Slope Stability Calculation Method of Highwall Mining with Open Cut Mines as an Example

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Slope Stability Calculation Method of Highwall Mining with Open Cut Mines as an Example

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Abstract: Highwall mining machines have been used to recover retained coal at the toe of highwalls and endwalls over the past few decades. However, there has not been a universal method to evaluate the slope stability using highwall mining while maximizing the recovery rate. Based on the required service time of coal pillars, this study proposes the concept of the target time pillar strength. To obtain time-dependent parameters for the coal, time-dependent shear tests were performed on specimens from an open-cut mine in Inner Mongolia. The highwall mining length was divided into three categories based on discontinuous structural plane theory: goaf, yielding, and elastic zones. The three zones were considered to all have resistances against shear stress. The basal coal seam is likely to become weak due to weight from the overlying strata, which may change the slope failure mode from circular to sliding along the weak layer. Numerical modeling was used to study the influence of the overlying strata and target time strength on the yielding zone development at the coal pillar ribs. The coefficients of the three zones were determined and substituted into the Mohr-Coulomb equation to obtain the time-dependent shear strength parameters. Subsequently, the influence of highwall mining on the slope stability was evaluated using the rigid body-limit equilibrium method (LEM). The optimized coal pillar width is determined to maximize the recovery rate without compromising the slope stability.

Keywords: open-cut mine; highwall mining; instability mechanism; web pillars; slope stability

1 Introduction

There is around 170 billion reserves of open-cut mining in China. There are approximately 30 open-cut coal mines at production scales of more than 10 Mt/a, with some that exceed 30 Mt/a [1]. However, open-cut mining inevitably leaves a significant amount of retained coal at the base of the highwall and endwall above the floor after open-cut mining. The preliminary estimate of retained coal is 20 billion tons, which results in a lower recovery rate. This not only leads to economic loss in coal mines but can also induce geotechnical and environmental hazards, such as spontaneous combustion and slope instability. With the development and improvement of highwall mining machines, coal extraction from basal coal seam ribs has gained popularity. In recent years, highwall mining has become the norm in open-cut coal mines in China due to highwall development within the country [2].

Highwall mining combines the advantages of open-cut and underground approaches. This technology allows mining soft and thick coal seams at the rear of the coal rib at the highwall/endwall toe. The entire

mining process is automated and controlled remotely to achieve unmanned intelligent extraction and transportation. Coal pillars should be left between each highwall channel to support the overlying strata. This helps prevent burying machines and slope instability. Hence, it is critical to propose a slope stability calculation method to determine the appropriate coal pillar parameters. A significant body of research [3–7] has attempted to develop reliable methods to determine coal pillar parameters using empirical formulas, laboratory tests, analytical solutions, and numerical simulations. Chen et al. [8] investigated the influence of the coal pillar parameters on slope stability based on the bearing capacity model and Catastrophe theory. They also proposed a slope stability failure criterion that includes the coal pillar parameters. Wang et al. [9] studied the coal pillar capacity under highwall mining via Catastrophe theory, time-dependent (creep) laboratory tests, and numerical simulations. Subsequently, they determined the appropriate coal pillar width under highwall mining. Wang et al. [10] revealed the failure mechanism and process of coal pillars under highwall mining based on the stress distribution at the rib of the pillar as derived from the I-II mixed mode crack model from fracture mechanics and failure criteria. The study results have enriched the knowledge of coal pillar failure mechanisms and parameters under highwall mining while solving complicated coal pillar design issues.

The edge of the highwall mining area readily forms a weak layer due to the weight of the overlying strata, which reduces the slope stability. The slope and coal pillar stabilities are interrelated, making it important to simultaneously ensure their stabilities. There have been numerous studies on slope stability using highwall mining [11–16]. Ross et al. [17] developed the Slope-W model based on analyzing steep slopes and implemented a method to practice it. The model proposed a highwall mining sequence for thick coal seams that starts from the top to the bottom of the seam, which improves the slope stability. Chandar et al. [18] studied the influence of the mining length, pillar width, and highwall channel number on the slope stability through numerical simulations. Subsequently, they categorized the slope stability case using multi-linear regression, logistic regression, and Naive Bayes classification methods. However, there has not been overall agreement on the influence of the coal pillar parameters on the slope stability [19,20]. This is primarily due to a lack of proven slope stability calculation methods for highwall mining. Hence, a series of time-dependent laboratory studies on coal pillar is proposed here to investigate the potential failure mechanism of slopes under highwall mining based on discontinuous structural plane theory [21]. The extent of plastic deformation at the rib of coal pillars was investigated under various mining lengths, supporting capacities, and time-dependent strengths. Subsequently, the slope stability calculation method of highwall mining under time-dependent behaviors was proposed, which is meaningful for Chinese highwall mining

technologies.

2 Experiments

Samples were collected from an open-cut coal mine in Inner Mongolia with a total length of 5.1 km. The major coal seams are Nos. 19 and 21. The current mining rate is at 360 m per annum with the requirement of fast extraction for the No. 21 coal seam to enable in-pit dumping, where the dumping tracking distance is 50 m. The floor dip of the No. 21 coal seam is relatively flat with competent basal sandstone beneath the floor. Figure 1 shows the lithology of the pit. The LDC100 highwall mining machine was used to extract the coal seam from the western toe of the highwall at a production rate of 60 t/h, which is suited for a coal stiffness (f) of less than 2. The cross-section of the highwall channel is rectangular at 2-m wide and 2.5-m high. The maximum mining length is 100 m, and the frequency of the retreat is three days. The slope height at the western end is approximately 100 m with an overall slope angle of 38°. Table 1 shows the mechanical properties of the rock mass above and below the coal seams.

3 Time-dependent Laboratory Tests of Coal Strength

3.1 Experimental Setup

As coal is always soft and exhibits rheological properties, its strength decreases over time. To ensure the slope is sufficiently supported under highwall mining, it is required to understand the coal pillar strength over time. The coal pillar strength at the end of the strip is assumed as the “target time strength,” which should be sufficient to support the slope until the end of its life. Hence, the coal pillar strength at the 20-day mark was used as the basis for the initial stability analysis. Considering variations in the mining rates at different sites allowed studying the coal pillar strength after 7 and 14 days.

Before the time-dependency tests, shear tests were performed to obtain the shear strength of the specimens. Then, time-dependency tests were performed accordingly to allow specimens to fail at the 7th, 14th, and 20th days. Each test series was repeated three times under four different normal stress conditions (0.6, 0.8, 1.0, and 1.2 MPa) to minimize bias in the results. To overcome the difficulty of preparing soft rock specimens with specified dimensions, a customized shear box was used for the time-dependency shear tests (Figure 2). The specimens were initially collected in-situ and prepared into a volume of 50 mm³. Then, the specimen was placed into the shear box and the space between the specimen and the box was filled with cement. Finally, a normal shear testing procedure was performed with a shear displacement measurement accuracy of 0.001 mm.

3.2 Time-dependent Behavior of Coal Pillar Strength

(1) Direct shear test results

After the specimens were placed in the box, a normal stress was applied and held constant while increasing the shear stress until failure. The shear strengths were obtained as the average of three tests, which were determined at the various normal stress conditions as 0.766, 0.840, 0.907, and 0.980 MPa, respectively. Thus, the parameters of the Mohr-Coulomb failure criterion are obtained as:

$$\tau = 0.56 + 0.36\sigma \quad (1)$$

where the cohesion (c) is 0.56 MPa and the friction angle (ϕ) is 19.8°.

(2) Shear strength at 7th day

Time-dependency shear tests use a stepped loading method. Figure 3 shows the deformation-time curve under various normal stress conditions at different shear stress levels on the 7th day. The shear strengths are 0.74, 0.81, 0.88, and 0.95 MPa at normal stresses of 0.6, 0.8, 1, and 1.2 MPa, respectively.

(3) Shear strength on 14th day

Figure 4 shows the deformation-time curve under various normal stress conditions at different shear stress levels on the 14th day. The shear strengths are 0.71, 0.78, 0.85, and 0.92 MPa at normal stresses of 0.6, 0.8, 1, and 1.2 MPa, respectively.

(4) Shear strength on the 20th day

Figure 5 shows the deformation-time curve under various normal stress conditions at different shear stress levels on the 20th day. The shear strengths are 0.68, 0.75, 0.81, and 0.88 MPa at normal stresses of 0.6, 0.8, 1, and 1.2 MPa, respectively.

The above figures indicate that the strain-time curve only exhibits primary (transient deformation rate) and secondary (steady deformation rate) creep stages under low shear stresses, while the tertiary creep stage (accelerated deformation rate) was not observed. Under these circumstances, the specimens did not fail and the deformation converged to a given value. On the other hand, the specimens underwent primary creep and subsequently entered the tertiary stage until failure under high shear stresses. Figure 6 reveals that the failure surface is relatively flat with some scratches. This means that microcracks develop and accumulate within the specimen to induce friction between the two sides during creep. In addition, the creep behavior of the coal specimen exhibits discreteness, which is related to the shear failure plane, particle distribution, and microcracks.

The Mohr-Coulomb parameters at 7th, 14th, and 20th days were estimated as:

$$\tau = 0.53 + 0.35\sigma \quad (2)$$

$$\tau = 0.51 + 0.34\sigma \quad (3)$$

$$\tau = 0.48 + 0.335\sigma \quad (4)$$

where the cohesions and friction angles are: $c_7 = 0.53$ MPa and $\varphi_7 = 19.3^\circ$; $c_{14} = 0.51$ MPa and $\varphi_{14} = 18.8^\circ$; and $c_{20} = 0.48$ MPa and $\varphi_{20} = 18.5^\circ$, respectively.

The mechanical properties of the slope mass are derived from the specimen properties with a reduction factor based on the Technical Code for Building Slope Engineering [22]. A study on the western highwall toe indicates that there was no obvious fracture development at the coal seam when the reduction factor was assumed to be 0.95. Hence, the cohesion and friction angle were respectively reduced to 0.53 MPa and 18.8° for the normal shear test; 0.5 MPa and 18.3° for the 7th-day shear test; 0.48 MPa and 17.9° for the 14th-day shear test; and 0.46 MPa and 17.6° for the 20th-day shear test. For shallow coal seams, the coal pillar shear strength parameters decrease exponentially, as seen in Figures 7 and 8.

The time-dependent cohesion and friction angle can be expressed as:

$$c_t = 0.18e^{-0.00243t} + 0.35 \quad (5)$$

where c_t is the time-dependent cohesion (MPa) and t is the target time (h).

$$\varphi_t = 2.84e^{-0.02735t} + 15.96 \quad (6)$$

where φ_t is the time-dependent friction angle ($^\circ$) and t is the target time (h).

4 Investigation of Slope Stability Calculation Method in Highwall Mining

To ensure the stability of highwall mining, coal pillars are left between highwall channels. Based on discontinuous structural plane theory [21], the highwall mining area can be considered as a discontinuous structural plane that consists of a goaf and coal pillar. This coal seam can become a weak layer under the weight of the overlying strata, which changes the potential slope failure mode from circular to sliding along the weak plane. The weak coal seam layer can be divided into the goaf, yielding, and elastic zones, as seen in Figure 9. The yielding and elastic zones both provide shear resistance during slope sliding. The proportions of the contact surface of the goaf, yielding, and elastic zones along the sliding surface are defined as K_1 , K_2 , and K_3 . The overall shear resistance can be expressed as:

$$\tau = K_1 C_r + K_2 C_p + K_3 C_e + \sigma (K_1 \tan \varphi_r + K_2 \tan \varphi_p + K_3 \tan \varphi_e) \quad (7)$$

where C_r , C_p , and C_e represent cohesions in the goaf, yielding, and elastic zones (MPa); and φ_r , φ_p , and φ_e represent the friction angles of the goaf, yielding, and elastic zones ($^\circ$). The C_r , φ_r , and C_p are negligible and assumed to be zero, while $\varphi_p = \varphi_e$, $C_e = C$, and $\varphi_e = \varphi$.

Comparing Eq. (7) with the Mohr-Coulomb failure criterion, the C_w and φ_w of the weak coal strata are calculated as:

$$C_w = K_1 C_r + K_2 C_p + K_3 C_e \quad (8)$$

$$\tan \varphi_w = K_1 \tan \varphi_r + K_2 \tan \varphi_p + K_3 \tan \varphi_e \quad (9)$$

Based on the “triangular load” of the slope, the coal pillar capacity should increase with the mining length. Thereby, the “target time strength” should gradually increase as there is a shorter coal pillar exposure. Based on the interactions between the coal pillar strength and “target time strength,” the widths of the yielding zones on the rib of the coal pillar should vary with the mining length. The capability of the highwall mining machine indicates it takes three days to complete a 100 m long highwall channel. A numerical model was constructed in FLAC^{3D} to investigate the plastic zone development at the rib of the coal pillar. The model was divided into 18 slices based on the 4-hour advancement rate (5.5 m), as seen in Figure 10. Based on the design parameter determination from Ref. [9], the minimum pillar width should be greater than or equal to 5.4 m at a 38° overall slope angle.

Seven model cases were constructed with pillar widths between 5.4 and 6.6 m to study changes in the pillar capacity and yielding widths under various loadings and times. The model was established based on the lithology. To mitigate boundary effects, a 60-m wide barrier pillar was left between the highwall channels. As the mesh size has a considerable influence on the computed results, the mesh density increased near the coal pillar at 1 m along the pillar direction, while 10 x 10 nodes were covered for the cross-section of the barrier pillar. The boundary conditions of the model were assumed to be zero horizontal movements on the left and right boundaries with a fixed bottom boundary, while the top and slope face boundaries were assumed as free-face. The Mohr-Coulomb model was used for the simulations with gravity loading. Figure 11 shows a schematic view of the model.

Substituting t at each slice into Eqs. (5) and (6) provides C_t and φ_t . The peak load (P_d) location and support capacity (σ_z) at each coal slice can be obtained from the numerical results. Then, σ_z can be used to calculate the yielding zone width (x_p) [23 and 24] and subsequently calculate the yielding width of each coal slice with different pillar widths. The results allow estimating the goaf, yielding, and elastic coefficients (K_1 , K_2 , and K_3) for the 500-m long extraction. Combining with target time (t), mining length (L), and P_d , gives estimates for C_t , φ_t , x_p , C_w , and φ_w , as seen in Tables 2–8. Overall, the influence of loading was greater than the “target time strength” on the yielding zone width. As the mining length increased, the loading increased, which contributes to the larger yielding zone width. In addition, the yielding zone width decreases with the increasing pillar width.

$$x_p = \ln \left[\frac{\frac{2(\gamma H \tan \varphi_0 + C_0)}{(NA \tan \varphi_0 + C_0)} X + \frac{w_m \gamma H \tan^2 \varphi_0}{h(NA \tan \varphi_0 + C_0)} + 1}{(X + 1)} \right] \quad (10)$$

where $X = 2A \tan \varphi_0 x_p h$, $A = (1 + \sin \varphi) / (1 - \sin \varphi)$, $N = (2c \cos \varphi) / (1 + \sin \varphi)$, and $C_0 = C_t$, $\varphi_0 = \varphi_t$.

5 Parametric Study on Slope Stability under Highwall Mining

Based on the highwall mining conditions and the current in-pit dump rate, it takes approximately 20 days to complete a dump. This means the time required for the No. 21 coal seam to become a weak layer is limited. According to 《Code for geotechnical engineering investigation》 (GB50021—2012) [25], the F_s of the western highwall toe is 1.1. The independently developed software based on the rigid body-limit equilibrium method (LEM) was used to study the influence of the coal pillar width on the slope stability, as seen in Figure 12. The

failure mode of the slope changes from circular to slip along the coal seam. The shear-driven back-break is extended from the topsoil to the No. 21 coal seam with the surface sliding along the seam. The F_S of the slope increased with the collar pillar width. The corresponding F_S with pillar widths from 5.4 to 6.6 m are 1.066, 1.082, 1.095, 1.107, 1.116, 1.124, and 1.131. The slope stability coefficient gradually increases while the resource recovery rate gradually decreases with the coal pillar width. Figure 13 shows the recovery rate and F_S under different pillar widths.

To maximize the recovery rate without compromising the slope stability, regression was used to correlate the slope stability and F_S through the expression

$$F_S = -10.20511\exp(-w_s/1.1705) + 1.16721 \quad (10)$$

where F_S is the slope stability index and w_s is the coal pillar width (m). The linear correlation was found as $R^2=0.99986$. Only when the slope stability coefficient is 1.1 can it be guaranteed to maximize the recovered retained coal resources while maintaining safety. Substituting $F_S = 1.1$ into Eq. (10) gives 5.9 m as the optimized pillar width. However, the stability of the slope may be compromised under this pillar width threshold.

6 Conclusion

(1) The concept of target time strength was proposed, and the time required for in-pit dumping was considered as the service time for coal pillars. The pillar strength at this time was considered as the target time strength. The time-dependent parameters of coal pillars were also collected from laboratory tests. The results show that the shear strength of the coal pillar decreased exponentially with time in a certain target period.

(2) Based on discontinuous structural plane theory, the highwall mining channel was divided into the goaf, yielding, and elastic zones. This suggests that the target coal seam has the potential to become a weak layer, which can lead to changes in the slope failure mode. The numerical simulation results considered the influence of the mining length and creep behavior on the plastic zone development at the pillar rib. Loading from the overlying strata has a greater influence on the plastic zone width compared with the target time strength. The loading increased with the mining length, which resulted in a wider yielding zone at the coal pillar ribs. As the coal pillar width increased, the yielding zone narrowed. A slope stability calculation method with highwall mining using the rigid body-LEM was proposed based on the Mohr-Coulomb failure criterion.

(3) The results from the proposed method were used to assess the influence of highwall mining on the slope stability. It was found that the slope failure mode changed from circular to sliding along the No. 21 coal seam. The coal pillar design was subsequently optimized to enable slope stability while maximizing the recovery rate.

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Table 1 Mechanical properties of rock and soil mass

Lithology	Compressive strength /MPa	Tensile strength /MPa	Cohesion /MPa	Friction angle/°	Elasticity modulus/GPa	poisson ratio	Density/kg·m ⁻³
Basal sandstone	45.19	3.40	2.18	23	15.16	0.22	2010
No.21 Coal seam	17.66	2.06	-	-	7.41	0.29	1270
Siltstone	25.76	3.02	2.35	25	14.58	0.21	2090
Coarse sandstone	51.43	4.90	2.12	22	15.62	0.21	1990
Topsoil	9.49	1.34	0.24	20	5.69	0.3	2671

Table 2 Each slice width distribution pattern and evolution weak layer parameters of coal pillar 5.4m

Time/h	4	8	12	16	20	24	28	32	36
Chamber depth/m	5.5	11	16.5	22	27.5	33	38.5	44	49.5
P_d	2.2	7.5	12.8	18	23.5	28.9	34.2	39.5	44.9
C_p /MPa	0.461	0.462	0.462	0.463	0.463	0.464	0.464	0.465	0.465
φ_d /°	17.61	17.62	17.63	17.63	17.64	17.65	17.66	17.66	17.67
σ_z /MPa	0.096	0.116	0.146	0.188	0.241	0.307	0.376	0.448	0.547
x_p /m	0.1	0.12	0.15	0.19	0.24	0.3	0.36	0.42	0.5
C_w /MPa	0.323	0.321	0.317	0.313	0.307	0.3	0.292	0.285	0.275
φ_w /°	12.8	12.81	12.82	12.82	12.83	12.83	12.84	12.84	12.85
Time/h	40	44	48	52	56	60	64	68	72
Chamber depth/m	55	60.5	66	71.5	77	82.5	88	93.5	100
P_d	50	55.5	60.9	66.2	71.5	76.9	82.2	87.5	93.8
C_p /MPa	0.466	0.466	0.467	0.467	0.468	0.468	0.469	0.469	0.470
φ_d /°	17.68	17.69	17.70	17.70	17.71	17.72	17.73	17.74	17.75
σ_z /MPa	0.653	0.777	0.940	1.131	1.355	1.619	1.928	2.293	2.887
x_p /m	0.58	0.67	0.78	0.9	1.03	1.17	1.32	1.48	1.71
C_w /MPa	0.266	0.255	0.241	0.226	0.21	0.193	0.174	0.154	0.125
φ_w /°	12.85	12.86	12.87	12.87	12.88	12.88	12.89	12.9	12.9

Table 3 Each slice width distribution pattern and evolution weak layer parameters of coal pillar 5.6m

Time/h	4	8	12	16	20	24	28	32	36
Chamber depth/m	5.5	11	16.5	22	27.5	33	38.5	44	49.5
P_d	2.2	7.5	12.8	18	23.5	28.9	34.2	39.5	44.9
C_f/MPa	0.461	0.462	0.462	0.463	0.463	0.464	0.464	0.465	0.465
$\varphi_f/^\circ$	17.61	17.62	17.63	17.63	17.64	17.65	17.66	17.66	17.67
σ_z/MPa	0.086	0.106	0.136	0.177	0.219	0.285	0.353	0.423	0.522
x_p/m	0.09	0.11	0.14	0.18	0.22	0.28	0.34	0.40	0.48
C_w/MPa	0.327	0.326	0.322	0.318	0.313	0.306	0.299	0.293	0.283
$\varphi_w/^\circ$	12.93	12.93	12.94	12.94	12.95	12.96	12.96	12.96	12.97
Time/h	40	44	48	52	56	60	64	68	72
Chamber depth/m	55	60.5	66	71.5	77	82.5	88	93.5	100
P_d	50	55.5	60.9	66.2	71.5	76.9	82.2	87.5	93.8
C_f/MPa	0.466	0.466	0.467	0.467	0.468	0.468	0.469	0.469	0.470
$\varphi_f/^\circ$	17.68	17.69	17.70	17.70	17.71	17.72	17.73	17.74	17.75
σ_z/MPa	0.626	0.749	0.894	1.066	1.285	1.522	1.822	2.175	2.751
x_p/m	0.56	0.65	0.75	0.86	0.99	1.12	1.27	1.43	1.66
C_w/MPa	0.274	0.263	0.251	0.237	0.222	0.206	0.188	0.168	0.14
$\varphi_w/^\circ$	12.98	12.98	12.99	12.99	13	13.01	13.01	13.02	13.03

Table 4 Each slice width distribution pattern and evolution weak layer parameters of coal pillar 5.8m

Time/h	4	8	12	16	20	24	28	32	36
Chamber depth/m	5.5	11	16.5	22	27.5	33	38.5	44	49.5
P_d	2.2	7.5	12.8	18	23.5	28.9	34.2	39.5	44.9
C_f/MPa	0.461	0.462	0.462	0.463	0.463	0.464	0.464	0.465	0.465
$\varphi_f/^\circ$	17.61	17.62	17.63	17.63	17.64	17.65	17.66	17.66	17.67
σ_z/MPa	0.076	0.096	0.126	0.157	0.198	0.252	0.319	0.388	0.472
x_p/m	0.08	0.10	0.13	0.16	0.20	0.25	0.31	0.37	0.44
C_w/MPa	0.332	0.330	0.327	0.324	0.319	0.314	0.307	0.3	0.292
$\varphi_w/^\circ$	13.05	13.06	13.06	13.06	13.07	13.08	13.09	13.09	13.09
Time/h	40	44	48	52	56	60	64	68	72
Chamber depth/m	55	60.5	66	71.5	77	82.5	88	93.5	100
P_d	50	55.5	60.9	66.2	71.5	76.9	82.2	87.5	93.8
C_f/MPa	0.466	0.466	0.467	0.467	0.468	0.468	0.469	0.469	0.470
$\varphi_f/^\circ$	17.68	17.69	17.70	17.70	17.71	17.72	17.73	17.74	17.75
σ_z/MPa	0.573	0.693	0.835	1.002	1.232	1.446	1.739	2.083	2.644
x_p/m	0.52	0.61	0.71	0.82	0.96	1.08	1.23	1.39	1.62
C_w/MPa	0.283	0.273	0.261	0.248	0.232	0.218	0.2	0.181	0.153
$\varphi_w/^\circ$	13.1	13.11	13.12	13.12	13.12	13.13	13.14	13.15	13.15

Table 5 Each slice width distribution pattern and evolution weak layer parameters of coal pillar 6m

Time/h	4	8	12	16	20	24	28	32	36
Chamber depth/m	5.5	11	16.5	22	27.5	33	38.5	44	49.5
P_d	2.2	7.5	12.8	18	23.5	28.9	34.2	39.5	44.9
C_f/MPa	0.461	0.462	0.462	0.463	0.463	0.464	0.464	0.465	0.465
$\varphi_f/^\circ$	17.61	17.62	17.63	17.63	17.64	17.65	17.66	17.66	17.67
σ_z/MPa	0.067	0.086	0.116	0.146	0.188	0.241	0.296	0.364	0.448
x_p/m	0.07	0.09	0.12	0.15	0.19	0.24	0.29	0.35	0.42
C_w/MPa	0.336	0.335	0.331	0.329	0.324	0.319	0.313	0.307	0.299
$\varphi_w/^\circ$	13.15	13.16	13.17	13.17	13.18	13.18	13.19	13.19	13.2
Time/h	40	44	48	52	56	60	64	68	72
Chamber depth/m	55	60.5	66	71.5	77	82.5	88	93.5	100
P_d	50	55.5	60.9	66.2	71.5	76.9	82.2	87.5	93.8
C_f/MPa	0.466	0.466	0.467	0.467	0.468	0.468	0.469	0.469	0.470
$\varphi_f/^\circ$	17.68	17.69	17.70	17.70	17.71	17.72	17.73	17.74	17.75
σ_z/MPa	0.535	0.653	0.777	0.940	1.148	1.373	1.658	1.994	2.541
x_p/m	0.49	0.58	0.67	0.78	0.91	1.04	1.19	1.35	1.58
C_w/MPa	0.291	0.281	0.271	0.259	0.244	0.228	0.211	0.193	0.166
$\varphi_w/^\circ$	13.21	13.21	13.22	13.22	13.23	13.24	13.24	13.25	13.26

Table 6 Each slice width distribution pattern and evolution weak layer parameters of coal pillar 6.2m

Time/h	4	8	12	16	20	24	28	32	36
Chamber depth/m	5.5	11	16.5	22	27.5	33	38.5	44	49.5
P_d	2.2	7.5	12.8	18	23.5	28.9	34.2	39.5	44.9
C_f/MPa	0.461	0.462	0.462	0.463	0.463	0.464	0.464	0.465	0.465
$\varphi_f/^\circ$	17.61	17.62	17.63	17.63	17.64	17.65	17.66	17.66	17.67
σ_z/MPa	0.057	0.076	0.106	0.136	0.177	0.23	0.285	0.353	0.423
x_p/m	0.06	0.08	0.11	0.14	0.18	0.23	0.28	0.34	0.4
C_w/MPa	0.34	0.339	0.336	0.333	0.328	0.323	0.318	0.312	0.305
$\varphi_w/^\circ$	13.26	13.27	13.28	13.28	13.28	13.29	13.3	13.3	13.31
Time/h	40	44	48	52	56	60	64	68	72
Chamber depth/m	55	60.5	66	71.5	77	82.5	88	93.5	100
P_d	50	55.5	60.9	66.2	71.5	76.9	82.2	87.5	93.8
C_f/MPa	0.466	0.466	0.467	0.467	0.468	0.468	0.469	0.469	0.470
$\varphi_f/^\circ$	17.68	17.69	17.70	17.70	17.71	17.72	17.73	17.74	17.75
σ_z/MPa	0.509	0.626	0.749	0.91	1.098	1.32	1.579	1.907	2.415
x_p/m	0.47	0.56	0.65	0.76	0.88	1.01	1.15	1.31	1.53
C_w/MPa	0.298	0.288	0.278	0.265	0.252	0.238	0.222	0.204	0.179
$\varphi_w/^\circ$	13.31	13.32	13.33	13.33	13.34	13.34	13.35	13.36	13.37

Table 7 Each slice width distribution pattern and evolution weak layer parameters of coal pillar 6.4m

Time/h	4	8	12	16	20	24	28	32	36
Chamber depth/m	5.5	11	16.5	22	27.5	33	38.5	44	49.5
P_d	2.2	7.5	12.8	18	23.5	28.9	34.2	39.5	44.9
C_f/MPa	0.461	0.462	0.462	0.463	0.463	0.464	0.464	0.465	0.465
$\varphi_d/^\circ$	17.61	17.62	17.63	17.63	17.64	17.65	17.66	17.66	17.67
σ_z/MPa	0.047	0.067	0.096	0.126	0.167	0.209	0.263	0.33	0.40
x_p/m	0.05	0.07	0.10	0.13	0.17	0.21	0.26	0.32	0.38
C_w/MPa	0.344	0.343	0.34	0.337	0.333	0.329	0.323	0.318	0.311
$\varphi_w/^\circ$	13.37	13.37	13.38	13.38	13.39	13.4	13.4	13.4	13.41
Time/h	40	44	48	52	56	60	64	68	72
Chamber depth/m	55	60.5	66	71.5	77	82.5	88	93.5	100
P_d	50	55.5	60.9	66.2	71.5	76.9	82.2	87.5	93.8
C_f/MPa	0.466	0.466	0.467	0.467	0.468	0.468	0.469	0.469	0.470
$\varphi_d/^\circ$	17.68	17.69	17.70	17.70	17.71	17.72	17.73	17.74	17.75
σ_z/MPa	0.485	0.599	0.721	0.88	1.066	1.284	1.541	1.864	2.317
x_p/m	0.45	0.54	0.63	0.74	0.86	0.99	1.13	1.29	1.49
C_w/MPa	0.307	0.294	0.285	0.272	0.26	0.245	0.23	0.212	0.191
$\varphi_w/^\circ$	13.42	13.43	13.43	13.43	13.44	13.45	13.46	13.46	13.47

Table 8 Each slice width distribution pattern and evolution weak layer parameters of coal pillar 6.6m

Time/h	4	8	12	16	20	24	28	32	36
Chamber depth/m	5.5	11	16.5	22	27.5	33	38.5	44	49.5
P_d	2.2	7.5	12.8	18	23.5	28.9	34.2	39.5	44.9
C_f/MPa	0.461	0.462	0.462	0.463	0.463	0.464	0.464	0.465	0.465
$\varphi_d/^\circ$	17.61	17.62	17.63	17.63	17.64	17.65	17.66	17.66	17.67
σ_z/MPa	0.038	0.057	0.086	0.116	0.157	0.198	0.252	0.319	0.376
x_p/m	0.04	0.06	0.09	0.12	0.16	0.20	0.25	0.31	0.36
C_w/MPa	0.348	0.347	0.343	0.341	0.337	0.333	0.328	0.322	0.317
$\varphi_w/^\circ$	13.45	13.46	13.47	13.47	13.48	13.48	13.49	13.49	13.50
Time/h	40	44	48	52	56	60	64	68	72
Chamber depth/m	55	60.5	66	71.5	77	82.5	88	93.5	100
P_d	50	55.5	60.9	66.2	71.5	76.9	82.2	87.5	93.8
C_f/MPa	0.466	0.466	0.467	0.467	0.468	0.468	0.469	0.469	0.470
$\varphi_d/^\circ$	17.68	17.69	17.70	17.70	17.71	17.72	17.73	17.74	17.75
σ_z/MPa	0.46	0.573	0.693	0.85	1.018	1.232	1.484	1.801	2.245
x_p/m	0.43	0.52	0.61	0.72	0.83	0.96	1.10	1.26	1.46
C_w/MPa	0.31	0.3	0.291	0.279	0.268	0.253	0.239	0.222	0.2
$\varphi_w/^\circ$	13.51	13.52	13.52	13.52	13.53	13.54	13.55	13.55	13.56