Application and Development Trend of Grouting Technology in Prevention and Control of Ordovician Limestone Water Disaster in North China Type Coalfields

Kan Xuedong¹, Tian Le²³, An Xuliang²³*, Guo Shuitao¹, Yang Xue²³ and Heng Peiguo¹

¹Jiaozuo Coal Industry (Group) Co., Ltd., Jiaozuo, Henan, 454002, China
²Beijing China Coal Mine Engineering Co., Ltd., Beijing, 100013, China
³National Engineering Laboratory for Deep Shaft Construction Technology in Coal Mine, Beijing, 100013, China
*Corresponding author’s e-mail: 57135343@qq.com

Abstract. The hydrogeological conditions of North China type coalfields are complex. With the large-scale development of deep resources, the probability of Ordovician limestone water inrush from coal seam floor increases. Ordovician limestone water disaster has become a serious safety threat to deep mining in North China type coalfields. Since the application of grouting technology can quickly block the water inrush passage and eliminate potential floods, it has obvious advantages in the prevention and control of Ordovician limestone water disasters in North China type coalfields. Equipment progresses, such as working face grouting, downhole directional drilling grouting and surface directional drilling grouting, promote the sustainable development of grouting technology for prevention and control of Ordovician limestone water disaster in North China type coalfields. This paper analyzed the development process of grouting technology in the prevention and control of Ordovician limestone water disaster in North China type coalfields, analyzed the problems encountered for surface directional drilling grouting in practice based on advanced Ordovician limestone water disaster treatment project cases, and pointed out the development direction of surface directional drilling grouting technology for regional water disaster prevention and control. This paper is of important reference significance for prevention and control of Ordovician limestone water disaster in deep mining floor of North China type coalfields.

1. Introduction

Distributed in Beijing, Tianjin, Shanxi, Hebei, Shandong and Henan, northern Liaoning, Jilin and Inner Mongolia, eastern Gansu and Ningxia Hui Autonomous Region as well as northern Shaanxi, Jiangsu and Anhui, North China Permian Carboniferous coalfields are known as North China type coalfield in general. Since the coal production of this region accounts for 60% of the coal production in China approximately, its safe and efficient mining is of important significance for guaranteeing national energy security, and steady and healthy development of local economy. Most North China Permian Carboniferous coal measure strata were deposited directly on Ordovician limestone without Silurian strata of Early Palaeozoic Era and Devonian strata of Late Palaeozoic Era due to geological evolution. In addition, Ordovician limestone has developed karst fissure featured by strong water abundance, and it is close to the Carboniferous Permian coal seam. The coal reserves threatened by
Ordovician limestone confined water inrush are about 57 billion t. In recent 10 years, the coal mining depth has been increasing continuously. The probability of Ordovician limestone water inrush from the coal seam floor has increased under the coupling action of high confined water and mining. On this background, Ordovician limestone water disaster has become a serious safety threat to deep mining in North China type coalfields. According to incomplete statistics, more than 80% production mines in North China type coalfields are threatened by Ordovician limestone karst groundwater. Taking Hanxing mining area as an example, the Ordovician limestone in coal measure basement is a very thick aquifer with high head pressure as well as developed collapse columns, faults and fissures. There have been more than 10 floor Ordovician limestone karst water inrush events causing heavy economic losses and casualties since 2000[1-5]. Prevention and control of Ordovician limestone water disaster during deep mining in North China type coalfields has become one of the major problems that need to be solved urgently for the coal industry in China.

The basic principles of “prediction and forecast, exploration in case of doubt, exploration before excavation and treatment before mining” and the comprehensive control measures of “prevention, blocking, dredging, drainage and interception” for water disaster prevention & control in domestic coal mines are determined in Coal Mine Safety Code (2018 Edition). According to Detailed Rules for Water Disaster Prevention and Control of Coal Mines (2018 Edition), the principle of combination of aboveground & downhole treatment and combination of regional and local treatment shall be adhered to for floor water disaster control. Based on specific conditions, treatment methods such as drainage depressurization, filling mining, curtain grouting, downhole grouting and surface regional grouting can be applied. Water disaster prevention & control technologies such as drainage depressurization, filling mining and curtain grouting are subject to harsh application conditions. But owing to the characteristics of wide scope of application, flexible use, high safety, good economy and low time cost, downhole or surface grouting can be used to block water inrush passages quickly and eliminate potential floor flood. For this reason, the latter has obvious advantages on Ordovician limestone water disaster prevention & control during deep mining in North China type coalfields[6].

2. Development status of grouting technology

Grouting technology originated from construction engineering. In 1802, a Frenchman, Charles-Berigny injected clay and hydraulic gypsum to the stratum to improve stratum stability and permeability for the first time. In 1864, a shaft of Ali Imprebe Hard Coal Mine was injected with cement for this first time. In 1885, Tietjens cut a shaft with surface pre-grouting method and got a patent for this. As an economical and practical rock and soil reinforcement and anti-seepage and water plugging method, grouting technology has been widely applied in the mine and municipal construction fields of UK, France, South Africa, the United States, Japan and the former Soviet Union after more than two centuries of exploration and development[7].

The grouting technology in China started from the 1950s. In the coal industry of China, shaft wall grouting technology was firstly used to plug shaft water leakage in Hegang Mining Area and Jixi Mining Area of northeastern China and Zibo Mining Area of Shandong Province. In 1955, working face pre-grouting was applied to the vertical shaft of Zhangzhuang Coal Mine in Xinwen Mining Area of Shandong Province, and good water plugging effect was achieved. In 1985, the water-plugging rate of surface pre-grouting for the main shaft and the auxiliary shaft of Xuecun Coal Mine in Fengfeng Mining Area of Hebei Province (starting and ending depth: 31~81 m) reached 96.3%, and that for the vertical shaft of Lizhuang Coal Mine in Jiaozuo Mining Bureau of Henan Province (depth: 180 m) reached 99.6%. Since the 1960s, grouting has become safer, and the grouting effect has become more significant along with the development of new grouting materials, new grouting processes and new grouting equipment[8]. In recent years, great progress has been made for the grouting technology in coal mine field. Thanks to the geographical space advantage of directional drilling technology as well as the reinforcement and anti-seepage effect of grouting technology, there is little restriction on site selection of directional drilling grouting, and the exploration & treatment scope is wider. For this reason, it has been widely applied to advanced prevention and control of water disaster of vertical
shafts of coal mines, pre-reinforcement of long-distance weak surrounding rock of deep level roadways, advanced prevention and control of water disaster of the roofs and the floors of deep coal seams, advanced exploration and treatment of fault water disaster, exploration and treatment of collapse columns, etc., which makes important contribution to ensuring work safety of coal mines.

Grouting technology can be classified into three aspects roughly, i.e. process, material and equipment. Equipment serves process, and equipment progress is able to drive the development of grouting technology significantly. Process parameters are determined by material, which is the determinant for grouting effect. Selection of grouting materials is determined by grouting purposes and the features of the grouting medium. Grouting effect is determined by the synergistic effect between the grouting material and the grouting medium, and affected by multiple factors such as material, medium and process parameters. Grout diffusion law and action mechanism are extremely complex, and the application of grouting technology is ahead of study on grouting theory. Grouting technology has been developed greatly with study means such as numerical simulation and model test. However, it is still hard to meet the requirements for fine and controllable process and accurate effect evaluation[9].

3. Ordovician limestone water disaster prevention and control grouting technologies for North China type coalfields

3.1 Working face grouting technology

Prevention and control for water disaster of the coal seam floor of the working face means grouting treatment for the stope face and the roadway that is not tunnelled by arranging the floor exploration hole and the grouting hole that are in the same direction with the roadway tunneling direction around the working face with ordinary tunnel drilling machine through the upper ventilation roadway and the lower transport roadway that have been excavated on the stope face.

In 1984, Feicheng Mining Area of Shangdong Province proposed modification of coal seam floor by working face grouting. Based on field practice, water disaster prevention and control for working face grouting was further developed in 1986, and water disaster prevention and control technology for working face grouting of coal seam floor was basically formed in 1989. This technology has been applied to Feicheng, Jiaozuo, Yongcheng, Zhengzhou, Xingtai, Fengfeng, Huaibei and Wanbei mining areas, etc., and relieved hundreds of millions of tons of coal resources that were threatened by water disaster[10].

Working face grouting water disaster prevention & control technology consists of grouting hole layout and drilling processes, grouting material and grouting process, quality inspection and effect evaluation. Drilling with existing roadways is featured by high pertinence and low cost. However, it also faces problems, such as occupation of roadway tunneling space, weak drilling capacity, low drilling accuracy, poor drilling azimuth control ability, low grouting pressure, small grouting volume, limited grouting transformation area, low construction efficiency, long construction period, great labor intensity and poor working environment.

3.2 Downhole directional drilling grouting technology

With the development of drilling equipment, coal mine enterprises, such as Daning Coal Mine of Shangxi Asian American Daning Energy Co., Ltd., Sihe Coal Mine of Jincheng Anthracite Coal Mining Group and Baijigou Coal Mine of Ningxia Coal Mining Group have introduced VLD-1000 kilometer drilling machine and supporting equipment from Australia for gas extraction through over-1,000 km downhole drilling and multi-branch drilling since 2003. To meet the actual demand for floor water disaster prevention and control of coal mines, CCTEG Xi’an Research Institute developed and manufactured ZDY-6000LD crawler type fully hydraulic drilling machine, and applied it to drilling grouting holes for prevention and control Ordovician limestone water disaster of coal seam floors(Figure 1 and Figure 2), and working face grouting technology was further developed into downhole directional drilling grouting technology[11-13].
Compared with ordinary tunnel drilling machines, ZDY-6000LD crawler type fully hydraulic drilling machine has stronger drilling capacity, can be used to drill a borehole over 1,000m in Ordovician limestone, and it’s able to realize long-distance exploration of floor Ordovician limestone water with drilling measurement equipment. Multiple coal mines, such as Zhaogu No.1 Coal Mine of Henan Coal Chemical Industry Group[14], Xin'an Coal Mine of Jizhong Energy Fengfeng Group[15] and Sangshuping Coal Mine of Shaanxi Coal and Chemical Industry Group[16], have applied this equipment to long-distance horizontal directional drilling, so as to explore coal seam floor aquifers and perform grouting transformation for water disaster prevention and control.

Due to restriction from downhole construction conditions and drilling equipment, rotary drilling and directional drilling in downhole directional drilling grouting are hard to be combined well, so the drilling speed is slow. Furthermore, small change range of drilling trace and drilling azimuth is hard to fully cover the treatment area, so that drilling blind zone is inevitable. In addition, downhole construction is featured by poor working environment, low grouting pressure, little grouting volume and limited transformation area. Compared with water disaster prevention and control by working face grouting, despite the construction efficiency is improved greatly, the overall efficiency is still very low.
3.3. Surface Directional Drilling Grouting Technology

Xinhu Coal Mine of Huaibei Mining(Grupo) Co., Ltd. has the mining depth of 1,000 m approximately, complex geological conditions and weak and broken rock stratum. In 2012, Beijing China Coal Mine Engineering Co., Ltd., Huaibei Mining Group, Anhui University of Science and Technology, etc. performed study on “key technology of surface pre-grouting through L-type borehole for surrounding rock modification of kilometer shaft” jointly. They constructed directional boreholes (2 main boreholes and 3 branch boreholes with the vertical depth of 1,002.5m and the length of the horizontal grouting section of 200 m) on the surface with high-power top drive drilling machine for grouting transformation of the weak and broken surrounding rock in the central pump room and the substation of the station at the shaft bottom of the kilometer-deep Xinhu Coal Mine, which reduced drilling work load, improved single-borehole grouting range and grouting effect greatly, thereby ensuring surrounding rock stability of the deep mine roadway[17-19].

Surface directional drilling grouting technology is becoming mature gradually and has been applied to Ordovician limestone water disaster prevention & control for deep coal seam floors. In 2015-2018, Beijing China Coal Mine Engineering Co., Ltd. explored and treated the regional water disaster of mining area 216 in Xin'an Coal Mine of Jizhong Energy Fengfeng Group with self-developed TD2000/600 fully hydraulic top drive drilling machine(Figure 3) and horizontal directional drilling method(Figure 4)[20]. Zhuzhuang Coal Mine in Huaibei, Anhui[21], Jiu Long Coal Mine in Handan, Hebei [22,23], Wanglou Coal Mine in Shandong[24], Hengyuan Coal Mine in Anhui[25], Zhaogu No.1 Coal Mine in Xinxiang, Henan[26-29], etc. have applied surface directional drilling grouting technology for deep coal seam floor water disaster exploration, prevention & control successively, and have got good results.

Figure 3. TD2000/600 fully hydraulic top drive drilling machine
Thanks to the good construction conditions of surface directional drilling grouting, strong drilling capacity, high drilling speed, wireless deviation measurement while drilling, high directional accuracy, large change range of drilling trace and drilling azimuth and wide exploration area of high-power top drive drilling machine, as well as high grouting pressure, large grouting volume and wide coverage of surface HP grouting, the exploration and treatment ability of Ordovician limestone water disaster in deep coal floors has been improved greatly, and new paths have been created for exploration and treatment of Ordovician limestone water disaster in deep mining floors of North China type coalfields[30].

Figure 4. Schematic diagram of floor water disaster prevention and control with surface directional drilling grouting technology

4. The cases of water disaster prevention and control by surface directional drilling grouting and problem analysis

4.1. Introduction on cases
Driven by equipment progress, surface directional drilling grouting has been developed into an effective prevention and control method for Ordovician limestone water disaster in deep mining floors of North China type coalfields[31,32]. Surface directional drilling grouting technology is being accepted by and implemented in mining area with rich water of North China type coalfield gradually for its advantages, such as high construction safety, high work efficiency and full-area coverage and advanced treatment before tunneling of the working face. The drilling and grouting parameters of a part of water disaster prevention and control projects undertaken by us are shown in Table 1.
Table 1. Parameters of water disaster prevention and control cases by surface directional drilling grouting

| Project (water disaster prevention & control) | Drilling | Grouting |
|---------------------------------------------|----------|----------|
|                                             | Length of horizontal section/m | Borehole spacing/m | Grout type | Grout density / (10^3 kg/m³) | Ending standard/MPa |
| Mining area 216 of Xin’an Coal Mine         | 931~1045 | 40~45    | Single-fluid cement grout | 1.05~1.25 | 10~14 |
| Working face 18011 of Zhaogu No.1 Coal Mine | 500~1000 | 45~50    | Clay-cement grout         | 1.25~1.4  | 10    |
| Working face 16031 of Zhaogu No.1 Coal Mine | 790~1104 | 45~50    | Clay-cement grout         | 1.25~1.4  | 10    |
| Working faces II634 and II635 of Hengyuan Coal Mine | 205~936 | 40~60    | Single-fluid cement grout | 1.2~1.6   | 10~12 |

Mining area 216 of Xin’an Coal Mine of Jizhong Energy Fengfeng Group is located in the footwall of normal fault F38 (throw: 180 m) that has the east-west width of 330 m and the north-south length of 1,200 m. To treat the area where concealed collapse column, fault, fissure and other permeable structures may be developed, 16 directional boreholes (including 1 main borehole, 10 branch boreholes and 5 secondary branch boreholes with the drilling length of 17,132 m) were designed and constructed on the surface with the Daqing Limestone Aquifer acting as the target stratum for regional hydrogeological exploration and pre-treatment of cement injection, so as to block the Ordovician limestone water channels, reduce the Ordovician limestone water inrush probability of the coal seam floor, and improve downhole roadway exploration, tunneling and stoping safety.

The Permian Shanxi formation II1 coal seam of Zhaogu No.1 Coal Mine of Henan Coal Chemical Industry Group has the average thickness of 5.8 m and the buried depth of 525~590 m. The upper limestone (limestone L9, L8 and L7) of Taiyuan Formation of the direct aquifer of II1 coal seam floor is 25.00~28.70 m from the II1 coal seam floor. Among them, limestone L8 is developed well with the average thickness of 8.75 m, developed karst fissures and the permeability coefficient of 9.82~10.94 m/d. The lower limestone (limestone L2 and L3) of Taiyuan Formation of the indirect aquifer and the middle Ordovician limestone karst fissure aquifer (limestone O2) are 89.27~104.36 m and 118.26~142.58 m from the II1 coal seam floor respectively. Limestone L2 is developed with the thickness about 15 m and high water abundance. Due to impact from fracture structure and fault, there was hydraulic connection between limestone aquifer O2/L2 and limestone aquifer L8, which brought about serious water disaster threat to mining.

Among them, the exploration & treatment area of working face 18011 was 954 m in length and 336 m in width. Three main boreholes (grouting borehole 1, grouting borehole 2 and grouting borehole 3) and 12 horizontal branch boreholes were arranged on the surface with the total drilling length of 13,858.64 m for exploration & treatment of limestone aquifer L8. 12,899.5 t cement, 18,914.9 t clay and 31,814.4 t dry material were injected in total. No floor bulge or effluent was seen during tunneling of two roadways of working face 18011 after grouting, so that coal mine work safety was guaranteed. Working face 16031 has the strike length of 1,611 m, the tilt width of 210 m and the area of 338,310 m². Besides, it was provided with 2 main boreholes (grouting borehole 7 and grouting borehole 8). Among them, grouting borehole 7 was provided with 5 branch boreholes, and grouting borehole 8 was provided with 6 branch boreholes with the spacing of 52 m and the total drilling length of 10,862 m. The treatment area of working face 18031 was about 950 m in length and 180 m in width. One main boreholes (grouting borehole 2) and 6 horizontal branch boreholes (horizontal spacing: about 45 m) were arranged on the surface with the total drilling length of 7,415.13 m. During construction, the trace deviation of the horizontal section was within 3 m, limestone interval and fault were revealed, and floor exploration and grouting treatment of the working face floor were realized.

Surface directional drilling grouting was applied to limestone aquifer L3 of the coal floor of the 6 coal seam working faces (II 634 and II 635) in Hengyuan Coal Mine of Wanbei Coal-Electricity Group. The treatment had the strike length of 1,750 m, the tilt width of 360 m, and it was designed
with 3 main boreholes and 28 horizontal branch boreholes with the spacing of 45~60 m, the longest horizontal borehole section of 936 m (Figure 5), and the design drilling length of 23,622 m. Moreover, the target aquifer was grouted with single-fluid cement grout having the density of \((1.2\sim1.6)\times10^3\) kg/m\(^3\) for transformation.

Figure 5. Schematic diagram of borehole layout for water disaster prevention and control with surface directional drilling grouting in Hengyuan Coal Mine

4.2. Problem analysis
Surface directional drilling grouting technology for Ordovician limestone water disaster prevention & control of coal seam floors is developing gradually in practice. In the projects that have been completed, some have achieved treatment objective and guaranteed work safety of mines, while some haven’t got ideal treatment effect due to borehole layout, grout selection, process parameter, etc. Currently, this technology is at the industrial experimental research stage. In consideration of incomplete standard system, the management rules for water disaster prevention & control of all places and the basic requirements in Detailed Rules for Water Disaster Prevention & Control of Coal Mine are taken as the basis in engineering practice. In addition, there are different opinions on the borehole layout of the treatment area, drilling trace control requirements, grout material selection, grouting method, grouting condition, grouting ending standard, effect evaluation, etc.

(1) Borehole layout: There are “fishbone-shaped” and “parallel type” surface directional borehole layout methods for regional treatment. However, branch borehole spacing and distribution mode are at the test stage in practice, so there is inadequate design basis for borehole layout. Taking layout of “parallel type” branch borehole as an example: Generally, the borehole spacing is designed as 40 - 60 m in practice. There is no data support for whether grout diffusion is able to meet the requirements for regional water disaster prevention & control.

(2) Grouting material: The understandings of grouting material and grout selection are inconsistent, and there are divergences on grouting material selection & proportion and proportion adjustment in project construction. Taking material selection as an example, there are single-fluid cement grout, clay-cement grout, cement-clay grout, etc. Besides, there is no theoretical and experimental data support for material selection.

(3) Grouting ending standard: The understandings of grouting ending standard are inconsistent. There are grouting pump capacity control and grouting ending pressure control methods, etc. in practice. Differences in the understandings of grout selection and grout properties plus lack of systematic study on grout diffusion law and action mechanism in the target stratum affect the establishment of scientific evaluation criteria and project economy.
(4) Process parameter management: Drilling trace control, grouting method and grouting condition are important contents of process parameter management. However, there are no theoretical guidance for engineering practice, no consensus for grout selection, no systematic study on key process parameter influence factors, no scientific basis for the values of important design parameters, and no recognized technical standards and specifications.

(5) Evaluation of grouting effect: Hydraulic pressure test, core drilling, downhole drilling, geophysical prospecting, etc. can be applied to evaluation of grouting effect in practice. However, non-uniform grouting effect evaluation methods, evaluation indicators and evaluation processes bring about many disputes to project effect evaluations by project construction enterprises and coal production enterprises.

The problems above have become the application and development bottlenecks for Ordovician limestone water disaster prevention & control of coal seam floor with surface directional drilling grouting, and in-depth theoretical problems that need to be solved urgently. Selection of grouting material is the core for the problems above. Therefore, it is necessary to perform study on grout selection, rheological characteristics and diffusion law, reveal the rheological evolution law and grout-water-rock action mechanism of the HP grout in the long-distance directional drilling area, establish scientific process technical standards, borehole layout & design method, grouting ending standards and an effect evaluation indicator system based on groutability evaluation of Ordovician limestone of coal seam floor and starting from fundamental theory of grouting, so as to provide theoretical support for Ordovician limestone water disaster prevention and control of coal seam floor with surface directional drilling grouting, and ensure work safety during deep mining in North China type coalfields.

5. Conclusions
(1) Since North China type coalfields have complex hydrogeological conditions, the probability of Ordovician limestone water inrush from the coal seam floor is increasing, and Ordovician limestone water disaster has become a serious safety threat to deep mining in North China type coalfields along with large-scale development of deep resources. On this background, grouting technology is being widely applied to floor water disaster prevention and control and developed continuously for its unique advantages.

(2) Development of grouting technology is driven by equipment progress. The Ordovician limestone water disaster prevention and control method for floor has been developed to downhole directional drilling grouting from working face grouting, and the latest surface directional drilling grouting method has created a new path for floor water disaster exploration and treatment during deep mining in North China type coalfields.

(3) Disputes on understandings of grout selection, borehole layout in treatment area, trace control, grouting method and condition selection, grouting ending standard and effect evaluation have become the application and development bottlenecks for Ordovician limestone water disaster prevention & control of coal seam floors with surface directional drilling grouting.

(4) It is necessary to establish scientific process technical standards, design principles and an effect evaluation method system based on study on groutability evaluation, starting from fundamental theory of grouting with study on grout selection, rheological characteristics and diffusion law acting as the core, thereby providing theoretical support for Ordovician limestone water disaster prevention and control of floors during deep mining in North China type coalfields.

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