Instead of utilization, I've put T in hours, raised to the power M, and M is this negative gradient. My emphasis is that utilization depends on time, so it's a very risky business to assume the TBM has to be chosen because the tunnel is long. Because U is time-dependent and tunnel length dependent and the negative gradient of deceleration is very important to quantify. T is total hours, a week is 7 x 24, it's 168 hours. Forgetting location, different times for shifts, just take the total time because that is the reality of completing the tunnel. This is the raw data: the green is the average performance, red is what you read about in the tunneling magazines, records, and, unfortunately, of these blue are some of these projects that stay in the mountain forever (Ref. PPT). We'll see a few photographs from some of those conditions. Some of you have much more experience of things like that, I think, because of the extreme amount of tunneling that is occurring in difficult conditions in China. Unexpected events I describe as, where faulting or extreme water, or combinations of faulting and water, perhaps that's the worst or squeezing conditions, or general lack of stand-up time, may block the machine for months, or even involve a new contractor driving a drill and blast bypass of opponently abandoned TBM. Here I mention that bypass is OK for water, it doesn't complain if it's turned round the corner.

But for a road or a rail tunnel you have to persevere through the blocked area. It may be a huge cavity larger than this room (and) you have to solve that problem. It's a very, very significant challenge sometimes. Why fault zones may delay TBM so much; just a figure to start with. This is a figure drawn by one of the world's most experienced TBM contractors, and the equations I'm going to show, I call Theo-Empirical. Theological and empirical because if you don't believe them, one pays the price. We need 3 basic equations, and they're all very simple ones. The first one is fundamental for TBM, except that U is time-dependent. Therefore, I also give the second one, $U = T$ to the power M. The third equation, if I walk across the stage here at a certain speed, advance rate, AR, the length I go depends on the time it takes (Ref. PPT). T is L over AR, obviously for all tunneling. If we combine these 3 equations we get still a very simple equation, but it's got a very important power term, and the problem is that M is negative. It may be very negative; it may be only slightly negative. This minus M is very related to low Q values in fault zones. So, the component becomes too big. Imagine if this M (Ref. PPT) becomes minus 0.5, minus 0.6, minus 0.7, then this component becomes four or five and suddenly have nearly an infinite time, and you get stuck in a fault (Ref. PPT). M is also shown on the left axis of this diagram. We're going from minus 0.1, that would be typical for double shield machines; 0.2 might be typical for open gripper machines, and then all these much increased gradients in a low Q value. In principle, one should try to pre-inject and drain in this area to limit or avoid problems.

Without probe drilling and then pre-injection, one is often too optimistic. These sketches are from an early article by Robbins, and they were breaking the world record at the time. They were not probe-drilling. It's tempting not to probe drill when they were breaking the record, and then they had many months delay in this zone (Ref. PPT). If they had probe drills, maybe it would have been above the machine, and of course, sometime it would have been below the machine. In many cases, one has to really have at four probe holes to be sure of not missing something important. And fault zone, they create great problems for double shield TBM; you see that this is a machine with PC elements. The problem is that the zone was not pre-treated. It was also a mistake for the contractor actually to withdraw the machine. (Ref. PPT). You see the chainage (?) here-two-two-four-one (2241 ?). If they had not withdrawn the TBM, they would have had less problems to tackle. In retrospect, it's easy to see that. Actually we can draw an analogy. This is an excavation for something quite different. (Ref. PPT) The time delay from here to here, and the low velocity is penetrating into this rock mass because of lack of support. It's the same thing when the TBM comes, and releases the stress at the face of the tunnel. This, again, is the most experienced TBM contractor. This is a totally unexpected faulted rock, with about four or five, even six, different joint directions, and a big overbreak occurring ahead of the machine, overboring, and a delay because of that. (Ref. PPT) In Q System terminology, we have some adverse parameters here, low friction, (and) small block sizes.

The advance rate of fifteen, twenty, twenty-five meters a day goes way down to two or three meters for several weeks, just because of some unexpected events like that. It was not anticipated; it wasn't probe-drilled and it wasn't pre-treated. Werth is one of the justifiably well-known machine manufacturers in the world. Werth, Herrenknecht, Robbins and Mashimatsu, you know these names very well and these were two wonderful machines for the Pinglin (?) Tunnel. (Ref. PPT) These TBM should go about fourteen kilometers from the east coast of Taiwan in the north, cutting across towards Taipei. Already the pilots TBM of five meters had gone ahead, but it got stuck many, many times. They had to bypass at least twelve or thirteen times around this pilot tunnel, so the pilot tunnel could not be used for pre-treating the ground. The pilot tunnel dives down a little bit (Ref. PPT) further into this mountain. These are some sketches drawn by the contractor, who had enormous problems with this meta sandstone, quartzite type of rock mass, with clay on several of the joint sets, and huge amounts of water in places. (Ref. PPT) You'll see a photograph looking back from this top heading where this is a very adverse situation. In one of these they passed through and there was an even larger collapse, destroying one of the TBM and could not use for the rest of the project. Looking back on to the big TBM, they've taken this opportunity to replace the armor because it gets worn out every few kilometers in this very abrasive rock. This is a picture looking back at the tenth or eleventh bypass of the pilot tunnel (Ref. PPT). I happened to be in Taiwan, several times, giving courses, and I visited this project two or three times.

I think I saw the tenth, twelfth and thirteenth bypass over a period of several years. We're going to move into the subject of faults with water, and actually the first two pictures is continuing with the same project because where they lost their TBM, they had to continue with NATM top-heading and benching. This looks like a regular sort of difficult problem. (Ref. PPT) They had to go many kilometers with this because they lost their TBM in the first one and a half kilometers, I think. This is a picture, a close up of that face, and actually we are one hundred meters behind the real rock face. The seven thousand cubic meters of soil, rock and water that flowed into the tunnel. Unfortunately, one of the casualties, I think in this project alone, they lost two miners each year for something like fifteen years; a very, very serious problem of loss of life.

We take a case of water and faults from Italy. This is a drawing I received after visiting the sites for the first time, and it was not available then. (Ref. PPT) This investigation had not been made by the geologists. They had done some two or three hundred meter deep bore holes, and seismic refraction profiling. They had missed, unfortunately, the swarm of faults that were parallel to the valley. This was in Northern Italy; a place called Pont Ventoux. Was the tunnel too deep for satisfactory geological investigation? That is an important question. First of all they had stress problems, and then water problems (Ref. PPT); you can see the level of water here, and most specifically, as they started to come nearly parallel to these fairly minor faults, with only about one, one and a half meter thickness of clay core. But it was very, very unfavorable. (Ref. PPT) In the second drawing they have superimposed the geologist's drawings. Each week he went in and sketched the developing dimensions, maybe the tunnel had moved, the TBM had moved a few meters. I've put these drawings over each other. The problem was the blocks kept on falling down the shaft with a lot of water, silt, and sand to continuously block the cutter head. This was not the only problem. They also had a delta of sand and silt building up behind the backup equipment where the water was very still. Each time the train came in, or trucks or mudcarts, they were often derailed. This void here (Ref. PPT), the trailing to the finger shield, probably ten or fifteen meters into the other side of this void. It goes up maybe two hundred meters because you can hear the blocks falling from a long way away. Now, a water and fog case from Kashmir. (Ref. PPT) This one is a geologist's sketch of the possible reasons for four thousand cubic meters inrush, amazingly of partly rounded quartzite pebbles, even though we're about nine hundred meters deep. Very active ground water flow here and there was sustained inflow, of like, sixty cubic feet a minute. This delayed the project 280 days. They had to make a separate tunnel to take the inflowing water.

Each of these three cases I've described, we could say they were unplanned hybrid solution, because all of them had to be rescued by drill and blast from the other end; going around the rusting TBM that stayed in the mountain forever. I suppose we could say that Jinping Ⅱ is also a forced hybrid, because you were not planning to complete the tunnels with drill and blast. Now, I go to what is also an important subject for deep tunnels—the deceiving velocity of faults at depth. I will show the source on this diagram (Ref. PPT). We have depth here going down to one thousand meters. We have P-wave velocity going to six kilometers a second here, and each of these lines is a constant rock quality, and constant Q value. The problem is when you illuminate faults at depth, ahead of a tunnel, they have a sort of a false [sic] but looks like a false high velocity. The difference is that (Ref. PPT) the one key thing, the country rock has even higher velocity. The problem is when you come to this fault you release the stresses and bring it up as if it was up here, and its true character is revealed. It may be a fault that should be two kilometers a second at the surface. There is this analogy again that when we have released the stress, the low velocity penetrates, and this material becomes much poorer, especially the strength clay fillings. Again, (Ref. PPT) this is the velocity, and now we have the Q manual at this axis. The depth is increasing along these lines, and my point is, at depth, at many hundred meters depth, the fault zone with a very, very low Q value will seem to have a high velocity. The key thing is, if it was compared to the country rock, the country rock would have even higher velocity, (Ref. PPT) it would be up here somewhere with a much higher Q value. This is a case of in tunnel seismic in Japan, where they were running along at 4.2 km per second, not very good, the rock, of course, and eventually the velocity is predicted to go down to about 3.7 km per second. But even when they drop just one km per second, excuse me, 0.1, they have a tunnel face collapse even though they are prepared.

A few words about the choice between double shield or open gripper. As you know, you can thrust off the last row of PC elements in a fault zone, and this can be sometimes very useful in moderately jointed and moderately faulted rock. When you cannot use the grippers (Ref. PPT), this is actually on a chart for open gripper machine and showing two results for double shield machine. These are the early learning curves in the first three or four months of a double shield machine that is struggling with very massive rock. The Q value may be five hundred or one thousand, RMR almost more than ninety-five if you can believe, so (Ref. PPT) this is a double shield machine. It's only performing the same as if it was open gripper. This is also double shield machine, but here the strong efficiency has managed to change two meters an hour average to something respectable by the end of 14 kilometers. That is the Guadarrama Tunnel, that's 4 TBM, two from Werth (and) two from Herrenknecht. They went fourteen kilometers in about 30–33 months using these principles. This is a picture from inside one of the tunnels (Ref. PPT), and of course, this is a huge investment to use double shields; to have all these elements. It's obviously very efficient, but it's an increased price, as far as the required support is concerned, because a lot of this tunnel was in rock of very high quality. This efficiency gave them the possibility to predict the end more easily than with open gripper machine. All TBM choices have problems when the rock mass and water pressure decide to combine resources to stop the TBM, which unfortunately often happens. (Ref. PPT)

This sketch of four conditions, actually taken from the oil industry, only one is positive for TBM. (First), this well-jointed one is ideal for very fast TBM advance. There we could get one, one and a half kilometers a month; maybe ten kilometers in a year if it continued. Number two is supposed to represent massive abrasive rock where the penetration rate might be just one or two meters per hour. Every two or three meters, except they wait until the end of the day [sic], every two or three meters one cutter needs to be changed. Because it needs to be changed so soon, some of the cutters will be ineffective for a big proportion of the following day, so the advance rate has to be reduced. Number three. As you can imagine, that may trap the TBM because of squeezing. Again, you get a steep gradient here of deceleration (Ref. PPT). Number four is supposed to represent falling blocks because of the fault zone, a church or cathedral-size fallout to exaggerate a little bit, could be an indication of rock burst and stress induced fracturing.

When you see core boxes like this, almost free of joints, and when all the rock mass parameters are butting on the right side of my Q diagram (Ref. PPT) a very high RQD, almost no joints, discontinuous joints or dry you may have very, very slow progress. Even though the rock is perfect, it's not perfect for TBM. One can use a prognosis method, if there is sufficient data available, or we could estimate the input parameters using engineering judgment. Here I've shown on this same diagram (Ref. PPT) the declining rates, the simulation of double shield machines with a star, and the open gripper machine with a cube. I've chosen slightly different cutter force 26 and 28 tons. The gradient here is roughly twice as steep as a double shield machine. As a rule of thumb there is some variation (Ref. PPT). In this simulation of a fracture zone, we're going way, way down, maybe as far as the floor. This TBM, because we haven't treated this fault zone, would stay in the mountain forever if it was a real condition. The input data, the last input for the fifty (50) meters of this very massive granitic gneiss. We call it Class One, but it is about the worst rock that we would want. It has high RQD, (and) only one joint set. We would need very high cutter force, like 32 tons; it's bad news for TBM. It's typical for the Sugar Loaf Mountain picture that you saw. Here's comparing open gripper and double shield prognosis. You see the open gripper prognosis is not quite so good as these line because of the abrasive nature of this projecting granite (Ref. PPT). There's a variety in the amount of jointing so some go quite fast. If we have a double shield we can have the efficiency of that, and go faster. The QTBM is actually the Q parameter (Ref. PPT) from additional machine-rock interaction parameters. Recently in Brazil, there's been a tunnel in this area, with extreme [sic] more than 50% of the rock have Q value more than two hundred, more than five hundred, and RMR was more than ninety-five (95) for 50% of the project for many kilometers (Ref. PPT). Very, very slow progress, even though the rock is supposed to be so good in our usual concept of good rock. The challenge of high rock stress, the challenge of deep tunnels in general in recent years have been many TBM tunnels with depth of cover of more than one kilometer. A few also of more than two kilometers and in two cases, that I know, even 2.5 kilometers for short sections. One of them was Jinping Ⅱ; another was Olmos in Peru. Both have suffered damage or destruction due to rock bursting. We heard this morning of the deaths in Jinping Ⅱ. I don't think there were any casualties in Olmos Tunnel, but there have been many, many casualties in these deep tunnels in the last twenty years and they continue in these present years.

(Ref. PPT) Here I've put on a single screen sort of theoretical challenges to the well being of TBM, lock spiral failure surfaces, and fracture mechanics modeling where there is a natural stress as high as forty, fifty, sixty MPA, and what happens if there is a little more jointing. Some of the explanations, perhaps of why you get a much deeper breakout when there is other jointing in place together with the rock burst problem. And physical models, this is drilling in sandstone in different directions to Sigma One, Two and Three, and a layered model. A new deck model with small block size, perhaps emphasizing why fault zones are such big problems where the rock is very jointed. If the rock is hard enough, and dilatent (?) enough, granular perhaps, granite would be an example, maybe the failure is dominated by extension rather than shear. But I've seen shear mode in massive schists, and marble, and sandstone.

In the Q System, we have one of the parameters called SRF stress reduction factor. (Ref. PPT) In this area here, where the ratio of tangential stress, the uniaxial (?) strength is climbing above 0.4, 0.5, 0.6, we get a sudden increase in the SRF number and a reduction in the Q value. This is case records before 1990 (Ref. PPT) published in 1993, mostly from deep road tunnels in Norway. One of our road tunnels is 1400 meters deep. Quite independently, this is a set of data that I found in one of the papers by Derek Martin. He probably published this many years before this reference (Ref. PPT). It's also showing when the stress to strength ratio reaches about 0.4, 0.5, you start to get the stress induced fracturing. Here are some pictures of stress induced fracturing (Ref. PPT).

This is the drill and blast at one of the headrace tunnels at Jinping; this is one of the TBM tunnels before the TBM was removed, and this is some deep stress fracturing in a very shallow tunnel in very hard basalts in Brazil. This is maybe the result of a minor rock burst in Jinping Ⅱ. This shallow project in Brazil, even though the tunnels are only sixty or seventy meters deep, we have these very high ratios of stress to strength, because of a fantastic, high horizontal stress here, giving a stress ratio, horizontal to vertical, maybe twenty or twenty-five, and a depth of failure as much as three meters. TBM, or drill and blast, all tunnels are affected in some way by some extremely weak or extremely hard rock, serious faults, too much water, and too high stress. However, the risk to TBM tunneling is larger in each case. So slight characterization is even more important before deciding on using TBM. Here we're going to make a small comparison between TBM and drill and blast. I'm going to show you that central well jointed rock qualities are required if the TBM is to be faster than the drill and blast, because it can be much faster, but it can also be slower. Then we address the question "are long tunnels really faster with this TBM." Here I' ve put together data from drill and blast tunnels (Ref. PPT). See this curve here, the whole range of Q based on cycle time that you' ll see. I' ve created this simple case record for TBM, doing at a reasonable speed the weekly, monthly and yearly performance. We need to have a rock quality, mostly in this area if the TBM will be faster than drill and blast. I show here, just for interest, the world record, I think for the average weekly advance in drill and blast is 104 or 105 meters. The fastest speed for drill and blast one face is 173 meters in one week. The previous record was 164 meters. Obviously, there are not so many rock masses or contractors that can drive tunnels as fast as that. It does point out that drill and blast can be faster than TBM if the rock is too massive, and drill and blast can solve (the) problem with faulting more readily than when a TBM is in the way of a creative contractor. The cycle times for drill and blast (Ref. PPT) are shown here go down to four or five hours per cycle time if the rock quality is very good and you don' t need rock support. The rock quality that is expected, we need to know the distribution. An especially important question for deep tunnel, with massive rock coincide with high UCS, with low cutter life index, high quartz content, and high mountain cover. Could fault zones have high water pressure on one side, and how many attack points, or add-its [sic] ventilation could make the drill and blast a preferable choice. In the case of a hydro-power head race tunnel, we could use the term nominally unlined, if the rock quality was very good. This is in massive schist that showed lock spiral failures in some sections with high cover. Nominally unlined could be a valid solution in massive hard rock.

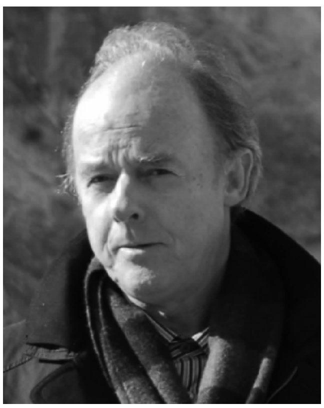
What happens, statistically speaking, when a long tunnel is planned compared to a short tunnel. I' ve just set up these thought exercises (Ref. PPT) a five kilometer tunnel with a certain Q value distribution, and a twenty-five kilometer tunnel with another distribution, but with some of the extreme values and the tails here. So very much massive rock, in this area, maybe hard massive rock HH instead of H, and maybe some more of the serious fault zones, the FF instead of the F. The problem of the long tunnel is, you are sampling more of the Earth' s crust, in a way, and you have a sort of a large scale of wide bore effects, that there are more flaws, meaning faults, then the larger the sample in general. If we could consider this long tunnel again (Ref. PPT), which would be the best tactic? The long tunnel should be by TBM or hybrid, and I think the result here would be by hybrid. The adverse extreme value statistics for the rock mass suggest avoidance of the TBM where there is FF and HH character, and maybe high rock cover. A solution could be to drive the left half with TBM; maybe this section could be more easily explored also (Ref. PPT) by deep drilling. Start the drill and blast from this end, maybe one year early, and try to come as far as this before meeting the TBM. The TBM may go very fast, but you have to wait for delivery may be very effective to do drill and blast through this section.

Central habits [sic] are an advantage if they are physically possible, and I will mention some solution for long drill and blast drives in the last moments of the lecture. Here we see a traditional choice of hybrid. This is a long water tunnel in Malaysia in a recent tunnel talk article. Here they've made the conventional choice (Ref. PPT) drill and blast on each end, and two TBM for the long mountain sections. Time will tell whether this conventional choice is a good or bad idea. They are about three years into this project at the moment.

Finally, a few words about drill and blast and single shell. As we've seen already, they could have world record rates of up to 160 meters, even 170 meters and more than 100 meters in a week for a whole project. Obviously, few rock masses and few contractors allow such a performance and 40–70 meters per week might be much more common with drill and blast. There would be variations according to the geology, hydro-geology, the given country, and according to the contractor experience. What is the Q value distribution of the project? (Ref. PPT) How will the Q value distribution look if we drew it down here? That must be part of the decision if the hybrid solution is a good idea.

If we have a lot of area here, we have to do a lot of pre-injection, and it's easier to do from drill and blast. If there is a lot of massive rock, we don't want to have TBM. The pre-injection can be done in between twenty and thirty hours, for one umbrella, and it gives a more predictable result, reducing the risk by pre-injection, it's easier than drill and blast than TBM tunnels. You solve the water inflow problem, and you improve the rock mass quality. If we can do pre-injection (Ref. PPT) we can come down this curve, showing the relative costs, according to the Q value, and we can come down this curve showing the relative time and cost. We can improve the Q parameters. A pre-injection umbrella could probably have prevented this several months delay. Pre-injection brings us from a very low quality up to some area here.

One page of conclusion only. Whether single shield or double shield, one must probe drill, and can then pre-treat major fault zones if their presence is known. Fault zones can be the "Achilles Heel" of TBM if unexpected or untreated. Faults are less dominating with drill and blast tunnels as they are more easily pre-treated. This pre-treatment must be started well before the fault is reached, otherwise it may be very difficult to perform. You need to have pre-treated ground ahead of your pre-treatment, if you understand my meaning. Continuous pre-injection is best in poor, variable ground. Pre-injection helps to improve most of the 6Q parameters. This gradient M is less negative for the TBM option. Obviously improved Q helps to improve drill and blast tunneling as well, because less support is needed. To assume TBM is best for long and deep tunnels is a source of risk, you avoid it. TBM may seem like the only alternative for a long mountain tunnel, but it is not. The drill and blast can be driven further if you use vacuum ventilation or blasts. In other words, if you're using stiff tubing and sucking out the blast gases, one should avoid increased cross-section, the jet fans, when it comes to the long tunnel, or the one that is actually being used, one should avoid increase cross-section, which I noticed was the case at Jinping Ⅱ, making for very bad pollution in the tunnel because the air was not moved effectively.



Nick Barton was born in England in 1944. He has a B. Sc. in Civil Engineering from King's College in 1966, and a Ph. D. in Rock Mechanics from Imperial College, London in 1971. He worked at the Norwegian Geotechnical Institute (NGI) for two periods, from 1971 to 1980, and from 1984 to 1999, when he was a Division Director for 5 years and a Technical Advisor for 10 years in the Dam, Rock, Tunnel, Avalanche and Reservoir Divisions. From 1981 to 1984 he managed the Geomechanics Division of Terra Tek (now Schlumberger) in Salt Lake City, USA. Since 2001 he has had his own international consultancy, Nick Barton & Associates, based in Oslo and São Paulo.

He developed the internationally used Q-system for classifying rock masses and for selecting rock tunnel and cavern support in 1974, and the Barton-Bandis constitutive laws for rock joint modelling in 1982. He is author or co-author of 270 published papers, and in 2000 published a book on 'TBM tunnelling in jointed and faulted rock'. He has also written a larger textbook on 'Rock Quality, Seismic Velocity, Attenuation and Anisotropy', published in 2006.

He has consulted on numerous tunnel, TBM and cavern projects, on reservoir subsidence, rock stress measurement, nuclear waste disposal and rockfill and arch dam projects, in 35 different countries in the last 40 years. In 2004 he received a Doctor Honoris Causa degree from the University of Cordoba, in Argentina. In 2011 he delivered the 6th Müller Lecture in the ISRM congress, Beijing.

Support Design under Rockburst Conditions

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Thank you for your kind introduction. It's great to be back in Wuhan. I was here, I think, about 20 years ago, and at the time was talking about support and rock burst conditions. Since then we have learned a lot, and I have again been asked to make a contribution on this topic. I'd like to introduce the co-author to this paper, Dr. Meng Cai, who is working with me on a revised guide for support design. This event is about safe construction and risk management in major underground structures, and there are many elements that are relevant for that.

Looking from the North American perspective, the first and most important one is corporate social responsibility. It is depending on the corporation's attitude towards safety, and towards risk management. I was pleased to listen this morning to see that there are major initiatives underway here in China to address these issues. In Australia it is called Social and Environmental Justice, which implies that there are even major legal implications.

The second element to it is systematic risk assessment and communication of risk so proper decisions can be made. I will comment on that tomorrow during the discussion period. Today, I will focus on the aspect of sound engineering for constructability, with safety in mind, and particularly talk about deep tunnels in highly stressed ground, and of course, the highly disruptive events of rockbursting and the support design product condition. I will start off to briefly introduce the Centre for Excellence in Mining Innovation, simply to illustrate that the issue of tunnel boring systems in hard rock under high stress will stay with us for quite a while. I will then talk about lessons learned from deep excavations, and then focus on the issue of challenges with respect to rock support to manage risk. Much of it is documented in the journal or the handout that you have, and I will focus on examples to illustrate the points that you have in the written text. The lessons learned come from Alpine tunnels in the civil world, as well as deep mining examples, excavations done to beyond 2500 meter depths. The case examples that I've used are really examples where the engineer designer did not take into account issues of constructability, the ability to construct the tunnel safely. The main reason for that is a lack of respect for stress induced fracturing, which we call spalling, deep fracturing, and the consequences for support selection.

As I indicated, I'm running a Centre for Excellence in Mining Innovation, and our mandate is to support step-change innovation in five key areas of safe metal mining. The word "for" in this title is very important because our mandate is to foster excellence, and to accelerate innovation. It's not about research alone; it's about the integration of new ideas and the execution and implementation of those ideas. When we talk about safety and risk, we certainly talk about the implementation more, let say, the academic research component. We have a division that was funded by Rio Tinto, one of the top three mining companies, The Centre for Underground Mine Construction. Its focus comes from one simple fact that this mining company has to go from open pit excavation to underground excavation. In that there is a very simple statement, and step-change has to be achieved because "time is money." One day of delay in a mining project costs in the order of 1,000,000 (a million dollars). For this purpose, they're in the process of developing three different types of mechanical excavations: a tunnel boring system by Werth from Germany and the second one, shown on the left (Ref. PPT), from Atlas Copco, and a shaft boring system by Herrenkneckt. That (last) machine has a diameter of twelve meters and is expected to excavate the shaft at about ten meters per day. In parallel, but totally separate, Anglo Ashanti Gold in South Africa is embarking on mechanical excavation simply because they cannot afford to take the rock out. They have to focus on the gold only, and they have a slogan of "Safe Minings" or "Safely mining the gold, only the gold, and all the time." With that they have started an initiative that at the first application will potentially be three TBMs, four haulage boring systems, as well as thirty-three raised boring systems. While I fully understand and appreciate very much the comments that we have heard of the difficulties with mechanized excavation, this will stay with us unless the initiators are proven wrong.

So what are the lessons that we have learned? When we're talking about high depths, the first one is the rock is less forgiving. What that means (is) when it's shallow, we can make mistakes, and we can get by. However, if we're at great depths, we cannot make mistakes, and we have to do proper engineering. Tomorrow, unfortunately, Charles Fairhurst is not here, but his talk is entitled "We Now Have the Tools." It means modeling tools, etc., but the key issue is if we're not designing so it can be built and can be built by the contractor in a safe, cost effective manner, then our tools are of not much use. When we see problems as illustrated in these examples; collapses underground or rockbursts as on the right (Ref. PPT), we have to ask ourselves "what did do wrong in the design?" Just to make it clear in terms of terminology, I'm talking to Pathe about brittle rock types that fail in tension by spalling as shown on the left (Ref. PPT), or fail in high stress by creating tier zones as illustrated on the right, the picture from South Africa in very deep mines (Ref. PPT). I'm also talking about processes that lead to the disintegration of the rock mass' near the excavation, two pictures near a cross-cut. (Ref. PPT) On the left, we see that relatively massive rock has been damaged by spalling, by stress fracturing and as more deformation occurs, we also get shear deformations in these types of failure mechanisms.

The primary challenge, before we can even talk about support design, is we have to fully understand how hard, brittle rock behaves under stress. The key thing is, when rock is failing in a brittle manner, we have to engineer so that we can manage that broken rock that I showed on the last slide. We have to manage fractured rock and we have to deal with the large deformations that occur when that rock is failing, and the support system has to tolerate these deformations—it has to be compatible with deformations.

That's the key method of my presentation today—support design has to focus on deformation compatibility. When you look at many examples underground, what a drill and blast ore excavated by TBM, you can see always the same picture; that is we have stress fracturing, the wall of the excavation is failing to various depths, in this case the greater depths because of a burst situation. In other cases, in a controlled depth as illustrated by these examples. But that process can also happen in clay shale type formations that are relatively weak. The point is very simple, this is a mechanism that we have to consider anticipate and take into account. Elasto-plastic numerical models that are widely used for engineering are not capturing this kind of process.

"The second thing is we have to anticipate the depth of failure, and Dr. Barton showed this figure, and he also illustrated that failure initiation starts long before the stress around the excavation, which we showed on the horizontal axis (Ref. PPT) the stress level occurs when the stress reaches about 40% of the UCS of the rock. It then increases more or less linearly, so on the vertical axis, on the depths of failure, we have more or less a linear increase. When we have this type of failure mechanism, we can anticipate the depth of failure. Also, Dr. Barton referred to the stress ratio, and he demonstrated a long time ago that when we have this ratio exceeded by 0.6, we're entering strain bursting conditions. He indicated then when the stress reduction factor reaches ten to fifty, we get to that stage. If we combine the two diagrams, we basically come to the very simple conclusion that when we have a depth of failure that exceeds about 20% or 30% (Ref. PPT) of the radius of the tunnel, we can expect that this failure process is not happening in a gradual way, but energy will be released, and we have a violent strain bursting failure mechanism. What happens if we take a rock through this stress path, and this is illustrated here on an example of a rock that is relatively massive, if you look up here, (Ref. PPT), but because it was deformed suddenly by horizontal convergence it was fractured by tensile fracturing. Because that rock increase is in volume, and it cannot go anywhere except into the excavation, it moves downward, loading, deforming the support. Most importantly, the massive rock is transformed into a blocky rock mass that has next to no cohesion, but much greater volume. This image, to me, is most important. It illustrates that the massive rock is transformed into rock that is very difficult to manage. We call this process bulking. I illustrate it here (Ref. PPT) on a model that is strained. You can see the individual blocks are not failing, but the boundaries between the blocks are opening up so we have a geometric volume increase that is associated with this failure process. (Ref. PPT) I'm not sure whether you can see this image, but it is rock stone with shear failure along discontinuities, but most importantly tensile fracturing of the blocks in between. Imagine, to strain this rock more, its volume will increase drastically. The picture again tells you that what we have to worry about when we design support is not necessarily the loads that have to be carried as most designs do, but we have to look at the deformation displacements that occur during that process.

We conducted some simple uni-axial tests with stress fracture code called Alphen. We take the rock over at peak strength, we fracture it, and then we plot on this diagram (Ref. PPT) as a function of confinement, what the bulking is and more or less a linear relationship. What is more important is that when we go underground, this is measurements from South Africa, we see the similar relationship though with a different slope. What is of practical importance is that when the confinement is less than about 2 MPa we have zero to 10%. That means one meter will become 1.1 meter in length. Around excavations that only happen(s) in one direction, uni-directionally into the excavation. This behavior is dependent on the confinement (Ref. PPT) we show the relationship for no confinement, 1, 2 1/2, 5 megapascal deformation, and you can see as we have tangential straining around the excavation, one radial straining in the other direction is about 6 to 5, to a minimum of 2 times the tangential straining. In practical terms, that means about 4-5 times as much straining as we imply on the rock is going into the direction of the tunnel because our support capacity is typically less than one, or maybe less than 0.5 MPa. If you think of two parallel tunnels with a pillar in between, that is being loaded as we excavate these tunnels we will have straining of the pillar, but most importantly, we have lateral straining of the broken rock near the excavation. As I have illustrated is in the order of 4-5 times as much as the straining of the pillar. This is found many times in mines. Here, an extreme example of a Kimberlite mine, where due to the straining in the vertical direction, a lot of bulking caused two very extreme convergences of a tunnel that was able to take relatively large equipment, about five meters wide. Most interestingly, when we excavate this tunnel, or this type of a tunnel, we find the rock is more or less stable all the way around, and that is just a small skin around the excavation that is being strained and bulks excessively. I hope by now you understand that the mechanism that happens around excavation is one of rock mass degradation and extreme volume increase that needs to be managed in underground excavations.

What are the implications for tunneling? The first one is time to maintain stability is significantly reduced. One stand up time is reduced that leads to delays and costs. The second one is this process doesn't happen nicely. It happens suddenly and that is what we call strainbrace, which again leads to delays and costs. (Ref. PPT) Here I'm showing the way we classify ground in various ways. The Earth and GSI systems and most others do the same; on this axis, we have the size of the blocks. On this axis we have the conditions of the joints. When we start with a massive rock, and we add stress, we get different displays of disintegration, in this case maybe to 1/2 meter or less in spalling. In other cases, this is quartzite that doesn't degrade down to the decimeter scale, ten centimeter block, and in this case even down to a millimeter to centimeter scale. The stress takes a rock mass, that in the logs would look very good to a rock mass that looks much worse. That means the stress is really a rock mass degradation component factor. In this diagram (Ref. PPT) of well established chart unsupported span against the stand-up time, in this case has a function of RMR illustrating that if we have a rock mass that is good, let's say with GSI or with an RMR of 65, the effect of stress is that it takes the rock mass to a condition that is no more stable. We have to use constructive means support to increase the stand-up time. Of course, we have to get the support in time.

This is real when you deal with hollow boring systems, and here is an example from Gotthard Tunnel, where the contractor estimated an advance rate of around 25 meters or better on average, but then only achieved about half the speed with an open tunnel boring system (Ref. PPT). The problem was not collapse as illustrated the fault zones. The problem was that stress fracturing occurred around the excavation to maybe a depth of about a meter. Stress fracturing that doesn't look very serious when you look at it, but it has huge implications because it splits the advance cycle into two, which means the machine can only excavate, and then you support. A good TBM construction site has a support system where you can support as you excavate. A little bit of stress fractured rock, in this case, that was not well supported, led to about a year delay on this project. Also, the tunnel didn't look like it was a tunnel boring tunnel because you can see that all around the excavation you have stress fracturing in some cases which are influenced by joints. But, in most cases, simply surface parallel fracturing due to stress. The support design has to take that into account.

How do we normally design support? (Ref. PPT)

In underground construction, strategy is the art of commanding the entire mining or tunneling operation. Tactic, on the other hand, is the skill of using various tools for the construction and for dealing with immediate needs in the field. Most engineers are forced to be tacticians as everyday tasks make them think of how to deal with the most immediate problems. To think strategically is more difficult and often demands long-term thinking to get out of the reactive mode to rockburst damage.

As Ralph Waldo Emerson, an American essayist, philosopher and poet (1803–1882), said, "As to methods there may be a million and then some, but principles are few. The man who grasps principles can successfully select his own methods. The man, who tries methods, ignoring principles, is sure to have trouble." Realizing the importance of understanding rockburst support design guiding principles, Cai and Champaigne (2009) summarized field experiences into a few simple and easy-to-understand principles.

The first principle is to avoid rockburst whenever possible. The supreme excellence in rock support in burst-prone ground is to avoid rockburst conditions. Hence, the best strategy is to stabilize the rock without fighting against the loads and stresses in the rocks using heavy rock support. Methods to avoid rockburst risks include changing tunnel location, use of different excavation shapes, changing the stope size and/or shape, altering mining sequence and potentially switching mining methods.

The second principle advocates the use of yielding support in bursting grounds. When a brittle rock fails, it is always associated with large rock dilation and may be subjected to large impact energy. Therefore, the installed rock support system must be deformable and able to absorb dynamic energy. It is often un-economical to prevent rockburst damage from happening by increasing the load capacity of rock support. The support behavior must be fundamentally changed to a deformable, yielding system that is able to tolerate large tunnel convergence without "self-destruction" while absorbing dynamic energy, thus providing support to ensure safety and serviceability of the tunnel. A yielding rock support system is a system in harmony with its surrounding failing rock mass.

A chain is only as strong as its weakest link. In conventional rock support systems, the retaining element is often the weakest link and connection between bolts and screen often fails in large rockburst events. Consequently, the effectiveness of a rock support system comprised of rock bolts and mesh depend on their capacity, but most importantly on the strength and capacity of the connections between the bolts and the mesh. Unfortunately, design procedures for rock support design focus mostly on checking how much load a rock bolt can carry, or how much energy the rock bolt can dissipate. The failure of the rock mass between the bolts and the impact of this failure on the rock support system is often not considered in design. The selection of surface support elements and the strength of the connections must be matched with the capacity of the bolts.

As a fundamental requirement, holding elements need to be combined with reinforcing elements such as rebars and surface support elements such as mesh and shotcrete to form a rock support system. There is no such thing as a "super" bolt or "super" liner that can be used alone to combat rockburst problems. Quite often, we need a rock support system that is comprised of different rock support components, because all three support functions (reinforce, retain, and hold) are needed to form an effective rock support system. Some support components have multiple roles but may be strong in one aspect and weak in another. It is essential that various support elements be combined to form an integrated support system. This is the principle of using an integrated system.

The fifth principle is the simplicity principle. Simplicity is powerful. Rock support elements should be relatively easy to be manufactured, installed, and maintained. Regardless of how effective it is, if a rock support element is complicated to manufacture and the cost is high, operators will be reluctant to use it. If it is difficult to install and production is adversely affected, its acceptance by the mine operators and the miner will suffer. When it comes to rock support in burst-prone ground, it is always beneficial to follow Albert Einstein's advice "Make everything as simple as possible, but not simpler."

Unfortunately, there is still a wide-spread assumption that rockburst-resistant support is expensive for use in highly stressed ground. While mining companies aim at reducing cost in order to stay competitive, they cannot do so at the expense of safety. The consequence of rockburst can be extreme, ranging from damage to underground opening with high rehabilitation costs, damage to mining equipment, loss of production, permanent loss of parts of ore bodies, to injury and fatalities. The cost associated with these items can be extremely high. For example, it is estimated that the rehabilitation cost may be 10 to 20 times higher than the initial development cost in underground hard rock mines. A major rockburst may shut down mine production or tunneling operations for an extended period of time. In other words, if the price tag for rockburst damage is high, the cost of preventing it in the first place, using a rockburst resistant rock support system, can be remarkably low. Damage prevention and control in burst-prone ground is most cost-effective.

The last principle advocates the ability to anticipate and to adapt. Burst-prone ground conditions and rockburst damage severity potential change constantly, and it is unrealistic to have a fixed design that cannot be changed. The underground excavation and rock support method therefore must be responsive to a variety of ground conditions that can be encountered. The art of rock support in burst-prone ground is not to rely on the low likelihood of unexpected ground behaviors, but on the readiness to manage them with an effective rock support system that is unbeatable. By understanding the seven principles, the ability to safeguard workers and investment risk can be improved. These core principles must guide rock support design.

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Risk Assessment of Collapse in Shallow Caverns Using Numerical Modeling of Block Interactions with DDA: Suggested Approach and Case Studies

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I want to present briefly a short lecture about the experience we have about the stability of varied caverns underground. The problem was started in the mine where they had Karst caverns underneath the mines. They needed to explore them somehow and geophysics didn't work. They needed to drill and then for drilling they needed to dimension the length of the drill holes and the distance between the drill holes to design the mine. The question of the critical relationship between the span of the opening and the covered height for the stability would dictate what the distance here is and what the depth of the drilling here is to leave a safe roof above the head.

We basically want to discover the relationship between span and cover, a classic problem of rock mechanics. Here is the approach we took. We were modeled the type of rock mass that is abundant in Central Israel which is horizontally layered and vertically jointed. We were careful not to just run joints systematically and synthetically but to generate a structure which is called mechanical layering; where joint extensive spacing of the constrained by the spacing of the thickness of the bed. You can see the joints are not going all the way through; they do terminate. They are conditioned by the thickness of the bed, and so we are getting a more realistic picture of the blocky rock mass structure, then just running joints all the way through the median. This is an example of a blocky rock mass structure. The parameters we are looking at, the relationship between them are B and H — a classical problem.

The method we undertook was to take a constant rock mass structure and then to change those parameters. The result would be relevant for this particular structure, but I will show you from case studies it's not so bad, and it can work pretty good for different blocky rock mass structures. What we have here is a bedding plain set of infinite span and two sub-ordinal and two sub-vertical octagonal joints sets. You will see the rock bridge that we leave between the same simulation of the joints is rather large to allow for this mechanical layering effect. You get the same effect if we limit the trace length and not make it run all the way through the model. We end up with an example of a structure that I showed you before. Then we run simulations, what we check on the simulations under gravity a roof the deflections of roof and the horizontal stresses that develop in the arching zone. That's four different measurement points at an evenly space in the roof: one in the immediate roof, and then two, three and four near the surface. The boundaries of the model are far enough to allow for the stress concentration to dissipate. This is the kind of geometry we are studying. Running those simulations we were able to define three types of stability configurations.

One is stable. Stable means when the upper three measurement points don't show any displacement; the arching stresses are stable, marginally stable [sic]. When we lost two measurement points and were left with two measurement points in place. Unstable is when either all three measurement points are lost, or the whole thing ruptures through the crown. This is an example of a stable configuration. We can tell it is stable by looking at the vertical displacement. You see after some immediate response, this is time, ETA is a dynamic code, so time is real here. You see that the vertical displacement is erect, then the horizontal stresses that develop in each one of the measurement points are also stable. We get a stable condition. We extend that to the case where we lose the lowermost measurement point, because that's okay when we're talking about a mine, or any kind of civil engineering structure on top, so, if we lose the median of the roof, it's not such an issue. When we're losing the roof, the other three measurement points remaining phase, you see the arching stresses, except for the roof, drop to zero, while the other arching stresses, horizontal stresses, indicate stability.

Marginally stable is when we lose half the roof, when two lowermost measurement points are lost. The two other ones are there, but it can be okay for a mine, (but) probably more complicated to have this situation in a city. See the picture at the top, the same is reflected in the stresses that we get.

The unstable configuration is when we lose all four measurement points, and there is a rupture all the way up to the surface. Zero horizontal stresses here because no arching can develop. To show some graphic examples, if we keep the cover constant, approximately 20 meters exact. So, we can see with the increasing span stability decreases. Again, if we keep the spacing, the span constant, then we change the cover. With decreasing cover we decrease the stability. One would assume the relationship should be linear would have to be, for deep tunnels. In reality that would have one-half rate relationship and that would be one relationship. The reality is more complex. As you see we get a non-linear response, where we get stability here, and relatively very little cover, only six meters up to eighteen meters span. Then suddenly we get a quick demand, increasing the demand of cover and for stability. When the depth is 30 meters, the ratio, the slope relaxes. You should realize it's very difficult to simulate because of the problem of thousands of blocks (and) it takes time to compute. We see that is the risk, mentioned by someone in the lecture this morning, we also get the same result—a quick demand or variant when the span increases its value here then relaxes when we get to below 30 or so meters. That result we got for synthetic rock mass.

I want to show you three different cases. One is an actual mine and two are historic underground openings and see if they obey this relationship that I discussed.

This is the biggest open pit mine in Israel. It's essential in Israel to mine material aggregates for cement. They have this terrible problem of Karstich caverns that collapse and sometimes they lose equipment. What they discovered and what we're talking about now, it's a 40 meter span cavern with a 30 meter cover. Here we really simulate the rock precisely. We measure the joints length, spacing friction, and then we generate the model. This is a model of the mine as it is today. If the numerical model will collapse today, we've got a problem, because this thing does stand today in a mine. This is what a numerical model, a discrete element model; a DDA looks like here. We have about 15,000 blocks, every block is about 1 meter square; so many blocks and they have to interact. Now we let gravity work. This is the result we've obtained. What we obtained is we are losing the immediate group, and some of the second measurement points exhibit stability and then some of the other ones also exhibit stability. So according to our definition we should call that marginally stable. Of course, the mines do not like these definitions, but these definitions are what we had to give then, and then go from there. It's a very extensive computational effort to see with all those blocks and the time it takes. The standard we see is 36 hours of time.

Another example (is) underneath the Old City of Jerusalem—a totally different rock mass. There is a huge cavern under the city. It was excavated in the Roman period 2000 or more years ago, when there was a temple in Jerusalem, and they extracted the stone. Some of the stones are 5-7 meters long from this underground quarry. That quarry has a central chamber of 40 meter span, and the cavern is 25 meters and you can see the structure of the rock. This cavern is very interesting. If you look at the roof it's a continuous beam, and if you apply the theory of elasticity then it has to fail because the tensor strength we're getting at the lowermost fiber is about 10 MPa, whereas the tensor strength we have is only 2.8. So it couldn't be explained by the theory of elasticity, or mechanics because simply a single beam at this width, at this elastic modulus, that, this span should have snapped in tension.

Another way to approach this problem is through the Voussoir Beam Analog thesis and published by Brady and Brown, and then a series of papers published on the topic by Canadian colleagues. Many people studied this because it's interesting; what it says is if tensor stresses are high enough to generate a tensile crack, then the tensile crack would probably go all the way to the top then and then cut the beams into two blocks we're getting. The problem is it's indeterminate, so we assume the width of this compressive zone, and its geometry, if it's an ellipse or not. Then you can solve all those massive compressive stresses. At the hinge points there are three failure mechanisms. One is failure by compression at the hinge points, one is created by shear at the abutment, and the other is snapped through buckling mechanisms. According to the geometry of the problem there, (it) should have snapped, or have done buckling, but did not. So the true methods to analyze the stability of this roof, through elasticity or through Voussoir, don't really work and why is the roof stable?

So to give you an answer, we need to introduce more joints—as the reality in the field, there are more joints. When there're more joints, the block length decreases and there's more interaction between the blocks. You can see the picture we're getting. Initial [sic] in the measurement points here, we're getting initial vertical displacement, but then after some initial vertical displacement, arching stresses come in and displacement is restrained, and you get displacement. The same with the stresses, at this point, when the displacement stops the stress is built up, and the fractured beam is locked in place. It does exhibit some displacement, some opening in the roof, enough to mobilize shear, and to create compression that will stop the beam from falling. Surprisingly, the jointing kept this roof stable.

The third case is also interesting. It's a 3000 year old water reservoir, 1000 BC. It's called the Israelite period in archaeology; in the time of King David and King Solomon. So they had this fortress not far from the university, my university, Tel El Sheva, and they had a very interesting structure going down the steps to the water reservoir area. The structure of the tunnel, the reservoir system and the cavern, and the underground system shows that it collapsed at the time of construction. The ancient engineers erected those pillars to support the roof, so they experience the collapse. We know this is a case study that says "collapse" and they restrained the collapse by building the pillar. The jointing pattern is basically parallel, the walls of the water system are parallel to the principal joints there, and to save energy in the construction they just used the joints to construct. What we have is two sets of orthogonal joints again, but very, very close in space—only 20 centimeters or so. We studied their spacing and shear strength, and so the normal stress in the field, that we assume happened in those blocks, we end up with a friction angle of about 35 degrees and this is the friction angle we have.

We can run this roof with DDA, with those parameters here, and show you that with 30 degrees it does not hold; with 35 degrees it begins to hold. And we end up with a function that shows the friction angle require(d) for stability as a function of block length, or the vertical spacing between the joints. You see it's an interesting function that the minimum, which is the optimal for us, requires the least amount of friction angle for stabilization, and then once the blocks are bigger, the demand for friction angle decreases. Now the difference of the slide is really an indication of DDA. It doesn't have stress distribution inside the blocks; if you want we run this with you there [sic], the formable blocks the line will look like (Ref. PPT). This is the result and so for the friction angle for the spacing, vertical joints in the field, the friction angle that is required for stability is more than 70 degrees, so it's not what we have, it's not stable. This explains why it's not stable. If I show you the three case studies on this map, and they are all published, you can see that basically this non-linear criterion for P and H supported by those three different case studies, each in a different kind of mythology. It could work for blocky rock masses at shallow depth, I guess with a modification for local site conditions there.

Sink hole collapse can pose a significant risk. We showed you a limiting relationship between P and H that was confirmed by three case studies. I want to use the few minutes that I have left to show you what we are doing now.

We have been asked, in collaboration with the excellent group of Professor Feng, to try to explore this problem of rock bursts. We should begin with a numerical manifold method, which is basically a super-position finite elements mesh on top of the DDA mesh. The work started in collaboration with Professor Feng and his team. The first problem we encountered was imposing initial stresses. Nobody speaks about it; it's a secret nobody want(s) to express, but it's a problem. If we use the existing module for *in situ* stresses in the code; once you start drawing the code, they disappear; they don't stay. The first problem we had was how to impose those high *in situ* stresses, and why do they disappear and try to resolve with the person who developed this code, its effect, why they do this, they don't stay [sic]. I'll show you how we solved it. We took *in situ* extensometer data collected by Professor Feng's team at the site, and used those data for inversion to find the best fit solution for *in situ* stress. I'll show this to you, it's a little bit different to what has been published so far, and then once we obtain the *in situ* stress properly, we know what it is; we know how to impose it. We are planning for next year to study rockburst generation numerically using the dynamic capabilities of DDA and we will try to model (Ref. PPT) according to Professor Feng's work—strain relaxation and dynamic coding. Both are possible with those methods provided you introduce the discontinuities in advance.

We don't know how to break a period; we will generate a structure and let it run either by extracting this or inducing a blast. As I said it's very difficult to obtain kinds of stresses. These different methods, Professor He published in the *News Journal*, a method to calculate, to measure these stresses underground. What we are doing is obtaining them by inversion. We do this by introducing the new capability that did not exist before, that is simulating the excavation sequence. We simulate the excavation sequence then let the extensometer data generate, if you will, in the model. So the way we impose the initial stresses, just by imposing many, many loaded points on the boundary, and then following those equations with computations, the model domain has to be square. (Ref. PPT) If we do three things for the boundaries, we apply existing *in situ* stresses everywhere in the domain, and then propose to fix the boundary with fixed points. Dr. Feng's team, this came out in *Engineering Geology*, they did extensometer data from these exploratory (Ref. PPT) drill holes. So what they did, they came into Tunnel A, they came up into those four boreholes, each one with a different kind of measurement, one with the extensometer. Then they came around and excavated Tunnel B and Tunnel F. With the extensometer already in place; they also have ultrasonic and velocity measurement devices, televiewers, etc. This is the manifold mesh that we used: (Ref. PPT) this is Tunnel A; this is Tunnel F; this is the line of the borehole, and some of the data. What we're going to do is check we know how to put initial stresses. So starting from this initial stress field that they gave us, which is their best estimate to date, we just put those stresses on the boundaries as I explained before, and check that they did. It took a lot of effort to arrive at this conclusion.

Now that we know how to do it, we can try to use this data from the borehole extensometer. We have 17 measurement points in the extensometer; each one showed the displacement of time. I try to see if we can be anywhere near those place. You understand if we are succeeding here, it means that the information that is measured in the extensometer data is completely elastic; there are no discontinuities, shear strike or others.

It's just the response of the rock to generating a tunnel (Ref. PPT). We start with Stage 1—no tunnel. Then we remove Tunnel A; come in and remove the top layer of Tunnel F, removing the bench of Tunnel F. We dig into the model, and each time extract the tunnel. This was a development that we did in the past several months; it did not exist in the original NMM code; it was a development for the NMM code, so we could simulate the excavation sequence. So now for the inversion. We have the data for the 17 measurement points and what we do now is assume the vertical stress is constant and is known.

Why shouldn't it be known? It's the weight of the overburden, that value which is assumed is a bit high for the depth of the point of interest, but this is the value that we kept constant in the model. Next we created a loop, changing Sigma X, Sigma Y on the boundaries at certain intervals seeking the best solution, the least rooting square of all the measurement points between the measurement and the numerical analysis. We got this result (Ref. PPT), the RMS, you can see here, so the minimal is somewhere —you can see the minimal is not so sensitive to the boundary, to the shear system boundary, but very sensitive to the horizontal components Sigma X, and it basically takes us up to here. If you remember we started initially when we just learned to impose initial stresses and a much higher initial stress horizontally. But this is a two-dimensional analysis of course. It takes us here to 30 MPa. So our best-fit solution is so many constant normal vertical stress of 66.5 MPa. The best-fit solution says that the horizontal stress on the tunnel in the X direction would be somewhere around 30 MPa. Now, with this stress field known, we can now try to study rock bursts and this is our plan for the future. Let me show you this—this is the best-fit solution between the 17 measurement points, and the numerical solution manifold with the best-fit stress (Ref. PPT). So, after, of course, for the last stage, where we just remove the last stage. You see, it's a perfect match, how we got it, and it basically says that those extensometer data, showing us the relaxation of the rock, due to the removal of the rock, doesn't have anything to do with the rock burst, only estimating the stress.

Now that we've arrived to this point, we will try to move to DDA because in DDA we have much more experience in dynamic modeling than blasting, vibration, or earthquakes so we'll now move to DDA. We've heard, firstly, how to impose initial stresses on DDA, then we will implement the excavation sequence in DDA. It doesn't exist yet, and then we will introduce joints to the DDA model, utilizing and taking full benefit of the discrete element model. We will look at the sidewall block and will see how it behaves in strain relaxation mode, or due to blasts; vibration that will be induced somewhere far away. Then we'll take it from there and begin to understand if it's possible at all to simulate the phenomenal rock bursts numerically.

Yossef Hatzor obtained his PhD from the Dept of Civil Engineering of the University of California at Berkeley in 1992 under the supervision of Professor Richard E. Goodman. In 1993 Hatzor established the academic program in Engineering Geology and installed the rock mechanics research laboratory at Ben-Gurion University of the Negev, Israel. He now serves as director of Engineering Geology studies and director of the Rock Mechanics Research Laboratory at BGU.

Professor Hatzor is the Founding President of Israel Rock Mechanics Association (IRMA), a national group of the International Society for Rock Mechanics (ISRM), and served as President of Israel Geology Society in 2004 – 2005. He is the recipient of several teaching awards from BGU and several national and international research awards. He is a member of the editorial boards of the two leading international journals in rock mechanics: *International Journal of Rock Mechanics and Mining Sciences* (Elsevier), and *Rock Mechanics and Rock Engineering* (Springer). In 2007 Professor Hatzor was appointed the Dr. Sam and Edna Lemkin Chair in Rock Mechanics by BGU Senate. In 2011 Professor Hatzor was appointed a Visiting Professorship for Senior International Scientists, Chinese Academy of Sciences.

Safety Construction, National Need and Frontier S&T Problems in China's Underground Hydraulic and Hydropower Engineering

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The topic of my report is "Safety Construction, National Need and Frontier S&T Problems in China's Underground Hydraulic and Hydropower Engineering". I would like to deliver my report from two aspects: (1) the technological status quo of underground engineering; (2) the national need and frontier scientific and technological problems.

China's hydraulic and hydropower engineering has been experiencing a period of booming and flourishing, constructing a lot of large reservoirs with high dams, long-distance water conveyance tunnels and large-sized underground power stations. All of these projects have been playing an important role in meeting the need for national economic and social development. At present, China has constructed 120 underground power stations. And the total length of the completed hydraulic tunnels is about 1100 kilometers. The Xiluodu Hydropower Station, which is the largest hydropower station in the world, of Jinsha River is under construction; and the excavated underground powerhouses on both right and left banks are 443 meters long, 32 meters wide and 79.6 meters high. Each of the underground powerhouses is equipped with 9 hydroelectric generating set of 770 MW, forming an installed capacity of 1386 MW.

Jinping – II Hydropower Station has an installed capacity of 4, 800,000 kW. Each of its four diversion tunnels is about 16.7 kilometers long; its excavated diameter is 12.4–13 meters, with the largest burial depth of 2525 meters. The Station has the property of "large burial depth, long tunnel line and wide tunnel diameter." What's more, the ground stress is high and there are abundant underground water resources.

Thus, there is a great technological challenge.

In the South-to-North Water Diversion Project, there is a water conveyance tunnel which runs across the Yellow River. The tunnel is 2.6 kilometers long, and its geological conditions are very complex. And it is a water conveyance tunnel which is constructed on a wandering river. Therefore, during the construction of the tunnel, Shield Tunnel Method and Concrete Lining Technology of Pre-stressed Cable have been adopted.

1. Technological status quo of underground engineering

Before 1980s, China's underground engineering mainly adopted borehole blasting excavation using hand-drill and mucking through manual work. And the stability maintenance of surrounding rocks mainly adopted the passive shoring method to prevent collapse from happening. Therefore, the construction was slow, inefficient and full of safety problems. After the Reform and Opening up to the Outside World, advanced foreign technologies, apparatuses and management experience have been introduced to China. After the process of digesting, absorbing and re-innovating, China has possessed a number of underground engineering technologies which enjoy proprietary intellectual property rights.

Five main achievements of underground hydraulic and hydropower engineering

① Safe construction technology of large-sized underground powerhouse;
② Safe construction technology of large sections and long tunnels under complex geological conditions;
③ Design and construction technology of high-pressure reinforced concrete bifurcation without steel liner;
④ Safe construction technology of high-pressure long inclined shaft;
⑤ Construction technology of concrete formwork in underground engineering.

This is the main experience about the rapid and safe construction of large-sized underground system of power generation by water diversion. We made overall planning for the construction procedure of the water diversion system, the three main chambers and the tail system. For the main powerhouses on critical lines, we adopted the rapid construction method of "multi-process in two-dimensional spaces, multi-layer in three-dimensional spaces," and initiated three-dimensional excavation of 3 layers for the construction of underground powerhouse.

This is the three-dimensional sketch map of 3 layers. The construction progress is very slow, because it is related to the excavation of bus tunnel which is large in size and requires high standard of shoring. In order to accelerate the construction progress, we directly start the excavation of the fourth layer from the penstock, which mainly covers the excavation of the upper section above the central axis of the powerhouse; the third layer mainly undertakes the side wall shoring and excavation of bus tunnel in the lower section of the powerhouse; at the same time, excavation of the bottom layer of the tunnel is conducted from the tailrace tunnel. The three-dimensional excavation can shorten the construction period for about half a year.

For the excavation of the vault of the powerhouse, we follow the excavation shoring principle of "center before sides, soft before hard." Let me explain the principle. If the rock mass is complete and hard, we usually excavate the middle pilot tunnel before the side ones. This is a picture of the excavation of the underground powerhouse in the Three Gorges, which adopts this principle. We can see the excavation effects of the underground powerhouse's vault. But for the stratified rock mass in which soft and hard rock distribute alternatively, we will adopt the principle of "center before sides, soft before hard." The dip angle of the stratified rock mass is about 60°, the excavation of the soft side is conducted first. And the stratified structural planes should be inclined to the free face. After shoring this excavation, a shoring rock pillar should be kept in the center. Then the excavation of the hard side can be conducted. For the excavation of the high sidewalls in the deeper place, the same principle should be followed. Excavation of the soft side first, and then complete the shoring. Longtan Hydropower Station on Hongshui River and the underground powerhouse of Gongguo Bridge on Lancang River are typical examples.

From the late 1980s, China has widely adopted the technology of rock-bolted crane beam. That is to say, the crane beam of the underground powerhouse is no longer adopting the beam column construction. Instead, the crane beam is bolted to the rock. Maybe, this is a great breakthrough in the crane beam technology of underground powerhouse. But it requires that the excavation of the rock bench should be shaped well. Therefore, during the excavation of the rock bench, we adopt the technology of "bilateral blasting, bolting on the locking angle." The key to assure the safe operation of the rock-bolted crane beam is the excavation of the rock bench. Therefore, bolts are added under the rock bench. From the picture, we can see that the excavation of the rock bench is shaping well. Adopting this technology can assure the safe operation of the rock-bolted crane beam in a long term.

In addition, for the high side walls of the powerhouse, we have summarized a stable excavation technology in recent years. It is "stratified construction, one pre-splitting, excavation from the thin layer, shoring following each layer." As we all know, stratified excavation should be applied to thigh powerhouse. For example, when we start the excavation of the third layer, which should be completed in one pre-splitting, about 8 – 10 meters, the excavation should be divided into two layers. When the excavation of the upper layer is completed, we should carry out shoring to the side walls timely. This is what we mean by "excavation from the thin layer, shoring following each layer." It is the same to the fourth layer, stratified and one pre-splitting. After half of the layer has been completed, about 4 – 5 meters, the excavation can be carried on only after the shoring of the side walls. We do this for the purpose of preventing the injurious deformation of the high side walls. This is the shaping effect of Xiluodu Power Station after the excavation blasting of the high side walls. It's very satisfactory.

The last technology is that for the high side walls of high hollowing rate, we follow the principle of "walls after the caves, reinforcement of the key points." Due to the requirement of deploying hydraulic machinery, the bottom layer of the powerhouse is deployed with draft elbow tube. Therefore, the excavation size has been limited. The rock mass left between two caves is less than 50%, some even as little as 40%, leading to unstability of the high side walls. We put forward clear requirements for the excavation procedure and shoring principles of this part. We should reinstate its three-dimensional stress by using strand anchors between two tailrace tunnels. At the same time, for the excavated pits, we can see that dike is left at the center. Therefore, the excavation should be carried out carefully and be reinforced at the key points. This can assure that no great or injurious deformation will happen to the high side walls of the powerhouse.

Now, let's talk about the safe construction technology of large section and long tunnel under complex geological conditions. I will mainly introduce the surrounding rocks of grade iv and v, the geological conditions of which are poor. Surrounding rocks of grade iv and v are usually the entrance and exit, with shallow burial depth, and deep air-slake. Moreover, some of the surrounding rocks will unavoidably run across the big faults and fracture zone. For those parts, we mainly adopt the surrounding rock stabilization technology of "advanced exploration, pre-reinforcement, stratified and divisional excavation, short footage, weak blasting, early sealing, strong shoring and frequent measuring," and establish a complete set of technology of "pipe roof pre-reinforcement with cement and sodium silicate, pre-reinforcement with self-propelled hollow grouting rock bolt, the method of divisional excavation with the joint stressing of systemic rock bolts and lattice beams or steel shotcretes, the eye method, and the core soil method." This is a typical method of divisional excavation of the grade iv and v surrounding rocks. These are the measures of pre-reinforcement. Sometimes we also adopt the method of hanging up the vaults by setting up rock bolts from the upper construction steps. This morning, Academician Qian has said that the safety risk of underground engineering mainly lies in the unfavorable geological conditions. In hydraulic and hydropower engineering, a basic principle of the safe construction of underground engineering is "to avoid or reduce collapse." Therefore, from the aspect of technology, we should first get familiar with the geological conditions, and then adopt a series of construction technology to prevent collapse from happening. Even collapse does happen, it should be limited to a certain height; or it will be difficult to deal with. Therefore, in hydraulic and hydropower engineering, accidents and casualties caused by inappropriate construction and uncertain geological conditions are rare.

Next, I would like to introduce the Jinping – II Hydropower Station. There are altogether four diversion tunnels in Jinping – II Hydropower Station. There are also two access tunnels, Tunnel A and B. The two access tunnels were excavated first. Before the excavation of the four diversion tunnels, we considered that the water yield here was large, so we excavated a drainage tunnel by TBM. The diameter of the drainage tunnel was 7 meters. In the construction planning, we actually adopted the compounded approach of TBM and Borehole-Blasting Method, hoping that they can make their respective advantages complementary to each other. The compounded approach operated like this: on the eastern side of diversion tunnels No. 1 and No. 3, the TBM Method was adopted; on the western side, the Borehole-Blasting Method was adopted. Both sides of diversion tunnels Number 2 and 4 adopted the Borehole-Blasting Method; and some supporting tunnels to them were excavated from Tunnel A and B, using the method of "short excavating of long tunnels"; if strong rock burst happens, these supporting tunnels can be used to assist the TBM when the TBM is blocked. I think that the implementation effects of the overall construction planning are satisfactory. Academician Qian also mentioned this: in the construction of a drainage tunnel of 7 meters, a strong rock burst completely buried the heading machine when 2/3 of the tunnel has been excavated; but the drainage tunnel is complicated by excavating supporting tunnels from the auxiliary tunnel and using Borehole-Blasting Method from the tail. At present, all the four diversion tunnels of Jinping – Ⅱ Hydropower Station have been complicated, and the first generator set will come into service this year.

Generally speaking, this construction planning is very successful; for it makes full use of the advantages of TBM and Borehole-Blasting Method, and makes their respective advantages complementary to each other. The Jinping – Ⅱ Hydropower Station has successfully adopted the TBM Method, with the monthly footage reaching 600 meters, and the largest daily footage reaching 60 meters. But due to the frequent rockbursts, the general efficiency is not high. The main geological problems of Jinping – Ⅱ Hydropower Station are rock burst and large water burst, with the largest volume of water burst reaching 7.3 m^3/s, the largest water pressure reaching 10 MPa, and the largest principal pressure of the surrounding rocks reaching 70.1 MPa, the tendency index of rock burst reaching 1.32 – 5.8. During the construction of the Jinping – Ⅱ Hydropower Station, lots of work about the engineering geological conditions and hydrogeological conditions has been done in the early stage. I think these work has laid a solid foundation. Especially, when we constructed the two auxiliary tunnels, Tunnel A and B, they were considered as access tunnels. Therefore, we have basically become familiar with the status of the strong rock burst areas and sections and the strong water burst sections along the line of 16.7 kilometers long. Being familiar with these conditions, we set up a special group for rock burst, and adopted the Geophysical Method to carry out advanced exploration. This is the key that we have overcome the strong rock bursts and water bursts.

Now let's talk about the specific measures. For strong rock burst, many experts have already talked about and will continue to mention tomorrow. In my opinion, there are no effective strategies and methods in dealing with strong rock burst. What kind of methods did Jinping adopt? Basically, Jinping adopted the method of revising the form of tunnel face and stress relieving method by pilot tunnel. This is a picture of the multi-boom drill smashed by a rock burst. We adopted pilot tunnel and stress-relieving blast hole to release part of the stress in advance. I think this method adopted by Jinping is very successful. In the TBM Method, when rock burst happens, we will actually excavate a supporting tunnel from the neighboring tunnel which is excavated by the

Borehole-blasting Method to support it. TBM cannot be used backwardly, so it cannot be used to deal with rock burst. But the pilot tunnel can release part of the stress. In addition, we adopt two technologies: one is sealing with nanometer organic artificial steel fiber reinforced shotcrete. This kind of reinforced shotcrete is different from the traditional ones. The traditional reinforced shotcrete which can only be sprayed 5 cm once or it will fall. But there is no limitation for this new one, even 20 cm is OK. Another technology is the rapid reinforcement by hydraulic expandable bolt and expansion shell pre-stressed bolt. Many experts have mentioned that the bolt should not be perfect rigid, it should have the ability to adjust to deformation, and its surface should be installed with large backing plate which is put into the concrete. Because the nanometer organic artificial steel fiber reinforced shotcrete is expensive, the steel fabric is usually hung on after this kind of shotcrete is sprayed 6-10 cm; then fiber reinforced shotcrete will be sprayed. This is a picture of a TBM machine with a diameter of 7 meters. It has been smashed pinned down. We can see the deformation caused by strong rock burst. In my opinion, the Borehole-blasting Method is better than the TBM Method in adjusting to rock burst.

In areas where the ground stress is high and the water inrush and mud surging are strong, I think the construction planning of Jinping is a successful example for the construction which has several tunnels. This is a picture of water inrush. We can see that the water has overwhelmed half of the tunnel. The principle of dealing with water inrush is "explore, drain, control and block." The first step is to explore the conditions; next is to drain the water; in addition, there are also controlling and blocking. At the early stage of experimenting, we once put forward the principle of "blocking supplemented with draining." But this principle failed, because the pressure was too high. It is impossible to block such a large underground water yield with grouting sealing method. Then we adopted the principle of "draining supplemented with blocking." When draining the water, the auxiliary tunnels had been through. And the water was mainly drained to the auxiliary tunnels and drainage tunnels. For those sections where the water yield was small, the grouting sealing method was adopted—spraying the nanometer artificial steel fiber to seal, and then carrying out concentrated drainage after drilling weep holes. Therefore, practice has proven that the management of the rock bursts and large water inrush of Jinping - II Hydropower Station is basically successful.

Next, I want to talk about the third technology—the design and construction technology of high-pressure reinforced concrete bifurcation without steel liner. China has established 18 pumped storage power stations, with a total installed capacity of 20,000 MW. Every pumped storage power station will deal with high-pressure bifurcation of large diameter. Take the Guangzhou Pumped Storage Power Station as an example. The inner diameter of the branch pipe at the bifurcation turned to 3.5 meters from 8 meters; the maximum static head of the bifurcation was 610 meters, the maximum dynamic head was 725 meters and the P. D. reached 58,000 kN · m. If conventional steel bifurcation had been used, high-strength steel plate with a thickness of 60 mm should be adopted. But it would cost much and encounter the difficulty of transporting. Later, cooperating with America, the new technology of high-pressure reinforced concrete bifurcation without steel liner was designed. The concrete primary lining was 60 cm, with the 28 – day compressive strength reaching 30 MPa. And a mono-layer of reinforcing steel bar was deployed. Our basic design idea is that the stress transferred from internal water pressure to the surrounding rocks through concrete should be less than the maximum principal stress of this area. The surrounding rocks should bear most of the internal water pressure. When the tunnel is empty, external water pressure should be beard jointly by the concrete primary lining and the surrounding rock which doubles in thickness, and the drainage system of the top of the bifurcation should be prepared. The concrete primary lining is used to protect the surrounding rocks and reduce roughness; and it will be convenient for high-pressure grouting. Consolidation grouting will be adopted in high/low-pressure channels; this is the fundamental difference between hydraulic & hydropower engineering and the tunnel of highway and railway. Using the high-pressure consolidation grouting to reinforce the surrounding rocks will rapidly transfer the water load to the surrounding rocks. High-pressure consolidation grouting can improve the anti-permeability and modulus of deformation of the surrounding rocks, especially the geological flaws; and it can also increase the compressive pre-stress by a certain degree. The effects of the concrete primary lining should be analyzed by the Finite Element Method; and the reinforcing steel bar should be deployed in accordance to the principle of "crack control." When we carried out basic testing for the Guangzhou Hydropower Station, about 95% of the internal water pressure was carried by the surrounding rocks; the water load carried by the concrete primary lining was little. During the three emptying check, the crack of the primary lining is 0.2 mm within the requirement of "crack control."

The fourth technology I want to introduce is safe construction technology of high-pressure long inclined shaft (and vertical shaft). The traditional excavation method of inclined shaft was that the upper part adopted the Borehole-blasting Method and manual slag removing, and that the lower part adopted the method of excavating upraising shaft by ALIMAK climber. This was the method of 1980s. In 1990s, we established a complete set technologies including excavation of shoring and concrete lining, which was safer than the traditional method. This is a picture of the inclined shaft of the Huizhou Pumped Storage Power Station. The inclination angle is 50°. The length of the inclined shaft is 301 meters. And this is a raise boring machine. In less than a month, the pilot hole with a diameter of 240 mm has been completed. And within half and one months, the enlarging hole of the pilot tunnel with a diameter of 1400 mm has been put into excavation. This indicates that China has made a technological breakthrough in the construction of long inclined shaft with raise boring machine. So far, the excavation depth of raise boring machine has not broken through the limitation of 300 meters. Recently, the Power Construction Corporation of China has undertaken the construction of DELSI – TANISAGUA Power Station in Ecuador. The deep vertical shaft of the diversion tunnel is 700 meters deep. And we have purchased a most advanced raise boring machine which can undertake the excavation of such a deep shaft. But the excavation has not been started yet.

The last technology I want to talk about is the technology of formwork in underground engineering. The difficulty lies in inclined shaft. The construction rate of the traditional inclined shaft formwork is slow, and there are a lot of safety threats. Therefore, we developed the technology of Inclined Shaft Slip-form which enjoys proprietary intellectual property rights, filling up the gap in this field. The major technological innovation is that the front and back hydraulic locks are fixed to the central beam of the borehole wall, so as to form a supporting system. The formwork can go up and down along the central beam under the control of the hydraulic system. In addition, we also developed a new kind of drive, the front and back hydraulic climber which has the function of self-locking. The climber can move along the rail wed plate at the bottom, realizing the continuous climbing of the inclined shaft' s concrete lining. The average climbing speed can reach 8 m/d, which is very amazing. In the underground water conveyance tunnel of the Three Gorges' permanent ship-lock, the inclined shaft was becoming large from the bottom to the top. Based on the equal diameter, we also developed changeable diameter; and the side walls were vertical walls; and there was a system of ogee slip-form beneath. We revised the central beam and made the formwork retractable, realizing the continuous climbing of so many inclined shafts in the water conveyance tunnel of Three Gorges.

As to the sections of the tunnel, the square-round sections mainly adopt steel trolley. And in hydraulic and hydro-power engineering, the size has reached 16 meters in span and 23 meters in height. For those round sections with a diameter less than 9 meters, needle beam formwork is adopted. For those round sections with a diameter more than 20 meters, we adopt steel trolley with inverted arch first and side vault next. In this way, rapid and safe construction technology of concrete formwork in underground engineering has been achieved.

2. National need and frontier scientific and technological problems

(1) In order to deal with climate change, Chinese government has promised that by 2020, non-fossil energy should account for 15% of the primary energy consumption, and conventional hydropower should account for 9%

Up to now, the installed capacity of China's hydropower has reached 200,000,000 kW, accounting for 40% of the technical exploitation amount. But that of foreign countries has reached more than 70%. Therefore, we must make full use of the major roles played hydropower in optimizing the energy structure and reducing the emission of carbon dioxide. According to the primary planning, by 2020, the installed capacity of hydropower will reach 380,000,000 kW, among which the installed capacity of pumped storage power station will reach 50,000,000 kW. A new round of the development climax of hydropower is coming. With the further economic and social development and with the acceleration of urbanization, we are faced with severe challenges like resource shortage, environment deterioration and land degradation. Some far-sighted person has put forward the call of "Think Deep", taking the underground space as a new type of territorial resources that we can develop and exploit. From the underground fuel storage services, underground converting stations, underground warehouses, mining engineering, to the development and exploitation of urban underground space, there is a great potential need for underground engineering.

(2) Innovative and frontier research

According to my long-term engineering practice, I put forward some of my opinions on the problems that need our further research.

① Basic theories

There deviation between the analysis results of three-dimensional non-linear finite element method and the actual-monitored data is great. It is difficult for the numerical model to generalize complex geological structures. And the numerical models need to be revised continuously according to the back analysis results so as to improve the accuracy of numerical calculation analysis and to transform the underground engineering shoring from experience-oriented to the integration of theory and practice. Take the Xiluodu Power Station as an example. The underground powerhouse is thick basalt, medium ground stress; the actually measured relaxation zone is only 0.4–0.8 meters; the maximum displacement of the high side walls is 46.2 mm. Take the Jinping – I Power Station as another example. The ground press is 35 MPa; strength-stress ratio of the surrounding rocks is less than 2; the actually measured relaxation zone is 8 meters; the maximum displacement of the high side walls is 238.3 mm. All of these figures are deviated from the numerical analysis. Due to the limitation of experimental methods, experimental apparatus and theoretical model, the experimental research of rock burst mechanism is at the stage of exploration. The current design idea and standard of hydraulic tunnels is not making full use of the bearing capacity of the surrounding rocks, making the concrete lining thick and the amount of reinforcing steel bar large. Therefore, improvement is needed.

② Technological innovation

Ground stress testing technology: errors exist in the current ground stress testing technology; therefore, further research is needed.

Engineering physical exploration technology: at present, it mainly adopts the method of geophysical exploration method and electrical exploration method; relative research about theories and analysis method should be conducted to improve the accuracy.

Computer simulation technology: based on the data of geological exploration, adopting simulation technology to establish a three-dimensional geological model and digital engineering information; this technology can detect the unfavorable geological conditions that the traditional technology cannot find, making it possible to establish corresponding strategies in advance.

Prevention and control technology of geological disasters: it mainly refers to the prevention and control technology of rock burst, the prevention and control technology of high-pressure water inrush and mud surging of large volume, and the forecast and control technology of the collapse of unfavorable geological structures.

Monitoring technology of engineering safety: the current safety monitoring of underground engineering operates in this way-firstly, the data of stress, deformation, seepage and seepage pressure etc. are collected regularly in the process of excavation; then the work behavior of the underground structure is evaluated; at last correspondent measures will be taken; in the excavation of the underground powerhouse of Xiaowan Hydropower Station, the computer information technology and the monitoring technology with digital camera are adopted to dynamically demonstrate the palisades deformation of the powerhouse; defects exist in this technology, so further research is needed.

③ Research and development of new materials, including spraying concrete materials, the bolting materials and blasting materials. All of these materials don't coincide with the current status of underground engineering.

In general, there is a great potential need for underground engineering in China. But we are still faced with a lot of challenges, mainly including that the significant fundamental research is not advanced enough, the technological innovation ability is not strong enough, the driving force of adopting new technologies is not sufficient, the research ability of new materials is poor, and the rapid application of research is difficult. However, with the improvement of China's technological innovation system, the national needs for developing underground engineering will be met, experience of various complex engineering will be accumulated, and new breakthrough will be made in the fundamental scientific research and tackling of key technology of China's underground engineering.

Hongqi Ma, academician of Chinese Academy of Engineering, graduated from Tsinghua University in 1967. As an expert in hydraulic and hydro-power engineering, he is a technology leader in the field of underground hydraulic and hydro-power engineering and dam construction. He established the basic principles and key technologies for the construction planning and construction safety of underground powerhouse. He developed the first climbing form which enjoys proprietary intellectual property rights for high pressure long inclined shaft, and thus solved many technical problems in the construction of high-arch dam and ultra high earth & rock-filled dams. He directed or took part in the construction of more than 20 large-sized hydropower projects, such as Lubuge Hydropower Station, Guangzhou Pumped Storage Power Station, Xiaolangdi Hydro-junction Project of the Yellow River, the Three Gorges Project of Yangtze River, Xiaowan Hydropower Station of Lantsang River, and Nuozhadu Hydropower Station. Prof. Ma has won 12 prizes above the provincial level for progress in science and technology including three 2nd class National Science and Technology Progress Award. He is author of more than 50 published papers, and 2 published books.

Uncoupling Blasting and Dynamics for Soils and Rocks

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Uncoupling blasting did not receive much attention until 1992 when a successful 10,000 tons explosive blast led by academician Qihu Qian was completed for the construction of Zhuhai Airport. The success wouldn't be possible without multiple researches. In applying the theory of uncoupling blasting, it is important to fully understand the theory. When conducting the explosion, we cannot adopt the previously-used method of filled charging, which effects directly on rocks in explosion and thus hardly ensures effective control over split dimension and rock throwing distance. We hereby propose the idea of uncoupling blasting and dynamics for soils and rocks, for which I'd like to explain three physical processes.

Considering that ammonium nitrate explosive was used in this explosion, rocks were craved and split by pressure reflected from rock surfaces after the explosive being transmitted for a certain distance in the air before reaching the rock surfaces. So here came three problems: First, what is the effect of explosion, bang and break triggered by the explosive? Second, how to calculate the pressure reflected from rock surfaces? Third, how to control the throwing distance so that villages nearby were not affected? These considerations prompted us to make careful calculations on uncoupling blasting.

Problems of explosion, bang and break in the blasting mainly lie in the measurement of rock dimension. In this case we made it 1.5 meters, and witnessed a successful explosion.

To work out these problems, we need to consider the following aspects.

First, what is the effect of explosion, bang and break triggered by the explosive?

We used a spherical container to store the charging, and measured the throwing distances by filling the container with 1000 g, 300 g and 125 g charges respectively.

Second, as the air nearby cannot be viewed as ideal gas, what is the characteristics of the actual air conditions? When the shock wave reaches 4 MPa (40 atmospheric pressures), its temperature climbed to 2000 degrees, breaking down such gases as oxygen and nitrogen; when the temperature reaches 8000 degrees, the air is turned into a multi-component gas deprived of any characteristics of an ideal gas. To understand the characteristics of the actual air conditions, we referred to researches that had been conducted in the United States. When the reflecting pressure of the ideal gas arrived at a maximum of 8 times that of the initial pressure, incomplete estimation of the reflection characteristics would lead to more problems in the study of the blasting theory.

Then we made careful calculations on the possible pressure exerted by the incidence shock wave and on the reflected pressure exerted by normal reflection. We found that if pressure from the incidence shock wave was 0.5 MPa, when its adiabatic index was equal to that of the reflected shock wave, the reflected pressure was 0.4 MPa; but if pressure from the incidence wave reached 5 MPa, when its adiabatic index was 1.34, the reflected pressure rocketed by more than 6 times to 38 MPa, representing an adiabatic index of 1.3. Even if the index continued to vary when the initial pressure was added by more than 20 times, pressures from both incidence shock wave and reflected shock wave remain close to each other with an adiabatic index of approximately 1.26. These experiments enabled us to work out the formula for the calculation of actual air conditions. Continuity equation, motion equation, energy equation were used in this calculation.

Now I'd like to brief you about the waveform and site of the blasting. As was demonstrated in the spherical charging waveform and in the free field distribution, pressure measured in the free field was 17 MPa and jumped to 48 MPa when reflected. According to the generally-used calculation, the incidence shock wave varied with the incidence pressure, but within the triple-charging radius, this incidence shock wave was followed by another pressure far greater than that of the shock wave. The case was also reported early in 1995, when an American scholar questioned on the formula for not having considered the existence of higher pressure waves after the shock wave. Through tests and theoretical calculation, we did find a higher pressure wave following the first shock wave. The higher wave, ranging from 100 MPa to hundreds of MPa, was actually resulted from the explosion and bang.

Similar observations could also be made in the flow field where a fundamental wave was followed by a higher wave. The second physical process is the strong shock wave reflected from rock surfaces. In calculating the reflected pressure, we need to consider its characteristics. Hence we applied a mode proposed by Polachek and Korotkov to calculate the relations between incidence pressure and reflected pressure. Normally we found the two are of sharp difference. The incidence pressure was usually low, say 0.000235 MPa, and based on this result, we could fairly calculate the reflected pressure.

The picture above indicates that reflected pressure varies with the pressure of incidence shock wave and can reach as much as 11 – 12 times higher, a result corresponding with that made in the United States. But we raised two magnitudes in high pressure, lowered one magnitude in low pressure, and produced a result on dynamical pressure, a result useful in estimating slender rod structural damage.

The result provided an answer to the possible pressure reflected from rock surfaces by using traditional charging. If explosion was done within a diameter of 1.5 meters, the reflected pressure could exceed 500 MPa, as the reflected pressure of the charging itself might reach tens of thousands of MPa. By adopting uncoupling blasting, on the other hand, the reflected pressure wouldn't exceed 500 MPa. It is fair to say that the success of uncoupling blasting was largely due to the proper selection of charging. The calculation in Dynamics for Soils and Rocks involves charging, air and rocks. The three elements are all essential for accurate calculation.

Next I'd like to share my view on the progress of the above-mentioned two processes. Some new ideas of vertical mine exploration have been applied, of which one successful example is to explore from the top and remove the dregs at the bottom. The new approach greatly raised efficiency by 7 times. Why? The answer is one-step blasting. In practice, we dug a vertical drilling hole of 30 meters deep with a diameter of 5 meters. Then we adopted different blasting approaches according to rock qualities in different places.

Then we had to consider how to remove the dregs after the completion of one-step blasting. High pressure water was used to wash away crushed rock meal in the middle of the bottom and gravels on the outer surface. In addition, spraying anchorage, shotcreting, slip casting and consolidation must also be involved in the work.

Tunneling with pilot pipes is another novel and widely-used method in China. The pipe has a diameter of 2.3 meters, forming altogether a clear span of 26 meters. Made of push pipe at its bottoms, the pilot pipe, technically speaking, is a great success.

The structure is a two-layer island platform with waiting room on the top and subway at the bottom. Then we put the pipes in the vertical mine, one after another. The technique is special in that pipes in the mine are connected transversely and circumferentially with each other.

As was introduced by several foreign experts, China is embarking on a big project for geotechnical engineering. In the past few years we mainly focused on traffic engineering, especially railway engineering; and in the coming years we will shift more attention towards the water conservation project. Admittedly, numerous problems and unbalances emerged in the process of construction and development, and numerous rock-related problems are still waiting to be solved.

It gives me great honor to share my views with experts from both home and abroad and I hope to see more cooperative researches and support in this field.

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In 1992, Mr. Zhou was selected as a national level young and middle-aged expert with outstanding contributions. In 1999, he was elected academician of Chinese Academy of Engineering.

Features, Mechanism, Warning and Dynamic Control of Rock Nucleating Process

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Distinguished academicians and experts, today I would like to make a report on the generating process of rockburst. In my report, research of the generating process of rockburst such as its characteristics, law, mechanism, warning, regulating and controlling will be introduced. Rockburst is a dynamic disaster caused by the excavation of the underground engineering in the particular situation of high stress and deep burying. There are various kinds of rockburst, such as stress rockburst, the lithoclase of which is quite complete, and stain-structure slip rockburst, the burst pattern of which is determined by structure face. From the aspect of excavation time, there are immediate rockburst (the excavation of which is conducted immediately) and time-delayed rockburst. Different rockburst has different evolution law and mechanism. According to our spot observation through borehole camera, new fractures will come into being in the generating process of rockburst, shown as the red area of the picture. One day after excavation, many fractures (shown in red) will come into being. The newly-born fractures which are not connected at first will be connected two days later, shown as the blue area of the picture. It will occur until rockburst happens at last. As to the width of the fractures, we can see that the width of both original fractures (fractures which are born before excavation) and newly-born fractures (fractures which are caused by excavation) can increase or decrease. This means that, in the generating process of rockburst, there are tensile failure, shear failure and even mixed failure of the two. From the evolution law of micro-seismicity information, we can see that, for most of the immediate rockbursts, their micro-seismicity events will continue to increase, and their space will continue to concentrate, and that there is no obvious quiet period before its occurrence. The evolution law, therefore, is "slight rockburst-medium rockburst-strong rockburst", indicating that as the intensity of rockburst grows, there will be more micro-seismicity events and stronger energy. This is a general law. As to energy releasing, it remains high with a decreasing trend. But before the rockburst, energy releasing has the trend of increasing. Deformation continuance of inelastic volume will increase, usually with a trend of sudden increase.

What is the generating mechanism of rockburst? After analyzing the monitored micro-seismicity events of the whole generating process through the analyzing method we put forward, we find that immediate stress rockbursts are mainly caused by tensile failure. Through the observation of the form of burst pits, we can also see that they are quite smooth and complete. Also, we can offer the length and occurrence of the fractures generated in each micro-seismicity event and recognize the evolution characteristics of the newly-born fractures' occurrence. If projected on the failure surface, we can analyze the formation of burst pit in a qualitative way—rock slices are continuously shot off, thus enabling the occurrence of burst pits. As to the immediate stress-structure slip rockbursts, most of the micro-seismicity events are caused by tensile failure. Besides that, there are also shear failure events and mixed failure events (which are shown in green). The form of immediate stress-structure slip rockbursts' pits is more complex than that of the stress rockbursts. From the form and length of the failure surface, we can see large changes. Seeing the projection drawing of the tunnel, we can find that there is shear slip on the original hard structural plane. On the failure surface of the tunnel, we can also see the rough generating process of the burst pits.

Does this law have the property of self-similarity? In order to find out the result, we have carried out a research on time fractal dimension. From these two pictures, the time fractal dimensions of the six different-graded rockbursts, including slight rockburst, medium rockburst and strong rockburst, are all increasing continuously during the generating process of rockburst. But at the time of occurrence, the time fractal dimensions will decrease. From the aspect of energy releasing of the micro-seismicity, time fractal dimensions continue to increase as the energy releasing grows. If several rockbursts happen at one area, their generating processes also possess fractal features. Within one area, if the number of daily rockbursts grows, energy fractal dimensions will increase. And with the increase of average energy releasing, the energy fractal dimensions will also increase. This indicates that the generating process of immediate rockbursts has the property of self-similarity to some extent thus providing a scientific basis for the establishment of rockburst warning system, which is established on the basis of the evolution law of the micro-seismicity evolution information.

Time-delayed rockburst: during the excavation, its generating process is basically the same to that of immediate rockburst. But after the excavation, there will be an obvious quiet period, with little or no micro-seismicity events. The quiet period can last for several days or even several weeks. As a result, the warning of such kind of rockbursts will be more difficult. From the evolution law of energy and inelastic volume deformation, the quiet period also exists. As to the mechanism, besides tensile failure events, there are also several shear failure events and several mixed failure events (which are shown in green). From the distribution of those micro failure events, time-delayed rockbursts are far more complex than immediate rockbursts. This is also indicated in the picture.

Based on these laws and mechanisms, how can we reasonably estimate, forecast and give a warning of the rockburst risks? As to the estimating, forecasting and warning of the rockburst risks, we hope that estimation can be presented before excavation. And during excavation, we should know how to carry out immediate warning of the rockburst based on practical geological conditions and real-time monitoring information of the micro-seismicity. Moreover, we should try our best to quantize the risk estimation and warning, including the possible occurrence area, grade and probability. More importance will be attached to the position of the rockburst's failure surface and the depth of its pit, which will make the prevention and treatment of rockburst more specific. In this picture, we can see that rockburst can happen at many different positions, such as the roof, left spandrel, right spandrel, left side wall, right side wall, left apsidal angle, right apsidal angle and even the baseplate. We should hence offer the risk estimation of the rockburst on specific position of the failure surface. For rockbursts, there are several grading methods, including the national standard. Our work is based on previous research, with the concentration on making a specific grading of the damage of the shoring and its effects on the project. In addition, we score it from four aspects: sound characteristics, failure characteristics and depth of the surrounding rocks, damage of the shoring and its effects on the project. According to the final score, we determine the grade of the rockburst: slight, medium, strong or extremely strong. Based on the index of micro-seismicity energy, we have established another grading method of the rockbursts. After grading these rockbursts, we can obtain a basic knowledge or a referential benchmark for the warning of rockbursts. Before excavation, we should make estimation for the tendency of rockburst. Therefore, we establish a new index called RVI, which takes a great deal of elements into consideration: ratio coefficient of the horizontal and vertical stress, tunnel model, stress-deflection, the composition, content and average particle size of the mineral, failure intensity, damage intensity, and drape, fault and hard structural plane caused by excavation (including one-way and double-way excavation, single/multiple-tunnel excavation) and geographical conditions. Then we will give a comprehensive RVI score to the tendency of the rockburst. Based on the RVI score, we can obtain the relationship between this and the depth of the burst pit after large quantity of analysis.

Secondly, we care more about the damage after the excavation of chamber and of the different surrounding rocks on the failure surface. Therefore, we put forward a new index—failure approach index, which can offer the damage degree of surrounding rocks on different positions. After the excavation of bottom bench, the injury and damage degree of the surrounding rocks will consequently increase. For rockburst, there is a problem of energy releasing. The partial energy-releasing rate will indicate the degree of energy releasing of different part of the surrounding rocks when failure happens. And after the excavation of bottom bench, we can see that the risk on specific positions is increasing. Based on the above analysis, we can estimate the possible risk of the failure surface in accordance with the volume, because this index—volume—can be used to obtain the total released energy of the area.

Thirdly, let's talk about the forecasting and warning of rockburst based on the evolution law of micro-seismicity information. Through spot observation, we have obtained the evolution law of micro-seismicity events with the change of time, including micro-seismicity events and their daily increasing rate, energy and its rate, inelastic volume deformation and its daily changing rate. Membership functions are established on the basis of these six indices respectively, including the membership functions of rockbursts of four grades: strong, medium, slight and even non-rockburst. Once one actual data is input, the membership probabilities of these six indices can be obtained. Adding them together, we will get the probability of the rockburst of each grade. This is the rockburst warning based on the micro-seismicity information. If there is obvious omen regularity, rockburst warning will be well presented. But in some circumstances, especially the time-delayed rockbursts, the omen regularity is not obvious. Now that we have plenty of project cases, can we use the Neural Network Method based on the study of these project cases? For example, in consideration of the burying depth, stress ratio, areal structure, strength-stress ratio, rock integrity, shoring effect and so on, we can establish the relationship between it and the depth of burst pit or the burst grade. The eight examples we give can show that under different depth and geological conditions, neural network can present good results. In this way, before excavation, we can use RVI, Neural Network Method and Numerical Analysis Method to forecast the depth of the burst pit and the grade of the rockburst, and to decide which position of the failure surface has a higher possibility of rockburst. Then, during excavation, we can timely use these three methods to update the forecasting results in accordance with the geological information revealed on the spot. In practical use, as to the evolution information of the micro-seismicity obtained in this area, the grade and possibility of the rockburst can be forecasted from the data obtained several days ago, using the method we just mentioned.

After the warning of rockburst, the most important thing is how to prevent and avoid the occurrence of rockburst. A Dynamic Controlling Method is put forward in allusion to/corresponding to the generating process of rockburst. Using the methods we just mentioned, we can carry out risk estimation of the rockburst's position and grade. Thus we boldly put forward a "three-step strategy." The first step is to decrease energy releasing; that is to continuously optimize the shape and size of the excavation surface, number of benches, excavation speed, shape and size of pilot tunnel, crossover distance etc. Through the optimization, we can decrease the energy concentration level during the excavation as much as possible. Then, if the pre-release and energy transfer need to be taken into consideration, we should do our best to pre-release and transfer part of the energy through the optimization of position, length and spacing of the stress releasing holes and the optimization of the concentrated transfer of stress and energy. If this still does not work, we need to take the third step: to absorb energy; that is to timely spray concrete so as to increase the ductility of the rock, and to absorb certain amount of energy as much as possible through the parameter optimization of shoring system, such as rock bolt. Certainly, we can also get some optimization suggestions about excavation and shoring measures through project cases, enabling us to design before excavation. During the excavation, we can further adjust the excavation and shoring in accordance with the newly-revealed information, and we can also dynamically revise the excavation and shoring based on the evolution law of the micro-seismicity information. As a result, rockburst can be prevented or avoided as much as possible.

For the failure surfaces of the same size, rounded chamber must be conducive to decreasing the risk of rockburst. For deeply buried tunnels of the same diameter, lower bench is better than higher bench at decreasing the risk of rockburst. Results of indoor experiments show that, in a certain range of stress, rock intensity is increasing with the increase of unloading rate. This means that once the rock is damaged, the energy it releases will grow larger. As the unlading rate increases, dilatancy angle will grow fast, indicating more macro fissures will be produced. Therefore, we should appropriately control the excavation unloading rate to decrease the risk of rockburst. As to the influence of excavation step-size, from the aspect of energy, the energy will decrease with the decrease of excavation step-size. But the plastic zone will not change greatly demonstrating that appropriate excavation step-size and rate is beneficial for decreasing the risk of rockburst. To take the regional energy releasing rate and ERE as index, and to optimize the excavation parameter on particle swarm and numerical calculation, we can obtain an excavation program that can meet the construction possibilities and requirements of the project.

As the experimental results show, under the situation of uniaxial compression, brittleness of the rock is larger, and adding small confining pressure will cause increase of the ductility to some extent. This indicates that immediate spray layer could provide certain surface confining pressure to increase the ductility of the surrounding rocks. How to design the parameter of the rock bolts? Based on the depth of burst pit and the rock bolt's effective length that exceeds the damage limitation, we can get the design length of the rock bolts. The energy that the rock bolts in a unit area absorb is related to the energy that a single rock bolt absorbs and the spacing between and the area of the rock bolts. Given the relevant energy calculation methods, how much energy can a shoring system, including rock blots, steel reinforced shotcrete, permanent rock bolts etc. absorb? We just need to make sure that the length of permanent rock bolts can reach the boundary that the long-term security coefficient of surrounding rocks is equal to 1. Energy that the shoring system in a unit area can absorb should be larger than the energy that rockburst in a unit area can release. The energy, from certain aspect, can be calculated on the basis of the partially released energy. For the convenience of spot usage, and on account of the rockbursts of four different grades, we take corresponding measures on geological survey, excavation, monitoring and warning, and shoring, including optimization of excavation, optimization of shoring design, performance requirements, and whether monitoring of micro-seismicity should be established.

This method has been successively applied to the deeply buried tunnels and drainage tunnels of Jinping – II Hydropower Station successfully. There are four deeply buried diversion tunnels in Jinping – II Hydropower Station. Each tunnel is about 16.7 kilometers long; the deepest burial depth is as deep as 2525 meters. The diameter of drainage tunnels is about 7 meters. On November 28th, 2009, an extremely strong rockburst happened. Since then, great importance has been attached to the spot monitoring and warning of rockburst. Based on the previous research, one of our jobs is to establish a top pilot tunnel excavation program for the TBM tunnel segment of strong and extremely strong rockburst. After the comparison and optimization of TBM full-face excavation, middle pilot tunnel excavation, and top pilot tunnel excavation of different failure surface sizes, we choose top pilot tunnel excavation method from the perspective of decreasing energy concentration. Now let's look at the results of spot monitoring of micro-seismicity. We can see that the program with pilot tunnel is on this side, the program without pilot tunnel is on another side. From the evolution of micro-seismicity events and energy, we can see that the program with pilot tunnel is obviously improved. We can also see this from the occurrence rate and intensity of rockburst events. This result can also be observed in actual occurrence of rockbursts. When there are pilot tunnels, two slight rockbursts happened in this area; while there are no pilot tunnels, several slight rockbursts, two medium rockbursts and one strong rockburst happened in this area. Therefore, this regularity can also be obtained from the intensity of micro-seismicity events. This indicates that pilot tunnels have obtained some achievements.

Now let's look at how to determine the depth and position of stress releasing holes at tunnel segment of strong rockburst. Our calculation shows that the length of stress releasing holes before the tunnel face should be about 6 meters, and that the length of the stress releasing holes on failure surface should be about 9 meters. Spot observation of experimental tunnel TBM 2-1 number 3 shows that acoustic emission induced by TBM excavation mainly concentrates on the failure surface within 9 meters and before the tunnel face within 6 meters. This indicates that results of spot observation are in conformity with the results of calculation. We have made suggestions on the shoring parameter of rockburst tunnel segment. The rockbursts belong to different grades, including slight, medium, strong and extremely strong rockbursts. Our suggestions cover initial shotcrete, rock bolt, reinforcing steel mesh and protecting pit. Calculation of the shoring system's capabilities shows that only shoring cannot solve the risk controlling of Jinping, the tunnels of which are deeply buried. That means we should decrease energy concentration and releasing through optimized strategy. We give different suggestions on the length of rock bolt for strong and extremely strong rockbursts. Most of our suggestions have been adopted by the design. We have carried out forecasting and warning and micro-seismicity monitoring for rockbursts at typical tunnel segment. The buried depth of the tunnel segment is 2150–2525 meters, involving diversion tunnels and drainage tunnels number 1, 2, 3, and 4. Our work has gained great achievements. Upon the request of the construction unit, we added forecasting and warning and micro-seismicity monitoring for the tunnel segments, the buried depth of which are 1600–2100 meters, and of diversion tunnels and drainage tunnels number 3 and 4. Total length of the monitoring and warning is 12.4 kilometers.

The general result is: there are 275 rockbursts during the micro-seismicity monitoring; there are 243 rockbursts which have been forecasted, accounting for 88% of the totally actually occurred rockbursts; 85.4% of the forecasted occurrence area is the same to the actual occurrence area; nearly 3% of the forecasted occurrence area is different from the actual occurrence area. There may be several reasons for the deviation between forecasted occurrence area and actual occurrence area. Firstly, errors do exist in the forecasting. Secondly, when the forecasting says that there may be high grade rockburst in this area, the shoring system will be reinforced; as a result, the rockburst may transfer to a neighboring area, where the shoring system is relatively weak. Thirdly, the omen regularity is not obvious. During the warning of rockbursts based on micro-seismicity information, there are 32 rockbursts which are not forecasted due to the non-obvious omen regularity, accounting for 11.64%; few of them are strong rockbursts, and most of them are slight rockbursts, and several are similar to stress collapse. As long as we make warnings, we can prevent rockbursts or lower the grade of rockbursts through adjusting excavation rate and reinforcing the shoring system. Here are three cases. In the first case, we forecasted that there would be a strong rockburst. But after our adjusting, it turned into a medium rockburst. As the excavation goes on, micro-seismicity energy continued to concentrate. In the first case, on September 8th, we forecasted that there will be a strong rockburst. Therefore, we lowered the excavation footage from 16.25 meters to 9.55 meters, and in some regions, we added 6 meters of the systemic rock bolts. As a result, only a medium rockburst happened. On September 10th, the tunneling rate was lowered to 6.25 meters, and another medium rockburst happened. Since then, this area has been under our control. In the second case, we forecasted that there would be a medium rockburst, but there was no rockburst after taking certain measures. With the increase of micro-seismicity events, we forecasted on October 28th that there would be a medium rockburst and suggested systemic rock bolts should be added. In the following three days, the shoring system was reinforced. In this way, micro-seismicity was well controlled and the rockburst was thus avoided. In the third case, before the connection of the tunnels, the two tunnel faces were tunneled from two opposite directions. When is it changed into one-direction tunneling? Our numerical calculation results showed that with the tunneling of the two tunnel faces, stress energy would continue to concentrate and the risk of rockbursts would continue to increase. On October 25th, we warned that before the connection of the two tunnel faces there would be a medium rockburst near tunnel face 2-1-E, and suggested that we should stop the tunneling of tunnel face 2-1-E and change the tunneling into a one-direction tunneling from tunnel face 1-1-W and that we should reinforce the shoring system. One day later, the medium rockburst happened. So after that we strongly suggested that the tunneling should be changed into a one-direction tunneling, finally enabling the appropriate control of the micro-seismicity. On October 29th, the construction unit restarted the tunneling of tunnel face 2-1-E. Then, its micro-seismicity increased. On October 30th, tunneling was only carried on from tunneling face 1-1-W until the two tunnel faces were connected; at the same time the shoring system was reinforced. The results were good. In general, we gave rockburst warning of different grades for the 241 tunnel segments, total length of which was 7.6 kilometers. As a result, rockbursts of different grades in 135 tunnel segments, total length of which was 4 kilometers, have been avoided; and the rockburst grade of 13 tunnel segments, nearly 400 meters, was lowered. In the whole area, micro-seismicity monitoring and rockburst warning played an important role in the prevention and treatment of rockbursts. During the construction of each monitoring tunnel segment, there were no severe results caused by rockbursts, guaranteeing the construction period and safety of people and equipments. In November last year, all of the four diversion tunnels and drainage tunnels had been connected.

In general, through real-time comprehensive experimental observation on the spot, information, evolution law and mechanism of gash, deformation, wave velocity and micro-seismicity for two kinds of rockbursts' generating process have been revealed. On that basis, we put forward the Information Dynamic Updated Rockburst Risk Estimating and Warning Method, including RVI Method, Numerical Method, Neural Network Method Based on Project Cases Analogy, and Evolution Probability Method of Micro-seismicity Information. Then, we consider using Dynamic Controlling Method—the "three-step strategy," which are energy concentration, energy pre-releasing and transferring, and energy absorbing, combined with Dynamic Controlling Method based on the dynamic evolution law of micro-seismicity information. Luckily our work has obtained the full support of some relevant departments and projects. What's more, through academic communication, we have gained more encouragement, especially from the EHDC, Design Institute of Central China, the construction unit, and the mine. It is their help and cooperation that makes our work develop smoothly.

Xiating Feng, BSc, PhD, obtained his BSc degree in Mining Engineering from the Northeast University of Science and Technology in Shenyang, China, in 1986 and his PhD in rock mechanics from the Northeastern University, China, in 1992. Afterwards he has been affiliated as Lecturer, Associate Professor (from 1993 – 1996) and Professor (from 1996 – 2001) at the same university. From September 1995 to March 1996 as a Visiting Researcher and from December 1996 to November 1997 as an ITIT Special Research Officer at National Institute for Resource and Environment, Tsukuba, Japan, and from May to November 1996 as a Senior Research Officer at Department of Mining Engineering, the University of Witwatersrand, South Africa. As a Professor of A Hundred Talents Program of the Chinese Academy of Sciences, he joined the Institute of Rock and Soil Mechanics

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His research interests cover 'intelligent' rock mechanics and engineering, including intelligent recognition of models and parameters, stability analysis, global optimum design, disaster prediction and prevention in rock engineering; coupled mechanical-chemical-hydraulic process of rock masses; and radioactive waste disposal.

Real-time Sensing and Early Warning for Construction Safety Risk of Crossing Passages in Yangtze Riverbed Metro Tunnel

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Firstly, I want to say how much I appreciate this conference. During the past two days, I have listened so many wonderful reports. I feel that I have learned many things. Yesterday morning, Mr. Qihu Qian pointed out that we should control construction safety of underground projects from two aspects—technique and management. He explained his opinion theoretically. What's more, he demonstrated his argument from macro level, giving us plenty of data. I am greatly inspired. Our research group has done a lot of work on construction monitoring and warning system of the contact passage between Yangtze subway tunnels. Today, I will talk about our findings from the aspect of project management.

1. Project background

(Explaining with the help of PPT) Cross-river tunnel of Wuhan Subway Line 2 starts from Jianghan Road of Hankou to Jiyu Bridge of Wuchang. The tunnel is 3100 meters long. According to the design standards, there should be a contact passage between two tunnels every 600 meters. The passage serves as an escape way. Therefore, there should be five contact passages in the cross-river tunnel. Two of them are right under Yangtze River. So they are under a construction environment of highly confined flowing water. The risk is very high. A little carelessness will cause disaster.

A typical accident case of contact passage construction is the accident that happens to the construction of contact passage of a cross-river (Huangpu River) tunnel in Shanghai. Due to the failure of freezing system, 270 meters of the tunnel collapsed; buildings and flood-control dam above it were greatly damaged. The direct economic loss of this accident reaches 600 million Yuan. According to the analysis of Pacific Insurance Agency, its loss percent is 60% without this accident. But when counting this accident in, its loss percent reaches 1000%.

In the process of designing, we usually try our best to avoid setting up contact passages. Take the Wuhan – Yangtze River Tunnel as an example. It is a highway tunnel. While designing, contact passage program was prepared. Due to the influence of the accident happened to Shanghai Subway Line 4, contact passage was cancelled after discussion. Instead, longitudinal escape way was adopted. Diameter of the tunnel is pretty large. So spaces are left under the road surface. These spaces can be used as longitudinal escape way. Nanjing Yangtze Tunnel and the submarine tunnel of Tokyo Bay also adopt this method.

The diameter of the cross-river tunnel of Wuhan Subway Line 2 is 5.5 meters. So contact passage cannot be avoided. There are contact passages number 2 and number 3. And there is a pump house just beneath passage number 3, making the construction more difficult. Geological conditions of the contact passages are: the tunnel lies in medium-coarse sand containing gravel; beneath the tunnel is moderate weathering argillaceous siltstone; above the tunnel is silty-fine sand. The distance from river surface to contact passage is as long as 37 meters during construction. Tunnel duct piece is 350 millimeters thick. The distance from one tunnel center to another is 13 meters. Net dimension of the contact passage is 5.5 meters long, 2.1 meters high and 2.55 meters wide. Volume of pump house beneath the tunnel is 10 m^3.

Construction of contact passage adopts the freezing method. Firstly, freezing pipes will be fixed to the surrounding soil around the contact passage. Then freezing pipes will be linked to refrigerating apparatus through racking pipe. Refrigerating fluid (saline water) will be delivered to freezing pipes through refrigerating apparatus and racking pipe. As a result, soil around the contact passage will freeze, forming a freezing waterproof curtain of high intensity. Then the construction of contact passage can be carried out through mining method. Thickness of the freezing curtain is 3.1 meters. Its average temperature is −10℃. The freezing time should be 45 days.

There are three main risks in the construction of contact passages. The first risk is related to the depth of the contact passage. Wuhan's contact tunnels are the deepest tunnels beneath Yangtze River. Therefore, construction experience is not enough. Under the circumstance of highly confined flowing water, freezing result of the sand layer is directly related to the safety of contact passages. The second risk lies in the transfer of weak point. The whole process is freezing-excavating-shoring-thawing. During this process, load-carrying situation is changing. So the risk is transferring from one place to another. The third risk is related to the constructors. They are working beneath the river. Once there is an accident, how to make them evacuate immediately? How to make them escape as soon as possible?

2. Establishment of multi-field coupling real-time sensing system

One of the effective measures to control the above risks is to strengthen safety information management during the construction, including information obtaining, monitoring, delivering, analyzing and applying. We'd better obtain safety information through on-line monitoring. In this way, we can get comprehensive, real-time and sufficient information, and we can make the construction risks under our control. What's more, we should track the position of workers and management staff. We should monitor and share the safety information of freezing soil and structure with workers. Once emergency occurs, workers and management staff should be immediately informed.

Our monitoring system is actually a real-time sensing and warning system. Its operating principle can be described as "sensing, delivering, informing and controlling." Firstly, we should install sensor on the soil, structure of contact passages and existing tunnels so as to sense safety information timely. At the same time, the workers should be equipped with portable wireless sensor. The safety information should be promptly delivered, through industrial Ethernet or 3G network, to signal analytical instruments for analysis. Once risks appear, workers and management staff should be immediately informed. Thus, a real-time sensing and warning network is formed.

Safety information is mainly the safety information of structure, including the safety information of contact passage's freezing effect. As to the monitoring of contact passage's freezing soil, we are mainly monitoring two kinds of data—temperature and stress (or strain). At present, we are still using traditional methods. For the monitoring of temperature, we adopt electro thermal coupling sensor. As to the monitoring of stress or strain, we are using earth pressure cell to monitor the frost heaving surface, or using electric resistance strain gage to monitor the deformation. There are several problems in these methods. Firstly, the location of the sensor monitoring temperature is not in conformity with the location of strain monitoring. Thus we cannot conduct electro thermal coupling monitoring. Secondly, the monitoring is conducted manually. So, on-line and real-time monitoring cannot be realized. Thirdly, these sensors are difficult to be installed to the deep area of freezing soil. So our wish to learn something about deep freezing soil cannot be fulfilled. Therefore, we have to using another method which is to sense safety information through Fiber Bragg Grating Sensor. It has several advantages: firstly, on-line monitoring can be conducted; secondly, different kinds of safety information can be monitored on the same position simultaneously, which means coupling monitoring can be realized; thirdly, its waterproofness is great. The real-time sensing system we establish mainly includes three aspects. The first one is real-time collection of data. The information is collected by the Fiber Bragg Grating Sensor. Then the information will be delivered to the Fiber Bragg Grating Analyzer. The second one is the storage and analysis system of data. The Analyzer will deliver the location and data to this system for the IPC to conduct analysis. The last one is independent power-supply system. In order to ensure the safe operation of the whole system, there is an independent power-supply system. When the power is off, this system will work automatically.

Now let's talk about the arrangement of the Fiber Bragg Grating Sensor. Difficulty lies in how to install it into the deep area of the freezing soil. This is a picture of the installment of Fiber Bragg Grating Sensor which is monitoring freezing soil. Arrangement of Fiber Bragg Grating Sensor is a technical process. The head is a drill head. The sensor is fixed in a seamless steel tube. After driving the drill head into the soil, the tube with a sensor inside should be connected. Then, another tube, also with a sensor inside. The two tubes should be connected by fiber cables. This is the on-site fabrication, and this is the producing and installing process of the steel tube.

Now let's turn our attention to the sensor arrangement after preliminary shoring of contact passage. There are mainly three locations—the vault and preliminary shoring structures on the two side-walls of the contact passage. What's more, safety conditions of existing tunnels should also be monitored. We install the monitoring of tunnels on three duct pieces, Ring number 956, 957 and 958. 3 or 4 sensors are installed on each ring. We select demodulator of SM130. After demodulation, we can start the monitoring.

3. Analysis of sensed information

First, let's make an analysis of the temperature data of the freezing pipe. Freezing started from January 18, ended on March 6. The time span is 40 days. During this period, contact passage's soil has some regularity in temperature change. Firstly, original temperature at the early freezing period is basically stable, ranging from 12℃ to 16℃. At the early period, temperature change is dramatic. Later, temperature change tends to be mild. At last, the temperature will be around −8℃ to −10℃, meeting the construction requirements. Only one sensor's temperature is a little bit high—original temperature is 16℃, freezing temperature is 5℃. This is because the sensor is close to duct piece of the tunnel, making its heat exchange with outside space larger. Therefore, we may conclude that joint of freezing body and tunnel is the weakest point in the freezing construction process. The second regularity is that strain change of freezing pipe at the same position should be in accordance with temperature change. That is to say, at the early freezing period, strain change is dramatic, later it tends to be mild, and at last it becomes stable. Therefore, we can say that coupling effect exists between freezing temperature and strain. They have a positive co-relationship.

This is a flash of the formation of freezing curtain. We can see that formation of freezing ring takes about 20 days. It takes 40 days for the freezing wall to grow as thick as 3.5 meters and as cold as −8℃, meeting construction requirements. Center temperature of freezing soil at right is higher than that at left. This reminds us that we should strengthen freezing work at right during construction.

We can get freezing soil's displacement regularity from this displacement picture. The largest displacement is above the tunnel. Displacement at the two tunnel sidewalls is smaller. This is caused by rigid constraints of the tunnel—as pore water moves upward, crustal stress above the tunnel increases.

Now, let's look at the early shoring of contact passage. Before spraying concrete, strain change is mild. After spraying concrete, strain change becomes concentrated.

This is the deformation analysis of existing tunnels. Strain of Ring 957 duct piece is larger. The reason is that this duct piece is at the junction of freezing curtain and non-freezing soil, forming concentrated strain. The two lines standing for duct piece K fluctuates greatly. Duct piece K is the last one to be installed. Its size is smaller than others; therefore concentrated strain appears.

After storing the designed warning value into the system, it will be able to work.

Next question is how to share the warning information, or how to guide people to behave safely. For this purpose, a sensing system needs to be established—sensing system of people's moving position. This is the arrangement picture of people's moving position sensing system. Down here is the tunnel, installed with many readers. The readers can recognize each worker's position, and send the information to the ground through air shaft. There is a wireless AP on the ground. It will send the signals to control center, or the project department. The identification card on each worker is a moving RFID. It can be used to communicate, warn, and position. There are two methods to calculate the position. One is to determine the distance between reader and positioner according to signal strength. Another method is to determine the distance through the time difference of different signals, with an error less than 1 meter. At the controlling center, workers' position can be seen. Once Fiber Bragg Grating Sensor senses any danger, wireless sensor will promptly inform the workers and management staff.

This is a report from CCTV after the completion of cross-river tunnels' contact passages.

Future research: further optimizing sensing program of deep freezing soil; exploring the frost heave and thawing settlement regularity of horizontal freezing; exploring generation mechanism of disasters; exploring mechanical response and damage mechanism of tunnel duct piece under frost heave and thawing settlement.

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Professor Ding has served as a member of the Science and Technology Committee and Deputy Director of Management Department at the Ministry of Education, Chairman of Engineering Management of Architectural Society of China, Director of Assessment Council of Engineering Management at the Ministry of Housing and Urban-rural Development. He is also the editor-in-chief of *Journal of Civil Engineering and Management* and a member of the editorial boards of an international journal *Automation in Construction*.

Seismicity and Mining in the Witwatersrand Basin: Monitoring, Mechanisms and Mitigation Strategies in Perspective

Keivin Riemer

Gold Fields of South Africa, South Africa

It's an honor for me to be here today all the way from South Africa. I appreciate the opportunity to come and address you here on some of our issues that we've had in South Africa, in South Africa with our deep level gold mining.

It's my objective today to give you an overview of our mining in South Africa, the associated mining, seismicity. We have been mining gold in South Africa for about 120 years. We have produced about half of the gold that's ever been mined in the world. During that process, we have encountered lots of seismicity. But when I came to China, on the first day, I went to Shanghai, and I found gold. It's on the water, and it's easy to get. And there is no seismicity. A word about hazards and risks, while I was in China, I came across a saying that says "Sharks always bite, no matter where they are." Hazards, how do we define hazards and risks? Hazard, in simple terms, is just anything that has the potential to cause harm or loss; risk, is the probability that harm will be realized. So in terms of our great white shark that we have in South Africa, which is 6 meters long, if the head was here, the tail would be passed the chairman's table. Its jaw would fit over my head and my shoulders. If you went into the water, one bite, you are dead. That's hazard. The risk is what is the potential of that actually happening; while if you stay on the land, the shark cannot bite you; the risk is zero. If you go into the water, the risk maybe one; you will die. There are two definitions of seismicity that I want to share with you. That's the one from IRCA, International Risk Control Africa; the second is from United Nations Disaster Relief organization. That is concerned with earthquakes. And they are more concerned in that definition with protection of architectural heritage. So, hazard is defined as a probability that an earthquake or cyclone will take place. And the risk is the expect to damage to the architectural heritage. Slightly different (in) different nations, but they are all mentioning them. Both of them are used in seismic fatality today.

Our scale of mining in South Africa is on a much bigger scale than what I have heard being talked about in the seminar. Our mines are kilometers long in length, we go down to depth of approaching now 4 kilometers. We have to do that through different shaft systems. And mining takes place out in the strike direction on the plane of the reef, which is very very extensive. To give you an idea, in 1970, our gold production peaked, we produced a thousand tons of gold, and that came from extraction of 28 square kilometers of reef material. There are two problems that we encountered. One is high temperatures; the second is rock stress problem, which is manifested itself through rockbursts and seismicity.

Safety statistics, the records in South Africa not being good, I just want to share some of the past history. You will see the death rates have been high, in the past about 800 hundred people have died on South African mines on the yearly basis. But the figure shows an increase and that may be because of the decrease in mining as well, but I also think it's also due to the effect from seismicity. We have been able to contribute something to what's controlling this rockburst problem. Just a word about analyzing data and statistics, if you look at accidents statistics, a lot of people today, quote, "accidents and turns rates per thousand people or per million hours worked." You will see from this graph through the history, that is not always the case, does not give you a clear indication. Because you will see these divergent graphs that one showing actual death rates, the other one, fatality rates, per thousand people worked. You have to look at both of those statistics to get an idea of your hazards. The safety statistics, one way to estimate hazards, you must have a look at your accidents and find them in categories, then you can begin to assess the risks and do something and contribute your efforts towards us.

But our greatest contributor has been in the past, has been rockfalls and rockbursts, and you will see that white line on the graph continues right into the future. If I just draw you the statistics 2010, that makes up our 38% of our accidents coming from rockfalls and rockbursts. My good friend Alex Mendecki in 2001, tried to define the mathematics of progress, where he said the progress is a function of technology, understanding, and experience. On the basis of that, I just want to advocate a strategy maybe for seismic monitoring; it may not suit you here in China, because I believe your problems are associated with tunneling, but in our case, that certainly the way we have approached the problem. Another way to look at monitoring, to then look at and understand the mechanisms that we learn from that monitoring, that data the monitoring gives us, and then to try and do something about the problem in terms of mitigating the risks. Just a word about monitoring, monitoring we can do it in two ways, you and I can observe things on our own, that is a very biased way to do monitoring, because if I put/take two people from this room and we monitor something, I will get two different ideas and two different interpretations. A far bit away, is to use data and technology to monitor and record the systems. That way we can analyze it and both be talking about the same problem. That is what happened over the years in South Africa; it's just the technology, which has changed so much and we have to keep pace with it. And one of the difficulties of our finding is that we cannot go back to data that was monitored in 1910, and I cannot produce it for you today, because it is not available, because of the compatibility problem. So if you are doing monitoring, I will urge to keep your data as much data as you can. Just a word about objectives. If you want to set objectives particularly for monitoring, objectives usually made up of three particular phases: there is action, there is standard, and there is condition. You need to attach all of those components to make an objective. So, if you want to make an objective for seismic monitoring, you need to sit down and do that. If you want to play golf for instance, you want to play golf, you need to hit a golf ball straight, your standard maybe that you want to win the US Open. Ok, the condition is going to be that you will need money and you need to devote time to practice. Certainly, around those objectives we have certain work functions. We will set targets, we will have planning meetings, and we will have to motivate ourselves to carry on with those objectives.

Down South Africa, I look back and the first earlier subjectives (objectives) that I can find only in 1980 by Klokow and De Jongh, who made objectives for the seismic monitoring in terms of immediate, medium, and long term objectives. The immediate objective was to get a falls location for rescue and management purposes. Those objectives follow through our research program SIMRAC (1998). But we also had additional objectives appearing there in terms of prevention, control, and warning system. Then the scale of monitoring we need to define as well. And I think we are on a very mind wide system. And I think here in China, you will be more involved with micro-seismic monitoring, which you are involving in the range of 1 thousand to 10 thousand events a day. I am not too sure what your entries are over here. The monitoring phases through the years of South Africa of Artlant in our paper with R. Durrheim identified seven different phases. But if you look at the history of the monitoring, for good half, 50% of the time in South Africa we are earning monitoring with one system which consists of six stations. That may sound bad. I think it's due to the technology explosion that is taking place in the world today. We have a very clear mark line in South Africa; I call it Coalbrook line. Because that's the disaster we had on the coal mine in South Africa with 435 miners being killed in a pillar collapse. It seems after that disaster, that the efforts were intensified to monitor South Africa in our country. We went through into systems and the modern day, quantitative seismic monitoring that we are doing today in conjunction with IMS, XISS.

The research systems for a certain phase of that period, most of the research work direct to the monitoring and interpretation of the data. But after the 1970s, objectives of the systems seem to change and we went more for falls locations for rescue and management purposes, that being a characteristic of our monitoring in South Africa. If I just quickly show you some kind of history of the monitoring in terms of three parameters: process events, the number of systems we've had, and A to D sampling rates, because that gives us an idea of the technology that were using. You will see that around about 1960s is where the big rapid increase in our technology takes place, that also leads to an increase in the number of events, which we are processing, and our understanding of seismology. It also ties in very well with developments on global seismology timeline. And you can see there in the 60s, when computers became available, we started to be able to find out things about seismic moment, about plate tectonics, and about source mechanism, through models like the Brune Model.

Network planning and sensitivities are very important issue of science monitoring. You need to plan and decide what sensitivity you want, what seismic accuracy you want, and the maintenance that you prepare to put into those systems. Now the early systems didn't have those facilities available; if you look into the early system of Artlant, the red circles they are the sensors that are put in by Cook in his research at ERPN mine. They are all scattered to the one side of the longwall. And if you look at the seismic locations close to those circles, they are very well close together. But on the opposite of the longwall, not so good. That's the location accuracy problem, which you need to guard against. Fortunately, today, we have brilliant software available to us, we are able to estimate errors in P wave velocity and in wave arrival time. We can actually try to estimate what sensitivity we have, what location accuracy we have on our systems. And remember that what I am showing you there is a diameter maybe of about 10 to 12 kilometers wide, with about 40 to 50 seismic stations.

The technology that we have today allows us to process events. We have 3 - dimensional seismic-grams we can look at; travel time curves to give location information; we can have the source parameter, analyze the seismic wave forms, come up with moment tense solutions, trying to work out what mechanisms are happening, and also to define what time the events are occurring. And you will see there are very big peaks later in the afternoon that are due to our blasting time, which takes place at about 6 o'clock in the evening every day. Mechanisms, I want to show you a graph here, because it highlights the problem that we have in terms of understanding mechanisms. During the period 1973 to 1981, and our clocks are still in South Africa. There were 10 events bigger than 4 - magnitude, all right, 86 fatalities from 8 of those events. It shows you that not every seismic event on our gold mine leads to a fatality. So, there is a question about defining risks in association with seismic events. The early theories about seismicity—what were they. Sometimes, we can be looking in all the wrong places for all the right reasons and we just don't see anything. The early theories, and I've highlighted these in the paper, but I just want to bring up two of them this morning. The Single Blow theory was actually a theory that they came up with because an error in the seismic monitoring. The sampling rises in the original Wiechert seismogram were too slow. So the events that were very close to the mining areas came up. And they were not able to identify P arrivals and S arrival times. And that led them to a theory there was a solid blow taking place in the mines. And they interpreted that as a different mechanism from the distance earthquakes that were picking up around about in Africa.

The second one that is quite interesting is the vibrations from batteries and stamp mills. The stamp mills in the early days were vertical stamp mills that crush the rock instead of churning it in a cylindrical fashion like we do today. But it was the pillars that really attracted the attention of the early researchers. They realized that there was a concentration of stress in the pillars that were leaving behind and this was causing rockbursts. The early theories about where all the rock deformation and movement was taking place. We've heard about yesterday about domes. The domes theories eventually led into a lot of research. The doming theories led to what we know today about continuums and elastic theories. And that took place in the 1970s. As a result of research work that was done by Prof. Nicola Solomon, we had an instrument—an electrical resistance analogue, which for the first time gives us the ability to estimate the stresses and strength on the reef plane. From there it's been an explosion of technology. We now have numerical methods that we use all around the world today to be able to estimate linear, non-linear, plastic movements in the rock mass. That certainly helps us with regard to seismicity.

Focal mechanisms of earthquakes and moment tensors. There are probably three gentlemen in the world I tribute knowledge of seismic event mechanism. One was Bunjiiro Koto. In 1893, he found that faults were certainly related to earthquakes. That changed a lot of people's thinking, from animals and monsters. The elastic rebound theory of Theodor Reid of 1906, when he studied the San Francisco earthquake. And Professor Honda from Japan, who actually found for the first time the differentiation of the two senses of polarity in the seismic waves, giving us the indication of fault planes, and fault plane solutions. Of course today, we have analysis involving events right in the moment tenses, share components, volume changes, and we are able to define different source areas and maybe estimate some of the sizes and shapes as Alex Mendecki has alluded to in his book.

Event distributions. We are able to now look at event distributions plotting in terms of moment and energy; we are sorting to see maybe two different distributions: the small fracturing events that take place around us, stope faces; and the destructive events that seem to occur on the geological features, further away from the mining. Those also manifest themselves if you look at frequency magnitude type distributions; you see what we call the type A and the type B distributions. We're also able to identify different times of the occurrence of seismic events and that would direct our efforts onto how we blast the rock and how we excavate it. But the main area of stress concentration around our mining phases is above and below in the hanging wall foot wall over reef. I have tried to summarize for you in terms of the rock wall condition factor, where you will see the problem, the shaded area. That is the area we want to avoid in terms of stress concentrations. It's the maximum difference between our σ_1 and σ_3 that gives us the biggest shear stress, that's why we do not want to locate tunnels and those are the areas we will find the rockbursts and large size mega events occurring.

Just a word that I had some personal work that I have done in terms of looking at event mechanisms. Sometimes, when you sample at very high sampling rates, you see complexities in the wave form. And here I am showing you very briefly, the occurrence of two seismic events in one seismogram, very close together, but that might be distant even tens of meters apart. You will see the different wave phases that I have identified for you. Sometimes, those events occur very close together in the same seismogram; sometimes, they are seconds apart, as you will see in the diagram bottom left. When you analyze some of those events, you will see that they occur quite, they could be up to 400 meters apart from each other; they can be different mechanisms. They are very difficult to analyze. And they sometimes occur on different geological structures or different mining areas. If you analyze them in terms of some kind of space, time diagram, you will see that they ranged two clusters there. And what is going through my mind we now do this work; I think that triggering is maybe responsible for the difference. Some are triggered by the P waves, onset of the P waves; some are triggered by the onset of the S wave. And some are just related to large strain rates of the event on the bottom right. What are the consequences of those types of events? Right. If you look at this interference problem that you have two sets of waves interfering with each other, we get a complex interference pattern. And that would certainly happen; if we have two events occurring with a large distance and time separation. The line of intersection from the two seismic waves emulating from the two different sources, they are very far apart, will intersect in a straight line. Now we need to ask ourselves what is happening at that point of intersection, because the waves can be different phases; there can be a P wave intersecting with a P wave, or a P wave with an S wave. And those waves might be vibrating into different directions. So, we need to ask ourselves what is the result of that line of intersection doing to our support. When the events get closer together, it's get a bit more complex. So, we would have a first event occurring, and I am showing you in blue there—the S wave radiation with time; we will have a second event that occurs some point further away, and that would be the P wave radiation because P wave radiation travels faster it catches up with S wave. And we get a locus of intersection, which is not circular anymore. It closes on itself; it's got a distance criteria. It looks very much like a polar graph, if you have r = a − a cos(theta). It's a very similar shape. But the question I ask myself is what would that do to our support along that line of intersection. So, very often we can look at the location of the seismic event; maybe our damage is very far from that location and we can't understand it. And maybe this is the reason for it.

Mitigation. Mitigation I want to present you in terms of three stages of approach and it comes from our deep mine project in South Africa. We are going to talk about prevention, about protection, and about prediction. I know everybody wants to know about prediction, so, I will give my thoughts on prediction. But, Alex Mendecki also outlined some differences between earthquakes and seismic events that allow us maybe a foothold into this question of controlling seismicity. Earthquakes come from a very different environment although they got the same seismic waves, the strain rates are very different with earthquakes. On plate boundaries, the strain rates are taking place at the centimeters per year; in our mining area, the strain rates are taking place at centimeters per day. So, we have two orders of magnitude between strain rate of earthquakes and mining seismic events. There is also this question of self-organization because there is a constant process that the earthquakes tend to self-organize the nucleation areas over a much larger distance, leading to larger events. There also in the mining environment is a strong concentration of stress in certain places and that leads us to slightly different mechanisms and slightly different releases of energy. So, for earthquakes, we don't really have any control over it. We must just take them when they come. And this we can predict it, but we haven't been able to do that yet. Mining events, maybe we control. We can control by looking at the mining, the volume that we mine, but analysis in terms of time is going to tell us nothing, because everything is very varying too much in the mining environment. How have we been able to adapt to different mining scenarios?

We reply "research." We've looked at different mining layers; we've looked at different designs. There, what I am showing you on a big mine—a Gold Mine, the three particular stages in history where we adopted different designs: A was a scattered mining area, but after a certain while, we found there were too many rockbursts taking place in that particular layer, there were too many problems. So we switched at B in the 1970s to a longwall mining method. And in C, we adopted in a new layer, at which I will show you just now in terms of deep pillars oriented at right angles to the strata stabilizing pillars that were used in phase B. What are the parameters that we come out of research I will just share a few of them with you. We can talk about them certainly in the next few days while I am in Wuhan. Firstly, energy, stress and strength ratios, and rock wall condition factors. Pillars, we talk a lot about in terms of width to height ratios, and try to design them accordingly. But the bottom diagram shows you the stope, and it shows you that stress zones that are going to lead to the occurrence of earthquakes. And you can see that they occur above and below the stope area in the footwall in the hanging when these lobs into sect of geological structures that's when we tend to get our problem. But we do get seismic related issues in the small area C around stope face with these low confinement where the people are working. That is the critical area. Dip pillar layouts, I told you about, I am just going to show you a very quick analysis in terms of dip pillars. There was a mining scenario that we took out. And I analyze it in terms of seismicity looking at, seismic, time on the bottom axis, and in terms of seismic moment and activity rate in the red. We will see the period when we started mining, those dip pillars, it was 1998 in July. There was a period of a year before we actually saw seismic response in our system. The little arrows at the top there are indicating to you the occurrence of the 2-magnitude of events. And those are occurring in a time gap of about one every month on this particular diagram. So, you could say in this area, every month we would have a 2-magnitude seismic event. And that is a big problem for us. But when I look at the actual face positions of the seismic events, I found that at that point of increase corresponded to a mining span of about 100 meters. So we saw that maybe there were something in the design of these particular pillars, maybe we need to make the spans much smaller, because the spans here were designed to go to 140 meters. We start to pick up problems at 100 meters. So we integrate that back to the design and try to change things.

That was very similar to what had been found by Cook in 1966, the famous rockburst paper. So the modern seismic systems, the question is are they telling us new. Maybe they are telling us something in more detail about what we knew 40 years ago. But it's certainly helping us with the design.

Centralized blasting. Just a quick word I want to say about centralized blasting. In the old days, we used to use what we call "stay-a lite" system. You lit up the face of the stay-a lite fuses, that take three hours to burn. Your blasting went off at any time in the day. It was more or less uncontrolled. And that had an influence on the occurrence of seismic events. Centralized blasting was motivated in order to control. And there is a safety feature to stop the misfires from happening. And for the seismicity, if we look at a normal seismic, ordered mining layout in South Africa, with centralized blasting we would have a panel of 30 meters, we would have 120 holes, the delays from their shots will be 200 millisecond, that would give us the total time for their blast to go off about 24 seconds. We will be blasting on the big mine 50 of those panels on a daily basis. So you can imagine the amount of energy and stress that put into the rock. But the main purpose of centralized blasting is to try to control the seismicity. We certainly start to see differences in our seismic grams and we see real seismic events modeled up with actual release of energy from the blasting energy become complicated to analyze.

Protection. I just want to say a word about protection. Prof. Peter Kaiser explained a lot about support methods yesterday. But, energy absorption criterion takes care of a gravitational component of NBH, MGH, and also a dynamic moment from velocity, half mv square, that's trying to design support to absorb energy. And you can see two different types of support systems there. The one on the right, which is mine poles, they are there because they've actually done some work holding up that stope face. I realized stope face is about a meter high. I am running out of time here. So, I am just going to skip through to, this emphasis on prediction.

Prediction. And I will just outline something for prediction. And then we can stop, because I know that everybody wants to know about the subject. Prediction goes back to 1939. During even post war periods, where work started with the US Bureau of Mines, certainly Obert and Duvall carried on with their work. They thought they could see a pattern of micro seismicity that were developed. In other words, accelerated event rate before a rockburst, they certainly continued with their process. In South Africa, we had the Coalbrook pillar collapse, where 430 people were killed. And it seemed after that, our efforts for prediction really started to take off. We had some micro seismicity monitoring that was done by Brink and Mountford in 1983. They saw in the circular area the few hours before the actual event when they were back analyzing they thought that they could see changes in energy event rate that would lead them to be able to predict large seismic event. Our moves, we didn't have any success of that. Our research went into trying to identify nucleation phases, in terms of one or two parameters like energy index and apparent volume. For changes, we would see one decreasing and the other one decreasing before large event. We had very little success with their approach. We are one in the phase where we use hazard assessments. In other words, we look at the seismicity around working places every day. We try to quantify in terms of different parameters and send two mining personals on the daily basis to give them the idea of the status of the work area.

The numerical modeling is an integration phase that is taken place. We haven't really talked about it much at this seminar. But it's been in operation for about last 10 years. People are actually trying to use numerical analysis to predict seismicity. And it's certainly an area which is expanding fast. And it's a very useful area of work.

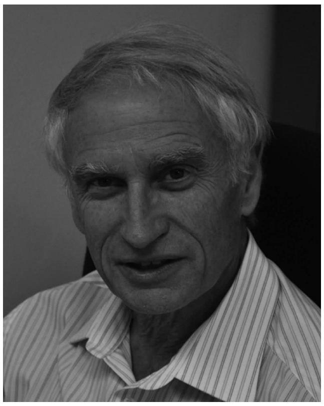
And then, lastly, I just want to mention some work which comes out of the United States. There is whole lot of authors. Granted AI, who looked at this problem and they say that they think they are seeing migration of electrons and atoms on the rock in stress. And that could be leading to electrical currency, electrical magnetic changes. And they have looked at animal behavior and try to understand animal behavior. And certainly making sense to me, because I can understand in sharks in their nose cones have the capillary system of fluid, which makes them sensitive to electrical magnetic radiation. It is the method that guides them to their prey. They use their eyes when they are far away; when they get up to their prey, they can't see, and this electrical magnetic or there is jelly in the nose cones allows them to detect electrical magnetic radiation, like your heart beat, anything electrical, and they will zoom in to there and bite you into half. So, there seems to be some connection here between some non-seismic variables that we need to go after and look for in regard to prediction. And I think it's useful it's certainly the most encouraging work that I have seen that maybe lead us into the direction of prediction.

The role of research is important. I just want to emphasize for your work here in Japan. That you need to keep a very close contact with your research organizations and your actual areas or tunnels. They need to be very close. We have the link in South Africa all the years. And it certainly has been a good benefit to us.

So, let me end with a slide of seeing a lot of incredible scenery here in China. I want to show you a picture, our natural world heritage site in Cape Town. It is an amazing mountain, the most amazing. Another thing about this mountain is it's flat. As you can see the cinemantry bear is flat. But 20 kilometers from this mountain, the mountains are folded into large intersecting zions of fault mountains with fault length about 20 or 15 kilometers. That's what makes this mountain unique. The scenery makes it very pretty. But the mountain in terms of geology is something else.

I want to just say that if we want to get progress in seismicity we need to integrate maybe our monitoring mechanisms in our mitigation method. It is going to be a function of those three variables. And then mitigation for us, I know for you it may be different, but mitigation is a function of protection, and prevention. We can add prediction if we want to. The ternary approach to seismicity, we need to be somewhere in the middle of that ternary diagram. And mitigation, we favor more the prevention and protection side of the ternary diagram. And lastly, research needs to turn our data into knowledge and wisdom. And I am benefiting from what Peter told us yesterday about the differences between knowledge and wisdom.

Thank you to the Chinese Academy of Engineering for inviting me here today. Thank you to Gold Fields—my company, who I work for 31 years. Thank you to French Malange Oksy Durrheim, who helped me coauthored this paper, and to you and China, I say "Xie Xie".



Kevin Riemer was born in Scottburgh, Kwa Zulu Natal, South Africa in 1951. He graduated with BSc Geology Honours from University of Natal in 1977. He joined the Engineering Geology unit of the Geological Survey in Pretoria and completed an MSc (advanced course) in Engineering Geology at the University of Durham in the United Kingdom in 1979. He continued working as an engineering geologist at the Geological Survey until 1980 and completed feasibility studies on various projects in the dams and underground section including the Vaal Dam Betterments program and the Theewaterskloof Water Storage Scheme in the Western Cape Province.

In 1980 he joined the Rock Engineering Department at Gold Fields of South Africa assisting with the design and planning of deep level underground layouts at The Venterspost and West Driefontein Gold Mines. He is currently still employed by Gold Fields and has served with the Company for a period of 30 years.

In 1982 he was transferred to the Seismic Department where he managed the Group Seismic Network for Gold Fields based at West Driefontein Gold Mine. This network consisted of monitoring equipment on five remote mines, all linked to a central site at West Driefontein main offices via UHF radio equipment. In 1996 the technology was decentralized and updated to the fully digital three dimensional systems marketed and maintained by Integrated Seismic Systems International (I. S. S. I.). During this time and following this change he has worked in close association with the individual mine seismologists and the Rock Engineering Consultants at the corporate offices based in Johannesburg. Current efforts have involved investigating the nature of triggering and association methodologies on the ISSI systems and in particular the use of constant higher sampling rates through the discarding of decimation processes. He is a South African citizen and currently a member of The South African National Institute for Rock Engineering (S. A. N. I. R. E.)

In addition to above he has also made numerous presentations at the Annual I. S. S. I. seminars held at Stellenbosch, South Africa and several internal presentations at the Rock Engineering and Mining technical seminars within Gold Fields.

Mechanism and Control of Rock Burst

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My report is divided into five parts. First part is the severity of rock burst damage. Let's look at rock burst damage and its severity from some pictures and cases we collected. This picture is taken when a rock burst happened in a coal mine. Before rock burst, roadway is very stable. But after rock burst, it is severely damaged. This is a picture of the rock burst of metalliferous mine; and this is the damage of a traffic tunnel and diversion tunnel of Jinping Hydropower Station. Now let's turn our attention to the on-site damage of two rock bursts. This is the accident site of a rock burst happened in Peru, which Professor Hudson had talked about on a conference in 2009. This is accident site of a rock burst happened in Jinping. Why do we review these accidents? There is a basic theory of philosophy—see through the appearance to perceive the essence. You must have understood something through these pictures. We can see that rock burst damage can be divided into strain rock burst and slashing rock burst. Our research group has devoted ourselves to these two kinds of rock burst for many years. We have done a lot of experiments. We further divided the two kinds of rock burst into six types. They happen at different time. Strain rock burst happens during excavation when tunnel is not completed. Slashing rock burst happens when the roadway comes into being. Slashing rock burst is formed after the tunnel is completed, bearing many other dynamic slashes. According to the type of project, strain rock burst can be divided into pillar rock burst and surface rock burst. Rock burst happens in tunnel or roadway has different free face. Without excavating, there will be no rock burst. Now, we can conduct an indoor representation through the experimental system of strain rock burst. Slashing rock burst happens because of lack of power after excavation.

Therefore, no slashing rock burst will happen during excavation. When the road is completed after smooth excavation, there may be some other slashes, such as slash from explosion, slash from the damage of mining roof, periodic pressure slash, and slash from fault movements. These different kinds of slashes will cause rock burst. We successfully conduct a slashing rock burst experiment through the design of a rigid loading system and dynamic load of a slashing loading system.

Now, let's look at the experiments of the two kinds of rock burst. First, let's focus on strain rock burst. This is the experimental system that we designed for strain rock burst. This is the acoustic mission collection system of strain rock burst, with one thousand frames per second. Strain rock burst has three sufficient and necessary conditions. The first one is sufficient depth (or high enough stress); the second one is strong enough compression power; the third one is excavation. After excavation, there will be a free face. Power will be suddenly released along the free face. These three conditions constitute the basic conditions of strain rock burst. According to these three basic conditions, we designed an experimental system of strain rock burst. And we had conducted more than 200 experiments of rock burst. Now, I will show you the experiment result. The first experiment takes a Canadian sample. It is granite, with a sampling depth of 2500 meters. We can see violent power release during rock burst. And we have noticed that fragments of rock burst are spinning in the air. And we can also see angles of attack. Different from general damages, rock burst is a kind of special damage. The second experiment takes Chinese granite as a sample. Sudden excavation unloads the loading of one direction. Thus power release happens to the granite. Power release in the experiment has three stages. During the first stage, particulate matter is ejected out. During the second stage is the comprehensive ejection of particulate matter and platy shaped particle. The last stage is rock burst, during which we can hear loud sound. The third experiment is the rock burst process of marble of phase Ⅱ taken from Jinping. Here is rock burst of sandstone. In horizontal bedding, rock burst happens near the roof; in vertical bedding, rock burst happens in the middle of rock sample; when the bedding is parallel to free face, rock burst happens to the whole free face. What we just saw are typical examples of strain rock burst. We have shown three kinds of rock to you: sedimentary rock, granite and metamorphic rock. We can conclude that rock type will not affect rock burst.

Another kind of rock burst is slashing rock burst. When requirements of strain rock burst cannot be met, that is to say, power is not strong enough to cause rock burst, strain rock burst will not happen. But after the completion of road way, other dynamic slashes will happen during the service life. This is what we call slashing rock burst. Therefore, slashing rock burst happen after the completion of road way. When it is not deep enough, static load will not cause slashing rock burst. In order to get enough strength, getting more energy from different slashing source becomes the characteristic of slashing rock burst. Experimental system of slashing rock burst has 16 basic wave forms. When we are testing on-site a complicated wave form, we can achieve the test through the combination of these 16 basic forms.

Now, let's look at several experiments of slashing rock burst. Experiment one: in order to test our experimental system, we continuously upload a dynamic loading on the vertical direction (Fy) based on statics. We can see the process of rock burst after perturbation. This is perturbation on grade II; this is perturbation on grade C; this is perturbation on grade D. Please pay your attention to grade D. Rock burst begins with release of gas—gas outburst in coal mine. Then gas and solid will burst simultaneously.

This is experiment two. Now we carry out comprehensive perturbation. On Fy and Fz, we carry out lateral perturbation on the red wave form and black wave form. This is the time axis. Will rock burst happen this time? In order to get the answer, we observe a lot of damages. At the beginning, damage does begin. This is the omen rock burst. But sometimes, the omen is not followed by rock burst. There is only omen. This is possible. Actually, this is a kind of damage. And out experiment ends here. This experiment tells us that perturbation from two directions will only lead to damage, not rock burst.

Now, let's turn our attention to comprehensive perturbation from three directions. We carry out perturbation from Fx, Fy, Fz simultaneously. They are perturbation of green wave form, red wave form and blue wave form. Will rock burst happen? Will damage happen like that of two-direction perturbation? As the result shows, damage also happens under three-direction perturbation. Energy is counteracted in the perturbation, so only damage happens, not rock burst.

In experiment four, there are two tunnels. One tunnel has been completed. Another is under construction. Following the perturbation of neighbor tunnel, there will be a sudden decrease of horizontal stress. This sudden unloading will cause rock burst.

This is experiment five; this is the omen of rock burst. The omen takes a lot of time.

You must be patient to see the rock burst after it. Excavation reduces the middle stress, causing fission. Rock burst happens immediately after the fission. Rock burst happens at this position. We can see clearly rib spalling, which is very subtle, during the experiment. Rock burst in experiment five is caused by the continuous loading on Fy. This rock burst has omen—beginning with damage.

Now, let' s look at experiment six, which carries out continuous perturbation of stress wave on the direction of Fy. Rock burst happens at last. At the beginning, stress wave level is very low. At that time, it is damage—the energy can cause damage, but not enough to bring rock burst. Rock bust needs more energy.

What can we conclude from these experiments? Firstly, rock burst is not general damage; it is a kind of special damage. What is the difference between rock burst and single-axis experiment? We have chosen samples and continuously uploaded. How does the rock burst happen? We have added confining pressure and loading in accordance with the on-site test. Then we unload the confining pressure and add lateral and vertical loading. Under this situation, velocity is not changing. What is changing is the high óc obtaining from instantaneous loading. This is a slow loading; this is a quick one. Due to the different loading velocities, there will be a high strength index. This one is about statics. Its power is like a shadow. The power is strong enough to bring cracks to rocks, making rocks into fragments. Redundant power will eject these damaged materials and give them into speed. The fragment will spin in the air and be ejected out for a certain distance. $\Delta E > 0$ maybe the condition of rock burst. When $\Delta E = 0$, there will be damage. When $\Delta E > 0$, redundant power will turn the damaged materials into speed. The power of rock burst can be divided into two parts: that can damage the rock, and that can cast the damaged materials. The latter one can turn damaged materials into something with energy, and turn acceleration into speed. This is our present understanding. For instantaneous rock burst, and rock burst immediately after excavation, the stress is ó1, ó2, and ó3. Once there is excavation, the free face will unload. Because loading velocity is different, once the deep tunnels unload, redundant power will be generated. This power is close to the energy of damage. Sudden radial unloading and double of tangential stress will generate redundant energy. As to retarded slashing rock burst, its own energy is not enough. But slash will bring redundant energy. In addition to excavation, energy becomes enough.

According to our research, we obtained six ways to get redundant energy. The purpose of our research, both indoor experiment and outdoor observation, is to prevent people from being hurt by rock burst and to make the rock burst site a safer place. After rock burst, space will change. This is very dangerous. Present shoring materials are very weak in front of this powerful energy. Both the bolt and anchor will be broken. Can we design a kind of material that will not break, making it bear the loading of energy? Our focus is on how to find this kind of material that will not break under sudden loading. Some foreign countries have done a good job. Professor Kaiser has designed a good product. This one is designed by Australian; its thickness ranges from 120 mm to more than 300 mm. But thickness of our product is only 100 mm. This one is designed by us during recent years. Its transverse arrest can reach 20–35 tons. After deformation, its thickness can reach 1000 mm. It is the transverse arrest deformation bolt that we designed.

In order to test its mechanical property, we conduct a tensile test. When stretched to 1 meter, we can achieve 300 or 500 under the condition of 13–14 tons. We can select in accordance to specific circumstance. We have bolt of 12 or 20 tons and anchor of 35 tons. Present coal mines need combination of 20-ton bolts and 35-ton anchor to resist the slashing loading of rock burst. We need to emphasize that all of the rock bursts and disasters are related to excavation. What is the purpose of shoring? Our purpose is to counteract the effect of excavation or to place the rock with shoring. The best method of replace is pre-stress. The higher pre-press is the better. The problem is that present materials will break under high stress; they cannot adapt to high-level deformation. The higher the stress is, the worse the ability to adapt to deformation becomes. But our 35-ton transverse arrest can give you a pre-stress of 35 tons. And our 20-ton deformation product can give you a stress of 20 tons. They will absorb energy in the process of deformation.

The above test is for slow tensile, which can adapt to great deformation. But can the products adapt to sudden loading? We conducted a slashing experiment with the experimental loading system of 200 000 J and 15 000 J. During the first five slashing, the bolt remains unbroken. But it breaks in the sixth slashing. A bolt can endure five slashing, which means that its ability to absorb energy is pretty good. Why is the energy absorbed? Plastic flow is generated. Plastic flow will begin to decrease when it reaches a high level. We achieve a stronger slashing through Hopkinson pressure bar. The bolt can also endure it. This is an experiment of single bolt. This is an experiment of bolt group. This is the constitutive relation of bolt relation, an equilibrium equation of the co-relationship between bolt and rock. We need to emphasize that the equilibrium equation can be solved when this special bolt is co-related to rock. In the past, the equilibrium equation cannot be solved because both the strength and deformation are changing. However, at present as long as the deformation force is constant, acting force of all bolts will be constant. Therefore only one variable is left—displacement. In this way the question is greatly simplified.

Our conclusions are: strain rock burst and slashing rock burst can be designed in laboratory, which will help us better understand the mechanism of rock burst; principles of rock burst are found through experiments, including redundant energy generated through static loading and dynamic loading; constant-resistance deformation bolt can absorb energy, which will help us control the generation of rock burst.

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Technological Developments in the Forecast and Management of Water Inrush of Underground Engineering

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At present, China's underground engineering has the largest construction scale and fastest development rate. Water inrush and mud surging in the construction of underground engineering are world-class engineering problems, with the characteristics of "great depth, strong lava, high water pressure, large flow". During the construction, unfavorable geological conditions, such as karst caves and faults, are usually encountered. Some of these caves are bearing water, some are not, and some others are even connected to an underground river. Once there is a water inrush, severe casualties and property losses will be caused. Let's take the Jinping – Ⅱ Hydropower Station as an example. Water pressure of its auxiliary tunnel has surpassed 10 Mpa, and the flow rate is more than 7 m^3/s, which make it an extraordinarily difficult project. Another example is the Yichang – Wanzhou Railway. The construction of this railway has witnessed the occurrence of several accidents of water inrush, mud surging, and even rock rolling which has a more powerful destructive force. While constructing the Yesanguan Tunnel of Yichang – Wanzhou Railway, one accident of water inrush and mud surging caused the death of 10 people; and there were altogether 19 large-scaled accidents of water inrush and mud surging in the construction of Maluqing Tunnel, leading to the death of 15 people.

The construction of the west section of Shanghai-Chongqing freeway has also witnessed the occurrence of several accidents of water inrush and mud surging. For example, Longtan Tunnel is running through an extremely long fractured zone in fault, which is 700 meters in length and has a total mud surging volume of 9000 m^3. But the accident was forecasted in advance, and therefore no casualty was caused.

In order to avoid the occurrence of water inrush and mud surging, we must try our best to forecast the unfavorable geology, and to prevent and control the accidents. But the problem is that, during the construction of hydro tunnels and highway/railway tunnels, it is very difficult to figure out all the unfavorable geological conditions alongside the tunnel at the early stage of the construction. The tunnels are usually excavated amongst the high mountains and lofty hills; some are even buried as deep as 2000 meters. Due to these extremely complex geological conditions, it is very costly to carry out geological exploration through surface drilling, which is difficult to be done in mountain areas. What's more, other geophysical prospecting methods cannot easily forecast unfavorable geological conditions. As a result, unfavorable geological conditions in the construction of tunnels cannot be discovered before the construction. Therefore, we need to do the forecast work during the construction. For the purpose of avoiding the above mentioned accidents, we carry out our work from two aspects. The first one is about the forecast and quantitative identification of unfavorable geological conditions. The unfavorable geological conditions include karst water-bearing systems (such as karst caves) and fractured water-control structures (such as faults). The quantitative forecast of filled water in unfavorable geological structures, which is a world-class problem, is extremely important. The second aspect is about the prevention and control of the accidents. If the disaster sources of water inrush ahead of the tunnel have been predicted, prevention and control technology, especially relevant theories, technologies and materials about the control of high-pressure dynamic water, will become the key points. Centered on these two aspects, I would like to make a report of the achievements we have made over the past few years.

Firstly, I would like to talk about the improvements we have made in forecast & positioning, theory and technology about quantitative identification of water-bearing structures. After years' of work, we have established a set of technologies to forecast the water-bearing structures ahead of the tunnel. The first technology is using Minimum Offset Seismic Wave Method, also called Land Sonar Method, to find the karst faults ahead of the tunnel and to realize long-distance positioning. This technology can give a definite object in view and make us prepared. The forecast distance can be as long as 100 meters. The Land Sonar Method has been improved by the mutual efforts of

Shangdong University and Professor Shihang Zhong. The advantage of this method lies in that it can be used to recognize the faults and small or medium-sized karst caves ahead of the tunnel within 100 meters. The second technology is medium-distance indentification and positioning of water bodies. This technology is using Whole-space Transient Electromagnetic Method to effectively identify and position the water bodies ahead of the tunnel within 80 meters. But this technology cannot be used to judge the water yield. The third technology is used to estimate the yield of the water bodies ahead of the tunnel. The estimation of water yield ahead of the tunnel is essential to the construction. The team of Shandong University has independently developed the Compounded Induced Polarization Method, revealing that there is a positive correlation between the induced polarization information and water yield. Based on this method, the estimation method of water yield within 40 meters has been established. The above three methods is a progressive and whole forecast technology, from far to near, from the positioning of water bodies to the quantification of water yield. The use of these three methods can lead to a better application effect.

Now please let me introduce the Compounded Induced Polarization Method in detail. This method is a core innovative technology researched and developed by the team of Shandong University. To be briefly, the operating principle of induced polarization is to put an electric field ahead of the tunnel. Deformation and displacement will happen to the ions in the water under the induction of the electric field. Then, when the power supply is cut off, ions in the water will gain the trend to move back to its original position. And due to the ion movement, an electricity field called the secondary electric field, also called polarization electric field, will come into being. The study found that, if the water yield is large, decay time of the secondary electric field would be relatively long; if the water field is small, decay time of the secondary electric field would be relatively short. Based on this principle, the induced polarization technology has been developed, and systematic physical model test and engineering application have been carried out. Our study found that there is an approximately linear relationship between the induced polarization information and the water yield ahead of the tunnel. What's more, experimental research has been done on the construction spot of dozens of tunnels. The experimental results have proven the existence of the linear relationship. At the same time, this method has broken through the limitation of the Three Dimensional Inversion Theory of the Advanced Detection of Water Bodies. This method can be used to carry out the three dimensional imaging and positioning of water bodies within 40 meters ahead of the tunnel face. Based on the above theories about the quantity and position forecast of water bodies using the induced polarization method, we have invented a compounded induced polarization logger, which has been developed to the third generation and has a stable performance and excellent engineering application effects.

The Whole-space Transient Electromagnetic Method is another technology developed by the team of Shandong University to detect water bodies. Here is the principle of Transient Electromagnetic Method: firstly, an electromagnetic field should be sent to the front of the tunnel; then the electromagnetic field should be cut off; if water bodies exist ahead of the tunnel face, induced electromagnetic field will be generated in the water bodies; at last, identification of the water bodies can be done through the analysis and inversion of the induced electromagnetic field, and positioning of water bodies within 80 meters can be carried out. Generally speaking, using the Transient Electromagnetic Method, we can figure out whether there is water ahead of the tunnel and where the water body is, but the water yield cannot be determined. For the transient electromagnetic of underground engineering, most people stick to the ground transient electromagnetic theories. But these theories belong to the Three-dimensional Half-space Detection Theory, which is completely different from the Three-dimensional Whole-space Theory of underground engineering. Therefore, the ground transient electromagnetic theories cannot be applied to tunnel forecast. To solve this problem, the team of Shandong University developed the Equivalent Conductive Plane Theory of Whole-space Transient Electromagnet, and established the Apparent Longitudinal Conductance Imagery. This new method has overcome the defects of the traditional method, such as false anomalies and low positioning accuracy. If there is a water body 30 meters ahead of the tunnel face, the traditional method will misjudge that the water body is 40 meters ahead, and the mapping range will be much larger than practical situation. However, if the Equivalent Conductive Plane Theory and Apparent Longitudinal Conductance Imagery are used, positioning accuracy and resolution effect will be greatly improved. Based on the above theories, the whole-space transient electromagnetic software and a set of apparatus have been invented, realizing the identification and accurate positioning of water-bearing structures within 80 meters.

After the efforts of more than a decade, the team of Shandong University and

Professor Shihang Zhong collaboratively created the Land Sonar Method, which has been proved effective in the construction of the auxiliary caves of Jinping Hydropower Station. Based on Minimum Offset Method, the Land Sonar Method is used to detect the unfavorable geological conditions through seismic wave. Based on a similar principle, foreign companies have already created a kind of apparatus called TSP. TSP can be used to detect faults which are intersecting vertically or with large angle to the tunnel axis. But TSP cannot be used to detect the small/medium-sized karst caves or the faults which are intersecting with small angle to the tunnel axis. Using the Land Sonar Method, the team of Shandong University enjoys a special advantage in the identification of small/medium-sized karst caves and inclined faults. From this picture we can see that the Land Sonar Method is satisfactorily accurate in the identification and positioning of bistratal karst caves and inclined faults. This method has been effectively applied in the forecast of Guangzhou and Dalian subway.

Using the above methods, a technological forecast system, which is progressive and comprehensive, of water-bearing structures has been established. The first stage is macro forecast, which is ranking the geological disasters based on the survey and analysis of the engineering geology. This stage is extremely important. Because geological work is the foundation of geophysical exploration, forecast of the tunnel's unfavorable geology must be combined with the geological work. Let me explain it analogically. For Chinese, the complete four-character idiom "ma dao cheng gong"(马到成功) will appear in their mind if any two or three of its characters are mentioned. But for the foreigners who are not familiar with Chinese culture, it will be difficult to do that. Similarly, geological work is the cultural background and deposits of forecast. Therefore, only with enough geological deposits can we soundly forecast the unfavorable geological conditions ahead. The second stage is long-distance forecast, which is combining the Land Sonar Method with TSP to carry out the positioning and identification of faults and karst caves within 120 meters ahead of the tunnel. The third stage is medium-distance forecast, which is using the Whole-space Transient Electromagnetic Method to carry out identification and positioning of water-bearing structures within 80 meters ahead of the tunnel. If there are only faults and dry karst caves ahead of the tunnel, no severe accidents will happen during the construction. But water-bearing structures ahead of the tunnel are great threats to the construction safety. The last stage is short-distance forecast which is combining the Compounded Induced

Polarization Method with the Georadar Method to realize the quantity identification and yield estimation of the water-bearing structures within 40 meters ahead of the tunnel. What's more, certain amount of drilling can be used to support the accurate judgment of the water-bearing structures ahead of the tunnel.

The employment of the above technological system will basically ensure the safety of tunnel construction. During the last decade, this technical system has been proved effective in the construction of dozens of high-risk tunnels, such as the West Section of Shanghai – Chengdu Freeway in Hubei, Yichang – Badong Freeway in Hubei, Dam Freeway of Three Gorges Dam, and the Kiaochow Bay Subsea Tunnel in Qingdao. Obviously, this system is not built in one day. It is gradually established based on the theoretical researches and engineering practices. During the establishment process, the accuracy of geological forecast is continually improved. This is the application example of the technological forecast system in Qiyueshan Tunnel of the West Section of Shanghai – Chengdu Freeway. The comprehensive employment of geological analysis, Land Sonar, Transient Electromagnetic and Induced Polarization guarantees the forecast of large-sized water-bearing structures, which provides appropriate references to the construction and receives praise from the headquarters of the West Section of Shanghai – Chengdu Freeway. This is the application of this system in Jinping – II Hydropower Station and this is its application in the Dam Freeway of Three Gorges Dam. Both of them have achieved satisfactory results.

Next, I would like to introduce the improvements we have made in the theories and technology of grouting treatment. After ascertaining the water-bearing structures ahead of the tunnel, disaster prevention and treatment should be carried out so as to control the water inrush and mud surging. Water around the tunnel surrounding rocks is usually flowing water, also called dynamic water. And sometimes, the water enjoys high pressure and flow velocity. How does the grout spread and move in the flowing water? What is its mechanism of plugging flowing water? What kind of materials, apparatus and technology are suitable to plug flowing water? How to carry out process control during the process of plugging? All these questions need to be answered in our research.

The team of Shandong University has designed a testing platform of grouting into the flowing water of the quasi three-dimensional fracture. The experiments show that the flowing water can only be controlled when the grout and water yield reach a certain proportion. If the proportion is higher or lower, no ideal effects will be achieved. For the treatment of flowing water, the grouting materials should be of excellent property, such as rapid hardening, strong resistance to flowing water erosion, good pumpability, relatively low price and easy promotion. In recent years, Shandong University has developed a kind of cementitious grouting material, which has a lot of advantages, such as adjustable initial setting time, strong dispersion resistance to flowing water, high strength at the early stage, environmentally friendly and non-toxic. The usage of this kind of material has been proved to be effective.

The most distinguished feature of the control technology developed by Shandong University in recent years is that an informationized comprehensive control system has been established. The major contents of "informationized" include: (1) based on the comprehensive geological forecast, detect the motion path of the flowing water in advance and determine the target area of grouting and control; (2) based on scientific plugging and draining plan, set up the control program in advance according to the forecast results and geological conditions; (3) adopting the effective overall monitoring method, monitor the information, such as deformation and pressure, of the surrounding rocks; (4) taking engineering need as research orientation, set up indoor material development laboratory and on-spot material laboratory centered on the material development and technology improvement, so as to improve the property of the materials.

Equipped with accurate forecast technology and grouting materials with excellent property, we can carry out scientific prevention and control of the water inrush and mud surging in the tunnel. During the control process of many water inrushes, it usually happens that the water has been under control in the early stage, but water inrush still happens later. This picture can illustrate this problem vividly. The major reason of recurring water inrush is that the water source is too close to the free face of the tunnel. As a result, the anti-inrush structure is too thick after the grouting, and its bearing capacity will be consequently low. Thus, break will happen under the pressure. When the water source is detected, key drilling can be deployed so as to block the supply path of the water at a certain distance away from the tunnel. In this way, a protective layer with strong bearing capacity will be formed. Although this control plan needs longer construction period and higher cost, the grouting amount is small and no recurring water inrush will happen. Thus more effective control results will occur. For example, during the construction of Liangshan Tunnel in Chongqing where the geological conditions is relatively poor, this control method has achieved excellent effects and prevented leakage of the nearby reservoir from happening, receiving praise from the Chongqing municipal government. Other examples can be found in Shandong Longgu Coal Mine, which has an annual out of 10,000,000 tons, and Jinan Zhangmatun Iron Mine. This control method has been adopted by them and brings satisfactory control effects.

Shucai Li, born in 1965, PhD, PhD supervisor, Distinguished Professor of "Yangzi River Scholars Program", recipient of the National Natural Science Foundation for Distinguished Young Scholar, subject matter expert of National High Technology Research and Development Program for Modern Transport Technology of China (863 Program), New century candidate of national project "Thousands of Talents", winner of the 9th China Youth Science and Technology Award. He is now the dean of Civil Engineering School of Shandong University, the director of Geo&Stru Engineering Research Center of Shandong University, the director of Large Underground Caverns Engineering Research Center of Ministry of Education, the chairman of Underground Engineering Branch of Chinese Society of Rock Mechanics and Engineering, the Chairman of Shandong Society of Theoretical and Applied Mechanics, the associate editor of Tunneling and Underground Space Technology and the editorial board member of Chinese Journal of Rock Mechanics and Engineering and Rock and Soil Mechanics.

The team he leads is selected in Innovative Research Team Program of Ministry of Education and Mount Tai Scholars "Climbing" Program in Shandong Province. His research interests include the disaster prediction and control of underground engineering and the construction process mechanics. He made important progress in the advanced forecast of adverse geological condition in tunnel and disaster control. He researched and developed the quantitative prediction technique of the water content of the water-logged stratum based on compound induced polarization and the water-logged stratum location and identification technique based on full space transient electromagnetic method. He established the theory method and technology system of the comprehensive advanced forecast of adverse geological condition in tunnel. His research results ensured the construction safety of dozens of major projects, including many high-risk karst tunnels of Hurongxi expressway in Hubei Province, Qingdao Jiaozhou Bay Channel Tunnel and high-risk tunnel groups of Sanxia – Fanba expressway, and had a good academic influence in the industry. He developed the construction process mechanics of underground engineering and established the analysis method of the minimum rock cover thickness of subsea tunnel construction with bored blast in China to confirm the minimum rock cover thickness of the first and second subsea tunnels (Xiamen Xiangan Submarine Tunnel and Qingdao Jiaozhou Bay Channel Tunnel), which is on world-wide leading level both home and abroad. He achieved important breakthrough and development in rock mass stability and security control of underground engineering and the test method and equipment research of large-scale geomechanical model. In recent years, he undertook 1 subject of The National Basic Research Program (973 Program), 1 project of the National High Technology Research and Development Program of China (863 Program), 2 projects of the State Key Program of National Natural Science, 1 project of the Major Joint Research Program of National Natural Science Foundation of China, more than 30 research subjects of national major or key projects. He published 7 monographs and obtained more than 20 invention patents.

Part Ⅲ

High-end Roundtable Panel Discussions

Topics: Strategy of science and technology development of underground engineering in the future 20 years, including

1) How to enhance management of the safety and risk in underground engineering

2) Development of science and technology:

   a) Mechanism, prediction and control of rockburst and water inrush

   b) Design theory for the safety of underground engineering

   c) Risk assessment theory

Current Status and Direction of Coal Mining Technology

Zhenqi Song

Shandong University of Science and Technology, Jinan, China

Energy is the foundation for the survival and development of human beings; the competition of the energy resources in the world has been increasingly fierce. Coal is always regarded as the main energy of China's fossil energy. In China, the coal storage accounts for 95% of the total fossil energy. By the end of 2010, the proven reserves of coal in China have reached 1.5 trillion tons, accounting for 97.9% of the total fossil energy storage.

At present, the major problems of the coal production are: Accidents about roof, gas, percussive ground pressure and water seepage haven't been controlled basically (that is on the basis of correct theoretical guideline, modern equipment and management methods), which influence the image of safety severely in China. Thus, to carry out a safe and high-effective exploration, to control the environmental disaster effectively, to explore the coal resources at the maximum, and to achieve a resource-saving, an environmental-friendly and sustainable development are the priorities of building resource security system and national economy development guarantee system.

Until now, the fully-mechanized mining technology (including the equipment standard and management level and technical and economical index) of the thin and medium coal seams with good occurrence conditions from the key large-scale state-owned coal mining has been listed at the advanced international level. The fully-mechanized mining exploration technology of the thick coal seams and the economical index has been in the international leading position. By now, due to lack of the theoretical guidelines and the lack of breakthroughs in the mode of management, serious accidents about gas, percussive ground pressure and water seepage constantly happen during the excavation of mining face. Under the corresponding coal mines and coal mine conditions, the importance of the adoption of the non-replacement pillar mining as a filling and exploration technology to control the major accidents and environmental disaster is not clear; the initiative of the promotion and application is insufficient.

For thousands of small-and medium-sized mines, accounting for 85% of the total, especially those thin and medium ones with poor occurrence condition due to tectonic movement, there is a lack of fully-mechanized mining equipments which are easily-disassembled and moved-down-side. This problem leads to the low proposition of the fully-mechanized mining and the low standard of the exploration technology and the low level of the equipment. Moreover, the management level still stays at the stage of relying on the experimental and statistical decision-making and the traditional guideline and regulation mode.

The space technology achievements of aerospace and navigation, together with the technological achievement and management level improvement of modern fully-mechanized mining technology, has laid the foundation of achieving the intelligentized mining under the ground in China. Through the intelligentized mining, we could further promote the development of the manufacturing mechanization, the information industries and the related industries. Furthermore, it has become the objective requirement to the industrialization and the development of the national economy. That is to say, the intelligentized mining under the ground has become the locomotive of the current industrialization development.

At present, the key technologies that need breakthrough in the intelligentized mining are:

(1) On the basis of deepening the theory of coalface roof control, we have successfully developed a way to send the information about the working support location such as information of a safe working environment, the information of the working condition of the equipments, and the dynamic information of roof movement and coal seam compression (distribution of abutment pressure) related to possible accident. We also have successfully equipped remote-controlled "supporting robot" (an intelligent mechanized support) and "bottom cutting and filling robot" (an intelligent road header of bottom-cutting and filling) to coalface of thin and medium coal seams, avoiding the roof

accident and the related accidents about gas, percussive ground pressure, water seepage from roof and water-inrush from floor. These measures can effectively solve the unbearable costs resulting from the traditional fully-mechanized mining of the hundreds of thousands of small-medium sized mines, and to change the high-cost, low-profit conditions resulting from the hard-disassembled equipments and low adaptability to the changeable geological condition of the coal seams.

(2) On the basis of deepening the theory of roadway pressure control, we have successfully invented "bottom cutting and filling robot" (an intelligent road header of bottom-cutting and filling) for roadways; and we have also successfully developed a way to send the dynamic information of the gas outburst or coal seam compression, or sinking roof, so as to ensure to prevent the ventilation of the old waste (the gob), and to ensure the drainage of the gas and prevention of fire with injection of nitrogen. On the basis of making breakthroughs of the compressible filling wall structures, we also need to achieve the intelligentization of "non-chain-pillar entry protection mining" technology.

(3) On the basis of deepening the practical theory of mining pressure control, we need to build an Intelligent Exploration Commanding Center (the frontline command center under the mine) at the lateral area of the tunnel. According to the need of the wireless communication and the operating distance of the electro-hydraulic control and the requirement of the working staff to enter the working place in time, the Center should forecast the accidents, control the accidents, make decisions towards the accidents, monitor the accidental conditions and protect the staff when accidents happen. The center should complete the system of collecting the related information and develop the decision-making software.

(4) Under the guideline of the theory of practical mining pressure control, we need to make practical breakthroughs in completing the forecast of the major accidents, decision controlling and carrying out the construction of surveillance-support system. The decision-support system integrating the function of accidents prediction, decision controlling mode, and related information infrastructure includes two parts. The first part is the accidents prediction before mining, the decision controlling, the judgments of the accidents control according to the stratum movement and the stress distribution collected by the means of monitoring instruments; the second part is to offer new implementation plans of controlling decisions.

The management department is really important. In the past, engineering management equals to statistical and experiential decision-making, which relies on the mode of guideline and regulation management. This won't work now. The way of management needs creativity; especially it needs to develop continuously. One of the major problems concerning the coal mine is management. The statistical and experiential decision-making, the mode of guideline and regulation management always influence the real technology development. The way to deal with the coal mine accidents still focuses on arresting the people. In fact, we should work out the reason of the accidents and learn from it, rather than simply arresting the people.

The management department of the Chinese Academy of Engineering is really a very important department, which studies the management problem in a scientific way. How to combine the pursuit of truth with the real truth is a currently rather important topic. The underground coal mine is the biggest underground engineering; we should focus on this topic and solve the problems.

Zhenqi Song, born in Wuhan of Hubei Province in March, 1935, has always been employed as tenured professor in Shandong University of Science and Technology (SUST). In 1991, he was elected as an academician of the Chinese Academy of Sciences due to his prominent contribution for practical theory of mining pressure. Academician Song dedicates himself to develop the fundamentals of practical theory of mining pressure and propose the relevant structural mechanical models for prediction on serious disasters occurring in mining field, which can greatly update mining procedure and improve safety mining effectively. In addition, Academician Song is also keen to not only develop higher education in China, but also innovate new teaching methods combined with research activity.

Risk Control of Underground Power House Complex in Pumped Storage Power Station Projects

Shaoji Luo

Guangdong Storage Power Generation Co. Ltd, Guangzhou, China

1. Background

Along with the fast social and economic development and the demand for stable power grid, Guangzhou pumped storage power station (PSPS) (Phase Ⅰ & Ⅱ) and Huizhou PSPS (Plant A and B) have been built, while another two, i. e. Qingyuan PSPS and Shenzhen PSPS, are under construction at present in Guangdong Province. For the distribution of the PSPS in Guangdong Province, see Fig. 1.

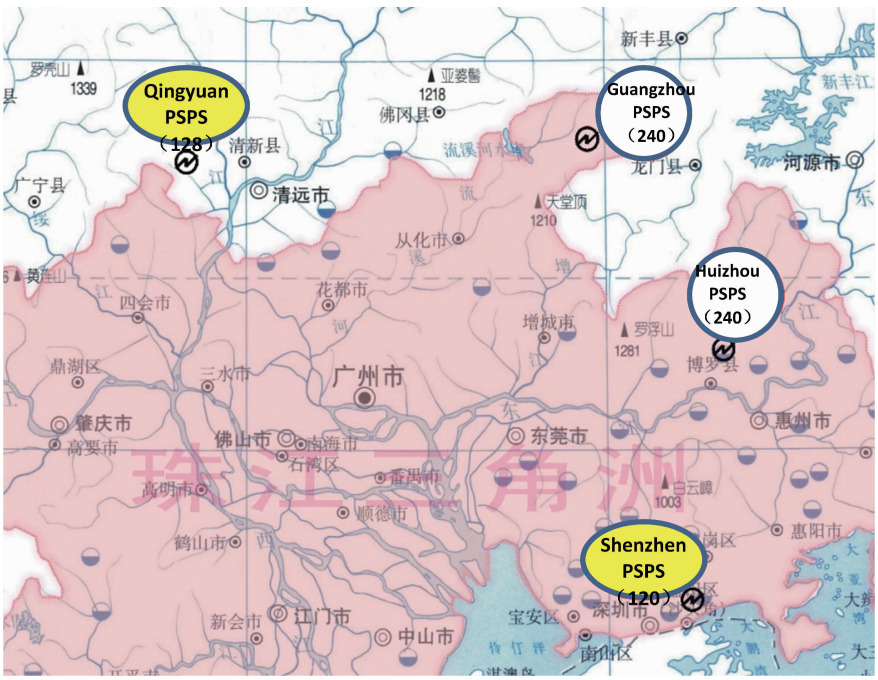

Fig. 1 Distribution of pumped storage power station (PSPS) in Guangdong Province

The PSPS consists of upper reservoir, lower reservoir and head-race & power generation system. The head-race & power generation system comprise long tunnels and underground power house complex. The PSPSs built in Guangdong Province are deeply buried underground power stations with high head, about 500 m difference between upper and lower reservoir heads. The burying depth of underground power houses are around 300 – 400 m. Reversible pump turbine units are adopted for the PSPS. With consideration of unit suction height in pumping mode, the unit installation elevation of underground power house is about 50 m (1/10 times the head difference between upper and lower reservoirs) lower than the normal pool level of lower reservoir. Therefore, both the upstream and downstream of underground power house complex of PSPS are located in complicated geologic underground environment which are below the high water level of reservoir.

In the underground projects of PSPS, the head-race system is mainly the long tunnel, including head-race tunnel, manifold, head-race branch, tailrace branch, tailrace bifurcated pipe, tailrace tunnel, surge shaft, etc. The head-race tunnel and tailrace tunnel are generally 2000 to 5000 m long and 8.5 to 9.5 m in diameter. Four units share one head-race tunnel and one tailrace tunnel. The head-race tunnel is connected with the underground power house through manifold and four steel head-race branch pipes. In order to meet the hydraulic gradient demand, the complex shall be arranged far away from the manifold with reinforced concrete lining as much as possible. The tailrace tunnel is connected with the underground power house through tailrace bifurcated pipe and four steel tailrace branch. There is about 150 m between the tailrace bifurcated pipe and the underground power house. According to hydraulic transient and different construction models, head-race surge shaft and tailrace surge shaft are usually arranged in the water delivery tunnel respectively, or either of them is provided. The surge shaft is 120 to 150 m high, including riser about 9 m in diameter and big shaft around 20 m in diameter. The underground power house complex includes underground power house, main-transformed cavern, bus bar tunnel, draft tube gate, traffic cavern, ventilation tunnel (air shaft), HV cable tunnel, drainage gallery, gravity drainage tunnel, etc. The underground power house has a span around 20 m, a height around 50 m and a length from 150 m to 170 m. The spacing between the manifold and the underground power house is from 130 m to 150 m. The main-transformed cavern is about 20 m wide, 20 m high and 150 m long, connecting the underground power house with four bus bar tunnels. In order to satisfy the stability of surrounding rock, the spacing between underground power house and the main transformed cavern is about 40 m. In view of complicated connection between deeply buried water delivery tunnel and underground power house, as well as complicated underground engineering and hydrological geology, it is of great importance for site selection, excavation and support, as well as underground water interception and drainage control system of underground power house. Figure 2 shows the longitudinal section of water delivery system in Qingyuan PSPS.

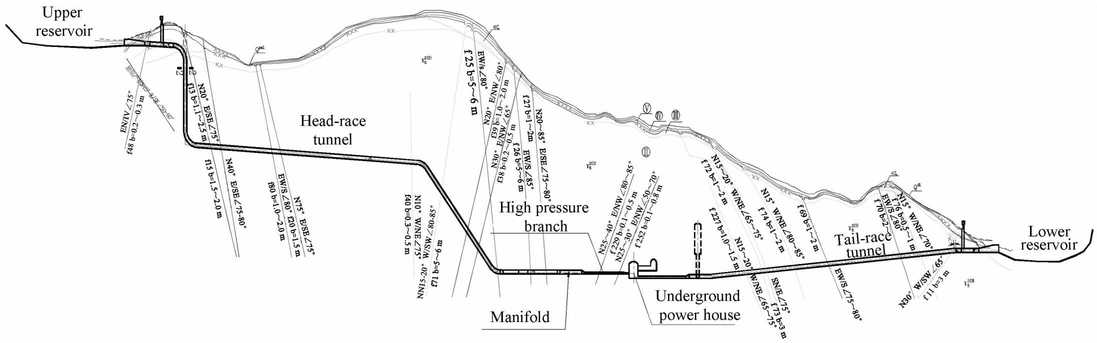

Fig. 2 Longitudinal section of water delivery system in Qingyuan PSPS

2. Site selection of underground projects

The underground power house complex are buried 300 m to 400 m deep. The manifold with reinforced concrete lining bears a kinetic head of 600 m to 800 m. Therefore, it is very important to select both sites of underground power house and manifold. The main factors influencing the underground projects involve fracture, alteration, ground stress and underground water, etc. In order to arrange the manifold and the underground power house on a relative intact rock mass, the sites shall be determined optimally step by step according to analysis of underground geology through different design phases during the geological survey of previous period and the underground power house site selection design phase.

First of all, from the perspective of topography, the construction model of power station is studied and determined, and the basic site scope of underground power house is proposed preliminarily. Then the site of underground power house is recommended on the basis of geological structure, fault width, strike and dip according to surface exploration.

According to the preliminarily proposed site, more than 400 m deep geological prospecting holes are drilled from the surface to the bottom of power house. After analyzing the passing faults, fractures, and underground water, the position and axis of underground power house could be optimized further.

More important, in order to determine the proper layout of power house, a more than 2000 m long underground testing tunnel is excavated in the almost determined position. The testing tunnel can be set only dozens of meters (this value could be changed according to different projects) above the crown elevation of power house under the consideration of uncertainty of deeply buried underground power house and small slope of testing tunnel. The geological bores have been set in testing tunnel as well.. Through unveiling the width, strike and dip of each fault by analyzing the testing tunnel and the geological bores, observing the underground water for a long term and testing the ground stress in this region, the site and axis direction of important parts of underground projects such as manifold and underground power house can be finally determined to be arranged on the relative intact rock mass with reasonable ground stress, deformation and landslide.

Nevertheless, during excavation of ventilation tunnel and traffic cavern, granite alteration was found. Through precise analysis, the strike of main fracture was determined and the key underground complex were arranged in a fresh and intact rock mass. For instance, the cavern position and shape of main power house, surge draft, manifold, etc. were all optimized after knowing the geological conditions. The long testing tunnel excavated above these structures and then supplementary bores drilled downwards. Another example is that because the direction of underground power house axis was altered from SN to NE80°, making the included angle between the axis and the main fault and alteration zone exceed 40°, thus the whole power house was moved 40 m westwards. The exposed altered rocks influenced stability of partial surrounding rock when they became dilated and disintegrated after contacting underground water and humid air. Through study and exploration, some effective measures have been taken to deal with the altered rocks and stabilize the surrounding rock, such as clearing altered loose material, shotcreting and supporting in time, and handling underground water properly.

Since rich experience has been accumulated from the site selection and the altered rock zone treatment of underground power house of GPSPS Phase Ⅰ, the key complex like manifold and underground power houses of GPSPS Phase Ⅱ, Huizhou PSPS (Plant A and B) and Qingyuan PSPS have successfully avoided being built in large-scale faults and intensive zones of cracks. Especially, the power house and the manifold of Qingyuan PSPS have been all arranged in class Ⅰ surrounding rock and a few in class Ⅱ surrounding rock, avoiding faults zones with directions of near EW and near NE. Up to now, the excavation of underground power house has been finished, and there is no rock explosion or landslide during construction. The safety risk of large underground projects under complicated geologic environment has been minimized and the excavation quality has received applause from famous experts in this field. It is proved that the site of underground power house was selected in an optimal geological condition, which saves quantities of supports and reduces construction period and investment.

3. Excavation and support control of construction

In addition to making proper selection of underground power house site and axis, a good excavation process control of underground power house is also very important to the safety of underground projects. The excavation of underground power house adopts the principle of "excavation in thin layer, support in time" and real time monitoring. The excavation blasting parameters are adjusted timely. Therefore, the excavation quality can be ensured, the surrounding rock can be prevented from being damaged and the deformation of power house side wall can be controlled.

In Guangdong province, the PSPS underground power house has a span of more than 20 m, height of more than 50 m and length of 150—170 m. According to respective construction passage and construction method, excavation is carried out in Ⅶ or Ⅷ layers. In order to guarantee the excavation quality and minimize the range of affected surrounding rock due to excavation, different construction methods based on the characteristic of each layer shall be taken. For PSPS underground power house in Guangdong, pneumatic drill excavation with central heading method is adopted for the first layer excavation; the expanding excavation of crown and upstream & downstream side is carried out with staggered distance; and the peripheral holes adopt smooth blasting for excavation. The second layer adopts pre-splitting in middle, reserving 5.5m protection layer on both sides and smooth blasting for peripheral holes. Smooth blasting with vertical and inclined holes is adopted for excavation of rock bench of rock anchored crane beam. From the third layer to the sump floor, it first carries out pre-splitting, and the excavation of upstream & downstream side is carried out with staggered distance or with full section.

Based on the good selection of underground projects sites and elaborate control of construction excavation, the PSPSs in Guangdong province take full advantage of self-stability of surrounding rock and adopt flexible supporting method combined with sprayed concrete and anchor rod. According to different surrounding rocks, sprayed concrete with hanging mesh method, and sprayed steel fiber concrete/polypropylene fiber concrete without hanging mesh could be both adopted for the crown. Provide 3.5—3.7 m long anchor rods. The arch foot is provided with two or three rows of anchor rods with a length of 5.3—6 m and the spacing between anchor rods is 1.5—1.8 m. The side wall shall adopt sprayed concrete with hanging mesh and set 3.5—3.7 m long and 5.5—6 m long anchor rods with spacing of 1.5—1.8 m. Three rows of 9 m long anchor rods shall be arranged for the rock anchored crane beam, two rows above and one row below, the spacing between anchor rods is 1.5—1.8 m. In order to make timely support after excavation and to guarantee the construction quality, three-boom rock-drilling jumbo is adopted to drill holes for anchor rods, Master grouting machine is adopted to grout for anchor rods and Master spraying vehicle is adopted to make wet spraying.

The quality of underground power house excavation will directly affect the deformation of surrounding rock. Especially the rock anchored crane beam has very high requirements on deformation of surrounding rock. Through elaborate excavation control and timely support, the power houses excavation of PSPS in Guangdong province have very good quality. Surrounding rock damage, such as landslide, has not occurred. The deformation of power house side wall is controlled within allowable range. For effect drawing of controlling deformation by support during excavation of Guangzhou PSPS, see Fig.3.

4. Control system for anti-seepage drainage

PSPS is deeply buried underground power station with high head. The high pressure head-race tunnel and manifold undertake inner water pressure more than 500 m. 40-60 cm thick reinforced concrete lining is adopted for both the high pressure head-race tunnel and manifold, which is designed per theory of high pressure pervious lining and

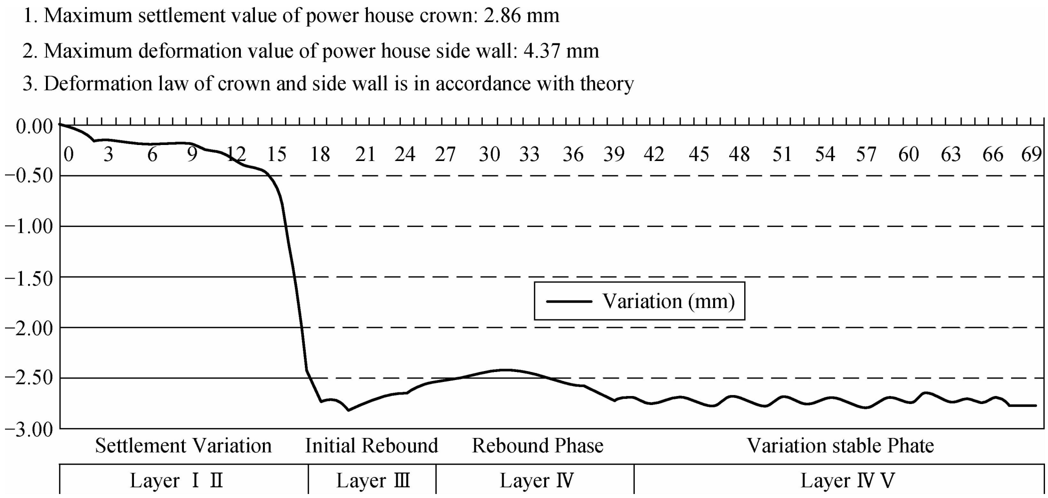

Fig. 3 Effect drawing of controlling deformation by support during excavation of Guangzhou PSPS

to restrict the width of cracks. Therefore, seepage of inner water will be caused due to high pressure water head during operation.

According to calculation, external pressure shall be mainly controlled for manifold and high pressure branch. Especially during emptying tunnel, rather high pressure will be imposed on the lining, which is very adverse to the steel lining branch pipe. Meanwhile, in order to reduce the underground water and high pressure seepage water to enter power house and main transformer chamber, so as to reduce the seepage pressure borne by the power house side wall, improve the operation environment of underground power house; it is very important to reasonably arrange anti-seepage drainage system for the manifold and underground power house.

In Guangzhou PSPS, five "defense lines" are provided to solve the problem of anti-seepage and drainage for manifold and underground power house. The principle of "prevent seepage first, drain water second" is followed. The first "defense line" is to adopt steel plate lining for the head-race branch pipe between manifold and power house, which is to ensure that no seepage of high pressure inner water will be caused within this range. The second "defense line" is to set anti-seepage curtain between manifold and steel branch pipe, which is to prevent the manifold seepage water from entering high pressure steel branch pipe and power house area. The third "defense line" is to set water drainage system on steel branch pipe surface, which is to directly drain the water on steel pipe surface so as to reduce external water pressure borne by the external surface of steel pipe. The "fourth defense line" is to provide drain holes for the 1# drainage tunnel between manifold and power house, which is to drain the water infiltrating into power house. The fifth "defense line" is to arrange two layers of drainage gallery around power house and main-transformed cavern as well as to drill drain holes to form water drainage curtain so as to drain underground water in this area and decrease external water pressure. For anti-seepage and drainage control system of manifold and underground power house, see following Fig. 4.

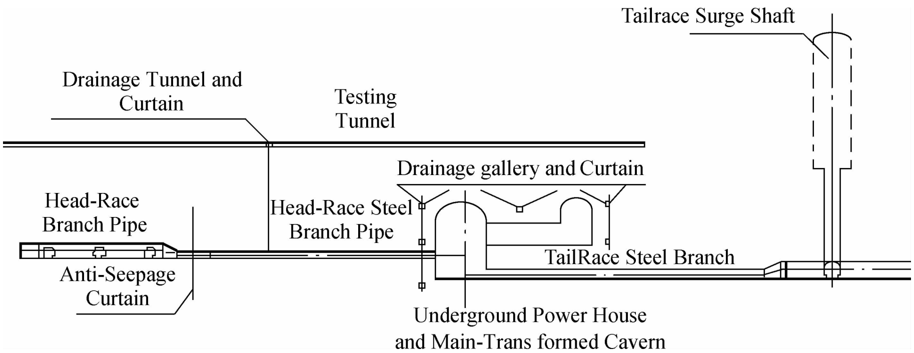

Fig. 4 Anti-seepage and drainage control system of manifold and underground power house

In addition to the above mentioned five "defense lines", both Huizhou PSPS and Qingyuan PSPS add gravity drainage system based on the advantageous topographical conditions, so that the water in underground power house complex and drainage gallery can enter the gravity drainage system through underground power house drainage system and then be drained outside of power house. By this way, the operation environment of underground power house can be highly improved.

For PSPS, if the water seepage of manifold and underground power house can be effectively controlled or not? If the seepage water can be drained properly or not? If appropriate operation environment can be provided for the underground power house or not? In a word, a proper control system of anti-seepage drainage is the key to the success of the project. All PSPS in Guangdong Province adopt reinforced concrete lining for manifold, which is designed per theory of high pressure pervious lining and to restrict the width of cracks. Through five "defense lines", the problem of anti-seepage and drainage for manifold and underground power house has been solved. The above mentioned measures are very successful. Compared with the expensive steel plate lining, much investment has been saved. However, during the process of implementation, some lessons could be leaned.

For example, bulging occurred at the steel lined transition section of tailrace branch pipe during initial water filling of Guangzhou PSPS phase I project, because backfill of concrete at outside of tailrace gate was not compact and grouting was not enough. Therefore, inner water in tailrace tunnel imposed pressure on outside of upstream steel lined transition section through tailrace gate slot concrete and acted as external water pressure linking with the lower reservoir water level. Deformation and bulging of different extends appeared on steel lined transition sections of all four tailrace branch pipes. After that, effective measures have been taken, such as to cut the deformed steel lining, to weld and repair the steel pipes and to set drainage system inside the steel lining gap, etc.

During the initial water filling for upstream waterway of Guangzhou PSPS phase II project, spurting high pressure seepage water occurred in the drainage testing tunnel above the concrete bifurcated pipe of upstream waterway. The maximum seepage amount reached 31.78 L/S. Overall check was carried out after emptying the waterway and it was found that there were 42 pieces of cracks in the concrete lining of manifold and reverse osmosis of external water existed in all cracks. Most of cracks were 0.5–1 mm wide, some were 2 mm wide. After emptying the waterway, all cracks were open. Through analysis, it was found the cracks of the manifold lining was the main cause of large seepage in the south and east adit; and the NW micro-open structure was the main discharge passage of the seepage water. Two kinds of treatments were made afterward: on one hand, high pressure chemical grouting was carried out for manifold, fine cement grouting and chemical grouting was made for the questionable sections and P4 osmometer hole; on the other hand, concrete backfill was carried out for the testing tunnel to the south of 1# drainage gallery. After treatment, the upstream waterway has operated safely for about 13 years, the total amount of seepage water in manifold area is about 2.3 L/S in general and the readings on osmometers in this area are also normal and stable.

The ground elevation of the high pressure tunnel of plant A of Huizhou PSPS is 425–435 m, the average buried depth is 260 m. The ground elevation of the manifold of plant A is 475–480 m, and the average buried depth is 340 m. The surrounding rock of water delivery system and power generating system is mainly granite. Surrounding high pressure tunnel and bifurcated pipe, several faults pass through. Among those, fault F304 has a width of 10–15 m and the broken degree is rather high, which is a controlling fault of the plant area. During the water filling of Plant A upstream waterway, a large quantity of water rushed both from fault F304 in the testing tunnel and from the exposing section of fault F59 in 1# grouting gallery. The actually measured total seepage amount of the testing tunnel is 781.5 m^3/h and the maximum seepage amount of the waterway is 811.4 m^3/h. When making water filling test for Plant A upstream waterway, rather dense cracks appeared in the concrete lining of tunnel. According to the situation of water filling, high pressure chemical grouting and strengthened consolidation grouting were carried out for the waterway after being emptied. Moreover, deep hole cement grouting and backfill blocking were made for the faults. After completing water filling for the second time, seepage were measured for testing tunnels, plugs and all drainage galleries of plant A power house, the total seepage amount is about 19 m^3/h and the total seepage amount of the 3122 m long upstream waterway is about 80 m^3/h. After emptying, the waterway was repaired and treated. Since then, the seepage of waterway is highly reduced and the seepage amount is within reasonable range.

5. Conclusions

(1) The selection of site of manifold and underground power house is of utmost importance in controlling project risks and saving investment. In preliminary work, various comprehensive measures such as earth surface survey, deep-hole prospecting and underground testing tunnel, etc. are taken to fully reveal the engineering geological conditions and hydro-geological conditions.

(2) The excavation of underground power house adopts principle of "excavation in thin layer, support in time" and real time monitoring. The excavation blasting parameters are adjusted timely. Elaborate construction excavation control and immediate support can effectively guarantee excavation quality; avoid surrounding rock failure and control side wall deformation of power house, etc.

(3) Major underground projects like manifold and underground power house, etc, adopt five security defense lines to solve anti-seepage and drainage, following the principle of "prevent seepage first, drain water second." Each procedure is of utmost importance and is the key to the success of a project.

Shaoji Luo, born in Nanhai, Guangdong in 1933, is a graduate of Tsinghua University. His career appointments have been President of Central South Survey and Design Institute of MWREP, Director of China Southern Power Grid Company of MWREP, Deputy Managing Director of Guangdong Power Office and General Management of Guangdong Storage Power Generation Co. Ltd. He currently serves as consultant to Guangdong Storage Power Generation Co. Ltd. He won twice the second-prize of National Scientific and Technological Progress Award and was elected academician of Chinese Academy of Engineering in 1999.

Risk Prevention of Projects Concerning the Development of the Underground Space together with the Construction of the Subway Engineering in Big Cities

Zhongheng Shi

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1. Grasp the great opportunity of the large-scale construction of the subway engineering project and properly plan and put into place the use of the underground space in big cities

As the rapid advancement of our economy and acceleration of urbanization, the population of cities in our country is increasing at a sky-rocketing speed, thereby resulting in a growing expansion of cities' sprawling space and an abrupt rise in the number of motorcycles. More crowding as it is, this leads to a more salient question existing in our traffic. What's worse, the urban land resources have become gradually limited. The issue becomes more challenging in that it is coupled with much more crowding of the buildings and progressively decreasing of the afforested areas. In an attempt to solve the traffic problems, big cities are prone to take measures such as constructing subways in a large scale; and in order to solve the problem of increasingly limited land resources in big cities, a prevailing concept of appropriately developing and utilizing the underground space has been engraved onto people's minds.

Since subways in the downtowns of cities are mainly underground lines, thus the railroad sections and underground stations occupy much of the underground space in cities. If taken into full accounts the proper utilizing of the underground space in the cities during the process of the subway engineering, much more room will be left for the future development of the underground space of cities, hereby enabling an easier use of the over-ground and underground space in a more comprehensive, integrated and optimizing manner.

This is also justified by the practice of the projects in the big cities both at home and abroad. For instance, the Kowloon comprehensive transportation junction in Hongkong has developed the underground streets, underground shopping centers etc with the construction of subways. Montreal and Toronto in Canada have developed the underground walk-through system and underground city, featuring a large-scale, multi-functional and rather convenient transportation. New York of America, moreover, has combined the subway system to develop an underground synthesis system involving underground streets, underground walk-through and underground shopping centers. In addition, the subway station-La Defense in Paris has established a "double-decker city", indicating that all the rail transit, roads and static traffics are set below the ground, whereas over the floor we can only see the landscape facilities such as the greenbelts, public activities space and the fountains. With regard to Japan, however, since it has a very limited land area and nervous usage of the land in cities, at the very early stage it had a well-planned program suggesting a hierarchical planning of the underground 30 – meter space: the first deck boasts a depth of 3 to 5 meters, mainly arranging a utility tunnel including the artery and branches; the second deck has a depth of 6 to 10 meters, mainly planning the underground walk-through, underground streets, underground parking lot and subway stations etc. or the same utility tunnel as the first deck signifies; the third deck has a depth of 10 to 30 meters, mainly laying out the subway routes, underground parking lots and subway stations. This planning, thus, witnesses Japan playing a leading role in highly-efficient use of the underground space, construction scale, skilled proficiency in the world. Besides, it now is planning the development of the underground 100 – meter space in a big way.

To the end of 2011, there are 13 cities in our country already having launched 53 urban mass transit lines, with the operating mileage up to over 1650 miles. Currently 36 cities have already accomplished the planning of the rail transit, among which 31 cities' plans have passed the examination and approval of the State Council. To 2015, 28 cities nationwide will boast 96 operating lines of subway, with its mileage totaling 4000 miles; and to 2020, the mileage all over the country will amount to over 7200 miles. In this case, our country is and will be in a critical period of massive construction of subways for a long time in the future. Thus, it no wonder suggests both great opportunities and daunting challenges in properly planning and developing the underground space of cities by relying upon the precious opportunity of large-scale construction of subways.

2. Many arresting problems exist in the current development and use of the underground space of cities in our country

Firstly, no specific legislature concerns the planning of the underground space; particularly there exist no relevant laws and regulations regarding the joint planning of the development of subways. This, thereby, causes a lack of legal basis in the planning of the underground space, exerting a tremendous impact on the sustainable development of the urban integrated planning, sustainable development of the urban rail transit as well as the development, usage and protection of the non-renewable resources in the underground space.

Secondly, many departments are bound up with the development and usage of the underground space. Also, barriers between higher and lower levels are very salient among different departments. This is demonstrated by the fuzziness of the functionary boundaries, several of whose functions being intersecting, which brings about a situation where no concerted efforts can be made for the coexistence of multi-managing mode and non-managing mode. Nevertheless, the development and usage of the underground space is a systematic engineering which is in exact need of the solidarity and coordination among all departments. The dissonance hence generates maladjustment between the management mechanism and system and the practical demands.

Thirdly, the planning of the usage of the underground space has been burdened with backwardness, lacking foresightedness, integration and coordination. This, undoubtedly, has given rise to a situation in which all departments do things in their own way and act willfully. Thus it causes the development plans being carried out separately and fragmentarily with a single function. Worse still, due to a lack of correlation and interconnectedness, it has received a particularly low comprehensive efficiency, resulting in a potential huge difficulty and high risk in the future integrated development and usage.

3. Significant measures should be taken to lower the risks of the development and usage of the underground space

Firstly, we should introduce some relevant laws and regulations as well as some standardized norms regarding the usage of the urban underground space without any delay. We must explicitly prescribe the management system of the urban underground space as well as the issues about the underground ownership, right of planning, right of management and right of use, etc. It is through this way that we can make the planning, designing and managing of the development and usage of the urban underground space obey the rules and abide by the laws.

Secondly, we should launch a mechanism of unified planning. That means we should include the usage of the urban underground space into the planning of the urban development, urban integrated traffic and urban rail transit for the sake of realizing the overall planning between the usage of the underground space, the urban traffic, subway hub and the stations, air-raid shelters and the municipal pipelines. We should, in the meanwhile, bring about the simultaneous planning, designing, construction and putting into use of the subway and the usage of the underground space. Few years ago, for example, Chongqing Municipality initially advocated the "Three Simultaneous" in the planning, construction of the subways and the development and usage of the underground space, then having come a long way.

Thirdly, we must make sure the completion of the prophase exploration work to efficiently lower the risks presenting in the underground projects. This indicates that in combination with the construction of the subway engineering, we should achieve a good effect of our exploration work in the subway stations and its surrounding developmental areas for the engineering geology, hydrogeology, surrounding buildings, underground utilities, underground structure and obstacles. If we exert stricter controls on the safety risks, we could enormously lower the risks of the future development of the underground space.

Fourthly, we should pursue the implementation of the risk assessment system regarding the planning scheme of the subway phase by phase. In this way we can effectively avert and timely control the risks in the planning phase for the future construction and operating process.

Fifthly, we will conduct researches on the large-scale underground project for its construction, designing techniques in a more in-depth and multi-functional way, therefore resolving the potential risks for the future massive development and usage of the underground space.

All in all, the urban underground space is a valuable resource of strategic importance but with a downside of high engineering risks. Thus, for us, to foster a well-planned scheme of the urban underground space incorporated with the current large-scale construction of subways is, therefore, without any doubt, a fundamental method of guarding against, and lowering the risks of the development of the urban underground space.

Zhongheng Shi, born in Shanghai in 1930, was a graduate of Tangshan Railway Institute in 1953. He joined China's Air Force to resist U. S. aggression and aid Korea; from 1955 to 1959, he took advanced courses in Former Soviet Union Moscow Institute of Railway Transport Engineering and returned home with Vice Doctorate degree. In 1999, he was elected academician of Chinese Academy of Engineering. From the 1960s when he engaged in the construction of Line 1 of Beijing Metro (China's first subway), he has been working in the field of Urban Mass Transit. His professional career has been Head of Beijing Research Institute of Underground Railway Engineering and General Engineer of Beijing Urban Construction Design & Research Institute.

He is currently an honorary professor of Southwest Jiaotong University, professor and supervisor of PhD students of Beijing Jiaotong University, Director of Expert Committee of Chinese Urban Rail Transit Association, Director of Expert Committee of Quality and Safety under the Ministry of Construction and Director of Transit Expert Committee of Beijing, Chongqing and Nanjing. In addition, he serves as an expert advisor of China International Engineering Consulting Cooperation and expert advisor of Beijing Municipal People's Government.

He has evaluated the feasibility study reports of Beijing, Shanghai and Guangzhou Metro, and authored *Design of Metro*—China's first national norms on metro design, *Design and Construction of Underground Railroad*—China's first monograph on Metro and the journal *Urban Rail Transit*. His research subjects include "Research on Subway Cost Reduction Engineering Management", "Strategic Research on the Spatial Pattern of Chinese Smart Cities", "Research on Integrated Transport Strategy and Key Technology in Chinese Major Cities", all of which have contributed tremendously to China's railway construction.

Underground Engineering Projects in Underground Nuclear Power Plants in China

Youmei Lu

Chinese Dam Association, Beijing, China

Thank you for giving me this opportunity to have a speech at this conference. I was supposed to make a speech about China's Underground Hydraulic Engineering. Yesterday Academician Hongqi Ma has made a comprehensive and thorough speech, so I will skip this part. Chairman Qihu Qian requires me to mention the concept of underground nuclear power plant, he and our other colleagues have offered this suggestion, so I'd like to have a summary.

First, we all know that the accident of Japan's Fukushima nuclear power plant was caused by the tsunami after an earthquake. The stand-by power of the reactor, a diesel generator, was not able to operate. The plant lost power and thus the cooling water circulating pump of the reactor stopped, resulting in the rise of temperature and melt of the reactor. So the nuclear leakage happened. After the accident, many dangerous and difficult ways have been used to solve the problem.

After the leakage, we came up with a new idea: we could put the reactor under the ground in case of various accidents and risks. Once accidents happen, we could close the underground reactor, the rocks can avoid nuclear leakage since they are very excellent anti-radiation medium. Thus we can feel at ease to build the nuclear power plant to meet the energy needs of the human beings. The technology of underground engineering has been perfected. Let me take some current engineering as examples. The Three – Gorge hydraulic power station has 32 units, including 6 units with 700 thousand kilowatts, which are put in the right bank of the mountain under the ground. The span of the plant is 32.6m with a length of 311.3m. The units will be put into operation in July this year. There are four giant hydropower stations along the lower reaches of the Jinshan River, including Xiluodu hydropower station which has 18 units with 770 thousand kilowatts. The total installed capacity is 13.86 million kilowatts, with an average annual energy output of 57.12 billion kilowatt-hours. Huge as it is, the units of the power stations are all installed in the mountains alongside the two banks. The span of the underground plant is 31.9 m, with a length of 444 m and an excavation height of 75.6 m. At present, the building project of the underground plant of Xiluodu power station has been completed; it will be put into operation next year.

For such a large-scale underground project like Xiluodu, why is there no severe rock burst or adverse geological environment in the process of construction? Because before we chose the location of the station, we had done a lot of exploration work. The harmful geological structure has been avoided, creating an excellent constructing condition. In the whole process of construction, except the accidents of electric shock or falling from high positions, no casualty resulting from tunnel collapse, flooded shafts or rock burst has been reported. These are the successful examples which prove that it is favorable to build underground engineering. However, when we plan the underground engineering, we must ensure that the location is far from the faults or the possible seismic fault lines. It is a very important preliminary process.

People would say that if we put our nuclear reactors under the ground, it would raise the costs. I will list some examples about cost. I have calculated that the cost of the underground power station is 100 dollars per cubic meter. Compared with the total cost of the station, underground engineering accounts for a little part; so it is acceptable economically.

Secondly, some people put forward problems concerning the safety of the rock structure. The nuclear reactor (like the third-generation AP100 in USA or the ERP in Europe) is a cylinder with a diameter of about 40 m. After examining the underground engineering of hydropower station, we do have the ability to design a cylinder with a diameter of 40 m. Since stress of its surrounding rocks is low, hydropower station can be achieved, so does the nuclear station and safety of the reactor. There is a reactor in the containment called pressure vessel, the lifting capacity of which is rather high. However, the lifting capacity of the powerhouse of hydropower station is above 2000 tons. Thus the problem of the lifting capacity of the pressure vessel can be solved.

Third, how about the earthquake-resistance capability? People worried that the earthquake-resistance capability of the underground power station may be low. A lot of researches prove that and so as the engineers think that the earthquake resistance capacity of the underground engineering is much better than that of the buildings above the ground.

Fourth, can the underground water be contaminated? Many measures have been taken to completely cut off the underground plants of the power station from the underground water, including consolidation grouting, drainage or the curtain grouting of the surrounding rocks. Some people worried that the radioactive substance of the underground nuclear plant will permeate into the underground water, which leads to contamination of the underground water. However, if the work of seepage control can be done properly, this problem may not be worried.

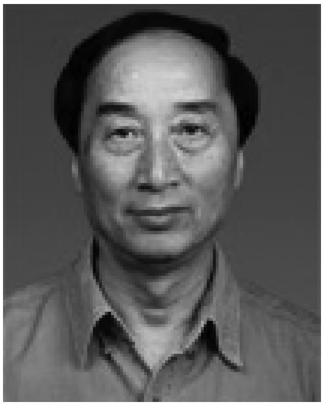
Fifth, there are many passageways and auxiliary plants in the underground plants, so we could build another underground cavern to store the low-radioactive substance; that is the storage of spent fuel. After we have processed the spent nuclear fuel, we could use them in the fourth-generation nuclear plant. If there is a nuclear leakage accident, all the passage ways will seal the door which is specially designed and anti-radiation. Thus the nuclear leakage will be prevented.

Sixth, a nuclear power plant needs a large sum of cooling water. Generally speaking, the nuclear power plants are built by the sea, so that they could make use of the processed sea water as the cooling water for the gas turbines. If we build the nuclear power plants in the inland areas where there are no sea water, a stable water resource will be needed. If we combine nuclear power plants with the reservoir of the hydraulic power station, we could solve the problem of supplying cooling water for the underground power plants.

To make a further assumption, we could combine the nuclear plants with the hydraulic power plants together, so as to get high-effective and clear energy. China's energy requirement needs quite a long process of improvement. For now, the annual electricity possession per capita is only 0.75 kilowatts; while in USA is 3 kilowatts, in Europe is 2 kilowatts. So we still have a long way to go. If we generate power by burning a lot of coals, it will lead to environmental pollution and the discharge of the carbon dioxide, which are very unfavorable.

The idea of the underground power plants is not primarily put forward in China, Russia and Europe has already studied on the feasibility of the underground power plants. China has launched a series of practical works. Changjiang Design Institute of

Changjiang Water Resources Committee has cooperated with Design Institute of Nuclear Power from Chengdu; and they offered a feasible alternative. On this conference of safety construction and risk management for the underground engineering, we put forward this topic of building underground power plants for your reference.



Youmei Lu, born in Shanghai in 1934, is an expert in hydraulic and hydro-power engineering. He obtained his bachelor degree from the East China Institute of Water Conservancy in 1956. In 2003, he was elected academician of Chinese Academy of Engineering. His main career appointments have been Deputy Minister of Ministry of Water Resources and Electrical Power, Deputy Minister of Department of Energy and Vice Chairman of State Council Three Gorges Projects Construction Committee. He is currently honorary chairman of Chinese Dam Association and professor of Tsinghua University and Hohai University.

He has spent his professional career in technology and management of hydraulic and hydro-power engineering. He was appointed general manager of Three Gorges Engineering Development Co. Ltd, from 1993 – 2003. In 2003, he completed the project of initial reservoir filling, generating unit and lock navigation. Besides, he is the author of *Three Gorges Concrete Construction*, *Management Practice of Three Gorges Construction and A Brief Introduction of Three Gorges Project Through Practice*.

Design and Risk of the Current Underground Engineering

Yingren Zheng

Logistical Engineering University of Chinese PLA, Chongqing, China

I really appreciate this conference which enjoys high efficiency and intensive topics. The people who attend this conference are those who have studied on those topics for so many years, while I really learned a lot of new things. After all, I'd like to make some suggestions on the design and risk of the current underground engineering.

First, I think the underground engineering design of our country is dissatisfactory. Comparing with other countries, the risk is much higher. Why the design is dissatisfactory? In China, most underground engineering are railway tunnels, highway tunnels and subways. There are two kinds of specifications in tunnel design. They differ a lot in the size of the tunnel structure. For example, in the National Standard of Shotcrete Support, favorable surrounding rocks, like surrounding rocks of Grade Ⅰ, Ⅱ, and Ⅲ, adopt thinner linings highways, railways and subways. And there is no secondary lining. As for the surrounding rocks of Grade Ⅲ, if the tunnel has a span of 10 – 15 m, there will be no secondary lining; and the total thickness of the preliminary lining is about 10 – 12 cm. We have employed this standard for more than 20 years since 1985, until now we still employ this size. However, if we employ the railway standard, under the same circumstance, the thickness is about 40 cm. Both of the two standards are based on experience. Why such a big discrepancy exists? It shows that our design methods are confusing, and less attention from the government is received. From my point of view, the difference is resulted from the different understandings from the engineering calculation world to the tunnel design; the current circumstance is irrational which needs more attention from the government.

Secondly, it is about the risk problem. I think the risk problem is related to the design method of the engineering designers. Nowadays, the tunnel design of the domestic transport pays much attention to the secondary lining. Since the preliminary lining is thin, the secondary lining bears the main loads, which leads to greater potential risks. The span of the tunnel is becoming greater. Situations like condition of surrounding rocks is poor and ground stress is large have become more and more common. So if the preliminary lining is still 20–30 cm, it will not be sufficient to bear the deformational pressure. Take loess tunnel as an example, in the past the span was 5 meters, now it is ranging from 12 or 13 meters to 17 or 18 meters. During the construction of the loess tunnel, the excavation has only reached several hundred meters, but two accidents have happened. During the first one, houses above the ground fell to the tunnel, three people died; and then the second accident happened, fortunately no one died this time. It shows that we pay less attention to the preliminary lining. The western countries hold the view that the preliminary lining should bear the major loads, while the secondary lining is just supplementary. I agree with the view, I think that we should pay much attention to the construction of the preliminary lining and reduce the construction risks, especially those tunnels with special geological conditions, crushed rocks, wide span and tunnels with high ground stress and complicated hydrologic condition. In many cases, the risk happens in the wide-span tunnel while the rocks are loose and soft. It is easy to damage the rocks of the two sides of the tunnel, which lead to a great collapse from the vault. So I think our design method is dissatisfactory. We should make great efforts on the preliminary lining. Under some circumstances some people start to pay attention to double preliminary lining to solve the risks during the construction. I think we should strengthen the preliminary lining while reduce the width of the secondary lining, so as to reduce the risk and waste.

Thirdly, according to my research and working experience, we should focus on the following points: the first is that we should employ many monitoring equipments; the second is numeralization—vast majority of computers should be used; the third is that we should employ information and visualization system. These three areas are current development direction. Unfortunately the discrepancy between China and other countries in these three areas is wide. Firstly, we need advanced monitoring equipments; but the advanced monitoring equipments are mainly imported from foreign countries. The domestic level is still at the beginning state. Since the development of the methodology falls behind, so we usually begin the project first, and then try to regulate and control through monitoring. What's more, developing methodology also needs test of monitoring. Secondly, the numerical technique has advanced both at home and abroad, thus many softwares have been developed. The numerical technique is a convenient and easy tool. Although scientific experiments take a lot of time, the numerical simulation is simple and quick. Once the simulation is accurate, it will cope well with the experiment. Of course if the simulation is not accurate, it will fail. At last, we need to employ information, animation and visualization system in the designing and construction. I hope we could achieve a lot in the system.

Fourthly, we need to work hard to develop the construction machinery and engineering equipments, doing our best to achieve industrialization, normalization and standardization. Comparing with foreign countries, the development of the machinery in our country is less advanced. Although we have large-scale machinery, we still fall behind. In fact, only if we have big changes in the construction machinery or equipments, can we achieve big changes in the designing methods or risk prevention; so the development of the large-scale equipments is important.

Water Burst, Mud Inrush in Underground Project Construction

Fengjun Zhou

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Today I want to talk about only one subject—the water burst and mud inrush in the underground tunnel. As for this, Norwegian Professor Nick has talked a lot in his speech, which I think is of great value. Currently, the most prominent problem in the underground project construction in China is the water burst, mud inrush and rock burst. Here are several cases that Academician Qian has referred to. For example, the water burst and mud inrush in Yuanliangshan Mountain. How does it feature? Firstly, the ground water level was 400 meters, where tunnels for the railway would be excavated. Secondly, many underground caves, which could be found everywhere, were connected with each other in the tunnels. Thirdly, however, the local people insisted the railway should be constructed here because they were too poor. According to the original planning, the railway does not go through this area, but the local people strongly requested, so the Ministry of Railway decided to construct the railway here. Surely they knew it was full of dangers, which I think can't be completely avoided. They, however, didn't draw back. What they did was to promote the development of the local economy. What problems did they encounter then? Small dangers were not big problems. However, once there was a big one. What was it like? We were likely to be cheated by the pseudomorph: the tunnel face earth and rocks were weathered and appeared to be dry. As there was no sign of serious water burst, we thought it would be safe. However, during the following excavating process, the water poured out in a sudden, so fierce that it drove all the weathered earth and the high-pressure water at the back of the tunnel out of the 9 – meter diameter cave. The earth from the cave pushed the working trucks moving forward for more than ten meters. We can imagine how fierce it was. Unfortunately, some workers died in this accident, the cause for which was that we did not geologically find out how deep the earth was, and how much water was stored behind its back. The radar was actually not useful for water geology. Behind the earth was very huge water there, the water here and the water 400 meters above was closely linked from east to west. So its water pressure reached 40 atmospheric pressures. Such a great pressure as 40 atmospheric pressure of water would push the earth. In this manner, the whole earth was pushed out at a high speed, thus resulting in a disaster like this. Although we had not imagined such serious accident, it happened actually. The second example was concerning the place of Yesanguan, where not only did water and mud burst out, but stones as well, about a cube with the stones from the tunnel face covering the whole 300-meter long road. Stones could be seen everywhere then. I got down examining myself, but I just could not understand. The excavated stakes spreading all over the tunnel face were much clear. So what was the real cause? But I realized that I do not specialize in geology and I was completely confused. Later, we invited some geological specialists for figuring out the real cause, then we were told that the underground river was opened up. Afterwards, we looked back and found the stones there were much different indeed, not the same kind. The stones of the underground river were washed away to the tunnel. Thus, the power of the nature is unimaginable, so certainly it would cause casualties. Then it's an accident happened in Maluqing on the railway line from Wanxian to Yichang. The water with its size larger than the auditorium was opened up, flying out like a river, with 200 cube water per second, causing lots of deaths. The underground water caused huge damages to us, however, we can learn a lot of lessons from it. Here I have three suggestions:

Firstly, much attention must be paid to the geological investigation, which shall not only be done well at the beginning of the engineering. Also we should redouble our efforts during the construction process since we are not clear about it. As we are unfamiliar with the geology, we are not sure whether there are bigger water-eroded caves or not. Sometimes we excavated very deep, only to find there was a big water-eroded cave ahead, which had not been found before the excavation. Geological exploration must be conducted during the construction process. When problem occurs, we should spare no efforts on spending more on fixing it. Often we think we and the proprietor have no responsibility after the project's being transferred to the construction unit, neither has the design party. Of course it is not right. The engineering is our joint responsibility which hence should be taken by us together. The geological investigation should be conducted carefully before construction, which cannot be simplified, and should be also throughout the whole construction process.

Secondly, we can perfect the measuring and danger forecast in the construction process. In the past, we have done a lot, but without much experience. Some of the accidents are resulted from the construction unit's too much care of the schedule, and being not careful, which we had also warned them of. The investigation work we had done didn't cover the vicinity of the construction tunnel face, so many accidents happened like this. Therefore, the measuring should be done near the excavation tunnel face to the utmost, which is absolutely very necessary. Additionally, the methods of measuring should be diverse and much bettered. Apart from the radar technology, some new technology, for example, the method Professor Shucai Li presented was very practical. When applied in the forecasting of the whole road tunnel later, it was much practical for forecasting water burst, with the success rate up to 80%, even 90%.

Thirdly, we should do much more on the grouting technology. There was too much gushing water in the tunnel, spraying 20 to 30 meters away. When one hole mouth was spraying water, how could we stop it? It was very difficult. But there should be some methods. In recent years, we have developed double liquid grouting technology. The water-spraying hole can be quickly jammed by the grouting. Also we have adopted the launching method to send out the grouting to the hole, and continue to grout the high-pressure areas through a pipe. The grouting in the hole mouth should be higher than the altitude of the whole water. If we want to get an injection pressure of 400 meters, the atmospheric pressure shall be above 40. At present, we can get 100 atmospheric pressures, leaving a much higher pressure of grouting. Besides, we must guarantee the successful operation of high polymer grouting, which would push the whole water up completely. The similar technology stopping water by grouting still needs continuous and progressive improvements. Therefore, we will have more methods to deal with the possible disasters.

国际工程科技发展战略高端论坛后记

科学技术是第一生产力。纵观历史,人类文明的每一次进步都是由重大的科学发现与技术革命所引领和支撑的。进入21世纪,科学技术日益成为经济社会发展的主要驱动力。我们国家的发展必须以科学发展为主题,以加快转变经济发展方式为主线。而实现科学发展、加快转变经济发展方式,最根本的是要依靠科技的力量,最关键的是要大幅提高自主创新能力,要推动我国经济社会发展尽快走上创新驱动的轨道。党的十八大报告指出,科技创新是提高社会生产力和综合国力的重要支撑,必须摆在国家发展全局的核心位置,要实施“创新驱动发展战略”。

面对未来发展的重任,中国工程院将进一步发挥院士作用,邀请世界顶级专家参与,共同以国际视野和战略思维开展学术交流与研讨,为国家战略决策提供科学思想和系统方案,以科学咨询支持科学决策,以科学决策引领科学发展。

只有高瞻远瞩,才能统筹协调、突出重点地建设好国家创新体系。工程院历来高度重视中长期工程科技发展战略研究,通过对未来20年及至更长远的工程科技发展前景进行展望与规划,做好顶层设计,推动我国经济社会发展尽快走上创新驱动的轨道。

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