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# Ordovician Limestone Karst Water Disaster Prevention and Control Technology for Feicheng Coal Field

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**Abstract** Based on the features of the coal bed of Taiyuan Formation of Feicheng Coal Field threatened by Ordovician limestone karst water, through exploration, experiments and analysis of Ordovician limestone stratum features and hydrogeological conditions of the mining area, the exploration method of the Ordovician limestone water inrush channel is put forward and the top large-area grouting reconstruction technology of Ordovician limestone is implemented, so as to prevent occurrence of Ordovician limestone water inrush accidents.
**Keywords** Ordovician limestone, karst water disaster, rock stratum features, grouting reconstruction, geophysical prospecting, prevention and control technology

## Introduction

North China Permo-carboniferous coal field is one of the main coal-bearing areas in China, with a reserve accounting for about 1/3 of the total reserves of the coal fields in China, and there are tens of billions of tons of coal resources in the coal bed of the middle deep Taiyuan Formation in the area, which can't be mined safely due to severe threat of the Ordovician limestone water at the floor. As the mining level of the mine becomes deeper and deeper, the Ordovician limestone water pressure becomes higher and higher and the probability of water inrush becomes higher and higher under the joint action of the mine pressure and the water pressure, with great influences on the safe production of. Feicheng Coal Field is a typical North China Permo-carboniferous coal field, as one of the well-known large water mine areas in China. Since mining of the coal bed of Taiyuan Formation, the shafts have been submerged by Ordovician limestone water inrush for 4 times (including the local mine submerged for once) and the horizontal shaft has been submerged for once, with the maximum inrush flow of 32,970 m³/h and huge economic losses. Lessons are learnt from previous floor water inrush accidents in the mine production process, meanwhile, the large-area grouting reconstruction technology for the thin limestone aquifer is studied and promoted through exploration and analysis of the hydrogeological conditions in the mine area and such technology has obtained a good effect through test and research for nearly 30 years. Such technology has been promoted in many similar mines in China and introduced to Regulations on Water Prevention and Control of Coal Mines and Manual for Water Prevention and Control of Coal Mines. In recent years, the mine area in Feicheng City has applied such technology to treat Ordovician limestone karst water disasters and has prevented occurrence of Ordovician limestone water inrush accidents for successive 11 years, so as to maintain normal production of the old mine area which has been produced for 55 years. Such technology mainly includes research of the Ordovician limestone water inrush mechanism, research of Ordovician limestone karst fracture development features, research of Ordovician limestone rock and mineral assemblage features and research of feasibility of top grouting reconstruction of Ordovician limestone and the grouting reconstruction mechanism, etc. The result of such technology has reached the international leading level, so as to explore a new way for prevention and control of Ordovician limestone water disasters of similar mines in North China.

## Hydrogeological features of coal field in Feicheng city

### *Geological structural features*

The main coal-bearing formation of Feicheng Coal Field includes Carboniferous Taiyuan Formation and Permian Shanxi Formation and it is a fully covered concealed coal field with an area of 98 km$^2$. The well field mainly includes fracture structures and it is developed with folds, hidden collapse columns and igneous rocks. Currently, there are 295 faults with a proven throw of greater than 5 m including 75 faults with a throw of greater than 20 m, 16 folds, 11 hidden collapse columns and 5 igneous rock walls. Structural development damages the integrity and stability of the coal stratum and provides the conditions for Ordovician limestone water inrush at the floor.

***Hydrogeological features***

Boundary conditions: Feicheng Coal Field is a fault basin enclosed by faults at the east, west and north, with outcropped coal stratum at the south. The Ordovician limestone at the southeast and south of the coal field has a large area of outcrop with an area of about 260 km$^2$, directly made up with atmospheric precipitation, with rich dynamic reserve, as the makeup water source layer of the aquifers of the thin limestone and coal-bearing formations.

Aquifer features: The coal-bearing formation has totally 8 aquifers from top to bottom, including main aquifers of Fifth limestone (briefly referred to as fifth limestone) and Ordovician limestone (OL) threatening the safe production of the mine.

Fifth limestone: With a thickness of 7-10 m, developed with karst fissures, with a specific capacity $q$=16.12 L/s·m, extremely rich water and a unit scanty rainfall of 533 m$^3$/h·m. The average distance from the top to Coal 8 is about 30 m, and the average distance from the top to Coal 10 is about 18 m. The distance from the bottom to Ordovician limestone is 1.4-15 m, as the direct makeup water aquifer to mine the coal bed of Taiyuan Formation.

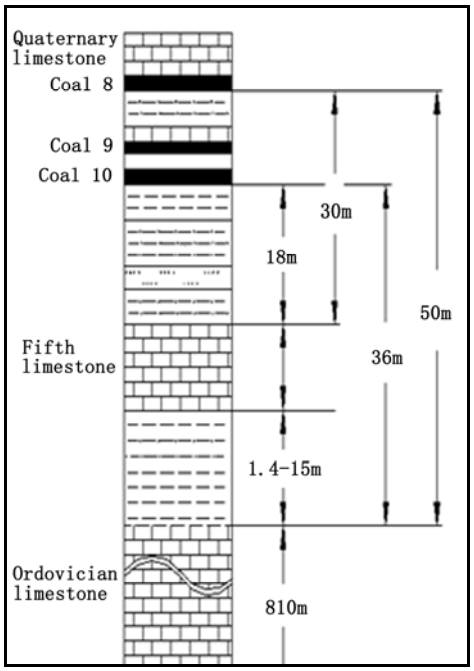


***Fig. 1*** *Hydrogeological section*

Ordovician limestone: With a thickness of 811 m, made of fine grained crystalline limestone, extremely developed with karst fissures, with a specific capacity $q$=101 L/s·m and extremely rich water, as the makeup water source layer of each aquifer of the coal-bearing formation.

Aquiclude: The floor aquiclude of the main coal bed has a small thickness, the average distance from Coal 10 down to Ordovician limestone is about 36 m, the lithology mainly includes clay rocks and sandy clay stones, and the compressive strength is low. Under the joint action of the mine pressure and the water pressure, floor water inrush is easy to be caused by the buried structures encountered.

## Structure of crdovician limestone aquifer and karst gap development features

### *Features of Ordovician limestone stratum*

By the end of 2013, the whole mine area had been constructed with 187 holes including Ordovician limestone exploration holes, observation holes, water plugging holes and water source wells, etc., including 86 S1 holes of Taoyang Mine which are complete holes running through the Ordovician limestone. Ordovician limestone has a total thickness of 811 m. Through descriptions of exploration and analysis of cores and indoor core sample identification experiments, the structure, water-bearing features and rock and mineral assemblage features of Ordovician limestone stratum, etc. are subjected to detailed analysis and research. Based on the chemical composition, structure and solubility of the lithology, considering the sedimentary features, Ordovician limestone is divided into 4 formations and 8 units from bottom to top. Liangjiashan-Yeli Formation has 2 units, with a thickness of 73.93 m; Lower Majiagou Formation has 3 units, with a thickness of 377.04 m; Upper Majiagou Formation has 2 units, with a thickness of 156.09 m; and Fengfeng Formation has 2 units, with a thickness of 203.94 m. The upper member of Fengfeng Formation is 154.68 m thick, the top 32.81 m is a dissolved weathered pack of the weak aquifer, the bottom 92.2 m comprises siliceous argillaceous dolomites sandwiched with dolomite mudstones, with weak rich water, and it can be considered as a relative aquiclude; and the middle 29.67 m has strong rich water.

***Table 1*** *List of formation features of upper unit of Fengfeng formation at top of Ordovician limestone*

| Stratum | | Aquifer | | | Chemical composition (%) | | | | Rate of karstification (%) | Porosity (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Formation | Member | Formation No. | Thickness (m) | Aquosity | Silicon | Aluminum | Calcium | Magnesium | | |
| Fengfeng Formation | (154.68)Upper member (154.68) | 1 | 32.81 | Weak | 6.39 | 2.39 | 43.79 | 5.29 | 1 | 50 |
| | | 2 | 29.67 | Strong | 1.25 | 0.41 | 48.84 | 5.64 | 14 | 33.3 |
| | | 3 | 92.2 | Weak | 1.47 | 0.58 | 50.44 | 4.12 | 5 | 17 |

### *Development features of Ordovician limestone solution fissures*

Based on summarization and analysis of previous Ordovician limestone water inrush data, analyzed in the horizontal direction, firstly, the karst rich water at the west of the coal field is stronger than that at the east and it belongs to a strong runoff zone of the karst and a discharge area of groundwater; secondly, the nonuniformity of distribution of Ordovician limestone karsts is distinct and 10 out of 11 hidden collapse columns are concentrated at the east, indicating the asynchronism of development of Ordovician limestone karsts in the coal field; thirdly, the development of Ordovician limestone karst is controlled by the structure of the main fracture and the main runoff direction is substantially consistent with the strike of the main fracture, indicating the important control role of the fracture structure to the

distribution of karst fissures. Analyzed in the longitudinal direction, seen from the boreholes constructed on the surface and down the hole, the 20 m section below the top interface of Ordovician limestone mainly comprises pore-fissure karsts and it is mostly filled with siliceous and argillaceous substances, with relatively weak rick water; the 20-40 m section is quite developed and mainly comprises fissure karsts with a good connectivity among fissures; the 40-60 m section is developed and mainly comprises karst runoff zones; and the section below 60 m is undeveloped, with a poor connectivity among fissures and weak rich water.

***Table 2*** *List of development features of top solution cracks of Ordovician limestone*

| Depth from the top interface of Ordovician limestone | Development degree of fissures (%) | Features |
|---|---|---|
| 0-20 | 20 | Fissures are filled. |
| 20-40 | 70 | Fissures have a good connectivity. |
| 40-60 | 90 | Cores are crushed. |
| Below 60 | 10 | The connectivity is poor. |

### *Rock and mineral assemblage features of Ordovician limestone*

In order to study the features such as the rock and mineral assemblage of Ordovician limestones, the Ordovician limestones on the surface and down the hole at the east, middle and west of the coal field are cored and drilled, 54 core samples are subjected to the X-ray diffraction experiment, 340 samples are subjected to the glass identification experiment, and 201 samples are subjected to chemical analysis. Through analysis and experiments, the top of Ordovician limestone has a layer of dolomitic limestones sandwiched with siliceous and argillaceous clay rocks, indicating that the top of Ordovician limestone is located in a shallow water environment with a relatively high salinity, which is unfavorable for development of karsts. The mineral crystals in the limestones at the bottom mainly include sand crystals accounting for 90% and the mineral composition mainly comprises $CaCO_3$ and secondly $CaMg(CO_3)_2$, favorable for the dissolution of limestones in groundwater. The cores 20-60m deep from the Ordovician limestone top interface are developed with fissures and crushed with a good connectivity, as a good water-filling aquifer and the key horizon for exploration and treatment at the top of Ordovician limestones.

## Analysis on Ordovician limestone water inrush conditions

Water inrush at the floor of the coal bed is a complex process and the division of water inrush types is non-uniform. Analyzed from the water inrush data of fifth limestone and Ordovician limestone in the mining area of Feicheng City, water inrush can be roughly divided into structural water inrush and non-structural water inrush. Structural water inrush mainly refers to that the mining activity directly exposes or the mining directly influences the water conductive faults, the hidden collapse columns and the fracture dense zones, etc. Based on statistics, water inrush occurs in fifth limestone and Ordovician limestone in the mining areas of Feicheng City for 153 times, where the structural water inrush accounts for over 90%. Most structural water inrush accidents are burst type and the water inrush flow reaches the peak instantaneously, with a rapid water potential, a large water flow, a high speed and a large impact, easy to cause shaft submergence accidents. On January 5, 1993, the water inrush ($Q$=32970 $m^3$/h) of the -210 m horizontal Beida Roadway of the original Guojiazhuang Coal Mine submerged the mine within 5 h. Non-structural water inrush refers to damages and disturbances of the floor aquiclude caused by the mine pressure at the stope, damaging the original stress status and stability of the floor rock stratum and resulting in water inrush under the joint action of the mine pressure and the water pressure. Non-

structural water inrush is mostly buffer type or backward type, the water flow becomes higher and higher gradually and the stable time is long. Some working surfaces encountered water inrush after mining for several days or months and such water inrush had a relatively low influence. Therefore, prevention of structural water inrush is the key to avoid or reduce significant water disaster accidents.

***Table 3*** *Schedule of Ordovician limestone water inrush conditions in mining area of Feicheng city*

| Mine Name | S/N | Water inrush type | Water inrush date | Water inrush flow ($m^3/h$) | Water inrush elevation (m) | Water inrush type | Remarks |
|---|---|---|---|---|---|---|---|
| Guojiazhuang Mine | 1 | -210m Beida Roadway | 1993.1.5 | 32970 | -210 | Fault | Shaft submergence |
| | 2 | 8101 Stoping face | 2002.12.27 | 16540 | -173 | Fault | Submergence of horizontal shafts |
| Yangzhuang | 3 | 9101 Exploration Roadway | 1985.5.27 | 4409 | -32 | Fault (backward) | Shaft submergence |
| Taoyang | 4 | 9507 Stoping face | 1985.8.6 | 17940 | -55 | Fault | Shaft submergence |
| Longzhuang | 5 | 5102 cut | 1997.10.25 | 22000 | -152 | Fault | Shaft submergence |
| Zhazhuang | 6 | 7901 Transport Roadway | 2005.3.10 | 309 | -343 | Fault | |
| Caozhuang | 7 | 81004 Stoping face | 2004.3.27 | 495 | -360 | Concealed fault | |

Practices have proven that any water inrush has three elements: the rich water of the aquifer, the water pressure of the aquifer and the water channel. Rich water of the aquifer is the material basis of water inrush, the water pressure of the aquifer is the force source of water inrush, the water channel is the condition for water inrush, and all of them are necessary. Changing the rich water of the aquifer and looking for the water channel is the work objective and key point to prevent large water inrush of Ordovician limestone.

## Prevention and control technology for Ordovician limestone Karst water

### *Exploration of water channel and rich water area at the top of Ordovician limestone*

#### *(1) Exploration of water channel*

Through comprehensive analysis of the previous water inrush cases of Ordovician limestone, the water channels mainly include water conductive faults (including buried faults), karst hidden collapse columns, dense fissure zones (weak zones) and poorly plugged boreholes, etc. The main water channels endangering the safe production of the mine are the water conductive faults and the hidden collapse columns. Therefore, the key point in the production process shall be exploration of the concentrated water conductive channels, i.e. the water conductive faults and the hidden collapse columns. The exploration methods include: firstly, the ground three-dimensional geophysical prospecting, transient electromagnetic method and controlled source audio-frequency magneto-telluric methods; secondly, the downhole geophysical prospecting, commonly including the underground channel wave seismic method, the gallery perspective method and the Rayleigh wave detection method, etc.; thirdly, the downhole advance drilling method. No matter which geophysical prospecting method is adopted, limited by the physical conditions of the formation, etc., the results have great differences and must be proven by drilling, so as to obtain a good effect.

### *(2) Exploration of rich water on the top of Ordovician limestone*

The Ordovician limestone in the North China Permo-carboniferous coal field with a large thickness and strong rich water are the main water source layer threatening safe production of the mine. However, the whole Ordovician limestone aquifer is not a complete and even water-bearing body and it can be divided into 4 formations and 8 sections. The upper section of Fengfeng Formation is 154.68 m thick, and the 32.81 m member below the top interface of Ordovician limestone is a dissolved weathered pack with non-uniform aquosity and relatively weak rich water. The key point is exploration of the relatively rich water area of the member, so as to provide the basis for drilling and grouting. The transient electromagnetic method, the three-dimensional high-density electrical method and the audio frequency electric perspective method, etc. are commonly used at present.

## *Grouting reconstruction technology at the top of Ordovician limestone*

### *(1) Feasibility for grouting reconstruction at the top of Ordovician limestone*

The safe mining technology by grouting reconstruction of thin limestones has been implemented for nearly 30 years in Feicheng mining area and has obtain good effects. As the mining depth becomes deeper and deeper, even complete grouting reconstruction of the thin limestone aquifer to an aquiclude can't meet the safe mining conditions and there are water inrush risks in the Ordovician limestone aquifer. Therefore, research of the grouting reconstruction technology at the top of Ordovician limestone has a significant meaning to safe release of a lot of coal bed resources of Taiyuan Formation.

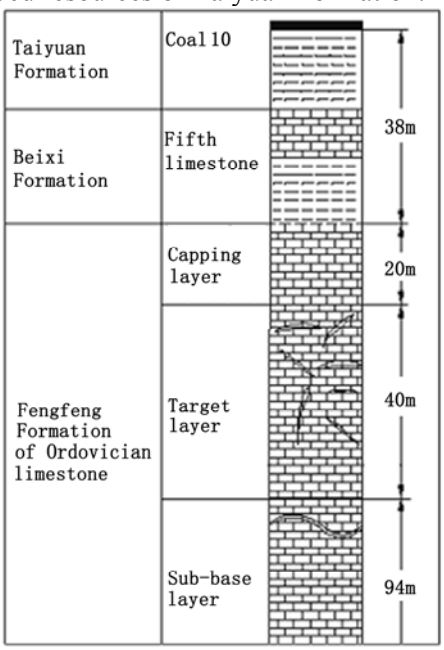


***Fig. 2*** *Schematic section of Fengfeng formation*

Through exploration, research and analysis, the scope 20 m below the top interface of Ordovician limestone is an aquiclude with relatively closed fractures and comprises the top 0.5-2 m weathered paleocrust with a relatively low strength and limestones with a high degree of crystallization. Most fissures are filled with siliceous argillaceous substances to form a complete hard rock stratum, i.e. “the capping layer”. The scope 20-60 m below the top interface has developed fissures and karsts, relatively good connectivity and good groutability and it is the target layer for grouting reconstruction. The scope below 60 m has a poor connectivity among fissures and weak rich water and forms the “sub-base layer” for grouting

reconstruction at the top of Ordovician limestone, favorable for preventing a lot of grouts from diffusion to the deep portion. Therefore, the best horizon for grouting reconstruction at the top of Ordovician limestone is the scope 20-60 m below the top interface.

***(2) Principle and function of grouting reconstruction***

Grouting reconstruction is used as the method and means to change the hydrogeological conditions of the rock mass (stratum). The basic principle is to dehydrate, consolidate or gelatinize the grout in the gap or channel in the injected layer originally occupied by water under certain pressure at certain time and enable the stone or the gel to form a complete water-resistant body with the surrounding rocks, so as to change the hydrogeological conditions of the aquifer. It has the following three functions: (1) The injected layer is grouted with a lot of grouts, which are dispersed, consolidated and filled along the karst fissures in the injected layer to displace the water, so as to enable it to exclude water or include a little water.(2)Under the grouting pressure, the grouts migrate, diffuse, consolidate and fill the water conductive fissures of the sub-base layer, so as to cut off the makeup of the aquifer of the lower member and enable the strong aquifer of the upper member of Ordovician limestone to become a weak aquifer or aquiclude, increase the effective thickness of the aquiclude and realize the objective of safe mining.

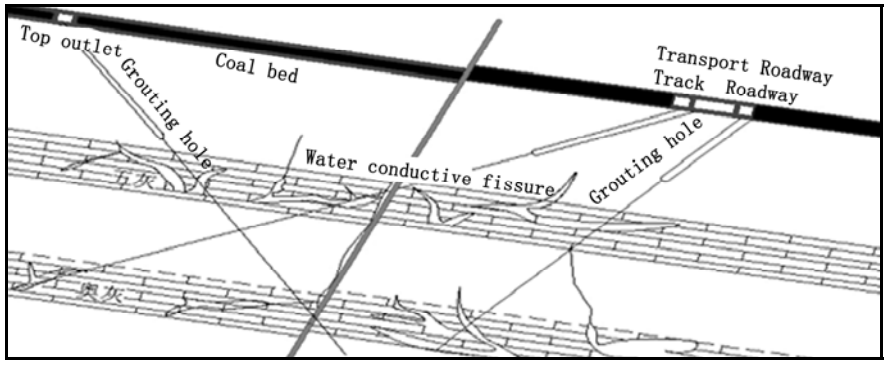


***Fig. 3*** *Diagrammatic profile of grouting reconstruction*

***(3) Grouting reconstruction mechanism***

Grouting reconstruction is the most effective treatment method to change the rich water of the aquifer. Theoretically, it is a process changing the turbulence to the laminar flow and the retarding flow. In such process, the grouts migrate, diffuse, deposit and gelatinize to form the structural flow with certain strength, so as to retard the flow of the groundwater in the injected layer. It is exhibited in the following aspects: Firstly, mechanical filling: The grouts flow and diffuse along the fissures under certain grouting pressure gradient. When the grouts go away from the grouting holes and the pressure gradient is reduced to the critical pressure, the grouting flow speed becomes slower, the turbulence changes to the laminar flow, the hydraulic materials are solidified, the viscosity is increased and the flow becomes slower and finally stops, while the particles of the non-hydraulic materials are gradually agglomerated and settled or adhered to the fissures, which increases the flow resistance and the static shear stress of the grouts and finally plugs the fissures. Secondly, chemical filling: the hydraulic materials in the grouts chemically react with water. When the laminar flow changes to the retarding flow, the solid materials in the grouts will be agglomerated with time to generate certain strength so as to accelerate the filling and water plugging process. As such process repeats, due to increasing grouting pressure, the rock strength becomes higher and higher, so as to plug the water.

***(4) Process flow of grouting reconstruction***

The surface-underground combined construction technology is adopted in the grouting reconstruction, i.e. establishing a grouting station on the surface for grouting, connecting the grouting station with the downhole transmission pipeline through the feed hole and performing reconstruction and drilling on the working surface. The grouts shall be injected into the injected layer under the pump pressure and continuous grouting shall be implemented. When the pump flow and the grouting pressure meet the design requirements, single-hole grouting is completed. When grouting of the working surface is fully completed, comprehensive evaluation shall be performed and the production shall not be organized until the design requirements are satisfied.

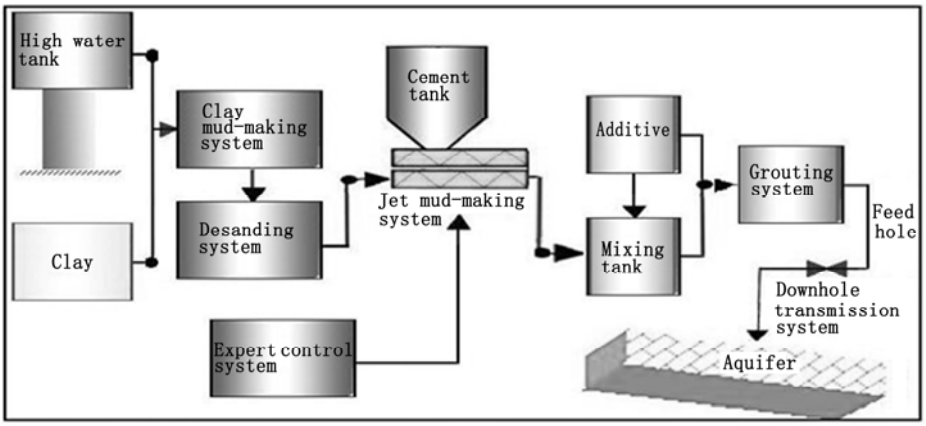


***Fig. 4*** *Process flow chart of grouting reconstruction*

***(5) Application of grouting reconstruction technology at the top of Ordovician limestone***

The mining area of Feicheng City has a mining history of 55 years, the coal bed of Shanxi Formation has been substantially mined, and normal production relies on mining of the coal bed of Taiyuan Formation. As the mining level goes deeper, the coal bed of Taiyuan Formation is not only threatened by fifth limestone water, but also mainly affected by Ordovician limestone water. Currently, the Ordovician limestone water pressure borne by mining Coal 8 is 4.6 MPa and the water inrush coefficient is greater than 0.1 MPa/m, so Ordovician limestone must be subject to grouting reconstruction. The premise to perform grouting reconstruction on Ordovician limestone is that the Ordovician limestone coefficient of normal sections is not greater than 0.1 MPa/m, and the water inrush coefficient of the floor section damaged by the structure is not greater than 0.06 MPa/m.

In recent years, 6 pairs of producing mines in the mining area are gradually subject to grouting reconstruction of Ordovician limestone based on complete grouting reconstruction of fifth limestone aquifer, with a distinct effect. By the end of 2013, the whole area has 5 pairs of mines and 31 working surfaces explored for grouting reconstruction of Ordovician limestone, the cumulative constructed Ordovician limestone grouting holes are 629 holes/65973.9 m, the cumulative drier quantity is 45503.2 t, the safely produced coal quantity threatened by water is 1.716 million tons, safe production is realized and Ordovician limestone water inrush accidents of the working surfaces have been avoided for successive 11 years.

Through analysis of construction situations: Firstly, seen from the horizontal direction, the Ordovician limestone rich water in the west of the coal field is stronger than that in the east, solution cracks are developed, and single-hole water amount and the grout intake are large; secondly, seen from the longitudinal direction, the Ordovician limestone rich water section in the west is 15.0-45.0 m below the top interface, 33.0-46.0 m in the east with a small water

amount and a small grout amount; thirdly, the mining elevation of the working surface is -120 - -450 m, the water pressure is 1.5-4.8MPa, and the water pressure in the east is lower than that in the west.

***Table 4*** *Statistics of Ordovician limestone frouting reconstruction works*

| Mine Name | Number of working surfaces | Number of $O_2$ holes/quantity (m) | Maximum water amount of single hole ($m^2$)/maximum drier grouting amount of single hole (t) | Cumulative drier grouting amount (t) | Vertical depth of inrush $O_2$ (m) | Water concentration section {below the top interface (m)} | Recovery (10,000t) |
|---|---|---|---|---|---|---|---|
| Baizhuang | 6 | 182/22162.9 | 300/1952.0 | 16206.4 | 16.2-59.2 | 20.0-45.0 | 39.5 |
| Caozhuang | 7 | 16/1347.0 | 46/415.8 | 224.9 | 19.38-39.4 | 33.1-44.5 | 71.3 |
| Zhazhuang | 6 | 168/19758.7 | 133/757.4 | 3998.5 | 8.8-66.0 | 23.0-62.0 | 24.0 |
| Xinguo | 11 | 257/21960.8 | 190/1023.0 | 24888.6 | 40 | 15.0-40.0 | 33.8 |
| Xingyang | 1 | 6/744.5 | 2/161.7 | 184.8 | 46.0 | 46.0 | 3.0 |
| Total | 31 | 629/65973.9 | 300/1952.0 | 45503.2 | 8.8-66.0 | 15.0-62.0 | 171.6 |

## Conclusions

(1) Through exploration and research of Ordovician limestone aquifer, it is feasible to implement grouting reconstruction at the top of Ordovician limestone, which is the most effective technical method to prevent occurrence of large water inrush accidents of Ordovician limestones.

(2) It is very important to strengthen the exploration and research of the concentrated water channel of the mine (water conductive faults and hidden collapse columns, etc.) and take advantage of the geophysical prospecting technology in prevention and control of water disasters of the mine.

(3) Analysis and research on water bearing capapcity of the top Ordovician limestone shall be strengthened so as to provide reliable geological basis for grouting reconstruction.

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