Analysis and evaluation of the instability chain of room and pillar goaf in Western China ecological fragile area

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Abstract. The Yushenfu mining area is a typical ecologically fragile area in western China. The ground subsidence accident caused by the sudden instability of a large area of coal mine goaf has endangered the local ecological environment and safety of production and life. Based on the case analysis of the instability of the goaf of the coalmine in the Yushenfu Mining Area, the paper analyzes the ultimate strength and stress of the coal pillar under the action of the coal and rock's own weight, and studies the influence of external factors such as static ground load, dynamic load, and mining disturbance. A chain analysis and evaluation of goaf instability under the influence of multiple factors has been carried out. Practice has shown that the chain analysis and evaluation of goaf instability is an effective method.

1. Introduction
The Yushenfu mining area belongs to an arid and semi-arid area. Most of the surface is covered by deserts and sandy hills. It is a typical ecologically fragile area in Western China. The Jurassic coal field in this area is a large coal field with the highest degree of coal resource enrichment, the best coal quality and broad development prospects in China. The coal seam is shallow and is one of the seven largest coal fields in the world. Before the 1990s, due to the backward production technology, most coal mines used room and pillar mining method. The coal pillars left over in the initial mining period can effectively control the collapse of the roof, so the ground will not sink significantly. With the creep and weathering of the remaining coal pillars, the blasting of the surrounding open-pit mines, the driving of heavy vehicles, and the disturbance of underground mining, ground subsidence accidents caused by the sudden instability of a large continuous goaf have occurred frequently, seriously harming local Ecological environment and safety of production and life[1].

The instability of the coal mine goaf begins with the study of the stability of the remaining coal pillars. Since the 1960s, scholars at home and abroad have studied the prediction of surface subsidence, the stress of coal pillars, the strength of coal pillars and the optimization of coal pillars after room and pillar mining [2]. For example, Bell believes that the main factors affecting the stability of coal pillars are Coal pillar thickness-to-width ratio, buried depth and dimensions of excavation space, etc. Szwedzicki's research obtained the difference in the time between the surface bending subsidence and the suspended roof, coal pillar slab, and fractured rock mass collapse. Wang Jinan et al. established the
relationship between the deflection of the goaf roof over time, and constructed a mechanical model of the goaf roof-coal pillar system considering the rheological characteristics of the pillar [3].

This paper analyzes the ultimate strength and stress of coal pillars under the action of coal and rock’s own weight based on the case analysis of instability in the goaf area of the Jinglaoyuan Coalmine in Yushenfu Mining Area, and studies the influence of external factors such as static ground load, dynamic load, and mining disturbance. In addition, the paper carries out chain analysis and evaluation of goaf instability under the influence of multiple factors. Practice shows that chain analysis and evaluation of goaf instability is with reality and is an effective method.

2. Case of instability of room and pillar goaf in western ecologically fragile area

On the evening of November 4, 2018, the coalmine goaf of the Baofu Highway from 57.5km to 58.5km in the Jinglaoyuan coalmine area suffered instability and damage, and large areas of ground collapse occurred, and such buildings as office building, gas station, restaurants, and car repairs along the road were affected to some extent. The maximum road subsidence is 1.80m, and the affected area is 262m wide from east to west, 790m long from north to south, and covers an area of about 135,000 m². According to the investigation and analysis, below the collapsed area is the room and pillar goaf area formed before 2010. The mining method is adopted by mining 4m and leaving 7m coal pillars. There are no faults, collapsed pillars and other geological structures in the area, the coal 3 and coal 4 have a thickness of 2.5-3.5m, and the average buried depth is 75m and 110m. The conditions in the subsidence area are shown in Figure 1.

In order to find out the collapse and compaction degree of the coal seam 3 and coal seam 4 goaf below the subsidence area of Baofu Highway, it is judged whether there is residual space and cause secondary damage, six detection drills were constructed for detection. According to drilling cores and drilling TV observations, it can be seen that the partial collapse of the room-pillar goaf area in the subsidence area is insufficient, and there is partial empty between the coal pillars below the subsidence area.

3. Analysis of instability of room and pillar goaf under coal and rock's own weight

The decisive factor for the stability of the coal pillar is the strength of the coal pillar itself, and the basis of the coal pillar stability analysis is the strength of the coal pillar (in-situ strength), that is, the maximum load that the coal pillar can withstand per unit area[5]. When the load on the coal pillar exceeds its
ultimate strength, the coal pillar will deform and damage. The strength of the coal pillar is not only related to the physical and mechanical properties of the coal itself, but also related to the size and aspect ratio of the coal pillar[6].

3.1. Ultimate strength of coal pillar
Bieniawski (1968) conducted a large number of tests on cube samples of coal and rock mass, and for the first time proposed the concept of "critical size", that is, the smaller the sample size, the higher the strength of the coal and rock mass; as the sample size increases, the strength of the coal and rock mass gradually decreases in the form of an exponential function. The proposal of the critical size provides a feasible method for the prediction of the in-situ strength of the cubic coal pillar, which is obtained by laboratory testing on standard samples of the same material,

\[ \sigma_{m} = \sigma_{c} \cdot \frac{D}{h} \]  

In the formula: \( \sigma_{m} \) refers to the average uniaxial compressive strength of the standard sample in the laboratory, MPa; D refers to the diameter of the standard sample in the laboratory, m; And \( h \) refers to the height of coal pillar (take 0.9 when the height of coal pillar is greater than 0.9m), m. According to laboratory tests, the average uniaxial compressive strength of coal pillar is 30 MPa, and the in-situ strength of the cubic coal pillar is 7.07MPa.

Through a large number of laboratory tests and on-site investigations, it is concluded that the stability of the coal pillar also depends on the aspect ratio of the coal pillar, namely \( W/h \). The greater the aspect ratio of the coal pillar, the greater the strength of the coal pillar. When the aspect ratio of the coal pillar is greater than 10, the coal pillar will not be damaged. The Bieniawski formula, which is widely used is based on the relationship between coal pillar strength and coal pillar width-to-height ratio,

\[ \sigma_{p} = \sigma_{m}(0.64 + 0.36\frac{W}{h}) \]  

In the formula, \( \sigma_{p} \) refers to the strength of the coal pillar, MPa; \( \sigma_{m} \) refers to the in-situ strength of the cubic coal pillar, MPa.The coalmine is to mine 4m and leave 7m. According to on-site drilling, it can be seen that the coal seam thickness of coal 3 goaf is 3.5m, and the coal thickness of coal 4 is 2m. The strength of coal pillars in the coal 3 and coal 4 are 9.615Mpa and 13.433Mpa respectively.

3.2. Coal pillar stress
The average stress of the coal pillar is calculated by the Tributary Area Method. In the calculation process, only the self-weight stress of the overlying strata is considered. According to the most dangerous state, the weight of the overlying strata above the goaf is considered to be supported by coal pillars[7].

\[ \sigma_{s} = \frac{\gamma H (W+B)(B+L)}{W L} \]  

Where \( \sigma_{s} \) refers to the stress of the coal pillar, MPa; \( \gamma \) refers to the average bulk density of the overlying strata, kN/m3; H refers to the mining depth, m; W refers to the width of the coal pillar, m; B refers to the width of the coal chamber, m; L refers to the length of the coal pillar , M.

According to calculations, the total stress on the coal pillars in the goaf of coal 3 and coal 4 is 5.206 MPa and 8.168 MPa respectively.

3.3. Safety factor of coal pillar stability
Whether the coal pillar can remain stable depends on the stress of the coal pillar and the strength of the coal pillar. When the load on the coal pillar exceeds the strength of the coal pillar, the coal pillar will deform and damage. The stability of the coal pillar can be evaluated by the safety factor. The ratio of the strength of the coal pillar to the stress on the coal pillar is called the safety factor of coal pillar stability[8],

\[ f = \frac{\sigma_{p}}{\sigma_{s}} \]
When f≥1.5, the elastic area of the coal pillars is larger, and the remaining coal pillars can support the overlying rock load well, so the goaf can maintain long-term stability; Therefore, when the coal pillar f<1.5, the stability of the coal pillar is poor. Therefore, in order to ensure the safe mining of the coal mine when room and pillar mining is adopted, f≥1.5 is generally adopted. According to the above calculation, it can be known that the safety factors of coal pillar stability in the goaf area of coal 3 and coal 4 are 1.85 and 1.64 respectively.

In summary, the safety factor of coal pillar stability in the Jinglaoyuan coalmine is greater than the safety factor of 1.5. It can be seen that most coal pillars can be in a stable state after room-pillar mining under the influence of only the weight stress of the overburden. However, during the early room-pillar mining in the Nursing Home Coal Mine, the coal pillars were extremely irregular, and the blasting coal was extremely uneven. The size of the coal pillar was basically less than 7m, and the irregular shape of the coal pillar was mostly dumbbell-shaped, and the effective bearing stress diameter of the coal pillar is much smaller than 7m, and the coal pillar stability factor is also much smaller than the calculated safety factor. Considering the influence of various external environmental factors such as coal pillar natural denudation, creep oxidation, and coal seam mining disturbance, the stability of coal pillar is greatly reduced.

4. Analysis of external factors affecting the instability of the goaf
The stability of the room and pillar goaf is not only related to the nature of the remaining coal pillars, but also related to external factors, such as regional geological and structural conditions, overlying rock and surrounding rock lithology, water accumulation, mining disturbance of the upper and lower and surrounding coal seams, the type and remaining time of the goaf[9], the static and dynamic loads on the surface. The main factors affecting the instability of the goaf in the Jinglaoyuan coalmine are as follows.

4.1. Static ground load
According to on-site investigation, the static load mainly includes surface buildings (gas stations on the roadside, coal mine office buildings, restaurants, auto repair shops, etc.) and vegetation on both sides of the road. These static loads increase the load on the coal pillar accelerates the deformation and destruction of the coal pillar[10].

4.2. Dynamic load of ground vehicles
A highway passes through the area. When a vehicle on the ground is driving, not only its own weight will generate a static load on the ground, but also a constantly changing dynamic load. It is a very complicated process for vehicle movement to generate dynamic load on the road surface. According to the purpose of the research problem, the vehicle load can be simplified into vehicle vibration models with different degrees of freedom. Here we choose a two-degree-of-freedom geometric model to represent the dynamic load of the vehicle on the road surface,

\[ P_d = k_1 (y_1 - y_0) + c_1 (y_1 - y_2) \]  

(5)

Where k1 is the vehicle tire stiffness; c1 is the tire damping; y2 is the vertical displacement of the vehicle body; y1 is the vertical displacement of the wheels, and y0 is the excitation of the road unevenness.

After calculation, the maximum load generated by vehicles on the ground is 0.204 Mpa. In addition, heavy highway driving, braking, vibration, etc. will produce additional stress on the coal pillar, further reducing the stability of the coal pillar.

4.3. Influence of mining disturbance
The coal 5 mining under the goaf will cause damage to the overlying strata, and the development of fracture zones will affect the coal 4 goaf. The remaining coal pillars support the roof for a long time to control roof collapse and surface subsidence, and the development of cracks in the lower coal seam destroys the stress state of the original rock, so that the core supporting force of the coal pillar gradually decreases, and the coal pillar produces cracks and slabs; The curved subsidence zone produced by coal
Seam 5 mining will cause deformation and failure of coal pillars in the coal 3 goaf, the plastic area of the coal pillars continues to increase, and the stability of the room and pillar goaf is greatly reduced.

5. Instability chain of goaf under the influence of dynamic and static loads

Figure 2 shows the instability chain of the goaf under the influence of dynamic and static loads[11]. In addition to considering the effects of overlying rock load, creep, and oxidation on coal pillars, static loads (mainly surface structures and vegetation in the mined-out area) and dynamic ground loads (such as ground blasting, trains on railways, and highways) should also be considered. Vibration caused by car driving, continuous vibration caused by engineering construction, etc.), dynamic load caused by sudden collapse of overburden (such as sudden roof instability in the overlying goaf, sudden break of old roof), underground dynamic load (underground tunneling) Blasting, pressure relief and blasting, mining vibration, etc.). Under the influence of dynamic and static loads, rock mass damage causes deterioration of the physical and mechanical properties of coal and rock mass, stress concentration, crack generation and expansion, etc., which accelerates the deformation and destruction of coal pillars and roofs in the goaf, resulting in instability of the goaf[12].

6. Conclusions

The decisive factor for the stability of the coal pillar is the strength of the coal pillar itself. When the load on the coal pillar exceeds its ultimate strength, the coal pillar will deform and damage. The strength of the coal pillar is not only related to the physical and mechanical properties of the coal itself, but also related to the size and aspect ratio of the coal pillar. For goafs that are considered safer considering only the influence of the overburden's own weight stress, considering that the size of the coal pillars on site is not standardized enough, plus various external factors such as natural denudation of coal pillars, creep oxidation, and disturbance of coal mining Environmental factors have increased the possibility of room and pillar goaf instability.

The stability of room and pillar goaf is also related to external factors, such as regional geological and structural conditions, overlying and surrounding rock lithology of the goaf, water accumulation in the goaf, and coal mining above and below the goaf. For the western ecologically fragile areas, static ground loads, dynamic loads and mining disturbances are the main influencing factors. The analysis of the instability hazard chain of the goaf under the action of static and dynamic loads is an effective analysis and evaluation method.
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