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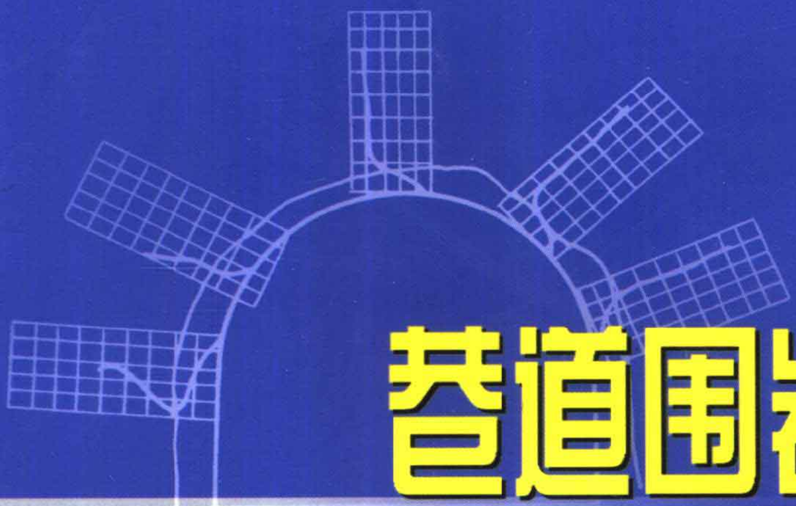

巷道围岩松动圈支护理论及应用技术

The Supporting Theory Based on Broken Rock Zone and Its Application Technology

董方庭　等著

煤炭工业出版社

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前　　言

客观的事物客观地存在着，发现它却往往是偶然的。在1979年，最初我只是对锚杆的作用机理感兴趣，我的第一个意识就是围岩的状态决定锚杆的作用机理。当时超声波测试刚刚在煤炭系统中应用。在这一观点的驱使下我在淮北矿务局朱仙庄矿进行了大量的超声波测试。这些资料清楚地告诉我，围岩存在着一个声波速度降低区，其规律性很强。从声测的机理分析这是一个围岩破碎区，这就是大量巷道开凿后的围岩状态。这一测试结果将我从原来的兴趣上引开，我提出了几个问题：(1) 这一状态产生的原因；(2) 这一状态与当时流行的支护理论有什么不同。

初步推论，这一状态的产生是围岩应力作用的结果，巷道开凿后，围岩原岩应力会发生变化，围岩应力以集中应力的方式在围岩中重新分配，围岩从三向应力的强度降低到二向应力的强度。这两种变化使围岩发生了超过围岩极限强度的破裂变化，即后来我称之为的围岩松动圈。开巷后围岩状态被确定，产生这一状态的原因被初步确定，我们的目标改为研究支护荷载问题，即支护理论问题。支护荷载决定于围岩状态：松散介质理论认为冒落拱内岩石重量是支护的外荷载；弹塑性理论认为控制弹塑性变形为支护的荷载，或者破碎区的岩石重量为支护的荷载；而松动圈理论认为围岩松动圈产生过程中岩石的碎胀力(碎胀变形) 为支护的荷载。

为了回到原先的研究目标，对锚杆的作用机理我们初步认为：无松动圈时锚杆无支护作用，中等松动圈时锚杆起悬吊作用，大松动圈时锚杆为组合拱作用。当时就在朱仙庄矿井进行了试验，并写出了两篇论文，其中一篇还在煤矿基建系统在杭州召开的学术会议上宣读，1980年获淮北市科技进步奖。

1982～1983年我们有机会与徐州地区的王庄矿合作，经过对该矿松动圈的测试，确定其中一部分巷道不用锚杆，确定一部分运输大巷的松动圈值为0.7m，使用长度为1.1m的锚杆。这在当时是我所知道的最短的锚杆 (原支护用锚杆为1.8m)。1982年由江苏省煤炭系统组织召开了鉴定会。事隔将近10年，该矿已大面积应用这项技术，这是松动圈支护理论首次完整的应用。它在技术上的最大特点是可用理论的方法确定锚杆的支护参数。此理论发展到目前，已经初步确定了自己的支护观点、分类方法和锚杆支护机理。

1984年淮北矿务局石台矿第二水平井底车场开拓工程被大量破坏，只有U型钢支护可以维护，其松动圈值大都是1.7m左右，我们确定采用有效长度1.5m的锚杆用组合拱理论进行支护，取得了成功，其成本降低了一半左右。组合拱理论是国外的模型研究资料，是我们首先将这一理论应用到工业试验，取得了成功，我们的成果是测到了破裂岩石锚固体强度。

1985年研究生闫凤山在洛阳89002研究所的相似模拟试验台上完成了重要试验。他在真三轴试验台上演示了围岩应力和围岩松动圈的发展过程，并且做出了锚杆的组合拱作用。这就在理论上证明了围岩松动圈理论，即开巷后围岩的弹塑性变形远远小于其岩石破裂时

所产生的碎胀变形。意外的是，在做了理论分析后，发现在试验条件下，巷道跨度、支护的强度对围岩松动圈值的影响较小。后来宋宏伟教授在不同实验台上的大量实验结果也证明，当跨度在 3～7m 范围内，它们的显著性很小。这样松动圈支护理论就给学术界提出了几个有趣的问题，也给这个理论的分类方法提供了充分的条件。因为如果巷道支护类型及强度在多数条件下都对松动圈值影响较大，则现用的围岩松动圈分类方法将失去应用基础。在这个试验的基础上我们的围岩分类方法于 1985 年在《建井技术》上正式发表了。实际上这一分类思想和具体内容在 20 世纪 80 年代初已经在我们的工业实验中应用了。

松动圈支护理论的产生有一个过程，1979 年到 1985 年，巷道围岩松动圈支护理论、分类方法和锚喷支护机理三个有机的部分初步建立起来。用三句话可以概括：支护的主要对象（荷载）是围岩松动圈形成过程中的碎胀力；松动圈是地应力与围岩强度的函数，它是一个综合指标，其值越大支护越困难，达到 1.5m 时即为软岩支护技术；根据围岩的状态、围岩松动圈的大小确定锚杆支护机理。

对这一理论的产生，争论点有二：第一，现有支护方法在开始能否提供足够的支护力使围岩不进入破裂状态。我们认为所有的支护不能及时进行，在围岩的弹塑性变形后才能施工。支护都与围岩有一个不密实的空间，支护力是从极小的值开始，围岩大变形后才能达到设计强度。因此，现有支护（超前支护例外，包括锚杆支护）没有能力阻止松动圈的产生和发展；第二，松动圈产生了，围岩的弹塑性变形、围岩的碎胀变形、围岩破碎带内岩石重量，它们谁是支护的主要对象。松动圈理论认为碎胀变形（力）远远大于其他两个荷载。

1995 年以后，我们进行了大面积推广和继续完善理论和技术工作，先后与数十个矿务局合作，在不同的地层和工程中实验推广这一理论和方法。其中，鸡西矿务局的 109m^2 大断面硐室，平顶山、淮南的软岩支护，开滦矿务局的 1160m 的深井支护，兖州南屯矿、潞安王庄矿和漳村矿的放顶煤顺槽锚杆支护等都取得了成功，并且获得了突出的技术经济效益。在此期间唯一的一次失败，是由于设计错误，发生在淮南矿务局的谢桥矿东风井。与此同时，山东矿业学院、西安矿业学院、黑龙江矿业学院的教师们，分别在他们的工作中推广。其中，辽源矿务局梅河矿在该局池祥赫副总工程师的带动下，一举使一个亏损的矿井年盈利 2 千万元左右。平顶山矿务局也已在全局推广。

这一理论经过 20 余年的发展，仍然有一些重要的问题待解决：在理论方面，各种岩石的碎胀力定量问题。这个问题的解决之日也是地下工程支护设计彻底摆脱经验方法之时，它的解决就是支护荷载定量问题的解决；在分类方法方面，简便、快速的测试手段需改进，软弱岩石的松动圈准确测定方法需研究；在锚杆支护技术方面，破裂岩石锚固体强度问题、组合拱的强度问题、组合拱的预留量问题等。还有我们未能预见到的理论和技术问题以及外荷载定量问题的解决，将使地下工程的支护设计完全可以使用理论的方法来解决。

岩土工程学科有三大部分：岩石性质、支护理论和支护技术。目前受弹塑性支护理论的影响，岩石极限强度以前的本构关系研究比较完善。而松动圈支护理论更看重岩石峰值后的本构关系，目前这一部分的研究工作非常薄弱。相应的支护技术，特别是锚杆支护理论和技术将用松动圈理论来分析问题和解决问题。因此，可以预见，随着这一理论的完善和发展，将从基础上影响岩土工程学科，特别是深部地下工程部分。

本书由我本人策划、定稿。第一章宋宏伟执笔，第二章靖洪文执笔，第三章郭志宏执

笔，第四、五、六章靖洪文执笔，第七章郭志宏执笔，第八章周荣章执笔。另外，这一理论和技术的发展已有20余年，我的十几位研究生，合作过的老师，现场工作人员，在不同点上都有贡献，他们的见解与结论在其各自发表的论文中各有表述，恕不一一例举。

董方庭

2000年12月

FOREWORDS

An objective thing is there in his way, but getting a discovery of it is really by chance. My early interests were only about the mechanism of bolts used underground. A sonic probing measurement firstly began to use in the coal industry in China. My No. 1 thought was that the mechanism of bolts should be controlled by the physical state of the surrounding rocks. With this idea, I conducted a lot of measurements of sonic probing at the Zhuxianzhuang Coal Mine, Huaibei Coal Bureau. The result told me that there was a drop zone of sonic velocity in the surrounding rocks, with remarkable laws. It was a broken zone according to the analysis using the principle of the sonic probing. That was a state of surrounding rocks after excavation for lots of underground projects. The results made me go away from the original interests. Therefore I made a few questions: (1) what caused those phenomena to occur? (2) what was the difference between supporting theories by this state and by the prevalent points of view that time?

Preliminary conclusions were that the phenomenon was the result of action of surrounding stresses. The stresses would be redistributed after excavation with a concentrated pattern around the excavation. The strength of rock mass is decreased due to stress state was changed from 3 dimensions into 2 dimensions. Those changes make the rock mass physical state shift into a broken state. That is what I called the Broken Rock Zone (BRZ) late. After the state was measured and the reason to produce this state was basically realized, our target was changed toward problems of the loads of a support. That is the problem of supporting theory. The loads that act on the support were determinate by the state of surrounding rocks. The loose ground theory considers the weight of loosed rock within loosening zone as the object of supporting; Elastoplastical theory considers the elastic and plastic deformation as the object of supporting, or the weight of rock in deformed zone as the object of supporting. While our supporting theory based broken rock zone considers the bulking force or deformation as the object of supporting.

In order to go back to the original target of the research, we concluded on the supporting mechanism of bolts basically that a bolt would have no action of supporting if there is no broken rock zone in the surrounding rocks; The function of bolts is to suspend the rocks in a middle size broken rock zone; The compressed zone would formed by bolts in a large size broken rock zone. An industrial test was then conducted at Zhuxianzhuang Coal Mine and two papers were published. One of the papers was presented at a academic meeting at Hangzhou on the coal mine construction. A award of progress of science and technology was given by Huaibei City in 1980.

We had a chance to cooperate with the Wangzhuang Coal Mine at Xuzhou area between 1982—1983. After probing of the broken zone around transportation roadway, reformed design of supporting was done. Bolts were token out in some area of the roadway and short bolts of 1.1m were used for the rest, based on the extent of 0.7m of broken zone measured. It was the shortest bolts even used. The bolts were 1.8m in original design.

The appraising meeting for this program was held in 1983. Ten years after we visited the coal mine. The technique was used widely in the mine. This is the first time that the supporting theory of broken rock zone is completely used in site. The remarkable peculiarity of this application is that the parameters of bolts were determined with theoretical method, that is, it was based on the supporting theory of broken zone. The supporting theory of broken rock zone was primarily developed as it could give its own point of view on the supporting, rock stability classification and the supporting mechanism of bolts.

In 1984, the shaft bottom projects were seriously deformed at the second mining level of the Shitai Coal Mine of Huaibei Coal Bureau. Only U section steel ribs could sustain the deforming. The broken zone was about 1.7 m in size. We used 1.5m bolts that were designed based on the principle of compressed arch. The test was success which cause the cost of supporting to decrease by 50 percent. The compressed arch principle is proposed in abroad. What we did is to measure the strength of bolted rocks. Therefore, we firstly applied this principle into industry and made a success, and passed appraise.

In 1985, my postgraduate Mr. Fengshan YAN finished an important model test on the frame of 89002 Institute at Luoyang. The test had demonstrated the process of the developing of a broken zone. Also the test had proved the compressed arch formed by bolts. This approved the supporting theory of broken rock zone theoretically. That is, the convergence caused by elastic and plastic deformation is much smaller than that caused by breaking of surrounding rock. It was by chance found that the size and supporting strength had smaller effects on the extent of a broken rock zone at the condition of the tests. Professor Hongwei SONG also had confirmed this result by lots of model tests late. By then the supporting theory of broken zone had proposed several interesting questions to academic circles. At the same time, these results are for our rock stability classification. Because our classification system would lose its base if the support type and strength at most conditions affect the extent of broken zone greatly. On the basis of this test, our classification system was formally published in Mine Construction Technology in 1985. In fact, this concept of classification and its contents were used in our early industrial tests and applications in 1980's.

If we say that the proposition of the supporting theory of broken zone is a process, the first stage should be between 1979 and 1985. The supporting theory, classification and supporting mechanism of bolt and shotcrete, which were based the broken rock zone, were primarily set up. They could be concluded with three words: the main supporting object (loads) is the bulking force produced during the developing of the broken zone; the size of broken zone is a synthesizing index. It is a function of rock stress and rock strength. The larger the broken zone is, the more difficult to support the opening. The surrounding rock will be classified as a soft rock if the size of the zone is more than 1.5m; According to the surrounding rock state, the bolting parameters can be determined based on the size of the broken zone.

There are two arguing points on this theory: firstly, whether the common supporting manner could provide enough force to prevent the surrounding rock from entering the broken state? We consider that the all-supporting types are not able to provide support force in time. A support is placed after the plastic deformation has occurred. There is a gap between the wall and the support. The supporting force increases from a small value, Only after the big deformation occurs, can the support reach the designed strength. Therefore, recent support (not include pre-supporting) do not able to stop occurring and developing of the broken zone. Secondly, when the broken zone has occurred, the elastic deformation of the surrounding rock, the bulking deformation, the weight of the broken rocks, which is the main supporting object? The broken theory considers the bulking deformation larger than other two main objects.

After 1995, we did both two jobs, extending the theory to a much larger area in China, and improving and perfecting the theory and technique. We cooperated with more than 10 coal bureau to extend our supporting theory to various rock conditions and projects. Among them, we successfully applied the theory and technique into projects: 109m^2 winch room at Jixi Coal Bureau, soft rock projects in Huainan and Pingdingshan, 1160m deep roadway supporting projects in Kailuan Coal Bureau, mining roadways in Nantun, Yanzhou Coal Bureau and Wangzhuang Coal Mine, Lu'an Coal Breau. The good economic effects were achieved in these projects. At the same time, teachers from Shangdong Mining Institute, Xi' an Mining Institute and Heilongjiang Mining Institute had extended our theory and technique in their own area separately. Headed by chief engineer Mr. Xianghe Chi, our theory and technique had been used completely in the Meihe Coal Mine in Liaoyuan Coal Bureau. This had made the mine become a payoff mine with earning 20 million yuan each year. And also the theory had been extended in Pingdingshan Coal Bureau.

But there are some important problems need to be further solved in our theory, although it has developed for 20 years. On the theoretical side, there is a quantitative problem of the bulking force of various rocks. The design of underground supporting will get ride of the empirical method in the day when this problem has been solved because it has solve the problem of supporting loads. On the issue of rock classification, there is a need to produce fast, cheaper tools for detecting the broken rock zone, especially in soft rocks. On the side of the technique, we need to assess the strength of bolted rocks, the strength of compressed arch, the final convergence and so on and to solve other problems theoretical and technical. We think that the solution of the supporting loads will lead to the design of underground project supporting by theoretical method completely.

Geotechnical subject consists of three parts: rock properties, supporting theory, and supporting technique. At present, influenced by elastic and plastic theory, the preperty of rock have been studied well, but the supporting theory of broken rock zone pays attention to the post property of rock. But the study of this field is very unsubstantial. The related technology, especially bolt supporting theory and technique will need to be developed based on the broken rock zone. Therefore, as the development and perfect of this theory, it will influence the underground projects in geotechnical subject on its foundation, especially on deep underground projects.

This book was masterminded and revised by Professor Fangting DONG; Professor Hongwei SONG wrote the chapter one; Associate Professor Hongwen JING wrote the chapter two, four, five, six; Associate Professor Zhihong GUO wrote the chapter three and seven; Lecturer Rongzhang ZHOU wrote the chapter eight. This theory has been developed for 20 years. My more than 10 graduate students, other teachers and site engineers and staffs have contributed a lot to this supporting theory. I do not to cite them here one by one, please see their papers.

Fangting DONG
December. 2000

目　　录

Contents

第一章　巷道围岩松动圈的研究

开巷后围岩的应力和物理变化过程是判断支护外载荷的基础，是支护理论建立的基石。松动圈支护理论是在研究巷道周围的岩石介质物理力学状态的属性的过程中发展起来的，所以，松动圈的研究始终贯穿于松动圈支护理论发展的整个过程中。对松动圈属性的深入认识是松动圈支护理论的立论基础之一。为此，这一理论在其发展和完善过程中，利用了相似模拟试验、现场实测、工程验证和理论分析等手段，对巷道围岩松动圈进行了较为全面的研究。其目的是为了深刻认识松动圈的性质，为松动圈支护理论立论奠定基础，并为这一理论的应用提供依据。

众所周知，采矿和地下工程都需要在地下开挖，形成一定大小的空间，并保持该空间的稳定。但是，在地下开挖后，将会扰动岩石介质，造成岩石内应力和岩石强度的变化，产生岩石应力转移、集中和岩石强度的减小，使空间周围岩石发生变形甚至破坏，发生岩石物理状态的改变。这个在开挖的空间周围所形成的破裂区，一般是围绕开挖空间形成环状（图1－1)。我们把这个由于应力作用产生的环状破裂带称为巷道围岩松动圈，简称为松动圈。在现场，可用声波仪、多点位移计等探测出围岩中的这个破裂带的厚度，称其为松动圈值。

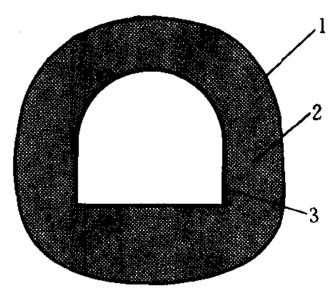


图1－1　巷道围岩中的松动圈

1—松动圈外边界；2—松动圈范围；3—巷道周边

松动圈的客观存在性及其性质，特别是松动圈与支护的相互作用，可从模型实验、现场实测和理论推导三方面加以证明。

第一节　松动圈的实验室相似模拟研究

如上所述，松动圈是围岩中的一个破裂带。围岩中破裂带的产生与许多因素有关，如地质条件、工程条件、施工方法等，因此，松动圈的形成因素的研究是一个复杂的问题。由于现代力学对岩石破裂后物理与力学性质的研究仍然是一个课题，现场测试研究松动圈又受人力物力的限制，使用模型研究成为松动圈及其性质研究的主要手段。对松动圈诸多相关因素的分析表明，松动圈的形成因素最终可归结为两类，即岩石强度和岩石应力。松动圈是围岩强度小于围岩应力条件下产生的。模型试验可以人为地控制试验条件，取得所要求的数据，有现场研究不可比拟的优点。我们进行的几次模型试验，取得了大量数据，对认识松动圈及其性质、特点以及它与支护的相互作用起到了重大作用。

一、关于围岩松动圈存在的相似模型试验

本次模型试验是1985年在中国人民解放军某部研究所的真三轴试验台架上进行的。模

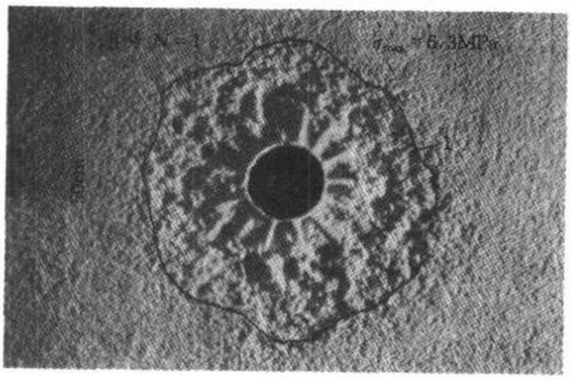
型试块尺寸为 500cm×700cm×20cm，采用“先加载，后开洞，再逐级加载至破坏”的试验方法，保持平面应变，静水压力，最大载荷为 6.8MPa。试块几何比为 $C_l=35$，应力比为 $C_p=8$。模型巷道为圆形，其直径为 100mm，共作 4 块试块，其材料为均质，用水泥、石膏、砂子等配制模拟材料，其单轴抗压强度都为 1.0MPa。巷道支护分别采用了裸体和锚喷。有支护的巷道模型，锚杆长为 40mm，间排距为 20mm×20mm，用铝丝模拟锚杆材料，其弹模 $E=26000$MPa。喷层用胶水与砂的混合物模拟，其单轴抗压强度为 2.6MPa。

试验得到了松动圈和它在不同加载应力级下的厚度（图 1－2）。根据 4 块试块内埋设的应变片得到了松动圈的数据，回归得到了原型上松动圈与原岩应力的关系式，对岩石抗压强度为 8MPa 的原型有：

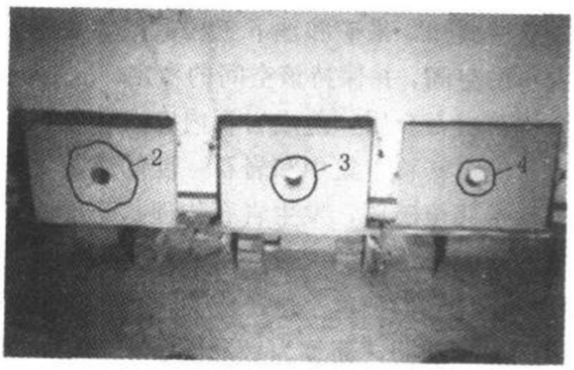
$$P_0=152e^{0.0037L_p} \tag{1-1}$$

式中　P_0——原岩应力，MPa；

　　　L_p——圆形巷道松动圈厚度，cm。



(a)



(b)

图 1－2　实验得到的相同强度试块上的松动圈

1—模型状态下松动圈；2—应力达到 6.5MPa 时的松动圈；

3—应力达到 6.3MPa 时的松动圈；4—应力达到 5.5MPa 时的松动圈

由式（1－1），在模型上，当 $L_p=5$cm 时，$P_0=1.019$MPa。

在解剖试验后的模型试块中意外得到了锚喷作用形成的圆形组合拱，其厚度为锚杆的长度（详见图 4－18）。

模型试验表明：有锚杆支护与无支护情况下，松动圈的厚度差别不大，即锚喷支护对松动圈的厚度或尺寸影响不大（详见后面的论述）；但是，有锚杆支护与无支护时，其围岩破坏状态差别很大，有锚杆的试块，其洞周受损区较大。

这一模型试验得到的主要结论是：当围岩应力超过围岩强度时，松动圈存在于巷道围岩中；围岩松动圈的厚度越大，巷道的支护破坏越是严重；锚喷支护不能明显影响松动圈的厚度，即支护对松动圈的作用不大，可以忽略（这一论点的进一步论证请参阅以后各章节）；原岩应力越大，处于其中的巷道围岩松动圈厚度也越大；锚喷支护在松动圈较大的围岩或“软岩”中，能把破碎的岩体重新约束和连接在一起，这些被重新约束在一起的岩体我们称为锚固体．锚固体是一个连续的挤压结构，它起支护巷道围岩的作用。

模型试验从根本上回答了：围岩松动圈的客观存在性；松动圈是原岩应力的函数，原

岩应力越大，松动圈越大，支护也越困难。由于松动圈的这些性质，因而用松动圈的厚度作为指标对岩石进行分类并确定支护的机理是科学和合理的。

二、松动圈及其影响因素的相似模拟试验

传统上认为，巷道围岩的稳定性或支护的难度，与地压、岩石的强度、开挖的空间尺寸以及支护阻力等有关。如果这样，松动圈值能否真正有效地作为一个合理的围岩稳定性分类指标，进而确定合理的支护参数呢？为此，我们严格按相似试验设计方法，再一次进行了研究围岩松动圈性质的模型试验。

本次试验在中国矿业大学研制的真三轴静力学试验台上进行。模型试验所选用的真三轴静力学台架，其上下左右六面可用液压枕分别控制加载，试块标称尺寸为100cm×100cm×20cm。采用“先开洞，后逐级加载至设计载荷值”的试验方法。试验保持平面应变，静水压力，最大荷载为4.81MPa。模型的几何比为$C_l=46$，应力比为$C_p=65$，密度比为$C_r=1.42$。试验用正交设计安排，考虑了模型强度、巷道尺寸和原岩应力这3个因素，共做了9块试块。正交设计的安排为：应力取6个水平，取值为2.77～4.81MPa，圆形巷道直径取3个水平，取值为9～15cm，试块抗压强度取3个水平，取值为0.45～1.09MPa。巷道的支护都采用同一参数的锚喷支护，其模型上锚杆长为4cm，间排距为1.7cm×l.7cm，喷层厚度为3mm。试块材料为细砂与石蜡混合物，喷层用碳酸钙与白色乳胶配制，锚杆用直径1mm铜丝及铁片制作。

根据相似准则，相似系数间存在有：$C_\sigma=C_\gamma\times C_l$（$C_\sigma$为模型与原型应力比；$C_\gamma$为模型与原型密度比；$C_l$为模型与原型几何比）。根据台架尺寸与原型巷道尺寸，相似材料用细砂与工业石蜡配制，有：$C_\gamma=1.4$，$C_l=46$；$C_\sigma=1.4\times46=65$。围岩用58号工业石蜡与细砂于150℃下混合，在高温下直接装入台架捣实。锚杆用ϕ1mm细铜丝制作；锚杆托盘用铁皮制作；金属网用塑料网制作。喷层、注浆和试块表面处理材料用白乳胶、轻质碳酸钙和水配制。

加载方法与测试技术为：分三向加载，上下左右以静水压力方式加载；纵向加一定比例荷载，使其保持平面应变。静水压力荷载从0开始，以0.2MPa级差逐级加载。加载在每级间稳定10min，每个试块的全部加载，约在8h内完成。

试验测试内容为：3个方向的加载应力值；巷道内上、下、左、右表面收敛值；巷道底板围岩中的应力值和围岩中的最终位移值和松动程度。

加载压力用压力表读数；表面收敛用杠杆放大后用百分表读数；对个别试块底板中应力，预先埋设小压力盒（ϕ10×0.5mm），用电阻应变仪读数，根据标定曲线得到实际应力值；松动程度用自制的强度探测器分8个方向测试得出。

试验得到了正交情况下的各松动圈厚度值。用其进行正交分析得到松动圈与各影响因素之间的关系式为

$$L_p=\frac{57.80P_0}{R}-51.56 \tag{1-2}$$

式中 L_p——松动圈的厚度，cm；

P_0——原岩应力，MPa；

R——岩石抗压强度，MPa。