Stability analysis of hyperbolic coal pillars with peeling and high temperature effects

Youyou Xu, Huaizhan Li, Guangli Guo and Xiaopeng Liu

Abstract
In this present study, a twice-peeling model was established to analyze the hyperbolic coal pillars stability in underground coal gasification and then propose the concept of stripping degree to show model details for numerical simulation. The data shows that hyperbolic coal pillars stability can be analyzed through the twice-peeling model. Considering the coal pillars peeling and high temperature effects, one side of coal pillars will decrease 3 m, and the stability coefficient is 1.6 which has enough bearing capacity. When the arch depth ratio is 0.6, the critical condition for the coal pillar instability is reached. In this paper, underground coal gasification industrial test area still had strong bearing capacity after twice stripping, and there was no sudden instability. The research results can provide reference for the gasifier design and the stability of non-uniform coal pillars in the future.

Keywords
Underground coal gasification, hyperbolic coal pillars, coal pillar peeling, high temperature effect, stability analysis

Introduction
Underground coal gasification (UCG) is a clean, comprehensive utilization technology that converts coal into syngas through in-situ thermochemical reactions, while combustion generates waste. During the gasification process, wastes (such as ash and gangue) are retained in
the UCG voids to avoid pollution that can contaminate the coal upper wells. It is known as the “second generation mining method” because of the syngas high calorific and clean characteristics. The combination of UCG and other technology is the direction of clean source utilization, such as Underground coal gasification (UCG)–Integrated Gasification Combined Cycle (IGCC) (Khadse et al., 2007), Underground coal gasification (UCG)–Carbon Dioxide Capture and Storage (CCS) (Friedmann et al., 2009; Michael et al., 2005; Yang et al., 2008), Underground coal gasification (UCG)–Hydrogen Underground Gasification (HUG), and Underground coal gasification (UCG)–Alkali Cells Fuel (ACF). It provides a clean and sustainable way for the energy industry. Therefore, UCG is not only important for the environment but also has great practical and long-term significance for the international coal industry to manage market demand and carbon supply.

As a technology that completely breaks through traditional coal mining methods (Singh, 2011), UCG has received widespread attention since its advent in the mid-19th century (Siemens, 1868), but has not yet been tested in actual engineering. After more than 100 years of theoretical development, the first UCG industrialization test base was established in Uzbekistan in 1961 (Klimenko, 2009). However, there are still many problems in the test base, such as high gasification costs and harsh geological mining conditions, which greatly limit the development of UCG. Currently, the international leading “strip mining-face mining” gasifier retraction gas injection UCG process causes the isolation coal pillar boundary not being a regular rectangular, but a “hyperbolic” type. Also, due to the effect of high temperature, the overburden layer physical properties on the coal seam and roof can be significantly altered. Thus, a considerable number of scholars have investigated for evaluation methods in physical properties at high temperature (Hettema et al., 1993; Luo and Wang, 2011; Perkins and Sahajwalla, 2007; Ranjith et al., 2012) and the coal pillar stability during UCG (Li et al., 2017; Najafi et al., 2014). However, these researches have not noticed whether the coal pillar will be peeled off under high temperature conditions. Based on the few existing researches on the coal pillar stability, it is considered that the coal pillar will undergo progressive stripping under the coupling of high temperature and ground stress analogy strip mining. The stability of coal pillars that experience the peeling under the high temperature is not analyzed, which is the entry point for the article.

By analyzing the hyperbolic coal pillar-bearing mechanism, a coal pillar twice-peeling model was established. The stress distribution under different stripping degrees, room, and high temperature effects was studied by numerical simulation. Besides, the coal pillar stability under high temperature was also investigated after peeling, and the related results can provide a certain reference for the UCG industrial development and have certain practical significance.

**Ultimate strength model and bearing mechanism of hyperbolic coal pillar**

It can be known from the process characteristics of the “Strip mining-regional mining” gasifier retraction gas injection control underground gasification and the related literature on the coal pillars combustion boundary (Kasani et al., 2017), the coal pillar will not present a rectangle shape due to the heating of the heat source. However, the heat source expands outward in an arc shape, and the isolated coal pillar formed should be hyperbolic form. The shape is compared with the rectangular coal pillar, as shown in Figure 1.
Under the same coal pillar size, the actual bearing space of hyperbolic coal pillars is smaller than that of the rectangular, so the uniform load on the overburden is large. Also, when the hyperbolic coal pillars curved portion is unstable or when the bending coal pillars under the pressure is broken and loses the bearing capacity, the hyperbolic can be approximated as a rectangular form. In such situations, the bearing pressure can be referred to the rectangular coal pillar. The coking degree is higher for stronger coking coal. Coal pillar-curved combustion boundary will be coking, the ability-resisting deformation can be improved to some extent, and the corresponding overlying strata load is also smaller than that of the rectangular coal pillar.

After combustion, non-volatile components, mainly inorganic solids (ashes) and coal tar, will be left in the cavities. Consequently, the coal pillar will be subjected to the lateral stress, and the limit will be adopted under the action of the three-direction stress. According to the limit strength theory and Mohr’s stress circle mechanical relationship, we can solve the principle stress (Wilson, 1983). In addition, the following equilibrium conditions under a three-dimensional stress state can be obtained in Figure 2.

\[
\frac{\sigma_1 - \sigma_3}{2} = \left(\frac{\sigma_1 + \sigma_3}{2} + c\cot\phi\right)\sin\phi
\]

(1)

The above formula can be solved, and correspondingly

\[
\sigma_1 = \frac{1 + \sin\phi}{1 - \sin\phi} \sigma_3 + \frac{2c\cos\phi}{1 - \sin\phi}
\]

(2)

where \(c\) represents the pillar cohesion (MPa), \(\phi\) is the pillar’s internal friction angle (°), and \(\sigma_3\) is the lateral stress (MPa), which is zero on the pillar edge. Lateral stress in the yielding
zone increases from the outside inward and reaches its maximum at the junction of the nuclear zone. \( H \) is the mining depth. Both cohesion and internal friction angle can be measured experimentally.

When the coal pillar is subjected under unidirectional stress, its lateral pressure is 0. When subjected to the three-dimensional stress, the pressure gradually increases until it recovers to the primary rock stress with the edge approaching to the core zone. When the mining depth is \( H \), the primary rock stress is \( \gamma H \), where \( \gamma \) is the average weight of the overlying strata (kg/m\(^3\)). Therefore, the coal pillar maximum lateral stress should be \( \gamma H (\sigma_3 = \gamma H) \), which can bring to equation (2) (Wilson, 1983). The \( \sigma_3 \) value can then be substituted into equation (2), and the result is as follows

\[
\sigma_1 = \frac{1 + \sin \varphi}{1 - \sin \varphi} \gamma H + \frac{2c \cos \varphi}{1 - \sin \varphi}
\]

(3)

It can be seen from the above formula that in the case of a certain depth of mining, and the maximum vertical principal stress carried by the coal pillar is related to the cohesion and the internal friction angle, which can be determined by the coal physical properties. In the engineering study of UlanQab, the coal type is lignite, which has the high conversion factor and high oil yield (Singh et al., 2016), the metamorphism degree is slight, and the cohesion and internal friction angle increase with the metamorphism degree, which means that the lignite maximum vertical principal stress is the smallest, and the damage is most easily achieved under the same mining width.

**Coal pillar state and stability**

Since the UCG uses a “Strip mining-regional mining” gasifier retrograde gas injection underground gasification process, the process of leaving coal pillars is similar to strip mining. However, unlike the rectangular coal pillars left in strip mining, the long wall mining method is used in strip mining, and the shape of the coal pillars formed is regular rectangle. UCG is by chemical reaction with coal, that is, using a fire source to burn, and the combustion form of the gasification fire source is “radiant combustion from the middle to the surroundings,” and its temperature characteristic is that the center temperature of the flame is the lowest, while the edge owning the highest temperature. Under the effect of temperature difference, the protective coal pillars originally set aside for gasification are non-rectangular. Therefore, the UCG causes the final shape of the isolated coal pillar to appear as a “hyperbolic,” as shown in Figure 3. In the study of the stability of rectangular coal pillars, the coal pillar peeling phenomenon is considered that may occur in the underground for a long time. In the “hyperbolic” coal pillars, the upper half of the coal pillars are

![Figure 3. Hyperbolic coal pillar schematic diagram (Li et al., 2017).](image)
curved coal pillars, which are under the equivalent pressure load, and coal pillar peeling is more likely to occur.

Coal pillar elastic area will decrease due to weathering, local yielding, or rib spalling (Merwe, 2003; Merwe and Mathey, 2013; Salamon et al., 1998; Vander, 1993) etc., thereby leading to the coal pillar size gradually diminishing and the coal pillar peeling phenomenon occurring. After the peeling, the ruptured coal blocks are scattered and accumulated in the coal pillar vicinity that provides a certain lateral stress, while the actual yield zone width has changed at this time. Therefore, when the working face is designed, coal pillar peeling should be considered (Yu et al., 2017). Figure 3 is a hyperbolic coal pillar schematic diagram.

**Coal pillar first peeling model**

Due to the special process of UCG, the shape of the isolated coal pillar is “hyperbolic.” Under the stress of the overlying rock layer, it is believed that the curved pillar at the top part will be the first to peel off: the top part of the coal pillar is directly subjected to the load pressure of the overlying rock layer, the bending part is subjected to the load, and the horizontal expansion deformation occurs, while the coal pillar yielding zone is stripped off the coal pillar under the action of the overlying load and the horizontal thrust inside the coal pillar. In order to better understand this process, the “hyperbolic” coal pillar stripping is divided into primary stripping and secondary stripping. The curved coal pillars in the upper half of the coal pillar are completely detached. The upper half of the coal pillar has a rectangular shape. The lower half of the coal pillar does not undergo morphological changes outside the coal pillar block that does not consider peeling and accumulation. That is, the upper half part of the coal pillar after stripping is rectangular. However, due to the restraining effect of the stripping body and the top plate scattered body at the bottom of the coal pillar, morphological change does not occur. The secondary stripping of coal pillars is the upper half of the rectangular coal pillars has the same stripping as the strip coal pillars. The stripped coal pillars are approximately equivalent to curves, which can be regarded as approximately one-fourth ellipse, and the flatness is approximately equal to the lower half of the coal pillars. Since its flatness ratio is small, it can be calculated as a flat elongated triangle when computing. In order to facilitate the modeling of mathematical equations, the original-curved coal pillars and the stripped bulk are approximated as a trapezoidal structure. Considering the symmetry of the coal pillars, half of them are studied here, as shown in Figures 4 and 5.

According to Figures 4 and 5, the following equations can be obtained according to trigonometric function and the equal area method ($d_0$ is the first peeling coal pillar width and $d_1$ is the accumulation body width)

\[
kS_1 + S_2 = \frac{(d_0 + d_1)M}{4}
\]

\[
S_1 = \frac{d_0M}{2} - \frac{\pi d_0 M}{8}
\]

\[
S_1 = S_2
\]
By combining the above formulas, the relationship between \( d_0 \) and \( d_1 \) can be attained as

\[
d_1 = d_0 \left[ \frac{4 - \pi}{2} (k + 1) - 1 \right]
\]  \( (7) \)

It can be seen that coal pillar-stripped width \( (d_0) \) is related to the broken expand coefficient and the arch depth degree after peeling. But the broken expand coefficient is fixed when the coal type is determined. Briefly, there is a linear relationship between them. So, \( d_1 \) is always greater than \( d_0 \) in theory. Therefore, the gradient should be greater than 0, so the above formula should have the following condition

\[
\frac{4 - \pi}{2} (k + 1) - 1 > 0
\]  \( (8) \)

To ensure that the above formula is right, \( k \) should be greater than 1.33. In the case of the conventional broken expand coefficient, \( k \) ranges from 1.05 to 1.8. So, \( k \) should be between 1.33 and 1.8 in the UCG hyperbolic coal pillar stripping. These values are consistent with the current study (Miao et al., 1997).

**Figure 4.** Hyperbolic coal pillar first peeling schematic diagram.

**Figure 5.** First peeling model for half of hyperbolic coal pillar.
In the past, when studying the coal pillar-stripping state, the repose angle can be selected by empirical values, generally between 30° and 40°; but, in this range, improper selection can lead to the large errors for UCG due to the large angle range. After fully considering hyperbolic coal pillars form, the repose angle can be studied from the arch depth ratio to investigate and study the stability.

According to the diagram shown in Figure 5, from the relationship of the trigonometric function, we can get

$$\tan\theta = \frac{M/2}{d_0 + d_1} = \frac{M/2}{d_0(k + 1)(2 - \pi/2)}$$ (9)

Since coal pillar boundary is approximately hyperbolic and is expressed in a certain arc, the bending degree is defined here as the arch depth ratio, and the formula is as follows

$$f = \frac{d_0}{M/2} = \frac{2d_0}{M}$$ (10)

Therefore, the formula (9) is equivalent to

$$\tan\theta = \frac{1}{f(k + 1)(2 - \pi/2)}$$ (11)

When $f = 1$, it is considered that the hyperbolic coal pillar boundary is a semicircle arc with a coal thickness as the diameter, and the coal pillar has the largest peeling degree at this time. In this case, the repose angle is between 39° and 45°, and the result is larger than the range of the general empirical value. Meanwhile, the one-side peeling width is half of the coal thickness, which is the outcome under the limit condition.

**Coal pillar second peeling model**

After the first peeling, the coal pillar shape is rectangular in the upper part and the trapezoidal shape in the lower part that will occur second peeling phenomenon in the rectangular area under the combined action of high temperature and overburden load. The stripping process is shown in Figure 6.

After the first peeling, the upper part is rectangular, and the actual load at this moment is

$$\sigma'' = \gamma L \left[ (d + 2d_0 + b)H - \frac{b^2 \cot\delta_1}{4} \right]$$ (12)

The actual load after second peeling is as follows by the same reason

$$\sigma = \gamma HL \left[ d_1 + \frac{b_1}{2} \left( 2 - \frac{b_1}{0.6H} \right) \right] = \gamma HL \left[ d_1 + b_1 - \frac{b_1^2}{1.2H} \right]$$ (13)
where $S_1$ and $S_2$ represent the hyperbolic coal pillar one-side curved portion; $d_0$ is curved part length; $d_1$ is accumulation body width; $M$, $k$, and $\theta$ are correspondingly the coal thickness, collapse coefficient, and repose angle; $\gamma$ and $H$ are the overlying strata average bulk density and mining depth; $d$, $b$, and $b_1$ indicate the coal pillar top width and equivalent combustion space area width after the twice peeling; $L$ represents gasification working face mining distance; and $\delta_1$ indicates the roof fall angle.

In the coal pillar-stripping model, the influence of high temperature on the top and bottom plates is not considered. Different coal types have different effect for rock strata simultaneously. Therefore, the coal pillar stability after twice peeling can be studied by numerical simulation under the high temperature effect.

**Numerical simulation**

The first and second peeling model in the paper are the most characteristic part during the dynamic peeling. It is only necessary to consider the coal pillar final state to analysis stability after twice peeling not the process. Thus, this paper introduces the concept of the arch depth ratio to indicate the peeling degree, as shown in equation (11). At this time, considering the influence of the boundary effect, the geometrical size of the numerical model should be greater than that of the actual gasification working face.

The UlanQab gasification coal seam is a 2# coal seam, which belongs to the near-horizontal coal seam. There are four gasification working faces, with the thickness of 5 m. The mining width is 16 m, the pillar width between working faces is 24 m, and the mining distance of a gasification working face is 173 m. A Mohr–Coulomb model is adopted for constitutive modeling of the numerical model. The model length is 600 m, the width is 600 m, and the height is 293 m. The grid plane size is $4 \times 4$ m, and the height varies slightly with the height of the rock strata. The model is divided into 382,940 units and 639,941 points. The specific geological parameters are selected according to the measurements before mining, as shown in Table 1 (Li et al., 2017). With the Mohr–Coulomb model, the bottom is the full constraint boundary, the left and right boundaries are horizontal displacement constraint boundaries, and the top is the free boundary. Self-gravity is the initial stress.

The above numerical simulation parameters are used before the gasification. During the gasification process, the high temperature will affect the surrounding rock mechanical properties, but the influence range is limited. The relevant literature indicates (Li et al., 2017) that
the UCG temperature field influence range is 16.7 m on the roof, 13.6 m on the bottom plate, and 8.7 m on both sides of the coal pillar. In the combustion space zone range of 4 m on both sides, the average temperature is more than 600°C. At this temperature, the physical mechanical properties of rocks have undergone major changes. It has also been found that as temperature increases, porosity of Ganurgarh shale increases up to 2.3 times of its initial porosity (Jha et al., 2016; Verma et al., 2016). For fires generating temperatures up to 650°C, a clear failure plane was observed with an angle between the major failure plane of the sandstone (Gautam et al., 2016). And then, elastic modulus is decreased by 160 times (Han, 2011). However, there does not exist good combination with high temperature effect in the formula derivation. The numerical simulation will take into account the high temperature effect. The specific experimental scheme is as follows.

In the numerical model established by the above, the cell grid is $4 \times 4$ m, so the temperature field has an integer effect on the temperature range of the roof and floor and coal pillars. The influence range of coal pillar is 16 m, 14 m, and 8 m. However, in the numerical simulation, under the influence of high temperature, the coal pillar stripping of the long-term stability of the coal pillar is not taken into account. Therefore, the secondary stripping model of coal pillars established in the previous section is introduced into the calculation of the numerical model, but since the stripped coal pillars are irregular in shape, thereby here proposing the concept of stripping degree. According to different coal pillar stripping conditions, six sets of stripping schemes are designed, and the stripping degree changes from 0 to 1. When the stripping degree is 0, it indicates that the coal pillar does not undergo any stripping, and when the stripping degree is 1, the bent portion of the coal pillar is completely stripped. Taking the target coal seam of UlanQab coal underground gasification as 5 m as the experimental research thickness, and taking the target coal seam thickness as half of the maximum coal pillar side stripping width, the specific stripping scheme design is shown in Table 3.

### Data analysis

When simulating different degrees of peeling, we regard the retaining and mining width as the fixed value. With $d_0$ as the independent variable, the numerical calculation is conducted as shown in Table 2. Lignite stress distribution is drawn at room and high temperature after

| Lithology                      | Thickness (m) | Elasticity (GPa) | Poisson's ratio | Tensile strength (MPa) | Cohesion (MPa) | Internal friction (°) | Density (kg/m³) |
|-------------------------------|---------------|------------------|-----------------|------------------------|----------------|------------------------|-----------------|
| Sandy mudstone                | 30            | 1.74             | 0.24            | 1.14                   | 0.14           | 31.24                  | 2252            |
| Coal                          | 5             | 0.80             | 0.3             | 0.50                   | 0.30           | 30.00                  | 1400            |
| Sandy mudstone                | 12            | 1.03             | 0.25            | 1.07                   | 0.24           | 30.35                  | 2316            |
| Argillaceous siltstone        | 15            | 1.20             | 0.25            | 1.00                   | 0.03           | 25.00                  | 2205            |
| Siltstone                     | 53            | 1.34             | 0.26            | 1.08                   | 0.0267         | 34.24                  | 2205            |
| Fine-grained sandstone        | 83            | 0.32             | 0.32            | 1                      | 0.0145         | 34.05                  | 2311            |
| Fine siltstone                | 18            | 0.8              | 0.29            | 0.77                   | 0.018          | 33                     | 2260            |
| Conglomeratic sandstones      | 24            | 0.43             | 0.29            | 0.3                    | 0.7            | 22                     | 2400            |
| Basalt                        | 21            | 1.1              | 0.28            | 0.3                    | 0.7            | 22                     | 2100            |
| Mudstone                      | 20            | 1.6              | 0.23            | 0.27                   | 0.8459         | 16.14                  | 2147            |
| Basalt                        | 12            | 1.1              | 0.28            | 0.3                    | 0.7            | 22                     | 2100            |
twice peeling for intuitively expressing the process. The lignite stress distribution at room
temperature can be regarded as the state of other coal samples at high temperature, which is
an equivalent process, as shown in Figure 7.

It can be seen from Figure 7(a) and (b) that under the same geological mining conditions,
the coal pillar principal stress of room temperature is much larger than that of the high
temperature. This is mainly because the lignite is a weakly coking coal and average Tmax
value (416°C) (Singh et al., 2017), and the elastic modulus decreases sharply under the high
temperature. The ability to resistance deformation has enhanced with the bulk modulus and
shear modulus increasing under the high temperature effect. Maximum peeling degree (arch
depth ratio = 1.0) is shown, respectively, in Figure 8 at room and high temperature.

Meanwhile, the different numerical model was designed to analyze the influence of dynamic
peeling degree; refer Table 3. The results are shown in Figure 8 and Table 4.

This paper overall uses the arch depth ratio to summarize the two processes of stripping,
because the first and second peeling models are complicated and difficult to construct. That
is, by changing the mining width, the limit case under the same arch depth ratio can be
simulated. From Figures 9 and 10 and Table 4, it can be analyzed that the maximum
principal stress is gradually heightened, and the location is also changed with the increase
of arch depth ratio. When the arch depth ratio changes from 0.6 to 0.8, the maximum
principal stress suddenly drops sharply, and the bearing position no longer appears directly
above the coal pillar. This indicates that when the arch depth ratio reaches 0.8, the coal
pillar is unstable, and the overburden load is transferred from the coal pillar to the coal
pillar on both sides. That is the reason why maximum vertical principal stress-bearing
position has changed. The experiment also demonstrates that when the hyperbolic coal
pillar arch depth ratios reach to 0.6, the coal pillar-bearing capacity is the largest, and
the instability critical conditions may also be reached under the high temperature effect.

**Figure 7.** Coal pillar peeling stress distribution at room and high temperature.

**Table 2.** The parameter of different coal types after UCG.

| Coal type                              | Elasticity (GPa) |
|----------------------------------------|------------------|
| Lignite (under high-temperature)       | 0.005            |
| Lignite (normal temperature)           | 0.80             |

References:

Xu et al. 1583
The research results can provide a direction for gasification working face design in the future for UCG. In the following section, we will elaborate on the above research using a practical engineering example.

**Study area**

The research object of this paper is taken from the UlanQab Coal Underground Gasification Area under the jurisdiction of the Inner Mongolia Autonomous Region of
China, which belongs to Xinao Gasification Coal Mining Technology Co., Ltd. The area is relatively flat, and the surface coverage is relatively simple. The located gasification area is mostly covered by the Quaternary system, a small amount of Tertiary basalt is covered, and the rock is exposed on the surface. The stratigraphic layers from the old to the new are the lower part of the Meso-Palaeozoic Jining (rock) group, the Oligocene Huerjing Formation, the Miocene Hanuoba Formation, the Shangxin Formation, the Baogedaula Formation and the Quaternary.

The UlanQab UCG experimental area is jointly funded by ENN and China University of Mining and Technology under the support from the China National High Technology Research and Development Program (863 Program). The gasification demonstration base for key technologies has been ignited to produce syngas in October 2007. The UlanQab UCG experimental areal adopts the SMFM, which is currently advanced technology for mines in China; so, this paper chooses this location as a case study. The gasifier position and distribution are shown in Figure 10.

The directional drilling method is used to generate gasification drill holes in the coal seam to form the gas removal channel and the ignition channel. The ignition gasification is started from the point A in the following schematic diagram, and the gasification surface is advanced by the backward control. After first gasification face is completed, the other gasification face begins until all face finished. Finally, the four voids are formed, with the four working faces separated by a 24-m retaining width with a 16-m wide gasification channel and advancing length of 173 m.

It can be seen that the load on the overlying rock strata in the voids is mainly shared by the coal pillars on both sides. This feature is basically in line with Wilson’s two-zone constraint theory. By establishing a hyperbolic coal pillar twice-stripping model and a numerical model influenced by high temperature, it can be found that the stress difference is much smaller than that at room temperature before and after the coal pillar stripping. But the coal pillar actual bearing stresses after peeling are basically the same under room and high temperature. However, in the absence of peeling, the room temperature coal pillar stress is much larger than high temperature bearings.

**Figure 9.** Maximum principal stress curve at different arch depth ratios.
The actual load increases on the roof and reduces on the coal pillar, because the physical properties have changed because of high temperature effects. At this time, it can be known that the stability is closely related to high temperature effects. Meanwhile, when the arch depth ratio is 0.6, the coal pillar-bearing capacity is the largest in which the value reaches 6.65 MPa. According to the ultimate strength theory, it can be calculated that the vertical maximum principal stress is about 15 MPa under the geological mining conditions of UlanQab. Therefore, the hyperbolic coal pillar is even smaller than the theoretical maximum vertical principal stress even in the case of arch depth ratio of 0.6 and the maximum load stress. By studying the bearing mechanism and coal pillar stress distribution under unconventional conditions, it can provide the reference for the gasification working face design and stability analysis in the future, which can indirectly promote the UCG large-scale commercial development.

It is worth noting that the high temperature effect emphasized in the article is to consider the final shape state after the end of gasification activity rather than the temperature process during gasification. As long as the final stability is stable, it can be considered that the whole process is safe. Thus, this parameter is also a reference to the mechanical properties after gasification rather than the dynamic change during the gasification process in numerical simulation.
Conclusion

In this paper, the hyperbolic coal pillar-bearing mechanism is studied by theoretical analysis. With consideration of the ultimate strength model and twice-stripping model, the coal pillar stability is conducted during UCG. The findings are as follows:

1. Based on comprehensive analysis of the UCG coal pillar shape, the twice stripping will occur under the self-weight pressure and high temperature effect. The first stripping occurs in the curved part of the hyperbolic coal pillar. After the stripping, the top half of the coal pillar is rectangular, while the lower half is approximately trapezoidal. The second stripping process is the same as the stripping of the rectangular coal pillar. Based on this, a UCG coal pillar twice-stripping model is established to assess the stability of the coal pillar.

2. The numerical simulation indicates that the reason why the bearing capacity and position have changed is the arch depth ratio. In this process, the high temperature effect is obvious, and the stability coefficient after twice stripping is about 1.6. Meanwhile, when the arch depth ratio is 0.6, the critical condition is reached.

3. The twice coal pillar-stripping model is applied in UlanQab, China. This paper considers that the twice-peeling model is reliable after second stripping, and the difference between actual bearing capacity and theoretical maximum can provide the working face design index for the industrial development of UCG.

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ORCID iD

Guangli Guo https://orcid.org/0000-0003-3786-6054

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