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An Investigation of a Floor Treatment Plan for In-Pit Dumps with an Underlying Weak Layer

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Abstract: To effectively manage the stability of in-pit dumps with an underlying weak layer, a new plan for the treatment of a staged floor during the life of a mine was proposed in this study. Based on direct shear test results, the shear properties of contact surfaces between the weak layer, dumped spoil, and mudstone were determined. Taking the Baiyinhua No.1 Open-pit Mine as an example, a direct shear test of the contact surface between the spoil and the mudstone determined its cohesion to be 25.78 kPa, and the internal friction angle was 17.58°. The cohesion of the contact surface between the spoil and the weak layer was 7.50 kPa, and the internal friction angle was 9.72°. Different floor treatment rates were subsequently determined based on discontinuous structural surface and limit equilibrium theories. The in-pit dump plan was divided into stages based on a 10-year mine plan; a "safety reserve coefficient" was used as the conditional factor to calculate the minimum floor treatment rate. The results of a numerical simulation analysis of the slope stability of the untreated and treated inner dumps showed good agreement with results obtained by the limit equilibrium method. The position and shape of the sliding surface were also found to be similar, indicating the validity of the established numerical simulation model and the reliability of the calculated results. Based on field application and economic effect analysis, it was found that this proposed method can minimize the floor treatment rate effectively while maintaining a sufficient factor of safety. The direct economic benefit of this method was approximately 1,694,259 dollars at the Baiyinhua No.1 Coal Mine. This method is of great significance to safe and efficient production, and can be widely applied.

Keywords: in-pit dumps; slope stability; weak layer; contact surface; floor treatment rates

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1. Introduction

Coal mining is divided into two types: underground mining and open-pit mining. Among them, open-pit mining has outstanding advantages, such as good safety conditions, high resource recovery rate, large production scale, easy automation, low production cost, and easy environmental repair [1]. It has become the main mining method of coal resources in many countries, and open-pit mining accounts for more than 90% in some countries [2]. Open-pit mine dumping refers to the operation of dumping stripped materials into the designated site from the open pit. There are two types of dumping sites: internal and external. The former is located inside the stope, with short transportation distance and low cost; the latter is set outside the open-pit mining boundary and takes up a lot of land. In-pit dumps in open-cut mining have a number of advantages, including minimizing the mining footprint, reducing long hauls, and improving productivity. It can also manage dust, spontaneous combustion, and slope stability effectively [3]. However the in-pit the dump is constructed, its stability is critical for coal mining and operational safety. Large-scale dump failures have occurred previously in numerous open-cut coal mines, especially with a weak underlying stratum beneath the pit floor. Such a layer usually has high hydraulic conductivity and clay content with low shear strength. It provides a slippery surface for a dump or low wall failures [4]. Therefore, it is of practical significance to study the stability control measures of the inner dump slope for the safe and efficient production of open-pit mines.

Researchers have proposed a series of control methods, e.g., reducing batter angle [5], backfilling rocks to squeeze out ooze [6,7], floor disruption [8,9], coal pillar buttressing [10], drainage [11,12], floor grouting [13,14], chemical treatment [15–17], and slope consolidation grouting [18]. Reducing slope angle will improve slope stability. However, it will reduce dump space at the same time. Mud base removal can improve shear resistance to some extent, although it is not effective with thick, or deep, weak layers. The effectiveness of dewatering is standard during coal mining and before dumping, which can not be used as the main floor treatment technique. Coal pillars can provide sufficient buttresses to low walls in the next strip. However, it results in economic loss. Electrochemical modification can improve the strength of mudstone, but the reinforcement cost is too expensive and it is not suitable for large-scale applications. Floor disruption can disturb weak layers, reduce the risk of slope instability, and improve operational safety. Chen et al. [19] used the friction model experiment to study the deformation and failure characteristics of in-pit dumps under the natural state the saturated state. Wang et al. [20] obtained the shear strength parameters of clay by performing triaxial shear and direct shear tests. Based on experimental results, they revealed the deformation and failure pattern of dumps with underlying weak layers. In order to solve the matter of the slope stability of dumps in anticline areas, zhao et al. [21] compared and analyzed three models to solve dump stability issues with steep floors, which include floor shot, floor trenching, and coal pillar buttressing. Based on model results, floor shot was selected as the most appropriate treatment plan. Based on experimental studies on changes in groundwater level, pore water pressure, soil sedimentation, and other indicators during the treatment of weak layers, Ni et al. [22] proposed a new floor treatment method called "vacuum dynamic consolidation". Although many studies have proposed floor treatment methods for weak layers, there is no universally accepted method that can be cost-effective and safe for the life of the mine.

Therefore, this study investigated the floor treatment methods for weak layers beneath pit floors in open cut coal mines. Based on the discontinuous structural surface theory, the method to determine the equivalent mechanical index of the contact surface corresponding to the different treatment rates of the weak base in the in-pit dump was proposed for the first time, and an innovative cost-effective staged floor treatment method was proposed. This provides a technical means for safety and an effective treatment method for sloped floor treatment engineering under similar conditions. The research results have broad application prospects.

2. Determination of Weak Layer Material Properties

As in-pit dumping is usually completed post floor treatment, the contact surface between spoil and floor is newly generated. This study reconstructed the spoil and floor rock samples based on moisture content, particle size distribution and physical simulation tests. Direct shear tests were then carried out to obtain the mechanical properties of the weak layer. The rock samples were supplied by the Baiyinhua No. 1 Coal Mine (Xilingol, China).

2.1. Test Instruments

The test instruments mainly include a weighing balance, oven, grinder, screening machine, ring knife, compactor, NT.IJD-1 strain controlled direct shear apparatus (Figure 1), etc.

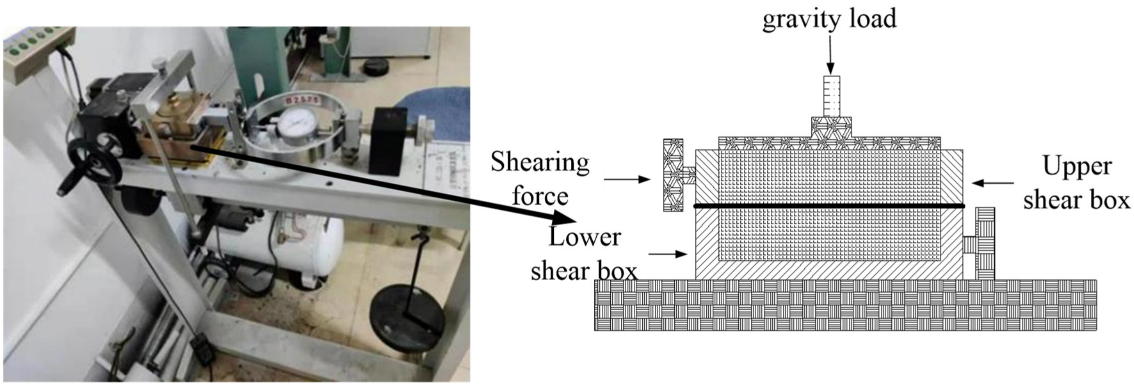


Figure 1. Schematic view of direct shear test.

2.2. Test Scheme

(1) Moisture content of rock specimen

The natural moisture content of the rock sample was determined using a drying method according to national standard GB/T 23561.6-2009 [23]. Results are shown in Table 1 below.

Table 1. Water content of rock specimens.

Rock Type	Weight Pre-Drying (g)	Weight Post-Drying (g)	Water Content (%)
Dumped Spoil	40.32	38.69	4.20
Mudstone	33.74	30.73	9.79
Carbonaceous mudstone	28.31	23.16	22.24

(2) Particle size distribution of rock specimen

Dumps are formed by spoil, for which the particle size distribution is one of its major indexes and a basis of its mechanical properties [24,25]. By crushing, drying, and screening the specimens, the particle size distributions of various rock types were obtained (see Figure 2). Results are shown in Table 2.

Figure 2. Specimen preparation. (**a**) Grinding; (**b**) Screening; (**c**) Weighting.

Table 2. Particle size distribution of specimens.

Rock Type	Particle Size Distribution (%)					
	>2 mm	1–2 mm	0.5–1 mm	0.25–0.5 mm	0.075–0.25 mm	<0.075 mm
Dumped spoil	4.711	14.317	33.268	13.842	22.515	11.347
Mudstone	21.344	14.625	26.383	10.968	18.182	8.498
Carbonaceous mudstone	11.037	27.414	26.346	11.927	16.318	6.959

(3) Rock remodel and direct shear test

Crushed material was mixed according to moisture content and particle size distributions to reconstruct rock specimens with 24 h sealed saturation, such that particles were fully mixed with water. When preparing a sample, the mixture was compressed three times with equal amounts of input material, and the compressive pressure was applied 9 times after each addition [26]. The rock sample was made into a cylindrical specimen of φ 618 mm $\times$ 20 mm. A dumped spoil and a floor rock specimen were combined into a set of specimens.

A direct shear test was carried out based on the national standard GB/T23561.11-2009 [27]. Normal stress was first applied on top of the specimen with the shear stress applied from horizontal displacement of the shear box. The shear stress was obtained through the deformation of the measuring force ring and the specimen failed along a shear surface. The shear stress vs. normal stress curves were plotted based on different shear strength results; associated cohesions and friction angles were then obtained. Results can be seen in Figures 3 and 4.

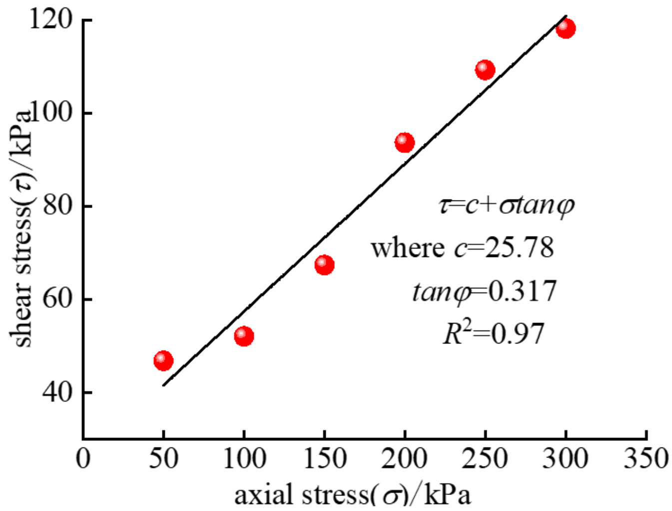


Figure 3. Shear stress vs. normal stress of the contact surface between mudstone and dumped spoil.

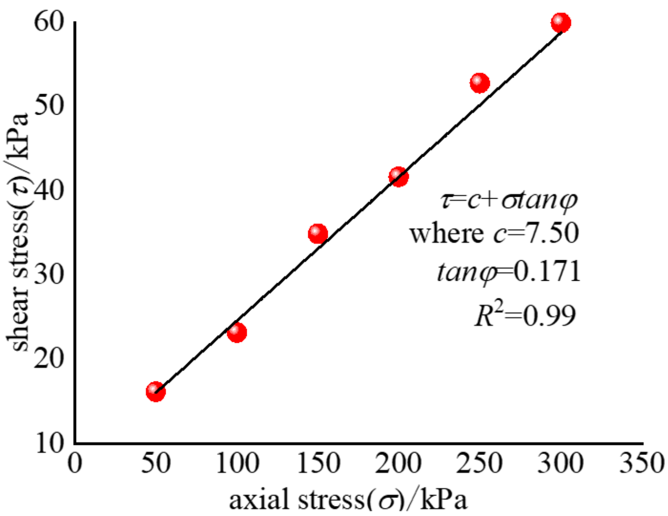


Figure 4. Shear stress vs. normal stress of the contact surface between the weak layer and dumped spoil.

Based on curve fitting equations, the cohesion of dumped-spoil–mudstone contact surface was 25.78 kPa with an internal friction angle of 17.58°. The cohesion and friction angles of the dumped-spoil–weak-layer contact surface were 7.50 kPa and 9.72°, respectively.

3. Optimized Staged Floor Treatment Plan for In-Pit Dumps

3.1. Determination of Weak Layer Shear Properties

The precondition slope stability calculation is determined by the mechanical shear properties of the contact surface corresponding to different floor treatment rates. This study estimated the mechanical properties of contact surfaces based on the discontinuous structural surface theory. Based on the theory, a discontinuous structural surface consists of a fracture surface and discontinuous rock bridges. During shearing, it is expected that both the fracture surface and rock bridges provide shear resistance [28–30]. By assuming the stress is evenly distributed along the shear surface, the continuity coefficient of the structure plane is P and the shear strength of the regenerated structural plane is [28]:

$$\tau = PC_j + (1-P)C + \sigma[P\tan\phi_j + (1-P)\tan\phi] \tag{1}$$

Based on the Mohr–Coulomb failure criterion, different treatment rates K_n are equivalent to the linear continuity coefficient P of the structural surface. Hence, the equivalent cohesive force C_i and the equivalent internal friction coefficient tanφ_i of the structural surface are obtained as:

$$\left.\begin{array}{l} C_i = K_n C_j + (1-K_n)C \\ \tan\phi_i = K_n\tan\phi_j + (1-K_n)\tan\phi \end{array}\right\} \tag{2}$$

where C_i, cohesion of contact surface, kPa; φ_i, effective friction angle of contact surface, °; K_n, floor treatment rate, %; C_j, cohesion of dumped spoil-floor rock contact surface, kPa; C, cohesion of weak layer, kPa; φ_j, friction angle of dumped spoil-floor rock contact surface, °; φ, friction angle of weak layer, °.

It can be seen from the above formula that the shear strength of the discontinuous structural surface is higher than that of the continuous structural surface, which is in line with reality. Before the floor treatment, dumped spoil is in contact with the weak layer; and post floor treatment, dumped material is in direct contact with mudstone under the weak layer. The shear mechanical parameters of two contact surfaces can be measured by a direct shear test of the contact surface. Based on different floor treatment rates, the mechanical properties of contact surfaces can then be substituted with Equation (2) for calculation, such that the equivalent mechanical properties based on various floor treatment rates can be obtained.

3.2. Analysis Method of Slope Stability

Take the i-th column on the sliding surface as an example; as i = 0, 1,... n, the base sliding angle of the i-th column is α_i, and the base inclination of the $i-1$-th column is α_{i-1}, the residual thrust of the $i-1$th column is E_{i-1}, and the force analysis of the block in the slider is shown in Figure 5.

Establish a tangential force balance equation for the direction parallel to the base of the i column [31]:

$$E_i = W_i\sin\alpha_i + E_{i-1}\cos(a_{i-1} - a_i) - S_i \tag{3}$$

Construct a normal stress equation for the i th column [31]:

$$N_i = W_i\cos\alpha_i + E_{i-1}\sin(a_{i-1} - a_i) \tag{4}$$

Based on Mohr–Coulomb failure criterion [31]:

$$S_i = \frac{C_i l_i + N_i\tan\phi_i}{F} \tag{5}$$

By rearranging the above equations, the residual thrust of upper sliding body E_i [10]:

$$E_i = W_i \sin\alpha_i + E_{i-1}\cos(a_{i-1} - a_i) - \frac{C_i l_i + [W_i \cos a_i + E_{i-1}\sin(a_{i-1} - a_i)]\tan\phi_i}{F} \quad (6)$$

where E_i, residual thrust of the ith column, kN; W_i, weight of the ith column, kN; S_i, shear stress of the ith column, kN; α_i, back-scarp angle of the failure envelope, °; N_i, normal stress at the bottom of the ith column, kN; C_i, cohesion of the ith column, kPa; φ_i, friction angle of the ith column, °; l_i, width of the ith column, m; F, reduction coefficient.

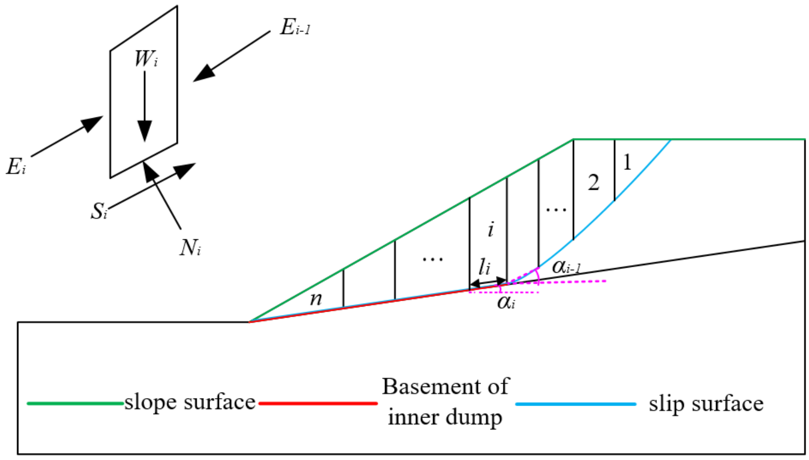


Figure 5. Force diagram of sliding surface.

Substituting the equivalent cohesive force C_i and the equivalent internal friction coefficient tanφ_i of the structural surface into Equation (6), the residual thrust under different floor treatment rates K_n can be obtained as:

$$E_i = W_i \sin\alpha_i + E_{i-1}\cos(a_{i-1} - a_i) - \frac{[K_n C_j (1 - K_n) C] l_i + [W_i \cos a_i + E_{i-1}\sin(a_{i-1} - a_i)][K_n \tan\varphi_j - (1 - K_n)\tan\varphi]}{F} \quad (7)$$

By adjusting the reduction factor F so that the residual thrust of the lowest block is 0, the factor of the safety of the in-pit dump at the slip surface can be obtained. According to this calculation, F_{min} calculated by self-programming is the stability coefficient corresponding to the most unstable slip surface, that is, the slope stability coefficient under a certain treatment rate.

3.3. Staged Floor Treatment for Weak Layers under In-Pit Dumps

From establishment to the completion of in-pit dumps, it is assumed that there are r typical engineering positions in the whole life cycle of its development, that is, r development stages, which are numbered 1, 2, . . . , n, . . . , r stage. When optimizing the floor treatment rate of the open-cut mine at each stage, it is assumed that the slope shape at the same stage does not change during the optimization process, and the slope stability is only related to the floor treatment rate. Based on this assumption, the floor treatment rate of each stage, under the condition that the slope stability meets the safety reserve factor, is determined stage by stage. Considering the rate of the floor treatment extent to the floor covering extent at a certain stage to be the floor treatment rate K_n, Fs is the slope stability coefficient, and Fst is the safety reserve coefficient. The specific steps are shown in Figure 6 below.

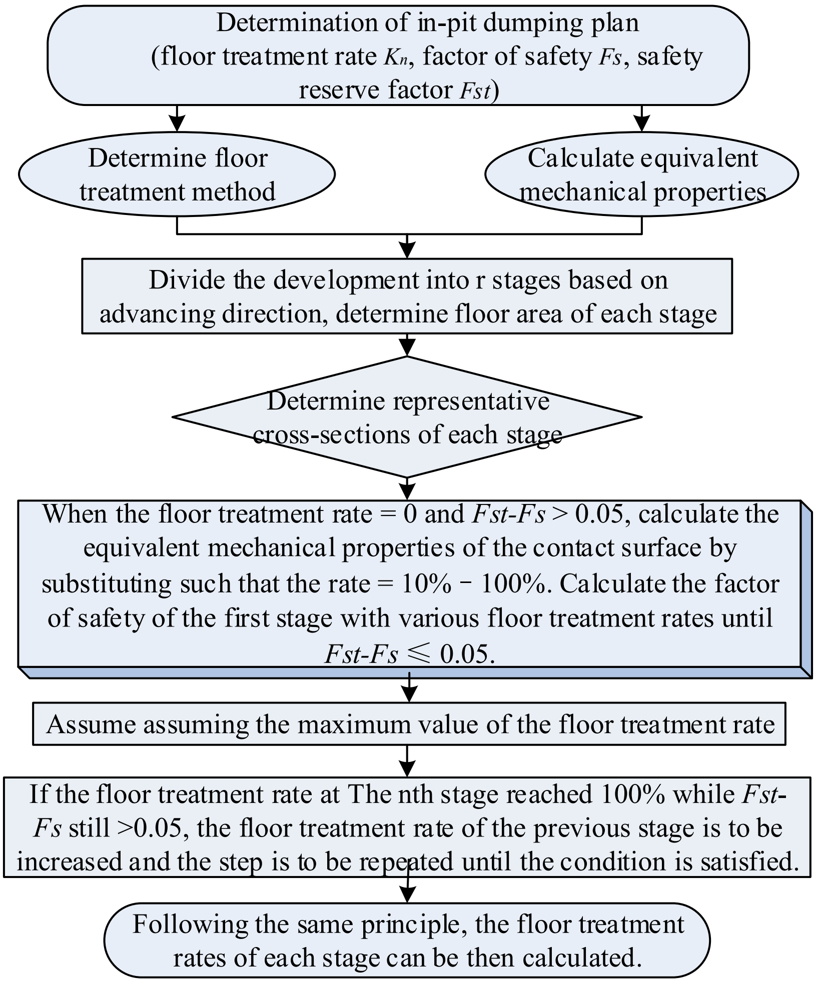


Figure 6. Flow-chart of staged floor treatment plan for in-pit dumping.

4. Field Application

4.1. Field Background

The in-pit dump of the Baiyinhua No.1 Coal Mine started in September 2018 and is located south of the pit. With the continuation of mining and overburden haulage, it is expected the dump height will keep increasing and result in a higher risk of slope failure. The high wall consists of Categories 3 and 4 sand, Cretaceous coal, and mudstone layers from top to bottom. The 33° dump batter is designed to be 13.5 m high with a 40 m bench. There is a continuous weak layer beneath the floor with an average floor dip between 8° and 14°. Such a pit-toward dipping floor is unfavorable to dump stability (see Figure 7). Therefore, treating the weak base layer is necessary to improve the stability of dumps.

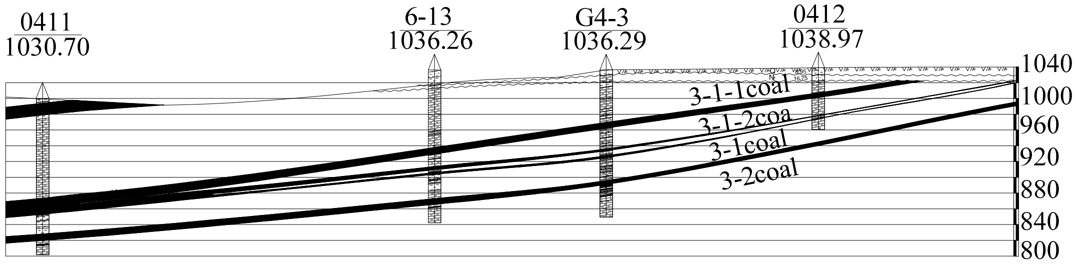


Figure 7. Geology of the Baiyinhua No.1 Coal Mine.

The development plan for the dump at the Baiyinhua No. 1 Coal Mine in the next ten years is to follow the advancing face to the north. The high wall face is arranged obliquely, such that the east is ahead and to the west of the dump is the reserve trench; the east advances towards the north to develop in a fan shape.

According to the provisions of the "Code for Design of Open Cut Mine in Coal Industry" (GB50197-2015) [32], the factor of safety of the in-pit dump needs to be at least 1.2. Due to the existence of a weak layer, it is prone to shear sliding along the layer. The physical and mechanical properties of the rock and soil mass used in the calculation of slope stability are shown in Table 3.

Table 3. Mechanical properties of strata.

Rock Type	Friction Angle (°)	Cohesion (kPa)	Test Weight (KN/m^3)
Dumped spoil	17.49	25.38	17.80
Category 4 sand	23.98	0.00	17.50
Category 3 sand	24.00	85.00	19.30
Coal	26.32	58.00	11.90
Mudstone	21.85	26.00	20.10
Dumped-spoil–weak-layer contact surface	9.72	7.50	20.20
Dumped-spoil–mudstone contact surface	17.58	25.78	20.20

4.2. Cross-Section Selection

According to the development plan of dumps at the Baiyinhua No. 1 Open-pit Coal Mine, it is divided into 10 development stages. In different stages, where slope dimensions or geological conditions change significantly, the cross-section perpendicular to the direction of the dump strike should be selected. A total of 18 calculation sections were selected with the first stage (2021) and the tenth stage (2030) as examples. Cross-sections of the calculated profiles are shown in Figures 8 and 9 (From AUTOCAD2016).

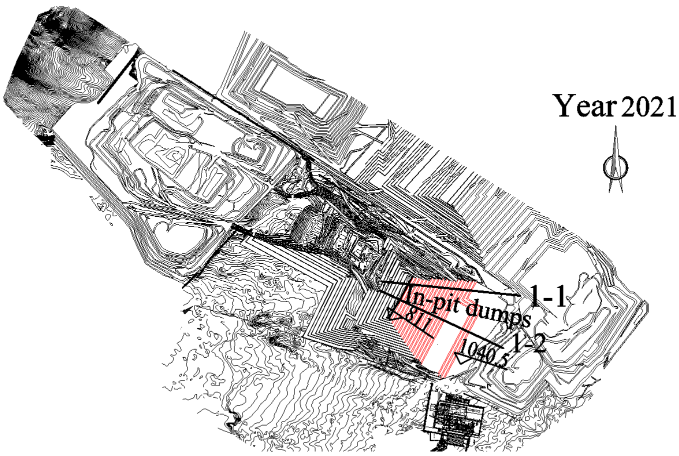


Figure 8. Pit layout for 2021.

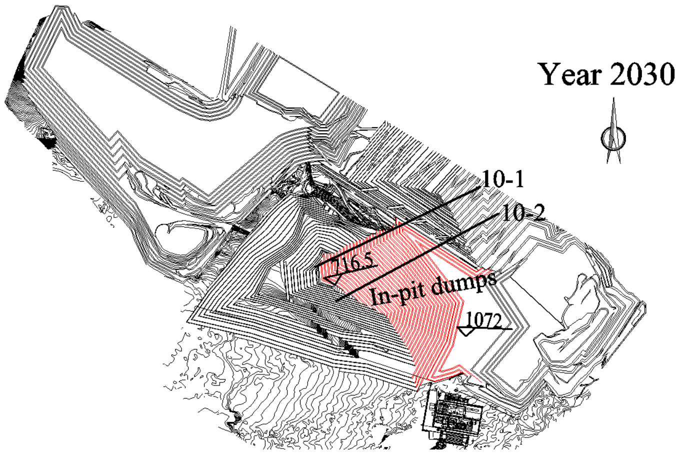


Figure 9. Pit layout for 2030.

4.3. Determination of Shear Resistance

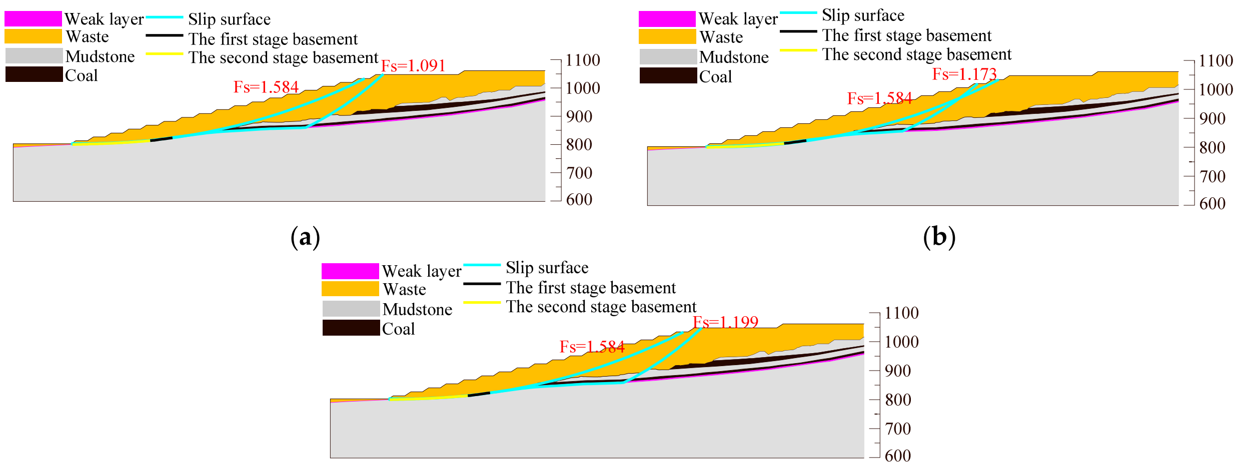
The base of the dump at this mine is 2~5 m thick and soft carbonaceous mudstone with mudstone beneath this weak layer. The mechanical properties of the contact surface between the dumped spoil and the weak layer, and the dumped spoil and the mudstone, were determined by the above-mentioned direct shear tests. Subsequently, the equivalent shear properties of the contact surface under different treatment rates were obtained via Equation (2) (see Table 4).

Table 4. Equivalent shear properties of contact surfaces.

Floor Treatment Rate (%)	Cohesion (kPa)	Friction Angle (°)
0	7.500	9.720
10	9.328	10.528
20	11.156	11.332
30	12.984	12.131
40	14.812	12.926
50	16.640	13.716
60	18.468	14.500
70	20.296	15.279
80	22.124	16.052
90	23.952	16.819
100	25.780	17.580

4.4. Determination of Floor Treatment Rate at Each Stage

According to the above-mentioned staged treatment method, the floor treatment rate of each stage was determined. Taking the process of determining the floor treatment rate of the second stage as an example, as shown in Figure 10 (From AUTOCAD2016), the rate of the 2-1 section selected in the second stage was calculated. When the floor treatment rate was 0% and 10%, the factor of safety of the slope was 1.019 and 1.073, respectively, which did not satisfy $Fst\text{-}Fs \leq 0.05$. When the floor treatment rate was at 20%, the factor of safety was calculated to be 1.199, which meets the criteria. Therefore, the floor treatment rate of Section 2-1 in the second stage was determined to be 20%. Following the same process, the factor of safety of Section 2-2 was calculated. When the floor treatment rate of the profile was 0%, the factor of safety was 1.303. This meets the requirements of the safety reserve factor. Therefore, the minimum floor treatment rates of the two calculation profiles selected in the second stage were 20% and 0%, respectively. To ensure the slope stability of all sections in the second stage, the higher rate was selected for the second stage, i.e., K_2 = 20%. By calculating the slope stability for each calculation section, the factor of safety and the floor treatment rate of each calculation section were obtained, as shown in Table 5.



(c)

Figure 10. Results of cross-Section 2-1. (**a**) Factor of safety of cross-Section 2-1 pre-floor treatment; (**b**) Factor of safety of cross-Section 2-1 at 10% treatment rate; (**c**) Factor of safety of cross-Section 2-1 at 20% treatment rate.

Table 5. Slope stability calculation and floor treatment rates of each cross-section post optimization.

Stage	Cross-Section	Relevant *Kn* (%)	Floor Treatment Rate (%)	Fs	*Kn* (%)
1	1-1	—	20	1.199	100
	1-2	—	100	1.196	
2	2-1	$K1 = 100$	20	1.199	20
	2-2	$K1 = 100$	0	1.303	
3	3-1	$K1 = 100$	0	1.358	0
		$K2 = 20$			
	3-2	$K1 = 100$	irrelevant	1.196	
		$K2 = 20$			
4	4-1	$K1 = 100$	0	1.269	0
		$K2 = 20$			
		$K3 = 0$			
	4-2	$K1 = 100$	irrelevant	1.283	
		$K2 = 20$			
5	5-1	$K2 = 20$	0	1.240	Repeated $K5 = 20$
		$K3 = 0$			
		$K4 = 0$			
6	6-1	$K2 = 20$	0	1.327	0
		$K3 = 0$			
		$K4 = 0$			
		$K5 = 20$			
	6-2	$K1 = 100$	irrelevant	1.210	
		$K2 = 20$			
		$K3 = 0$			
		$K4 = 0$			

Table 5. *Cont.*

Stage	Cross-Section	Relevant *Kn* (%)	Floor Treatment Rate (%)	Fs	*Kn* (%)
7	7-1	$K4 = 0$	0	1.205	0
		$K5 = 20$			
		$K6 = 0$			
	7-2	$K1 = 100$	irrelevant	1.199	
		$K2 = 20$			
		$K3 = 0$			
		$K4 = 0$			
		$K5 = 20$			
8	8-1	$K5 = 20$	20	1.198	20
		$K6 = 0$			
		$K7 = 0$			
9	9-1	$K8 = 20$	0	1.241	0
	9-2	$K1 = 100$	irrelevant	1.267	
		$K2 = 20$			
10	10-1	$K9 = 0$	0	1.251	0
	10-2	$K4 = 0$	0	1.217	
		$K5 = 20$			
		$K6 = 0$			
		$K7 = 0$			

4.5. Numerical Simulation

(1) Establishment of numerical simulation model

A numerical simulation analysis was conducted to investigate the effect of weak floor treatment on the slip mode and slip mechanism of inner dump slopes. The stability of the inner dump slope with an untreated and treated base was analyzed by constructing a numerical simulation model for the 2-1 section. The model range (length × height) was determined to be 1800 m × 447 m based on actual terrain and excavation conditions, and the section design consisted of 5757 nodes and 18,363 cells, as shown in Figure 11. The stratum distribution was: the first layer was the waste, the second layer was the Quaternary sand, the third layer was the Tertiary sand, and the following was the ore body. The physical and mechanical parameters of the rock mass are shown in Table 3.

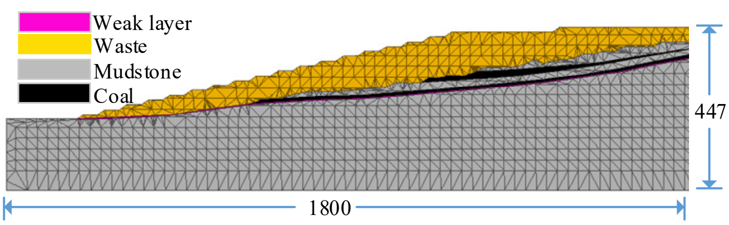


Figure 11. Numerical simulation model.

(2) Initial-boundary conditions

The simulation calculation for the stability analysis of the inner dump slope only considered displacement constraints in the horizontal (X) direction on the left and right boundaries, under the condition of self-weight stress. Vertical (Y) displacement constraints were applied to the bottom boundary of the model [33,34], while the top and step slope positions were free boundaries to ensure the balance of the entire system. The failure criterion of the rock mass was determined using the D-P criterion, and the connectivity of the plastic zone and the mutation of displacement of characteristic parts were used as instability criteria [35].

(3) Analysis of effect

The simulation results obtained by calculation are shown in Figures 12 and 13 (From FLAC3D5.0). Analysis of displacement and shear strain contours revealed the formation of an arc-like shear failure zone beneath the slope due to the presence of a weak layer. This zone was sheared along the weak layer by the slope's gravity, resulting in the formation of a sliding plane. The numerical simulation results were found to be consistent with those obtained from the limit equilibrium method, with the position and shape of the slip surface closely matching, thus indicating the correctness of the numerical simulation model and the reliability of the calculation results.

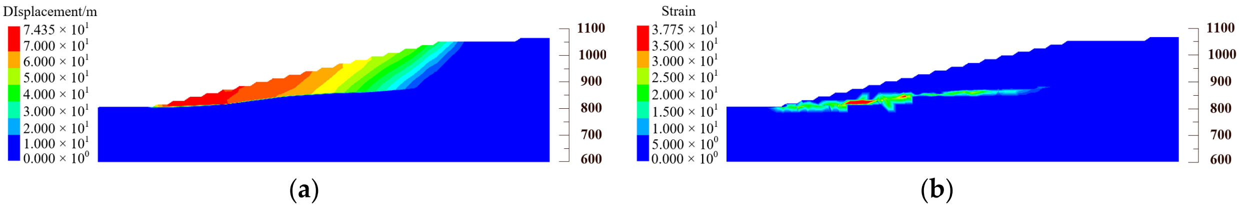


Figure 12. Simulation results pre-floor treatment. (**a**) Displacement contour; (**b**) Shear strain contour.

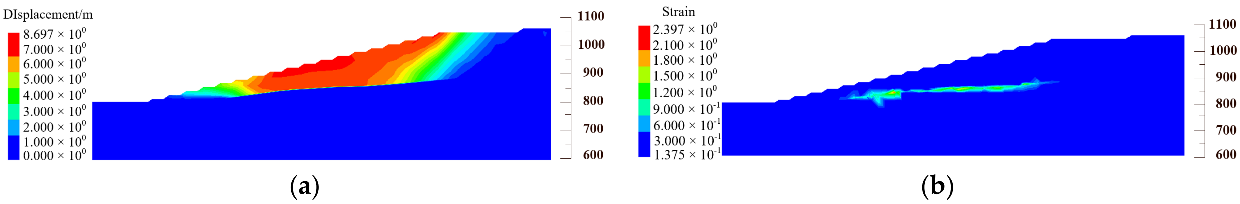


Figure 13. Simulation results post floor treatment. (**a**) Displacement contour; (**b**) Shear strain contour.

5. Results and Discussion

According to the treatment process of the in-pit dump base stage by stage, the slope stability was calculated for each calculation section one by one, and the treatment rate of the base at each stage was obtained. The floor treatment range at each stage is shown in Figure 14 (From AUTOCAD2016). Among them, the treatment rate of the first stage was 100%, the second, fifth, and eighth stages were all 20%, and the treatment rate of other stages were 0%.

Analysis from numerical simulation results, post floor treatment, showed that the shear strength of the contact surface between spoil dump and base increased. At the treated location, the upper deformation and shear strain increment were significantly reduced and the slope stability was significantly improved. The factor of safety was improved from 1.10 to 1.21. The failure mode and factor of safety are basically consistent with the results obtained by the two-dimensional calculation. The two methods verified each other, which proves the validity of the slope stability analysis.

From the economic benefit point of view, the base treatment cost was calculated according to the optimization results of the base treatment rate of each stage. By referring to the previous floor treatment cost of the Baiyinhua No. 1 Mine, the estimate was based on the treatment unit price of 1.17 dollars/m^3. The total volume of the weak layer in the first, second, fifth, and eighth stages of the in-pit dump was 2,711,400 m^3; and the volume of the weak layer to be treated after the optimization was 1,263,315 m^3. The cost of the original process was about 3,172,338 dollars, whereas the optimized substrate processing cost was about 1,478,079 dollars. This optimization saves about 1,694,259 dollars. Under the condition that the floor was not treated, we must adopt the design scheme of the gentle slope to ensure the stability of the in-pit dump. After the design, the slope angle of the in-pit dumps was 9.5°, which was 4° lower than the floor treatment scheme. The gentle slope scheme reduced the dumping amount of the in-pit dumps, so it was bound to increase the dumping amount of the out-pit dumps. This scheme not only increased the land purchase cost of the out-pit dumps, but also added to the transportation cost. Compared with other floor treatment methods, the floor treatment plan also had a slight advantage. For example, Zhao et al. [21] proposed a blasting treatment method for the floor. This mode needs high processing costs, a long cycle, and the blasting scheme needs to be tested and designed, which is not suitable for large-scale floor treatment. Tang et al. [36] applied the reserved coal pillar method by the example of the Huolin river open-pit mine, and the slope stability coefficient was obviously improved. However, the method of reserving coal pillars was bound to cause coal losses. At present, there is no mature method to optimize the parameters of reserved coal pillars.

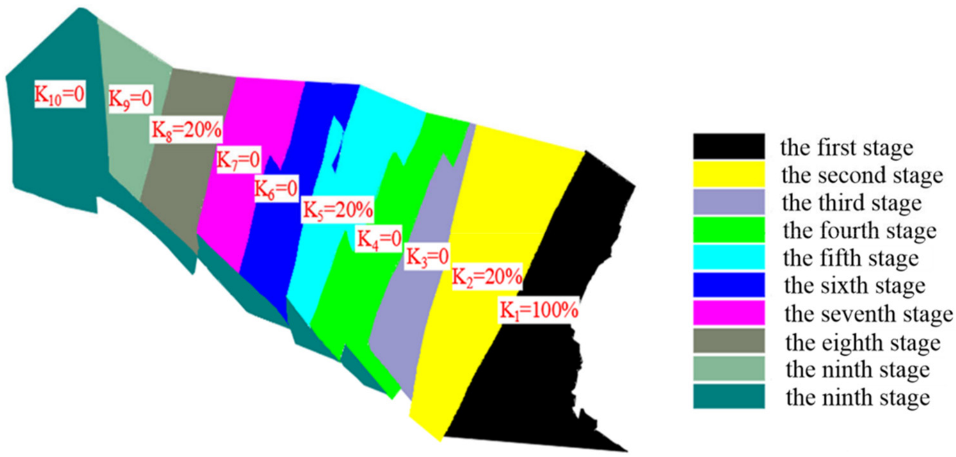


Figure 14. Results of floor treatment rates at different stages.

Land is a valuable property and a key element for sustainable development. By treating the floor of the inner dump, the capacity of the dump can be increased, and existing land resources can be utilized more efficiently. This, in turn, can reduce the land occupation of the outer dump, leading to a reduction in transportation costs, land expropriation expenses, ecological damage, and the cost of ecological restoration. Therefore, the proposed treatment method is beneficial for the sustainable development of open-pit mines. Moreover, improving slope stability can effectively prevent casualties, equipment damage, and the destruction of surrounding facilities caused by landslide disasters, leading to significant social benefits. The optimization method presented in this study serves as a reference for the treatment of inner dump bases in other open-pit mines and provides useful guidance and reference.

6. Conclusions

This study is based on the Baiyinhua Open-pit Coal Mine in Inner Mongolia, China. The main findings are as follows:

(1) A direct shear test of the contact surface between the spoil and the mudstone determined the cohesion to be 25.78 kPa, and the internal friction angle is 17.58°. The cohesion of the contact surface between the spoil and the weak layer is 7.50 kPa, and the internal friction angle is 9.72°. The determination's methods of effectiveness, such as the contact surface corresponding to the different treatment rates of the weak layer, was proposed based on the theory of discontinuous structural surface theory. This provided fundamentals for the calculation of slope stability.

(2) By considering the factor of safety of dumped spoil at each stage of development and associated safety reserve coefficient, together with the aim of minimum floor treatment, a new staged optimization treatment method for the weak layer for the life of the mine was proposed. The Baiyinhua No.1 Open-pit Coal Mine applied this method to optimize the treatment of the inner dump base, and the treatment rate of the first stage was 100%, the treatment rate of the second, fifth and eighth stages was 20%, and the treatment rate of other stages was 0%. Through comparative analysis, the treatment cost of the scheme was about 1,694,259 dollars less than that of the base full treatment scheme, which effectively solved the slope stability problem of the dump in the soft base and improved the economic benefits of the open pit mine.

(3) The numerical simulation analysis results show that the failure mode before and after the floor treatment was sliding. However, the maximum deviation and shear strain increment at the floor treatment location were significantly reduced, while the slope stability was significantly improved. This was consistent with the two-dimensional stability analysis results.

(4) The floor treatment plan for the inner dump can significantly enhance slope stability and increase the utilization rate of inner dump space. This, in turn, reduces the occupied area of the outer dump and minimizes the impact on the natural environment, making it an effective measure for controlling coal spontaneous combustion and dust, with potential ecological and social benefits.

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