Failure Characteristics of Shaft Lining in Eastern Chinese Coal Mines and Its Treatment through The Application of An Underground Continuous Impervious Curtain

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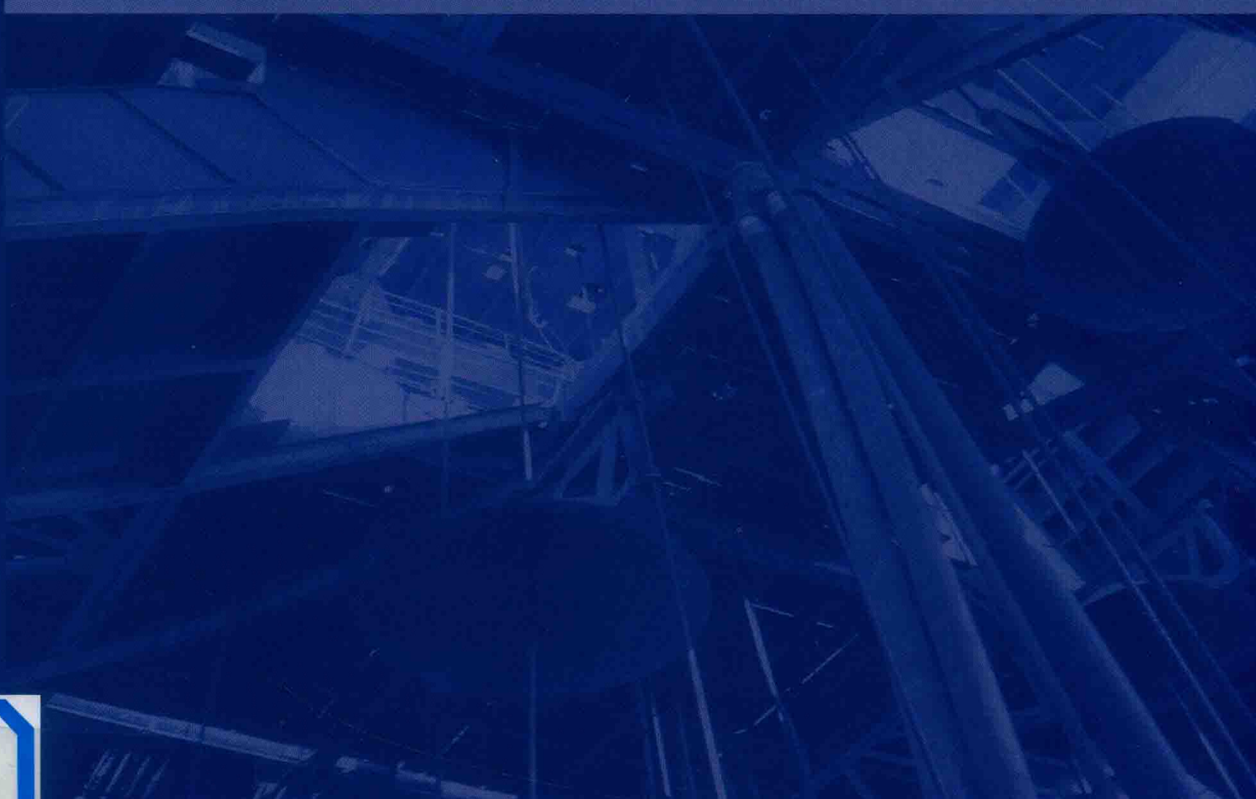

中国矿业大学出版社
China University of Mining and Technology Press

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内 容 提 要

本书主要研究了深厚表土层中煤矿立井井壁破坏特征及治理方法，内容包括：对井壁破坏原因进行数值模拟分析，分析了含水层厚度与上覆土层厚度对井壁破裂位置的影响；分析了煤层开采对井壁的影响，并分析了采用地下连续墙对减少保护煤柱和增加煤炭开采率的可行性；对新型连续墙施工方法进行了试验和应用分析；提出了地下连续墙治理井壁破坏新方法，对其效果和应用范围进行了模拟分析，并制定了初步施工方法。

本书可供高等院校矿业工程、岩土工程等专业的师生和工程技术人员参考使用。

图书在版编目(CIP)数据

华东矿区井壁破坏特征与地下连续隔水帷幕的应用治理 = Failure Characteristics of Shaft Lining in Eastern Chinese Coal Mines and Its Treatment through The application of an underground continuous impervious curtain：英文 / 于庆等著. —徐州：中国矿业大学出版社，2017.11

ISBN 978-7-5646-3760-6

Ⅰ.①华… Ⅱ.①于… Ⅲ.①煤矿—井壁破坏—研究—英文 Ⅳ.①TD7

中国版本图书馆 CIP 数据核字(2017)第 270962 号

书　　名 Failure Characteristics of Shaft Lining in Eastern Chinese Coal Mines and Its Treatment through The Application of An Underground Continuous Impervious Curtain
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责任编辑 杨　洋
出版发行 中国矿业大学出版社有限责任公司
（江苏省徐州市解放南路　邮编 221008）
营销热线 (0516) 83885307　83884995
出版服务 (0516) 83885767　83884920
网　　址 http://www.cumtp.com　**E-mail**:cumtpvip@cumtp.com
印　　刷 江苏淮阴新华印刷厂
开　　本 787×1092　1/16　**印张** 7.75　**字数** 200 千字
版次印次 2017 年 11 月第 1 版　2017 年 11 月第 1 次印刷
定　　价 30.00 元
（图书出现印装质量问题，本社负责调换）

Preface

Serious shaft lining failures have often occurred in the shafts constructed more than 10 years ago in the eastern part of China, such as Datun, Xuzhou, Huaibei, Huainan, Yanzhou, Yongxia, and so on, since 1987. All these shaft linings are constructed in similar geological conditions and they pass through the deep topsoil of Quaternary strata, about 100 ～ 200 m thick and more than 20 m thickness of aquifer composed at the bottom of deep topsoil. The serious deformation and failure in their shafts linings have occurred even though enough coal pillars have been left around their shafts. The main cause of these shaft lining failures is considered to be additional stress concentration induced by the drawdown of aquifer. The ground water level in aquifer had dropped due to the effects of mining operations, and then this phenomenon gave rise to the compaction of aquifer and the subsidence of the alluvium. The failure firstly occurs at the inner surface of the shaft lining, and then develops further on the inside. As for the counter measures for shaft lining failures, several treatments such as the set of wall method, stress-relief groove method, strata grouting method, and so on, have been applied so far. However, these treatments effects were temporary and (or) limited due to the complex and unique geological conditions. In serious cases, some shafts experienced a second failure, even after the first treatments.

From these backgrounds, this study develops and suggests a new treatment method for preventing shaft lining failure using an underground continuous impervious curtain around the shaft lining, which uses a chain conveyor cutter based on the results of an investigation of shaft lining failures that have occurred in eastern Chinese underground coal mines and its mechanism. Then, this study also discusses the method by which to apply and its applicability in order to establish a guideline of its application.

At first, the background and conditions of the shaft lining failures that have occurred in eastern Chinese coal mines are introduced. The research conducted on the shaft lining failures so far and the current treatment methods are reviewed. The objectives of the study are described in this chapter.

Secondly, the mechanism by which the shaft lining failures have occurred in eastern Chinese coal mines is investigated, based on the results of site investigation conducted at one coal mine and numerical analyses. Namely, the ground behavior induced by the drop in ground water level in aquifer and its effect on the stability of the shaft lining were discussed. From the results, the mechanism of the shaft lining failures can be made clear: the lowering of the water level causes the subsidence of the upper layer. Then, the stress concentration which happens in the shaft lining is caused by the subsidence of the layer of the surrounding shaft. As the subsidence occurs in the aquifer and the upper layer, a large stress concentration appears in the shaft lining near the interface between the aquifer and bedrock and the risk of shaft lining failure is high in both boundaries of the aquifer. Therefore, shaft lining failure is considered to occur around these parts. Moreover, it can also be clearly understood that the thicker the aquifer is, the larger the magnitude of stress concentration is. When the thickness ratio of the upper layer to aquifer is greater than 9.0, the lowest strength factor appears near the upper boundary. Many treatment methods for improving the stability of shaft lining have to be adopted in order to prevent shaft lining failures. Moreover, based on the results of a series of numerical analyses, it can be thought that the set of wall methods only reinforce the shaft lining and it cannot control the influence of the water level decline in aquifer. Moreover, as the average settlement of the ground surface was about 0.024 m/year, the stress-relief groove method just plays a temporary role in preventing shaft lining failure due to the constant compression and the decline of their effects. The strata grouting method is meant to change the property of the aquifer around the shaft and it is considered to be one of the solutions for shaft lining failures. However, due to the process of grout injection into the soil layer, the effect is dependent on the actual geological conditions and it cannot be guaranteed. Besides, as the high grout injection pressure is needed when this method is applied in aquifer, the injection pressure may have an obviously negative impact on the shaft lining. From the above results, it can be concluded that a new treatment method has to be developed in order to control shaft lining failure under the depths and geological conditions in eastern Chinese coal mines.

Then, the new treatment method developed in this research is described in order to prevent shaft lining failure and solve the problems of conventional treatments. This method is meant to construct an underground continuous impervious curtain (UCIC) around the shaft lining in an aquifer using a chain conveyer cutter (CCC) with the freezing method. The CCC was originally developed for improvement of ground which mixes the cement and soil or rock during cutting the ground. The construction of UCIC consists the four steps of drilling freezing holes, freezing an aquifer, constructing UCIC using CCC and thawing an aquifer. As the operation of this method can be done from the inside of the shaft, the UCIC can be constructed at any depths. The CCC can also create a required quality and homogeneity UCIC at certain areas around the shaft lining. Moreover, as the cement grout is directly mixed with the excavated gravel or soil in this method, the impact on shaft lining is reduced compared with that of the strata grouting one. From the above advantages of this new treatment method, it seems to be a practical way to construct the UCIC.

After that, a series of the numerical analysis are conducted using an axisymmetric finite element model in order to evaluate the effects of the new treatment method on preventing shaft lining failure and developing guidelines for the appropriate design of UCIC. From their results, it can be said that in the case that the depth of aquifer is about 150m, the ground behavior induced by dehydration and drawdown of an aquifer can be controlled by the construction of UCIC with about a 2 m thickness, and then the stress concentration appearing in the shaft lining can be reduced. As a result, the shaft lining failure can be prevented effectively by this new treatment method. Moreover, it can also be made clear that this new treatment method can be applied widely for several geological conditions if the width and strength of the UCIC are designed appropriately according to the depth of the aquifer and the geological conditions.

Finally, the effect of the extraction of a coal seam on the stability of the shaft lining in which the new treatment method is applied is discussed by means of numerical analysis. The closer the mining panel is to the shaft, especially to the aquifer, the larger the stress concentration occurs in shaft lining and the risk of occurrence of shaft lining failure is increased dramatically. Hence, compared with the basic standard of the design of shaft pillars that the width should be more than that of the depth, wider shaft pillars have to be left around the shaft lining, especially in the aquifer. However, if the new treatment method is applied, the stress concentration in the shaft lining induced by the extraction of the coal seam is relieved, and the stability of shaft lining in the aquifer can be maintained by leaving a coal pillar the same width as that of the basic standard. Hence, the application of this new treatment method not only can maintain the stability of shaft lining, but also can increase the extraction ratio.

The main content of this book is completed by the first author, and other authors provide experimental and field data. Authors are grateful for financial assistance provided by the Natural Science Foundation of Jiangsu Province, China (No. BK20130179), A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions, National Natural Science Foundation of China (Nos. 51504237) and National Key R&D Program of China (No. 2016YFC0600900).

Yu Qing

Aug. 2017

Contents

Chapter 1 Introduction

1.1 Background

Serious shaft lining failures have often occurred in the eastern part of China, such as Datun, Xuzhou, Huaibei, Huainan, Yanzhou, Yongxia, etc., since 1987 (see Table 1-1). The shaft lining failure which occurs in deep alluvium is a sudden coal mine hazard. The number of failure shafts and their large ranges have never been seen before in Chinese mining history and are also rare in the world.

Table 1-1 Basic information of shaft lining failure in eastern Chinese coal mines[1-4]

Mining area	No.	Shaft name	Completion time	Failure time	Inner diameter /m	Outer diameter /m	Failure depth /m	Alluvium thickness /m
Datun	1	Longdong main shaft	1983.3	1987.8	5.0	6.8	210	212
	2	Longdong air shaft	1983	1988	—	—	150~162	159.2
	3	Kongzhuang air shaft	1975.7	1987.8	4.0	5.4	151.7~155.8	160.4
	4	Kongzhuang auxiliary shaft	1975.2	1989.3	6.0	7.9	142~145	156
	5	Xuzhuang main shaft	1975.12	2005.4	5.0	6.6	152	155.1
	6	Xuzhuang auxiliary shaft	1977.7	2004.12	6.0	6.8	158	153.2
Huaibei	7	Haizi main shaft	1982.8	1988.10	6.5	9.0	211.7~219.7	248.7
	8	Haizi auxiliary shaft	1983.4	1987.8	7.2	10.0	232.8~237.4	247.2
	9	Haizi middle air shaft	1980.5	1988.6	4.7	7.1	226.8~234.5	245.2
	10	Haiziwest air shaft	1980.11	1989.5	6.0	8.3	231.5~234.75	240.9
	11	Linhuan auxiliary shaft	1979.3	1987.7	7.2	9.8	239~241	239.1
	12	Linhuan east air shaft	1980.11	1994.4	5.0	6.5	207	214.5
	13	Linhuan west air shaft	1979.12	1993.6	6.0	7.9	227.4	244.5

Table 1-1

Mining area	No.	Shaft name	Completion time	Failure time	Inner diameter /m	Outer diameter /m	Failure depth /m	Alluvium thickness /m
Huaibei	14	Luling main shaft	1964.4	1987.8	5.2	7.0	206.97	235.2
	15	Luling auxiliary shaft	1964.3	1987.6	6.1	7.7	212.1	235.2
	16	Qianling north air shaft	1978.12	1987.10	3.5	4.7	112.6~113.9	96.2
	17	Renlou main shaft	1978	1993.10	—	—	217.9~272.9	275
	18	Tongting main shaft	1984.11	1991.4	5.5	6.4	224.1~242.8	230.4
	19	Tongting auxiliary shaft	1983.12	1991.4	6.55	7.55	160~270	230.5
	20	Tongting air shaft	1982.3	1992.5	5.0	6.8	224.8~226.8	225.3
Huainan	21	Kongji air shaft	1975.7	1987.8	—	—	151~155.8	156.4
	22	Panyi east air shaft	1991.11	1992.7	7.0	9.0	292.5	292.5
	23	Pansan west air shaft	1984.11	1988.8	7.8	8.8	444.4~447.9	440.8
	24	Xieqiao east air shaft 2	1989.7	1991.6	—	—	475.0~478.5	421.0
Xuzhou	25	Jiahe main shaft	1968	1982	—	—	100~104	78.6
	26	Zhangji main shaft	1973.6	1981	5.0	6.4	101~102.6	105.3
	27	Zhangji auxiliary shaft	1973.12	1981	5.5	6.9	104~105	105.3
	28	Zhangshuanglou main shaft	1983.6	1987.8	5.5	7.5	240~244	243.0
	29	Zhangshuanglou auxiliary shaft	1982.12	1987.7	6.5	8.9	229.3~230.6	243.2
	30	Zhangshuanglou air shaft	1979.11	1992.6	4.7	5.7	245~247	252
	31	Zhangxiaolou auxiliary shaft	1973.12	1983.10	5.0	6.2	104.2~108.5	103.5
Yongxia	32	Chensilou main shaft	1989	1999.7	5.0	6.6	362.5~371.6	405
Yanzhou	33	Baodian main shaft	1979.5	1995.7	6.5	8.5	136~144	148.7
	34	Baodian auxiliary shaft	1979.11	1995.6	8.0	10.2	126.7	148.5
	35	Baodian north air shaft	1979.10	1996.8	5.0	6.6	168.4,180,204	202.6
	36	Baodian south air shaft	1979.8	1996.8	5.0	5.8	158.1~159.3	157.9
	37	Taiping main shaft	1987.12	1989.3	—	—	123~166.9	166.9
	38	Henghe main shaft	1987.1	1993.6	4.5	5.9	122.1~139.1	149.6
	39	Henghe auxiliary shaft	1987.6	1995.3	4.5	5.9	136~141	144.1
	40	Jisan mine air shaft	1992.12	2004.8	7.5	8.4	168~172	180
	41	Taiping auxiliary shaft	1987	2003.12	—	—	166.9	166.9
	42	Xinglongzhuang main shaft	1977.8	1997.6	6.5	8.7	150, 184	189.3
	43	Xinglongzhuang auxiliary shaft	1977.6	1995.10	7.2	9.6	154	190.4

Table 1-1

Mining area	No.	Shaft name	Completion time	Failure time	Inner diameter /m	Outer diameter /m	Failure depth /m	Alluvium thickness /m
Yanzhou	44	Xinglongzhuang east air shaft	1977.5	1997.6	5.0	6.4	157	176.5
	45	Xinglongzhuang west air shaft	1976.8	1995.10	5.0	6.4	165.6~171.6	189.5
	46	Yangcun main shaft	1984.12	1997.2	5.0	6.6	176.5	185.4
	47	Yangcun auxiliary shaft	1985.1	1997.12	—	—	160,176	184.5
	48	Yangcun north air shaft	1984.10	1997.2	4.5	5.9	150~156.6	173.4

The geological conditions of all these spots are almost the same. All these shaft linings pass through deep alluvium of Quaternary strata, for which the composition of the bottom aquifer is complex. The results of a series of technical surveys showed that there is a thick bottom aquifer under the steady impermeable layer and the aquifer is in direct contact with the weathered rock which is in the top of bedrock in all broken shafts[7,8]. Their geological conditions of hydrology and geology have some of the same characteristics. All these shafts pass through the deep alluvium in Quaternary strata. Quaternary strata are divided into upper, middle and lower groups; the seam below the strata is the coal-bearing rock. The upper one is the water-bearing stratum, the middle one is a relatively impermeable layer, and the lower one is the confined bottom aquifer. Before the shaft linings failure occurred, the water pressure of the bottom aquifer around the shaft had reduced significantly and the larger subsidence occurred due to the influence of mine drainage.

During the mining process, the failure of shaft lining is a serious hazard to mining operation and mine safety. The main feature is that the part of the shaft lining which passes through the aquifer has the serious deformation and failure under the condition of enough shaft pillars left around the shaft. The settlements of the mining fields which happened the shaft lining failure were about 0.2 ~ 0.5 m and it increased with increasing the distance from the shaft.

When shaft lining failure occurs, the inner shaft lining delaminates and spalls, longitudinal steel bows inward, transverse cracks form and intersect in the horizontal direction along circle, seepage occurs or even sand gushes, and mostly seriously, concrete blocks fall out and break the equipment in shaft (see

Figure 1-1)[5]. In addition, the shaft bends up; cage guides, drainpipes and pressure ventilation pipes are in longitudinal bending, and in serious cases the cage is stuck due to torsional deformation. Thus, the shaft lining failure has a serious impact on the operation of the coal mine and the safety.

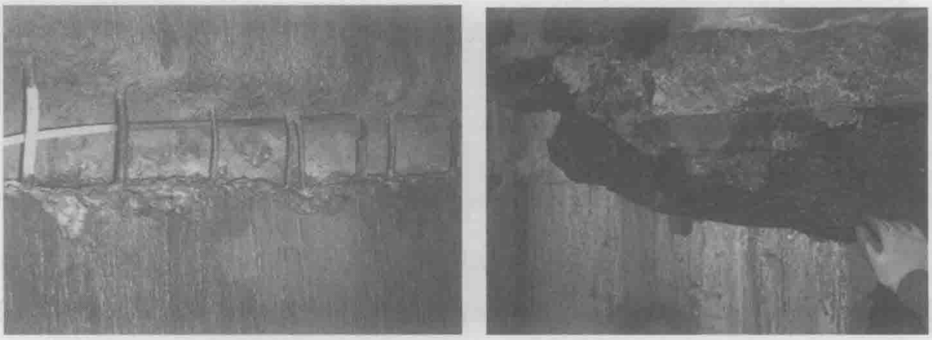

Figure 1-1 Pictures of shaft lining failures
(a) North air shaft of Yangcun coal mine[5]; (b) Main shaft of Hulusu coal mine

According to the statistical data of the shaft lining failures in alluvium, the elapsed time after completion and location of failure has its own rules. Generally, the type of shaft lining failures is divided into three phases[6].

(1) Failure during the freezing shaft sinking: horizontal cracks caused by temperature variation are initiated and propagated.

(2) Frozen wallthawing: horizontal and inclined cracks caused by temperature variation are initiated and propagated.

(3) Surface subsidence after several years elapsed: horizontal and inclined cracks caused by surface subsidence are propagated, especially, this phenomenon is occurred near the boundary between aquifer and bedrock.

For the first and second phases, the failure time is specified and the treatment is easy to apply. These failures just occur during the shaft construction and the amount is less than in third phase.

Most of the shaft lining failures belong to the third phase and the failure time can not specified. As these subsidences might be related to the bottom aquifer drainage and consolidation settlement, the most important and difficult task is how to prevent the shaft lining from the effect of the aquifer drawdown in deep alluvium. Main treatment ways are the strengthening of shaft lining and the reinforcement of surrounding strata. The current researches mostly focused on the causes, mechanism and solutions for these kinds of geotechnical issues. However, there are still not conclusive solutions or treatments for these issues.

1.2 Literature Review

1.2.1 Shaft lining failure

After the shaft lining failure occurred, many researchers worked on the mechanism of the shaft lining failure and got many results. For the mechanism of shaft lining failure, there are a few hypotheses proposed by some researchers such as the construction quality hypothesis, the new tectonic movement hypothesis, the earthquake hypothesis and the vertical additional force hypothesis. Among these hypotheses, the vertical additional force hypothesis may play a dominant role in shaft lining failure[9-16].

(1) New tectonic movement

This hypothesis was obtained from the research on the failure time which many shaft lining failures in Huanghuai area mostly happened in 1987 and 1988. It indicated that the cause of shaft lining failure is the crustal stress change which is due to the new tectonic movement. However, this hypothesis cannot explain the other shaft lining failures and is also lack of more evidence to be supported.

(2) Earthquake

Because the failure time is relatively concentrated, the earthquake is thought to be the reason of shaft lining failure. However, during the failure period, there was no earthquake, and the failure caused by earthquake in Kailuan coal mine occurred in 20 m depth, is different from the characteristics of shaft lining failures happened in eastern Chinese coal mines.

(3) Construction quality of shaft

This hypothesisindicates that the poor construction quality is the main reason for the shaft lining failures. It is the right that the stability of the shaft lining relates relationship with the shaft lining quality, and the poor shaft lining is easy to break under the pressure. However, from the investigations of the broken shafts, it can be seen that some good quality shafts which the actual strength of the concrete is higher than the its designed one also had been failed, for example Linhuan main shaft, Baodian main shaft, Yaoqiao main shaft, etc. Although the quality of the shaft lining is the important factor to the stability of shaft lining, it is not the basic reason of the shaft lining failures.

(4) Vertical additional force

After many years' researches, the mechanism of the shaft lining failures has become to be cleared. The vertical additional force theory is described as follows. The special mining activities and the artificial drainage cause the water levels drop in the aquifer. According to the drop of water level in the aquifer, the stratum of aquifer deforms and then the effective stress increases in the aquifer. This causes consolidation of the ground and subsidence of the surface. During the process of strata settlement, the soil layer imposes a vertical additional force on the outer surface of the shaft. While the vertical stress increases gradually to its limitation, the shaft lining cannot resist the force and then is failed. The failure mostly occurred near the interface between aquifer and bedrock, sometimes in the alluvium a few metres above the bedrock as shown in Figure 1-2. The results of shaft lining destructive tests and the data of in-situ experiment conducted in mining areas of Huaibei, Xuzhou, etc. confirmed the existence of vertical additional force and its influence on the shaft

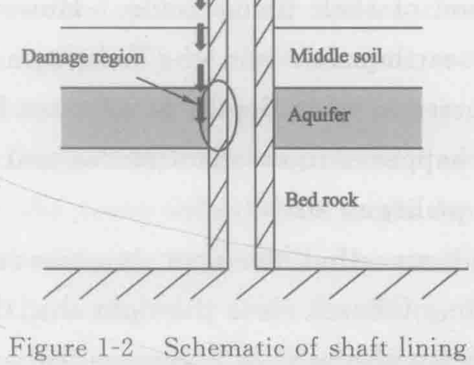

Figure 1-2 Schematic of shaft lining under additional stress

lining failures[1-17,23]. Many researchers did a lot of works on laboratory test and field test to verify this theory and made a great achievement.

In 1989, Cui and his group conducted the similar model test in order to prove that the vertical additional force was the main cause of the shaft lining failure[2,9,14,58]. Large-scale testing system simulated the value of vertical additional stress after the aquifer drawdown in Zhangshuanglou auxiliary shaft of Huanghuai area (see Figure 1-3). The height of the model of shaft lining was about 2.0 m and the outer diameter was 0.4 m. The self-weight of soil layer was simulated by using the top lifting jack. From the results of these tests, the variation of the additional stress was obtained as follows:

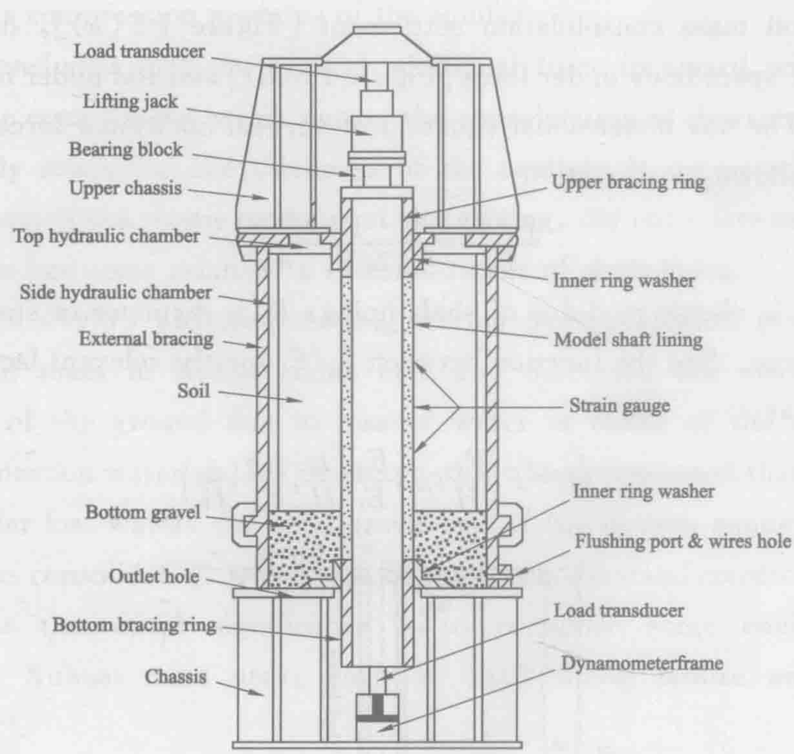

Figure 1-3 Simulation experimental table of shaft acted by force[58]

(1) As the water level in the bottom gravel was dropped, the compaction of the soil was recognized. At the same time, the movement of surrounding soil exerted the vertical additional stress on the shaft lining.

(2) The drainage rate in bottom gravel had a significant influence on the