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Analysis of Characteristics of Roof Fall Collapse of Coal Mine in Qinghai Province, China

Ya-Jie Wang [1], Lin-Shuang Zhao [1,*] and Ye-Shuang Xu [2,*]

[1] Department of Civil and Environmental Engineering, College of Engineering, Shantou University, Shantou 515063, China; 20yjwang1@stu.edu.cn
[2] Shanghai Key Laboratory for Digital Maintenance of Buildings and Infrastructure, Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
* Correspondence: lshzhao@stu.edu.cn (L.-S.Z.); xuyeshuang@sjtu.edu.cn (Y.-S.X.); Tel.: +86-754-8650-4551 (L.-S.Z.)

Abstract: This paper presents the roof fall collapse of a coal mine that occurred, causing 20 deaths and 1 injury, in Qinghai Province, China, on 14 August 2021. After the primary investigation of this incident and a brief description of the rescue action undertaken, this report discussed the possible reasons behind this disaster. The fissure water and damaged rock mass are the dominant triggering factors of this incident. Little concern for risk assessment and monitoring systems is one of the main man-made mistakes. Consequently, the reflections and suggestions are put forward to reduce or prevent the occurrence of roof fall incidents in coal mines. The noteworthy actions that are necessary in coal mine projects are conducting risk assessments based on geological condition and building proper support systems for coal mines considering he situation in situ.

Keywords: roof fall collapse; rescue measures; incident; risk assessment; coal mine

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1. Introduction

Although the clean energies, such as wind, solar, and water, are booming in the modern age, coal is still the largest source of energy for generating electricity in the world. With the rapid development of megacities, the demand for coal resources is increasing. Nevertheless, underground coal mines suffer many hidden hazards during the coal mining process, such as roof fall, gas explosion, surface subsidence, and so on [1–3]. As can be seen from Table 1, roof fall is the most frequent and serious hazard, causing injuries and fatalities, and is a great concern for underground coal miners [4]. Some authors [1,5] reported that roof falls threaten the life of miners directly and have the potential to result in the loss of coal mine companies' property, which includes damage to underground equipment, downtimes, etc. Given the serious destruction of roof falls, many researchers [6–8] made great efforts on the occurrences of roof falls associated with underground coal mines. Some scholars [9–11] summarized the main contribution factors of the development of roof fall hazards, and these factors include geological uncertainty, stress change, mining condition, the surrounding environment, and enterprise safety management.

Table 1. Casualties of coal mine roof fall accidents in various regions of China in recent years.

Date	Site	Casualties	References
4 January 2017	Defeng County of Henan province	12 deaths	[12]
17 January 2017	Shuozhou City of Shanxi province	10 deaths	[13]
11 November 2017	Shenyang City of Liaoning province	10 deaths and 1 injury	[14]
12 January 2019	Shenmu County of Shaanxi province	21 deaths	[15]
19 June 2019	Ningwu County of Shanxi province	6 deaths	[16]
28 October 2019	Nandan County of Guangxi province	2 deaths and 11 missing	[17]
29 February 2020	Qujing City of Yunnan province	5 deaths	[18]
26 May 2021	Weishan County of Shandong province	3 deaths and 3 injuries	[19]

Through appropriate mine design, the stress condition and mining condition can be estimated during the mining process. However, geological uncertainty is the nature of underground space and is very difficult to estimate. The uncertainty in geology would change the stress condition and increase the risk of roof falls. The risk assessment is a necessary task during the whole mining process. Some researchers [20–22] realized the importance of risk assessment for engineering projects and performed lots of interesting studies in different fields, such as water resources [21,23], underground constructions [20,24–26], infrastructures [27–31], etc. Additionally, the surrounding environment of the mine is complicated, and the seepage of water is one significant impact on the stability of a mine's roof. The seepage of water in the rock fissure may weaken the strength of the roof and trigger the collapse of the roof [32–34]. It is necessary to have clear knowledge on the development of a roof fall during the mining process. The geological survey and numerical simulation [9,35,36] are essential. The combination of digital models and an appropriate monitoring system is a reasonable choice to assess the possible risks associated with coal mining [37–39].

This study investigates a roof fall, and the following rescue is reported as well. The potential reasons for this roof fall disaster were discussed, and some reflections were presented. Based on this roof fall, some suggestions were put forward for future coal mining control.

2. Materials and Methods

2.1. Overview of Collapse Event

On 14 August 2021, the roof fall collapse of a coal mine occurred in Haibei Prefecture of Qinghai Province, China (see Figure 1a). Figure 1b depicts the disaster site. The accident occurred in the Chaidar coal mine, located in Gangcha County (see Figure 2a). The accident was caused by the mixing of fissure water and coal ash in the upper part of the working face to form coal slime, which poured into the working face. The mine was an open pit, 160 m deep, and had been backfilled to 80 m when this accident occurred. The backfill part is mainly sandy soil, and the geological conditions are complex and extremely unstable. The accident trapped the victims at a location about 1.2 km from the mine's entrance, the vertical distance between the accident site and the ground surface is 90 m, and the mud flow backward is 70 m. At the time of the accident, 21 miners were working in the mine, 1 person was dead, 1 person was injured, and other 19 workers were trapped in the mine. Due to weather and seasonal factors, there was a constant seepage around the pit (see Figure 2b). The accident occurred at a high altitude and in the frozen soil, the coal mine roof is poor, and the coal seam is powdery. The rescue was extremely difficult. During the progress of drainage and desilting (see Figure 2c), the internal pressure of fluid changes, the unstable balance of coal slime in the upper part of the working face is broken, and coal slime continues to flow into the working face, resulting in secondary disasters (see Figure 2d) of coal slime gushing twice in two hours during the rescue and desilting the rescue team. By the early morning of September 13, the accident rescue work had essentially ended; all 19 trapped people had been found, no vital signs. According to the notice issued by the emergency management department of Qinghai Province (http://yjt.qinghai.gov.cn/

Mobile/Article.html?lmid=1&sjid=6712&type=0, accessed on 16 January 2022), all mining enterprises have learned the lessons from the roof fall accident of the Chaidar coal mine, and comprehensively carried out the general survey and treatment of potential disaster-causing factors in coal mines. The legal representative of coal mining enterprises is the first person in charge. All coal mining enterprises are required to strengthen risk analysis, to find potential danger, and to propose treatment measures. Experts from inside and outside the province are called together to investigate the reason behind the collapse and to propose countermeasures to maintain coal mine safety. The final report should be presented to the provincial emergency management department before 31 May 2022.

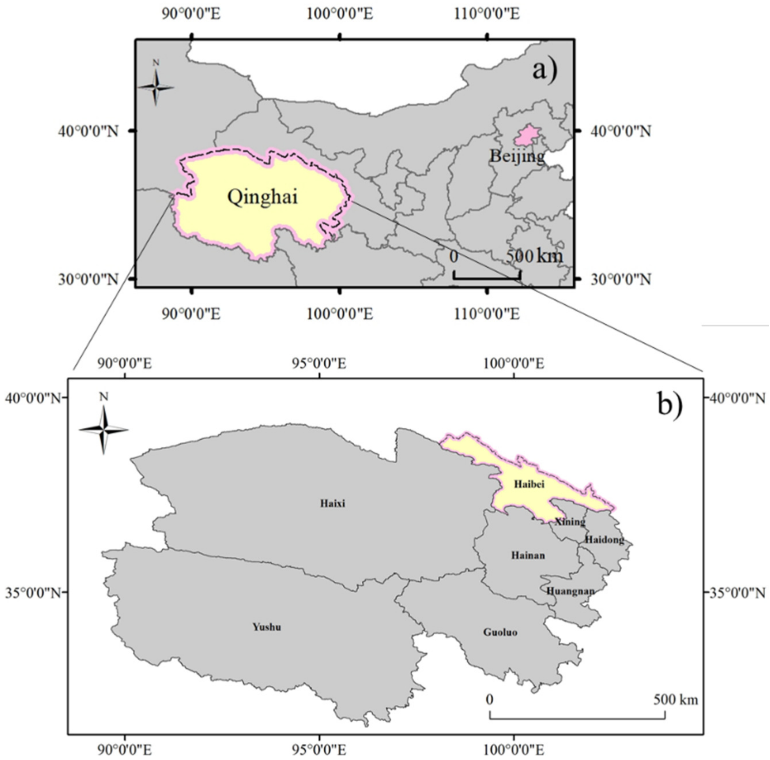

Figure 1. Location of the collapsed site: (**a**) Qinghai Province in China; (**b**) disaster site of Haibei Prefecture in Qinghai Province.

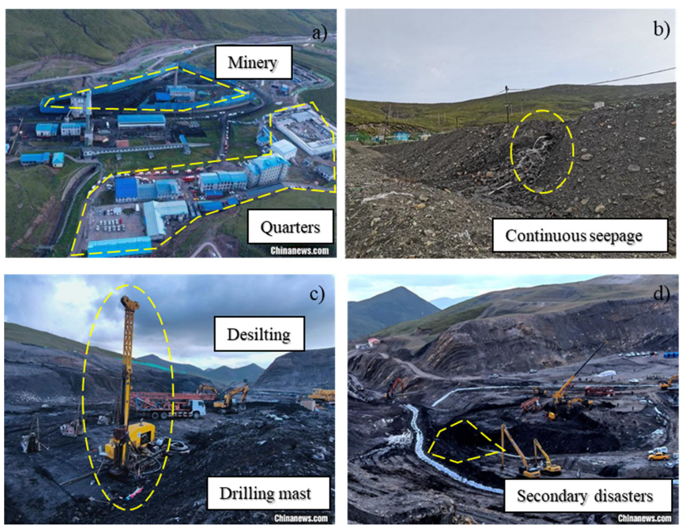

Figure 2. Roof fall collapse of coal mine: (**a**) full view of Chaidar coal mine (recreated based on [40]); (**b**) a continuous seepage (recreated based on [41]); (**c**) borehole desilting; (**d**) secondary disasters (recreated based on [42]).

2.2. Data Source

To analyze the event, the weather data records of Gangcha County were collected from the public records (https://www.tianqi.com/gangcha/, accessed on 16 January 2022), which included the monthly average highest temperature, the monthly average lowest temperature and the daily rainfall recorded by the weather channel in August.

2.3. Recuse Effort

After the accident, based on the principle of "life first and full rescue", Qinghai Province quickly set up an on-site headquarters to take urgent action, transfer rescuers and rescue equipment from all over the country, and comprehensively organized emergency rescue. At that time, 140 firefighters from the surrounding counties arrived on the scene immediately. A total of 121 vehicles were on duty, and more than 7720 pieces of rescue equipment arrived as well. Additionally, 26 members from the national mine emergency rescue team, together with two high-pressure underground mud pumps, reached the scene to carry out the rescue. Furthermore, 38 national mine emergency rescue team members, 9 rescue vehicles and 3 high-pressure downhole mud pumps were dispatched by the national work safety emergency rescue center to the scene at 6:00 on 13 August to participate in this rescue. At the same time, 12 experts on coal mines participated in the technical guidance of the emergency rescue, nine of whom are from Qinghai Province. Since then, more than 1000 emergency, fire, medical, public security, health and other rescue workers have continued to rescue at the accident scene at an altitude of more than 3800 m for nearly 30 days. By the early morning of September 13, the rescue work had essentially ended, and all 19 trapped people had been searched for and found without vital signs (see Figure 3).

Figure 3. Emergency rescue teams: (**a**) rescue teams in Qinghai Province (picture source: [43] (**b**) rescue medical staff (picture source: [44]).

3. Analysis and Discussion

The roof fall accident was caused by the complex geological conditions and the coal slime formed by the upper fissure water and coal dust gushing into the working face. The strength of coal mine roof is weak, the roof is extremely fragile, and the joints and fissures are richly developed. The coal seam is powdery, and the water inflow of the working face is large, so that the rock mass is damaged under the action of accumulated pressure (see Figure 4). Secondly, the effective management at the working place is insufficient. The support system was not well designed and did not have a comprehensive understanding of the geological condition of the roof, especially on the formed coal slime. This meant that the working resistance of the designed support system was too weak to bear the pressure from the coal roof. Additionally, managers did little to ensure the quality of the monitoring system and personnel safety management during the mining process.

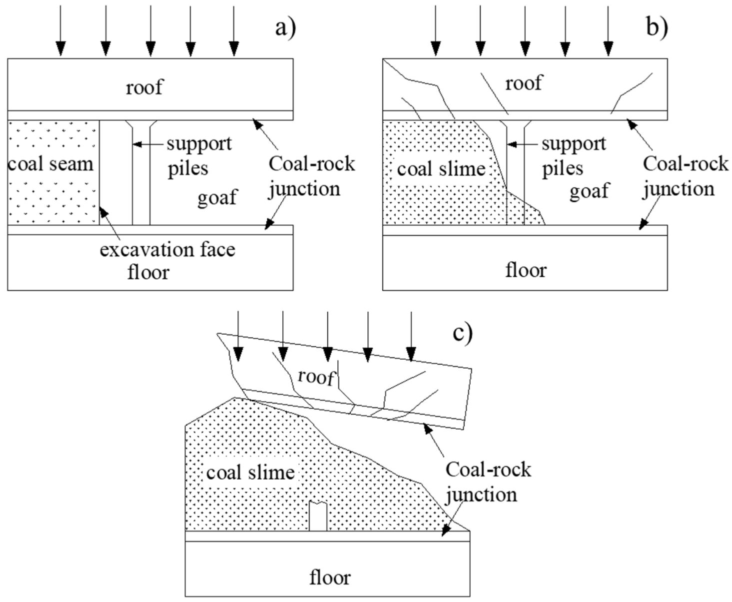

Figure 4. Mechanism of roof fall: (**a**) normal excavation face; (**b**) roof damaged, coal slime into the working face; (**c**) complete collapse of roof.

3.1. Environmental Factors

3.1.1. Complex Geological Conditions

The Chaidar mine field in Haibei Prefecture, Qinghai Province, is mainly composed of nappe structures, which are generally tongue-shaped and shovel-shaped wedges from coal-bearing strata that overlap with each other. The properties of each nappe are the same, but the shapes are different. Its genesis is related to the uneven pushing of the fault into the mine field, resulting in the local stress concentration and the formation of a series of imbricate slip bodies [45]. The rest of the nappe bodies are in the process of formation, the residual energy is released, and the stress diffuses along the arc surface of the nappe to M1 (see Figure 5), resulting in the weakness and deformation of the coal seam and the sharp change in the occurrence of the roof and floor in a local range. Therefore, the nappe structure can affect the coal seam, roof and floor. The slope in the same working face changes many times, the mining process is blocked, and the safety factor is reduced [46].

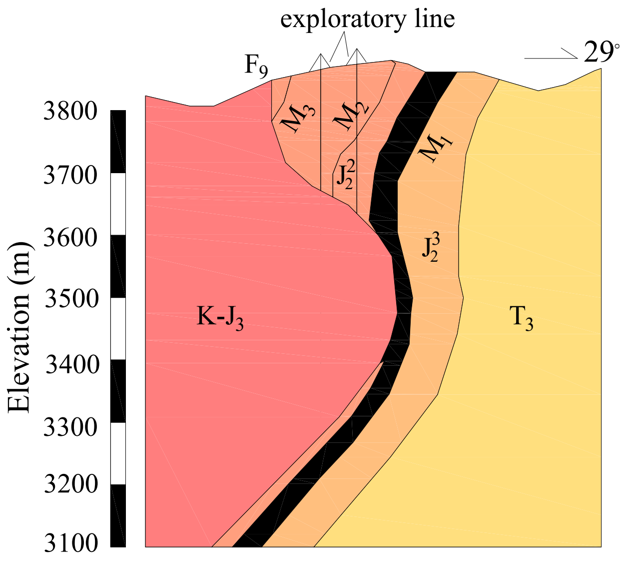

Figure 5. Structural profile of nappe (recreated based on concept of [45]).

3.1.2. Climate Change

The Chaidar coal mine is dominated by alpine landform with discontinuous distribution of island frozen soil and seasonal frozen soil. The thickness varies from tens of centimeters to about 60 m. In summer, the thawing depth is only 1–2 m, and the local low-lying surface layer is mostly swamped. July–August in Gangcha county is the highest temperature period of the whole year (see Figure 6. data from https://www.tianqi.com/qiwen/city_gangcha/, accessed on 16 January 2022). Climate change causes seasonal frozen soil melting, changes soil moisture, and then affects the water runoff process. The water runoff at the ground surface and the upper part of underground soil would change as well. In addition, the mining of the coal mine breaks the process of water and heat exchange in the active layer and changes the surface water, shallow groundwater, and their migration. These can accelerate the melting of the frozen soil layer and increase the infiltration of surface water. Consequently, large-area ponding may occur in the pit [47,48].

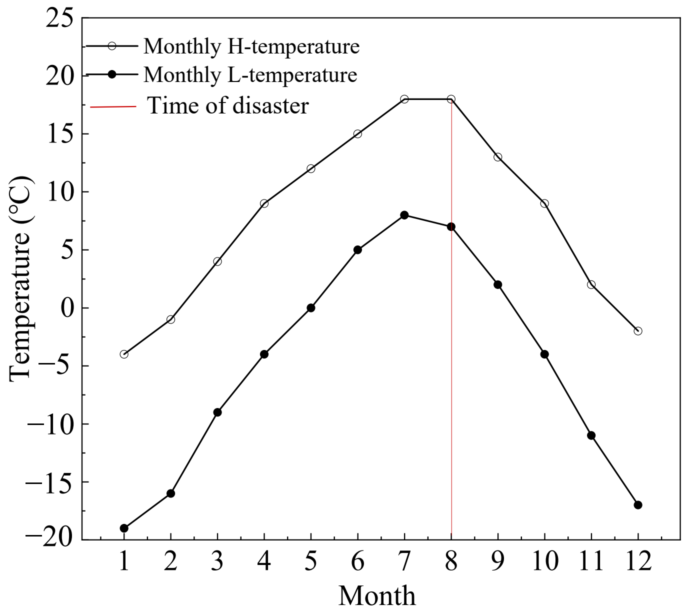

Figure 6. Annual average temperature.

3.1.3. Rainfall

The groundwater in the mining area is mainly supplied by atmospheric precipitation and deicing water. Figure 7 (data from https://www.tianqi.com/gangcha/, accessed on 10 January 2022) shows the daily rainfall in August in Gangcha county. It can be observed that, before this accident, there were seven days of light rain in the two weeks. These rainfalls can change the pore water pressure of the surrounding soil, which may weaken the unstable roof. After the accident, the daily rainfall on the 18th, 22nd and 30th exceeded 10 mm. These can further reduce the strength of the surrounding soil and make the situation more unstable. These post-accident rainfalls may be the reason for the secondary disaster, which caused great difficulties and delayed the rescue time.

3.2. Extral Factors

3.2.1. Support Structure

To ensure the personal safety and work needs of on-site staff, it is necessary to strengthen the supporting system in time for the exposed roof after coal mining. Nevertheless, this coal mine was in the maintenance stage and needed rectifying before the collapse of roof fall. Sludge was observed at the coal mining face, which was probably caused by untimely coal seam roof support or insufficient support strength.

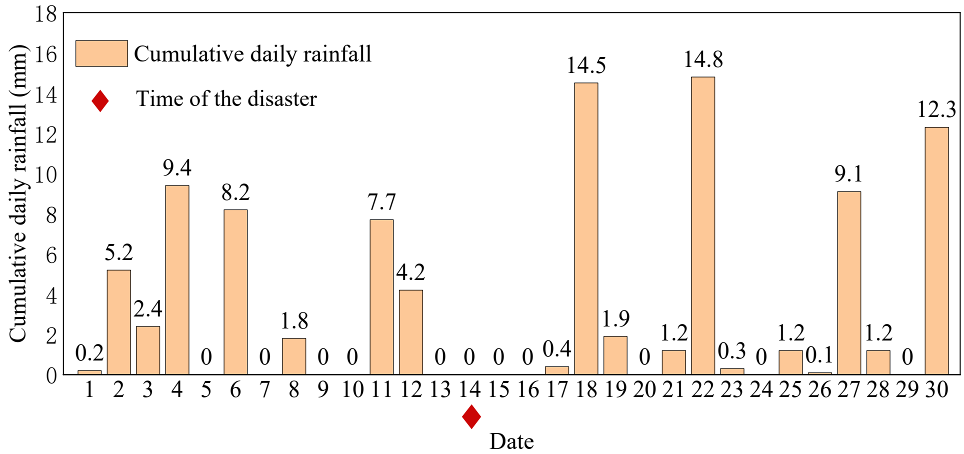

Figure 7. Cumulative daily rainfall in August in Gangcha County.

3.2.2. Organization and Management

Many coal mining enterprises in China have weak management teams, which is urgently in need of improvement. The Chaidar coal mine was required to be rectified on 2 August [49]. At the time of the accident, some workers were still working at the site, indicating that the mine workers had an insufficient understanding of the risks associated with the coal mine and did not make a correct judgment. The low level of safety management and the lack of safety education for workers are two of the reasons for this serious disaster.

3.3. Reflections

Roof fall accidents are the most common type of accident in coal mines. The Chaidar coal mine has a high altitude and complex geology. Although the coal mine was ordered to stop production for rectification by Qinghai coal regulatory bureau on 2 August, this coal mine still caused heavy casualties, which attracted public attention and criticism from China and the rest of the world. Due to the lack of effective exploration means for roof lithology change and fracture development, it is difficult to realize the continuous change in roof conditions, resulting in this serious roof fall accident. Preventing roof falling accidents and reducing the potential risk as much as possible have become two of the most urgent problems, which should be the concern of the authorities. On the other hand, great problems also exist in the production organization and management of enterprises, and the safety management system needs to be improved [50].

3.4. Suggestions

Complex geological environments have always been a difficult problem in coal mining. If there is no perfect detection means and monitoring system, it will lead to heavy casualties. The roof fall accident of the Chaidar coal mine in Qinghai has brought a painful lesson to the Chinese people (20 people died). For future coal mining in complex geological environments, this paper puts forward the corresponding countermeasures from three aspects: monitoring, protection and management:

(1) Geological conditions, climate change, mining methods and many other factors will have an impact on coal mining. Therefore, it is necessary to conduct risk analysis on the local environment and the situation of the coal mine, classify the risk level, and formulate a safe and reasonable mining plan to ensure the safe and effective mining of the coal mine. The available risk analysis methods include analytic hierarchy process, fault tree analysis, etc.

(2) It is suggested to strengthen the monitoring frequency of both ground pressure and coal seam water content distribution and to summarize the dynamic ground pressure and coal seam water content distribution in time. With the continuous excavation of the working face, the direct roof strata collapse for the first time, causing the loss of the arch

effect. This process produces an increase in ground pressure and then the roof collapse may happen at the working face. On the other hand, the disturbance of secondary stress leads to the development of cracks in roadway-roof-surrounding rock, resulting in the increase in water content. With the increase in water content, the strength and elastic modulus of mudstone show a downward trend, which further weakens the strength of the roof-surrounding rock. Some new coal-mine-monitoring systems can be developed, e.g., the neuro fuzzy system, optical fiber sensing technology, etc. [51]. These new monitoring systems can deal with the influencing factors related to roof fall accidents so that the potential changes in ground pressure and water content can be predicted [52–54].

(3) Some novel roof support system could be adopted in combination with the field situation of the construction site. According to the existing research, the transportation and layout of anchor mesh in the permanent support operation of the coal mine roadway mainly rely on workers' operation, which has the problems of low work efficiency, high labor intensity and high risk. Recently, an anchor net transportation robot system with automatic net operation has been proposed [55]. A three-dimensional model is established by SolidWorks in the robot system, and the mechanical analysis of the structure can be conducted. The working process includes establishing the operating mechanism of the system, establishing the kinematics model, analyzing its workspace and solving the motion trajectory. The robot system has strong reliability, high stability and high transportation and placement efficiency [56]. In addition, other new techniques, e.g., the Internet of Things (IoT) technique, can also be used to monitor the mechanical response of support systems in real time, which could provide effective information for the assessment of the safety of the support system.

(4) It is necessary to strengthen the training of miners and to improve the safety awareness of construction personnel. It is essential to regularly conduct safety construction training and education activities for construction personnel and management personnel, so that everyone in the mining area can establish a correct safety concept, enhance safety skills and improve safety awareness.

4. Concluding Remarks

This paper reports the roof fall collapse that took place on 14 August 2021, in Qinghai Province in China. According to the preliminary investigation and analysis of the roof fall, some conclusions can be described as follows:

1. The roof fall accident in the Chaidar coal mine in Gangcha County, Qinghai Province, killed 20 people and injured 1. The disaster was caused by the influx of coal slime formed by fissure water and coal dust in the upper part of the coal seam pouring into the working face.
2. Complex geological conditions, climate change, rainfall and other environmental factors are important reasons affecting coal mining. In the mining process, the ground pressure changes constantly under different geological conditions, and the mining difficulty is different. Temperature change and rainfall will change the water content of the soil, as well as the runoff direction and runoff of surface water and shallow groundwater, thereby changing the ground pressure of the coal mine roof.
3. For roof fall collapse, it is suggested to develop a new ground-pressure-monitoring system. Reasonable support methods shall be adopted during construction. Additionally, it is essential to strengthen training and improve the safety awareness of construction personnel.

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