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Water-resisting Property and Key Technologies of Grouting Reconstruction of the Upper Ordovician Limestone in North China's Coalfields

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Supervisor's Foreword

Mine water inrush events often occur during coal mine construction and production; they account for a large proportion of the nation's coal mine disasters and accidents in China. As mining depth and mining intensity continue to increase, the encountered hydrogeological conditions are becoming more complex. One challenge is to prevent water inrushes from the Ordovician limestone aquifer that underlies many of the coal seams in north China's coalfields. The Ordovician aquifer is a regionally important karst aquifer and contains valuable water resources. The traditional dewatering method is not only less effective to reduce the water inrush risk in the strongly heterogeneous karst aquifer at greater depths, but also not in compliance with the current regulatory policy of "green and water-conservation mining". It is imperative to carry out research on new technologies to ensure safe mining while minimizing or even eliminating dewatering of the Ordovician limestone aquifer.

In this thesis, Dr. Hao Wang presents an innovative technology that utilizes and reconstructs by grouting as needed in the upper part of the Ordovician limestone. The technology takes full advantage of both the lateral and vertical heterogeneities of the karst aquifer. Based on the detailed analysis of karst development in six mining areas including Xingtai, Hancheng, and Jincheng, He constructed the most comprehensive depositional and evolutionary model for the Ordovician limestone. The upper Ordovician limestone was divided vertically into weathered and filled zone, water-invaded zone, and water-bearing zone. The water resistance performance of the weathered and filled zone and its feasibility of functioning as an aquifuge were studied using laboratory and in-situ tests. The testing results were used to develop the integral technical system that consists of hydrogeological and geotechnical criteria under which the weathered and filled zone is considered to have competent strength and reliable water resistance performance against water inrush and the methods to calculate the thickness of grouting reconstruction in the upper limestone when these criteria are not met. Theoretical analysis and laboratory experiments were conducted to investigate the grout movement in fractured limestones. Presented in the thesis is the formula that uses pulverized coal ash as the grouting material.

The integral technical approach was applied to working face #3105 of Sangshuping Coal Mine, Hancheng, China, with excellent results. Approximately 450,000 tons of coal reserves that were once seriously threatened by the Ordovician karst aquifer were mined safely without dewatering. The successful case study set an example for "green and water-conservation mining" for coal mines in China and the world. It should be pointed out that the integral technical system is not limited to coal mining but applicable to any underground engineering works.

I congratulate Hao for this excellent work. His thesis is one of the best in China Coal Research Institute because of the innovative approach, volume of reliable data, defensible scientific analysis, and world significance of the research results.

Xian, China
July 2019

Prof. Shuning Dong

Parts of this thesis have been published in the following journal articles:

Wang Hao, 2019. Experimental study on fly ash-based material performance in coal floor grouting modification. Coal Geology of China, 31(7): 48–53.

Wang Hao, 2019. Study on time-dependent viscosity of the slurry and its diffusion model. IOP Conf. Series: Earth and Environmental Science. DOI:10.1088/1755-1315/295/4/042016.

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Contents

Executive Summary

The rapid development of China's coal industry has led to the exhaust of the shallow coal resources in North China Coalfields (NCCs). Coal mining has been progressively extended to greater depths. The deep coal seams are closer to strong aquifers, in particular, the Ordovician limestone aquifer, which is characterized with high potentiometric pressures. The high potentiometric pressures often result in an exceedance of the critical water inrush coefficient and frequent occurrences of disastrous water inrushes. The prolific nature of the Ordovician limestone aquifer makes the traditional depressurization through dewatering less effective in reducing the water inrush risk. In addition, dewatering tends to result in damage of the groundwater resource, which does not comply with the general policy of "green and water-conservation mining". It is therefore essential to carry out research on new technology to ensure safe mining under threat of the confined Ordovician limestone aquifer.

This doctoral thesis puts forward an innovative technology that utilizes and reconstructs by grouting as needed the top of the Ordovician limestone (TOL) to achieve safe mining of the lower coal seams under water pressures. The technology takes advantage of the heterogeneous characteristics of "planar division and vertical zonation" within the TOL. The depositional and evolutionary model of the Ordovician limestone was constructed based on systematic studies of the mechanisms of karst development in the TOL in six different NCC mining areas including Xingtai, Hancheng, and Jincheng.

The understanding on the hydrogeological significance of the TOL was significantly improved through a theoretical study on the water-bearing and water-resisting characteristics. Quantitative water yield properties of the TOL were studied with the establishment of an assessment indicator system of karst water yield property and the improved method of weight coefficient based on the correction of trial estimation. From top down, the upper Ordovician limestone was divided into weathered and filled water-resistant zone, transition zone with vertical rising water, and water-enriched karst fracture zone.

The water resistance performance of the weathered and filled zone of the TOL as well as the feasibility of using the zone as an aquifuge were comprehensively studied using laboratory tests, in-situ tests, and spatial distribution features of the regional strata. The research results show that the weathered and filled zone has competent strength and reliable water resistance performance and can be used as a water barrier where the weathered and filled zone is ubiquitous with little influence of tectonic structures.

Also constructed in the thesis was the integral technical system of utilization and grouting reconstruction of the TOL. The integral system includes the criterion for utilization of the water resistance zone of the TOL and grouting reconstruction of the water-bearing section and the method to determine the thickness of grouting reconstruction of the TOL. Theoretical analysis, laboratory experiments, and equation derivation were conducted to investigate the spread mechanisms of grout in fractures of the TOL. The optimal formula which uses pulverized coal ash as the grouting material for the TOL was put forward in the thesis.

The evaluation and reconstruction methods of the TOL were applied to working face #3105 of Sangshuping Coal Mine, Hancheng, China. Safe mining was realized without dewatering, and approximately 450,000 tons of "idle coal reserves" that were once seriously threatened by the Ordovician limestone aquifer were emancipated. The successful case study verified the importance of understanding the water-bearing and water-resisting properties of the TOL and proved the reliability of the proposed integral technical system in the utilization and grouting reconstruction of the TOL. The integral technical system is not limited to coal mining but applicable to any underground engineering works.

Chapter 1
Introduction

1.1 Research Background and Significance

Coal is an important energy resource in China. The coal production concerns the national economy and the people's livelihood as well as the sustainable and stable development of the economic society. The North China Coalfields (NCCs) are important coalfields in China, also the coalfields that have been most seriously threatened by groundwater hazards. The major coal seams in these coalfields are located in the Permo-Carboniferous strata. Because the Lower Carboniferous, Devonian, Silurian and Upper Ordovician formations are generally absent in the coalfields, the Permo-Carboniferous strata overly directly the massive Middle Ordovician limestone. Mining practices in these coal mines demonstrate that the Middle Ordovician limestone is a strong aquifer with very heterogeneous karst fractures and characterized by intense recharge and high water pressure. The Ordovician limestone constitutes the major threatening water source from the coal seam floor [1].

With the rapid development of coal industry in China, the shallow coal resources in many large mining areas in the Permo-Carboniferous coalfields in North China become gradually exhausted. The coal mining extends downwards progressively. Because the deep coal seams are closer to the strong aquifer of the Ordovician limestone, bearing the high water pressure and large water volume, disastrous water hazards have occurred frequently [2, 3]. For example, a water inrush from the Ordovician limestone occurred in Fangezhuang Mine, Kailuan in 1984 and flooded the mine. The water inrush from the Ordovician limestone that occurred in Dongpang Mine, Xingtai, Hebei Province in 2003 flooded the mine. The water inrush from the Ordovician limestone that occurred in Luotuoshan Mine, Wuhai of Inner Mongolia in 2010 also flooded the mine. All these water hazards resulted in significant economic loss and casualties. Select mine-flooding accidents induced by floor water inrushes from the Ordovician limestone are listed in Table 1.1.

According to the related requirements, the mining conditions under the Ordovician limestone water pressure in coal floor were assessed in different mining areas. It was found that the water inrush coefficients of the Ordovician limestone in the floor of

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Table 1.1 Select mine-flooding water inrushes from the underlying Ordovician limestone in NCCs

No.	Date	Province	Mine	Maximum water inflow (m^3/h)	Loss
1	1960.6.4	Hebei	Mine #1, Fengfeng Mining Area	4212	Mine Flooded
2	1964.6.4	Shandong	Pandong Shaft, Panxi Mine, Xinwen Mining Area	10,640	Mine flooded
3	1976.8.6	Shaanxi	Magouqu Mine, Hancheng Mining Area	12,000	Mine flooded
4	1980.12.26	Henan	Mine #9, Hebi Mining Area	4090	Mine flooded
5	1984.6.2	Hebei	Fangezhuang Mine, Kailuan Mining Area	123,180	2 mines flooded
6	1985.5.27	Shandong	Yanggezhuang Mine, Feicheng Mining Area	4409	Mine flooded
7	1985.8.6	Shandong	Taoyang Mine, Feicheng Mining Area	17,940	Mine flooded
8	1988.10.24	Anhui	Yanggezhuang Mine, Huaibei Mining Area	3153	Level flooded
9	1993.1.5	Shandong	Guozhuang Mine, Feicheng Mining Area	32,970	Mine flooded
10	1995.11.5	Henan	Xin’an Mine, Yima Mining Area	4260	Mine flooded
11	1995.12.3	Hebei	Wutongzhuang Mine, Fengfeng Mining Area	34,000	Mine flooded
12	1996.3.4	Anhui	Renlou Mine, Huaibei Mining Area	34,570	Mine flooded
13	1996.11.24	Hebei	Sunzhuang Mine, Fengfeng Mining Area	9000	Mine flooded
14	1997.2.18	Jiangsu	Zhangji Mine, Xuzhou Mining Area	24,098	Mine flooded
15	1997.5.3	Henan	Lugou Mine, Zhenzhou Mining Area	7680	Mine flooded
16	2003.4.12	Hebei	Dongpang Mine, Xingtai Mining Area	70,000	Mine flooded

(continued)

Table 1.1 (continued)

No.	Date	Province	Mine	Maximum water inflow (m^3/h)	Loss
17	2004.9.26	Hebei	Niuerzhuang Mine, Fengfeng Mining Area	5160	Mine flooded
18	2004.10.20	Hebei	Desheng Mine, Handan Mining Area	7000	Mine flooded
19	2009.1.8	Hebei	Mine #9, Fengfeng Mining Area	7200	Mine flooded
20	2010.7.25	Henan	Hezhuang Mine, Yushan Corp, Coking Coal Group	1500	Mine flooded
21	2010.10.15	Shanxi	Dayun Mine, Xinzhou Mining Area	1390	Mine flooded
22	2010.3.1	Inner Mongolia	Luotuoshan Mine, Wuhai Mining Area	60,036	Mine flooded
23	2011.8.7	Shaanxi	Sangshuping Mine, Hancheng Mining Area	20,000	Mine flooded
24	2011.12.11	Hebei	Huangsha Mine, Fengfeng Mining Area	22,800	Mine flooded
25	2012.5.26	Hebei	Shenjiazhuang Mine, Fengfeng Mining Area	750	Mine flooded
26	2013.2.2	Anhui	Taoyuan Mine, Huaibei Mining Area	29,000	Mine flooded
27	2013.4	Anhui	Taiping Mine, Anhui	1000	Mine flooded

the deep coal resources (mainly the lower coal seams) in many mining areas of the Permo-Carboniferous coalfield in North China have exceeded the critical safe values. These mining areas are seriously threatened by water hazards and cannot conduct safe mining [4].

In order to emancipate the deep coal resources that are seriously threatened by water hazards of the Ordovician limestone, the technical thinking commonly adopted for water control includes reduction of water pressure in the Ordovician limestone aquifer and/or increase of the thickness of the aquifuge underlying the coal seam floor [5]. For reduction of the water pressure in the Ordovician limestone aquifer, depressurization through dewatering may be adopted. For increase of the thickness of the effective aquifuge of the coal seam floor, grouting reinforcement of the aquifuge of the seam floor and grouting reconstruction in aquifers may be adopted.

In terms of the Ordovician limestone water control with depressurization through dewatering, there exist two major problems:

- Firstly, the major water-bearing section of the Ordovician limestone has generally strong water yield property and is characterized by heterogeneity and anisotropy. The effect of depressurization through dewatering tends to be poor, and the dewatering cost is high.
- Secondly, North China is short of water resources. There are more than 300 cities deficient of water in North China. It becomes more and more prominent in many coal mines that water demand exceeds water supply. With the deterioration of water quality of shallow groundwater and the decrease of exploitable water resources, the deep Ordovician limestone water is used in many areas as a major source of water supply. If the technology of depressurization through dewatering is adopted, the groundwater environments will certainly be seriously affected, influencing the recharge of urban water sources.

Under the above-mentioned background, in order to accomplish safe mining of the deep coal resources under water pressure, the technical thinking of increasing the thickness of aquifuge of seam floor becomes the viable option for the Ordovician limestone water control in the coal seam floor. Through research some experts and scholars found that the top of the Ordovician limestone (TOL) has some water resistance in some mining areas. The typical research results include the following:

- In 2009, Dong Shuning and Liu Qisheng studied the water–resistant property of the top of the Ordovician strata in the Permo-Carboniferous coalfields in North China. They put forward the detection method of the relative water–resisting section in the TOL [6];
- In 2011, Liu Jiacheng and others studied the characteristics of karst development in Fengfeng Formation and Upper Majiagou Formation in the TOL in Tunlan Mine of the Xishan mining area. They considered that the paleo-weathered fractured filled zone of approximately 30 m thick in the upper part of the upper member of Fengfeng Formation in Tunlan Mine of the Xishan mining area might be used as the key water-resisting layer for local water-abundant zone of Fengfeng Formation [7].
- In 2015, Rong Huren and others studied systematically the characteristics such as lithology, fracture development and filling degree of the TOL in Longgu Mine. They considered that there exists a relative aquifuge of approximately 60 m thick at the TOL in the mine [8]. However, the filled water-resistant section in the top of paleo-weathering crust has limited thickness and does not exist in all mining areas of North China coalfields. For example, the drilling results in the TOL in Tuanbai Mine indicated that when the borehole entered into TOL the leakage of flushing fluid increased remarkably. Further analysis showed that the reason for the increased leakage was that the karst fractures in the paleo-weathering crust at the top of the Ordovician limestone were not completely filled.

In summary, sufficient implementation of the technical thinking of “increasing the thickness of the aquifuge of seam floor” for control of the Ordovician limestone water needs not only to conduct the research on the utilizability of the weathered and filled section in the TOL, but also to study the grouting reconstruction technology for the TOL. Otherwise, the deep coal resources in many mining areas of NCCs will become idle reserves. Therefore, the research on utilization and grouting reconstruction technology of the TOL is extremely urgent and imperative.

1.2 Current Research Status

1.2.1 Research on Water-Bearing and Water-resisting Properties of the TOL in NCCs

1. **Research on water-resisting performance and utilizability of the TOL**

When evaluating and predicting water inrush risk from the Ordovician limestone in coal mines, we regarded different layers of the Ordovician limestone as a unified aquifer in the past. One did not consider their possible water-resistant properties and followed the thought that deeper coal seams would have larger water pressures in the Ordovician limestone thus bigger water inrush risks. The predicted water inrush risks were sometimes too big in some mines or mining districts that a great amount of coal resources of the lower coal seams have been considered as idle reserves [9–18]. With the mining of the lower coal seams in many mines in the Permo-Carboniferous coalfields in North China, it is very important to study the heterogeneity of karst development and the water-resistant performance of the TOL. For this purpose, Chinese researchers have carried out research on the hydrogeological conditions of the TOL in many mining areas, analyzed its water-resistant performance, and evaluated the feasibility of using it as additional aquifuge to prevent the Ordovician limestone water.

As early as in 1978, the Geological Exploration Institute of the Ministry of Coal Industry (the predecessor of Xi'an Research Institute of China Coal Technology and Engineering Group Corp.) pointed out in "Research on the karst development regularities and hydrodynamic characteristics in south, north and central units of Hanxing" that according to sedimentary cycle, the Middle Ordovician limestone could be divided into three formations and eight members. Different formations and members had different water-bearing and resisting characteristics. They realized that in the Hanxing mining area the top of the Middle Ordovician limestone had a relative water-resisting zone of different thickness, weak permeability and low water abundance. The zone was the product of the paleo-weathering crust, which was further destroyed by anaphasis tectonics of the TOL. Mostly the zone is filled with clay and calcareous materials and has certain barrier function for the recharge of the Middle Ordovician karst water to the overlying coal-bearing measures. This research set the precedent on studying the water-resisting properties of the TOL [19].

Several Chinese experts and scholars carried out research later on the hydrogeological conditions of the TOL in multiple mines or mining areas, analyzed its water-resisting performance, and evaluated the feasibility of using it as an aquifuge for preventing the Ordovician limestone water. In 2009, Dong Shuning and Liu Qisheng took the Lou'an mining area as example in which different detection methods were used to observe the relative barrier layer sections in the TOL [6]. They analyzed further the genesis of each section. In the same year, Wang Changshen and others used rock thin section test, microstructural analysis and other methods to study the samples taken from Zhangcun Mine. They concluded from the study results that there exists an aquifuge of stable thickness and poorly developed karst in the TOL, confirming the existence of the aquifuge in the TOL from the experiment and microscopic view [20]. In 2010, Bai Haibo and others took Wangzhuang Mine in the Lou'an mining area as an experimental site. The analysis of petrographic composition, test of micro-pore structure, surface and underground geological and hydrogeological drilling were used to study the seepage characteristics in the TOL and the evolution history of faults in the mine. The results showed that there exists a carbonate aquifuge of more than 60 m thick in the TOL in the mine [21]. Since 2010, Bai Xiqing, Chen Jinqiang, Liu Ruiqiang and others have carried out research on the water-resisting performance of the TOL in several NCCs including the Xinyi coalfield, Qinshui coalfield, and Longgu Mine [22–28].

The above research results laid a solid foundation for further research on the TOL. They provided support for the present thesis in the following aspects.

- They put forward and demonstrated the water-resisting characteristics and formation mechanism of the carbonate formation of the TOL;
- They studied the genesis of the relative water-resisting section of the TOL in NCCs;
- They gave the methods for detection of the relative water-resisting section of the TOL;
- They summed up the thickness of the relative aquifuge in some mining areas.

However, these previous research results are mostly based on the scale of a mine or a working face and have little systematic results about the regional distribution regularities of the TOL.

2. **Research on vertical zonation of the TOL**

The karst strata of the TOL are the consequence of a long term action of the interior and external dynamic geology on soluble rocks [29–33]. The previous researchers have paid attention to the regional and vertical difference in karst development intensity [34–41]. Zoning of the vertical change of karst was conducted according to different purposes and understandings, which could be summed up as follow:

(1) Zoning on the basis of the mode of groundwater movement: Because the mode of groundwater movement is different, the underground formed karst forms and karst development intensity are different from each other. In the vertical seepage zone, also known as aeration zone, karst caves are mostly vertically developed. In the seasonal variation zone of groundwater, karst caves are developed at