Study on defining developmental basement and treatment measures of collapse columns in Pingshuo Mining Area

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Abstract. In order to realize the rapid treatment of concealed collapse columns in the 19108 Working Face of Anjialing No.1 Underground Mine in Pingshuo Mining Area and achieve safety mining of the working face, the method of “treatment combining with exploration and design” was used to grout and treat the collapse columns. Based on the analysis exploration data and the borehole verification data after grouting of the collapse columns, and combined with the previous geological data of Pingshuo Mining Area, the basic formation conditions and distribution regularities of the soluble-salt-type collapse columns in Pingshuo Mining Area were studied; and hydrogeological characteristics of the soluble-salt-type collapse column was obtained; and targeted treatment measures were put forward. The results showed as follows: (1) The type of collapse columns developed in the Pingshuo Mining Area is a soluble-salt-type, the basement of collapse column developed in Carboniferous coal measure strata; (2) The concealed collapse columns in the 19108 Working Face are all soluble-salt-type sinking column, which does not pass through the Ordovician limestone karst aquifer; (3) The treatment measures for the collapse columns of the working face were effective.

1. Introduction
China has abundant coal resources. The development and utilization of coal resources is an important part of China's national economic development. However, the hydrogeological conditions of many coalfields in China are very complicated, and the mining of coal seams is threatened by a variety of water bodies, especially the Ningwu coalfield in North China. The floor of its main coal seams is the Ordovician limestone karst-fracture aquifer(group). Once the water bursts, it often causes serious disasters[1]. Collapse column is a special vertical structure commonly found in North China Coalfield. They often connect the upper and lower aquifers. Once exposed, water inrush accidents are very easy to occur[2]. Therefore, how to detect and treat concealed collapse columns is an urgent problem to be solved[3]. At present, there are four basic viewpoints on the formation mechanism of the collapse column at home and abroad: the gypsum collapse theory, the cyclic collapse theory, the gravity collapse theory, and the vacuum ablation collapse theory[4]. Geophysical methods such as seismic and electromagnetic methods and drilling method are used to detect the collapsed columns, and the main treatment methods are grouting to block water, grouting to strengthen the coal seam floor, grouting to transform aquifers, and dewatering and depressurization[5]. However, the formation of collapse columns is affected by many factors, and its water abundance conditions are complex and the rules are variable[6]. If the development base of the collapse column and the location of the conductive aquifer cannot be accurately defined, it is often impossible to take pertinence measures, which causes a waste of engineering funds and treatment time, and if strong aquifers are conducted, water inrush accidents are prone to occur[7]. On June 2, 1984, a karst collapse column water percolation disaster occurred at
the 2171 Fully-mechanized Mining Working Face in Fangezhuang Coal Mine of Kailuan Coal Mining Administration, which is rare in the world’s mining history. The maximum volume of water blast was 2053 m$^3$/min, forcing the mine to stop production and endangering the adjacent mines. The direct economic losses amount to several hundred million yuan[8]. Therefore, to find out the formation mechanism and distribution regularities of collapse columns, and to take reasonable prevention measures are the prerequisites for the safe production of coal mines[9]. Now 19108 Working Face of Anjialing No.1 Underground Mine is taken as an example to introduce the research on the definition of the development basement of the collapse column and its control measures in Pingshuo Mining Area.

2. Overview of Collapse Columns in Pingshuo Mining Area
The Pingshuo Mining Area is located at the northern end of the Ningwu Coalfield in Shanxi Province, about 100 km north of Datong City, and spans Pinglu and Shuocheng districts in Shuozhou City. Its geographic coordinates are approximately 112°17′-112°26′ east longitude and 39°24′-39°24′ north latitude. It is bounded by the Maying River and 11$^\text{th}$ coal seam outcrop line in the east, with 11$^\text{th}$ coal seam outcrop line as the natural boundary in the north and west, and the Danshuigou Fault in the south. The north-south length is 23 km, the east-west width is 22 km, and the total area reaches 376 km$^2$ and the geological reserve is about 1.26×10$^{10}$ t. The location and mine fields subdivision of Pingshuo Mining Area are shown in Figure 1. Due to its large thickness, shallow burial, and convenient transportation, it has become one of the key open mining areas in China. Carboniferous-Permian coal measure strata are reserved in Pingshuo Mining Area, including Benxi Formation, Taiyuan Formation of Upper Carboniferous and Shanxi Formation of Lower Permian, with 16 coal seams. The main minable coal seams in the mining area are all in Taiyuan Formation of Upper Carboniferous. Its coal content is as high as 30% to 40%, especially in the lower sections(from the top of the Benxi Formation to the top of 9$^\text{th}$ coal seam). Among them, 4$^{\text{th}}$, 9$^{\text{th}}$ and 11$^{\text{th}}$ coal seams are the main minable coal seams in this mining area[10].

![Figure 1. Sketch map of the location and mine fields subdivision of Pingshuo Mining Area](image)

The collapse columns are relatively developed in Pingshuo Mining Area[11-18]. Because of the inertia, they have been judged as Ordovician limestone karst collapse columns, especially Anjialing...
No.1 Underground Mine, Anjialing No.2 Underground Mine and No.3 Underground Mine in the area were revealed multiple collapse columns[11-15] during the period from 2005 to 2015, which were unanimously determined to Ordovician karst collapse columns. Generally, the method of skip-mining or grouting water blocking combined with reinforcing roof and floor was used. It has increased mine production costs and has a greater impact on the improvement of business efficiency.

3. New Understanding of the Developmental Base of Collapse Columns in Pingshuo Mining Area

In 2016, through the underground advanced geophysical prospecting and drilling verification, a water-rich geologic anomalous body was found in the 19108 Working Face of Anjialing No.1 Underground Mine in Pingshuo Mining Area, and a borehole was drilled to explore the water. Water inflow was 95 m$^3$/h in the initial stage of the borehole drilling, which decreased to 30 m$^3$/h after about 3 hours. The China Coal Pingshuo Co., Ltd. and the Mine immediately organized an intensive inspection, and formulated special exploration design and safeguard measures. A total of 14 intensive inspection boreholes were designed, namely: 3 boreholes (RB1~RB3) for the coal roof, 6 boreholes (CB4~CB9) for the coal seam, and 5 boreholes (FB1~FB5) for the floor (Figure 2). After all the intensive inspection boreholes were constructed, the borehole gushing water decreased to about 16 m$^3$/h and tended to be stable. The intensive investigation basically delineates the spatial development status of anomalous geological bodies. After reviewing by water experts from Xi’an Branch of China Coal Research Institute, Beijing Dadi High-tech Company, China National Coal Group Corporation and other units, it was determined that the abnormal geological body was an Ordovician limestone water diversion collapse column (CC19108-1). It was decided to entrust a domestic professional underground grouting reinforcement team to carry out grouting and water blocking design and be responsible for implementation.

![Figure 2. Layout of boreholes for collapse column exploration](image-url)
depth 2798.2 m, cleaning bottom of hole and re-grouting reached 42 times, and a total of 1364.5 t of cement was grouted. The water-cement ration changed dynamically during grouting: in the early stage, the ratio was about 1:4; and in the late stage, the ratio was approximately 1:1.18. The grouting water blocking level was 57–37 m below the 9th coal seam floor and 10 m above and below the interface of Ordovician roof. An artificially simulated and constructed "water blocking plug" was used to block the water diversion channel[18] (Figure 3).

![Figure 3. Layout of boreholes for collapse column treatment](image-url)

During the treatment process, it was found that the cylinder deep grouting, complementary grouting and verification of the drilling exploration results had a large deviation from the general understanding and prediction results of the collapse column. Firstly, the deep fractures of the drilling column did not develop, although there were local differences in drilling speed phenomena, there were no obvious geological features in and out of the column boundary; secondly, the amount of gushing water in the boreholes at different depths under the column did not increase but decreases, it was inconsistent with the understanding that the amount of water near the base of the Ordovician base should increase; thirdly, the design slurry could not be injected, and it was very difficult to make up injection by water injection fracturing. After analysis, the following two understandings were obtained: (1) the early geological determination was accurate, and the exploration results showed that the filling in the column body was dense, the degree of cementing was high, the hardness was great, the water channel was restricted, and the water volume was not small, grouting boreholes should be added continuously to strengthen the treatment; (2) the collapse column was a shallow collapse column, not an Ordovician collapse column, and the bottom of the column was an original rock entity. The water blocking work should be turned to strengthen roof and floor of 9th coal seam. Considering that the collapse column was very harmful, the China Coal Pingshuo Co., Ltd. adopted relatively safe measures to continue the treatment of the collapse column. After treatment, the total gushing water volume of each observation and verification borehole was about 0.3 m$^3$/h, which basically achieved the treatment purpose and effect of "no water leakage and no grout consumption" in all boreholes. After the implementation of the special safety measures for the collapse column in the coal mine, the coal seam of the working face was mined. Mining exposure showed that only 1/4 and 3/4 of the 9th coal seam from the bottom floor...
were destroyed by corrosion, and the 9th coal seam was continuous, these verified that "Understanding (2)" was basically accurate: the collapse column was a shallow collapse column. Due to the existence of dissoluble carbonate and sulphate rocks in the Carboniferous and Permian strata, under strong dissolution and mechanical actions, the formed small karst caves and lost roof support to the overlying strata, thus caused the overlying strata to collapse downward continually and formed a columnar collapse body.

4. Formation Mechanism and Distribution Characteristics of Soluble-salt-type Collapse Column

4.1. Formation Mechanism
Soluble-salt-type collapse column is the product of soluble salt erosion and is controlled by geotectonism. It is the result of the joint action of water chemistry, hydrodynamic action and mechanical action. Its material and dynamic conditions are as follows:

4.1.1. Material Conditions. According to the evolution data of the geological age, the Carboniferous climate in North China was humid and hot, coal fields were formed, reptiles and insects emerged, the terrain was low and flat, and amphibians thrived. After that, the climate changed drastically, glaciers became widespread, the largest transgression occurred in southwest China, and the orogenic movement was intense, the Permian era began. Due to sudden climate change, alternating cold and heat, and strong metamorphism in the Middle and Late Carboniferous, some rock minerals gathered to form some deposits. In the strata of coal measures exposed in the Pingshuo Mining Area, it was found that there are many pure, strip-shaped or thin-layered soluble rocks, such as calcite, kaolinite, gypsum, limestone and so on. This certifies the Pingshuo Mining Area has the material conditions for the development of soluble-salt-type collapse columns.

4.1.2. Dynamic Conditions. In the early Carboniferous, the terrain was low and flat, the rivers developed, the plants and animals were prosperous, and the strata received sediments and formed coal fields. However, the Carboniferous period lasted 72 million years, geological effects such as earthquakes and weathering were still frequent and intense. Some small faults, fissure-intensive zones and weathered areas were locally formed. This kind of action occurred from time to time in the same coal seam deposition (Figure 4). Under the long-term dissolution of faults(fissures) and groundwater, these caves were getting larger and larger. In the long-term effect of geological tectonic force and overlying strata gravity, some karst caves collapsed, and the sedimentary strata overlying them also collapsed, it provided the dynamic conditions for the formation of collapse column.

![Figure 4. Schematic diagram of small faults in inclusion of 4th coal seam in Pingshuo Mining Area](image)

4.2. Distribution Characteristics

4.2.1. Controlled by stratigraphic texture. The stratigraphics where the soluble-salt-type collapse columns develop are mainly distributed in the Middle and Late Carboniferous, which were mixture constructions of soluble carbonate and sulfate rocks.

4.2.2. Controlled by geological structural conditions. Soluble-salt-type collapse columns are mainly controlled by NW-SE direction fault dense belt, they distribute in the fault zone and its edge in moniliform(Figure 5), consistent with the distribution of calcite development zone in the mining area. In the Pingshuo Mining Area, most of the 7 collapse columns that have been exposed in Anjialing
No.1 Underground Mine and No.3 Underground Mine are distributed near some water-conducting fault zones. The developing depth mainly depends on the developmental conditions of the soluble salts. Most of them are located in coal seam 9th and its roof; the developing height is mostly in the Early Permian fault, and some of them develop to the Middle and Late Permian strata, not reach the surface. At the same time, the surrounding rock near the collapse column is developed with dense strip joints and fissures, filled with calcite, or the filled calcite is dissolving, forming a 0~300 mm wide crack.

![Figure 5. Ground plane graph of location relationship between collapse columns and faults in 19108 Working Face](image)

4.2.3. Relatively developed in concentrated drainage area of underground spring. Most of the exposed collapse columns in Pingshuo Mining Area are concentrated in the mining and driving area of Anjialing No.1 Underground Mine and No.3 Underground Mine. The two mines belong to the supply source of Qilihe River. The concentrated runoff channels of underground water are relatively developed, the surrounding spring mouths are very developed, the drainage conditions are good, and the dissolution of soluble salt with higher purity is more intense, so the collapse columns are generally developed. According to the distribution characteristics of the exposed collapse columns, the development sites: firstly, some of the developed parts are located on the strong runoff zone of groundwater in a certain geological history period, and most of the collapse columns formed at this time have no water; secondly, some others are located in the centralized drainage zone of modern groundwater, most of the collapse columns developed here are rich in water, with strong water conductivity and great harm; thirdly, it is the widespread distribution of medium-sized(0.1~2 mm) structural fractures in the developed strata, and large-scale fractures(>2 mm) are often seen in underground working faces.

5. Hydrogeological Characteristics of Soluble Salt Collapse Columns
The threat degree of collapse column to the mining of working face depends on its water abundance. The research on the water abundance of soluble-salt-type collapse column is one of the important contents of water prevention and control in coal mine. Its water abundance mainly depends on the dissolution degree of soluble salt in the column and the supply of the aquifers in coal measures strata, while the water pressure in the column is generally the water head pressure of the aquifers in coal measures strata. Generally, the earlier formed collapse columns have limited amount of accumulated water, while the later formed or in the process of forming collapse columns have sufficient decomposed water and supplemental water, so the water abundance is high. According to the analysis of the field observation data of the collapse columns in Pingshuo Mining Area, the main hydrogeological characteristics of the soluble-salt-type collapse column are as follows:

1. Generally speaking, the development scale of soluble salt in coal measures is small, and the development scale of soluble-salt-type collapse column is affected by the development scale of soluble...
salt, so the development scale of collapse column is also small. The maximum length axis of soluble-salt-type collapse column found in Pingshuo Mining Area is no more than 80 m, and some small collapse columns even only have a few meters hollow, with limited water supply, which can be drained generally.

(2) The basement of soluble-salt-type collapse column is developed in coal measure strata, which is shallower than that of Ordovician limestone karst collapse column. However, due to the supply of soluble salt and aquifers in coal measure strata, more than 85% of soluble-salt-type collapse columns are rich in water, which is different from that of Ordovician limestone collapse column. Table 1 shows the characteristics of collapse columns exposed in Anjialing No.1 Underground Mine and No.3 Underground Mine in Pingshuo Mining Area.

(3) Anhydrous collapse column: usually in the early stage of formation, many cavities were formed, and a small amount of bedrock fragments are distributed in the basement. There are calcite and argillaceous filling between the surrounding rocks, which are generally water-proof. The mining practice shows that this type of collapse column does not have the condition of water inrush. For example, there were no traces of groundwater in CC19108-1 collapse column of Anjialing No.1 Underground Mine and 3 collapse columns exposed in Anjialing No.2 Underground Mine. Even under the water pressure of 0–6 MPa in the Ordovician limestone aquifer, there was no moisture or water dripping; the 450 collapse columns exposed in the early stage of the adjacent Yangquan Mining Area in Shanxi Province were not in the groundwater discharge area or runoff zone, nor connected with the aquifer. Except for a few of them, which were exposed close to the surface, they were generally dry and waterless, so they could be mined normally.

(4) Water abundant collapse column: most of the collapse columns exposed in Anjialing No.1 Underground Mine and No.3 Underground Mine in Pingshuo Mining Area were rich in water (Table 1). The filling material in the column had not been cemented yet. When drilling, it was sometimes fast and sometimes slow, often accompanied by the phenomenon of air pushing. The water inflow varied in different depths of drilling. The water inflow of a single borehole reached 30–95 m³/h. The spindle angle of core rock block was significant, and there were a large number of cavities, which were developing collapse columns and have high water abundance. Once exposed directly, the lighter result would be causing changes in the mining layout, and the heavier result would be causing some casualties.

To sum up, the soluble-salt-type collapse column has high water abundance, which must be paid attention to and studied. However, not all the soluble-salt-type collapse columns lead through the Ordovician limestone water and form a water inrush channel. Only when the base of the soluble-salt-type collapse column develops to the Ordovician limestone strong runoff zone, can it constitute a potential water inrush risk. Therefore, it is reasonable to study the cause of formation, location and water conductivity of the collapse column, and take corresponding treatment measures on the basis of finding out the hydrogeological characteristics, groundwater volume and water pressure of the collapse column.

6. Treatment Measures for Soluble-salt-type Collapse Columns

Although the soluble-salt-type collapse column is usually rich in water, the supply is limited. As long as it is discovered in advance, it can be safely passed by using the drilling, dewatering and drainage technologies, which not only liberates geological reserves, but also is economical and reasonable. In special soft areas, it is assisted by grouting reinforcement measures for roof and floor of a coal seam.

The main implementation process can be divided into the following 4 steps:

(1) Design drilling exploration at the place 100 m from the edge of the target body of the excavating roadway, and use dense drilling to shield the roadway safely to 60 m place. The detailed investigation must be carried out by additional drilling design. According to the detailed investigation, formulate safety technical measures to continue excavating.

(2) Explore water to 30 m place from collapse column, conduct comprehensive exploration of geophysical exploration and drilling to find out: ① the irregular cylinder surface and peripheral fissure
development of the collapse column; ② the nature and characteristics of the fillings and its water abundance; ③ the occurrence change, lithologic combination, arrangement and age of the coal seam and rock layers inside and outside the collapse column; ④ the water head height of each water bearing body within the scope; ⑤ the development height and depth of the collapse column to determine the development shape and size of the collapse column; ⑥ the position and distance of collapse column in roadway excavating and working face mining; ⑦ genetic type and water content.

### Table 1. Statistics of collapse column characteristics

| Mine name | Location | Discovery time | Geological characteristics | Discovery method | Developmental range | Outflow situation | Column structure |
|-----------|----------|----------------|-----------------------------|------------------|--------------------|------------------|-----------------|
| Open-off cut of 19102 Face | August, 2005 | Underground | 15 m long and 15 m wide | Drained 3 million m³ accumulation water and still gushing water | Straight through the top, similar to a cylinder. |
| Anjialing No.1 Under-ground Mine | August, 2014 | Roadway exposure | 15 m long and 8 m wide | Drained 3 million m³ accumulation water | The small hole |
| In 19108 Face and 33 m away from the south side of its auxiliary haulageway | May, 2016 | Water-rich area by underground geophysical exploration | 44.3 m long and 33.8 m wide | 61,800 m³ water have been dewatered, and the water inflow is 14.1 m³/h | Approximate a elliptic cylinder |
| 165 m from the opening of 34201 main haulageway | January, 2014 | Before approaching it, the coal seam tilted down 10° | 82 m long in east-west direction, 50 m wide in north-south direction | Dewatered 2300m³ water | The rock mass inside the cylinder was oxidized seriously by weathering and oxidized into yellow oxidized mud |
| About 312 m from 34202 main haulageway | March, 2014 | Before approaching it, the coal seam tilted down 13° | 80 m in north-south direction, 45 m wide in east-west direction | No water | The rock mass inside the cylinder was oxidized seriously by weathering and oxidized into yellow oxidized mud |
| No.3 Under-ground Mine | July, 2014 | Within 100 m of the excavation of the roadway from it, small faults and cracks on the roof of the coal seam are more developed, and the water drenching is larger. | Mining | 48 m long in north-south direction, 43 m wide in east-west direction | The water inflow decreased from 70 m³/h to 0 | The rock mass inside the cylinder was oxidized seriously by weathering and oxidized into yellow oxidized mud |
| Among the three main roadways of the east wing panel, about 500 m away from industrial square of the return air shaft in the east | March, 2015 | Underground | 50 m long in north-south direction and 35 m wide in east-west direction | The water inflow decreased from 3 m³/h to 0 | The rock mass inside the cylinder was broken and no oxidized mud was found |
(3) Prepare a detailed investigation report, evaluate and judge the nature, water volume and water pressure of the collapse column according to the previous geological exploration results, and propose a treatment plan.

(4) In the treatment process of collapse column, use transient electromagnetic (when the structure is deep and the scope is large) or high-resolution electrical method to evaluate the effect in the middle stage of treatment; after treatment, develop a comprehensive verification design for geophysical and drilling, and verify the treatment effect; evaluate the treatment effect and put forward the next mining opinions; according to the mining opinions, the mine organizes skip mining, turning knife handle mining or direct mining.

7. Conclusions
(1) Before 2015, the collapse columns exposed in Pingxiao Mining Area were all determined to be Ordovician limestone collapse columns, with a large investment in treatment. Based on the continuous analysis and understanding of the treatment process of collapse columns in Anjialing No.1 Underground Mine in 2016, it is believed that there are soluble-salt-type collapse columns in Pingxiao Mining Area, and most of the collapse columns exposed in the early stage are soluble-salt-type collapse columns. The development basement of soluble-salt-type collapse column is located in the Middle and Late Carboniferous coal measure strata. The supply water sources are soluble-salt dissolution water and aquifer water of coal measures strata, and their water heads are basically close to the water levels of coal measure aquifers.

(2) Most of the soluble-salt-type collapse columns are rich in water, with large amount of water at the initial stage of exploration, but they are easy to be drained. After drilling and releasing in advance, they are generally safe and have little impact on production, but if they are exposed directly, the security risk is high.

(3) The soluble-salt-type collapse columns are not all connected with the Ordovician limestone water to form a water diversion channel, and only the basement developed to the Ordovician limestone strong runoff zone can constitute a potential risk of water inrush. Therefore, when meeting the collapse columns, it is necessary to find out their hydrogeological characteristics, groundwater volume and water pressure, study their causes, location and water conductivity, then the treatment methods adopted are safe and reasonable.

(4) The treatment of soluble-salt-type collapse column usually can adopt the method of drilling borehole drainage, supplemented by the method of grouting reinforcement to roof and floor of coal seam in the soft section, using the drilling borehole to drain the water in the upper cavity and replace the water in the lower crack with slurry, improving the quality of roof and floor rocks of coal seam, and preventing roof falling or floor subsidence in advance. Before, in and after the treatment, the verification of treatment effect and expert evaluation should be organized in stages to make the treatment work reach the standard and purpose of "no water leakage and no grout consumption" in drilling and grouting.

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