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Research Article

Stability of Step-shaped Dump Slope and Reinforcement Optimization Analysis of Anti-slide Piles

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Abstract

The geotechnical material in slope engineering of mine dumps is loose, under severe conditions such as heavy rain, there is a risk of landslide in the dumping site. Therefore, to evaluation on the stability of the dump slope in the dumping site is essential to ensure the safety and property of the mine. Taking Jinhaili dumping slope in Chengde as engineering background, based on the site survey and laboratory test, a three-dimensional numerical calculation model of the dumping slope was constructed by using FLAC3D, and the loading process and the stability of the step-shaped dumping slope were carried out. Then the reinforcement optimization analysis of anti-slide piles for potential slip was analyzed. Based on the calculation results, the landslide mechanism of the dumping slope was revealed, and the key part of the potential slip of the slope during the step-by-step loading process was determined. The reinforcement scheme of the anti-slide piles for the potential sliding part was proposed also. The conclusions obtained in the study are of important theoretical value to similar dump slope engineering.

Keywords: Dump slope, Landslide mechanism, Numerical simulation, Anti-slide pile, Stability

1. Introduction

Mine dump slopes are the product of open pit mining activities. In the production process of open pit mines, a large amount of geotechnical material is stripped off. It is necessary to select suitable sites for dumping slope. The dumping slopes often occupy a large amount of land resources, and the production cost ratio which caused is significant. So it is a hot issue to expand the capacity of existing dumping sites in mines. The design and the safety of dumping slopes in mines have attracted the attention in the world over the past years [1-2].

The development of high-step dumping technology and the construction of multi-step dumping sites are effective measures to reduce occupying land [3]. As the dump slope becomes steeper and steeper, although the economic benefits will be significant, the probability of slope instability will increase. This mutually restrictive relationship constitutes a sharp contradiction between safe production and economic interests. Due to the loose structure of the rock and soil materials in the dumping slope, under the severe conditions such as heavy rain, the instability risk of landslide in the dumping site is large, which posing a security threat to local residents [4-5].

The landslide catastrophe is a transformation system that is influenced by internal and external factors, from quantitative change to qualitative change, from gradual change to sudden instability. Therefore, it is important to carry out the step by step dumping analysis and evaluation on the stability of the dumping slope to ensure the mine production.

2. State of the art

In recent years, with the development of the mining industry, the stability analysis technology of the slope engineering in mine has been further developed and deepened [6-11]. Compared with other slope problems, the stability studies on dumping slope started late [12-13]. For example, considering the gradation characteristics of the materials, Wang et al. established the slope model of the ultra-high dumping site, and carried out the stability analysis of the super-high dumping slope [14]. Tao et al. used fiber optic sensing technology to monitor the stability of the dumping slope with a height of 300 m in Nanfen Iron Mine, and determined the deformation rule of the soil under different loading loads and rainfall conditions [15]. Wei et al. delineated the landslide dangerous zones of the dump slope, and analyzed the stability of the dump slope by comprehensive utilization of multi-source, collaborative remote sensing technology and numerical method [16]. Wang and Chen analyzed the instability failure mode of the dump slope by using the FLAC3D and floor friction model tests [17]. Yang et al. used numerical methods to analyze the variation of the wetting line before and after the dumping, the pore water

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pressure and the solpe stability after anti-sliding reinforcement [18].

For the optimization scheme of the slope stability of the dumping site, Han et al. proposed a scheme to improve the stability of the dumping slope by reducing the slope angle of the soil slope and the base inclination angle or improving the roughness of the base by mechanical analysis of the Shengli open pit mine [19]. Fehmi et al. analyzed the damage between two adjacent slip surfaces of the slope after heavy rainfall by using the back analysis method, and they recommended conducting long-term monitoring of the groundwater level and adopting an effective surface drainage scheme [20]. Wang et al. put forward the countermeasures and optimized the controlling method of time and spatial steps by studying on the nonlinear effect caused by excavation of west edge slope in Antaibao. In addition, the anti-slide piles countermeasures were proposed for the cut-and-cover tunnel on the inclined slope [21-22].

The existing research pays more attention to the overall stability analysis of dump slopes in mines under the influence factors such as rainfall, earthquake and weak base. There are few studies on the stability of dumping slope during the step-by-step loading process. Based on the dumping slope in Jinhaili mine, this study determined the key parts of the potential slip of the dumping slope by analyzing the stability of dumping slope during the step-by-step loading process, revealed the slip mechanism, and optimized the reinforcement scheme of the anti-slide piles, which provides a basis for the stability analysis and control of multiple step-level dump slopes.

The rest of this study is organized as follows: Section 3 establishes a three-dimension computational model for analyzing the landslide mechanism, stability and reinforcement scheme of the dumping slope. In Section 4, the related results are analyzed and discussed. Section 5 provides the relevant conclusions.

3. Methodology

3.1 Engineering Background

The Jinhaili dumping site is located in the V-shaped valley in the north-east direction of the middle part of the Yanshan Mountains. It is a denuded landform in Pingquan County, Chengde, China. The central part is divided into two valleys by a U-shaped ridge. The V-shaped mountains on both sides are basically symmetrical, and the mountain dip is from 20 ° to 30 °, the terrain near the site is high in the north and low in the south.

The mountain is gentle, and there are Quaternary coverings on both sides of the valley and the gully. The gorge is mainly in the valley. The vegetation on both sides of the mountain is well covered, and the satellite image of the bedrock on the mountain is shown in Fig. 1.

The elevation of the dump site is between 802 m and 894 m, the maximum height difference is 92 m, and the total height of the design dumping stack is 88 m. The rock and soil are discharged by grading and stacking, with a total of 7 steps. The minimum width of the top platform of the dumping step is 30 m, and the minimum width of the safety platform is 5 m between adjacent steps. The slope of the first to seventh step of the dumping slope is 23°, 21°, 28°, 31°, 30°, 25 °, and 25 °, respectively. The current status of the surface of the local dumping slope is shown in Fig. 2.

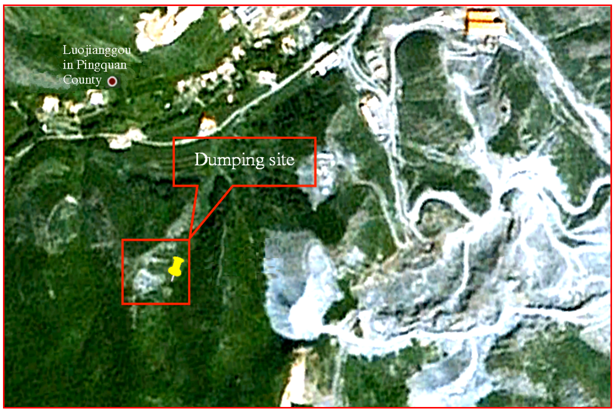
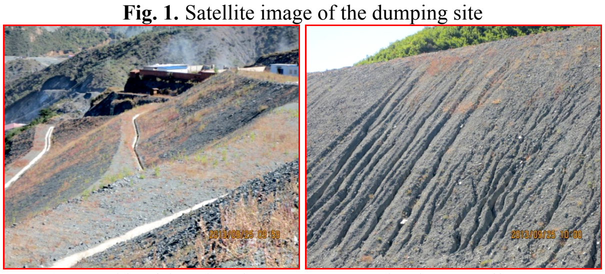


Fig. 1. Satellite image of the dumping site



(a) West side of dumping slope (b) Slope runoff

Fig. 2. The current status of the surface of the local dumping slope

The bedrock of the dumping site is gneiss, and the dumping soil is mainly fine-grained waste slag, partially containing gravel, which is about 2.5 m thick from the top surface of the dumping site. The lower part is a block stone with a larger particle size, and the block stone gap is filled with waste slag and silty clay. Based on the results of indoor and outdoor experiments, the physical and mechanical parameters of the materials in the dumping slope are listed in Table 1.

Table 1. Calculating parameters for the model

Lithology name	Thickness (m)	Unit weight ($kN \cdot m^{-3}$)	Elastic modulus (MPa)	Poisson's ratio	Tension (kPa)	Cohesion (kPa)	Frictional angle (°)
Upper rock and soil	2.5	16.0	70	0.35	0.50	10	30
Lower rock and soil	-	21.5	70	0.30	0.50	10	30
Silty clay	1.5-4.0	19.8	10	0.30	0.50	80	22
Gneiss	-	26.5	120	0.22	1800	9800	59

3.2 Building Computational Model

There are seven steps in the dumping slope in Jinhaili mine. The surface morphology of the dumping slope and bedrock is complicated. The three-dimension geometric model was established by MIDAS/GTS software and imported into FLAC3D software through data conversion program. The size of the dumping model was 592 × 160 × 150 m^3, the displacement of the bottom of the model was fixed, the horizontal displacement of the lateral sides of the model was fixed, and the upper surface was set as the free boundary.

The dumping materials were divided by tetrahedral solid elements, and the bedrock and surface soil were divided by hexahedron and five-sided wedge-shaped elements. The total number of units was 194,662, and that of nodes is 67,471.

The Mohr-Coulomb constitutive model was used and the three-dimensional grid model of the slope before loading was shown in Fig. 3.

The initial stress balance calculation was conducted and the displacement fields were cleared before dumping loading. The simulation was carried out by step-by-step stacking, and the overall model of the slope after dumping loading was shown in Fig. 4.

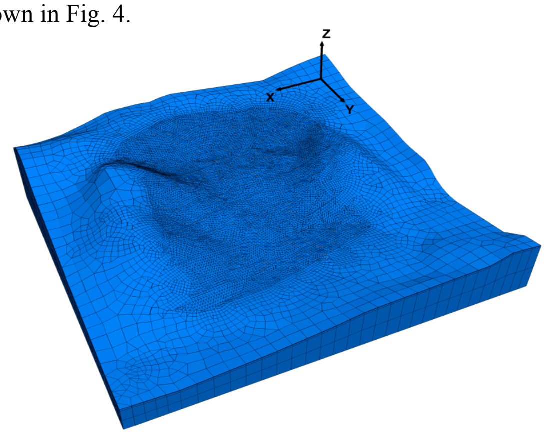


Fig. 3. The model and its meshes before dumping loading

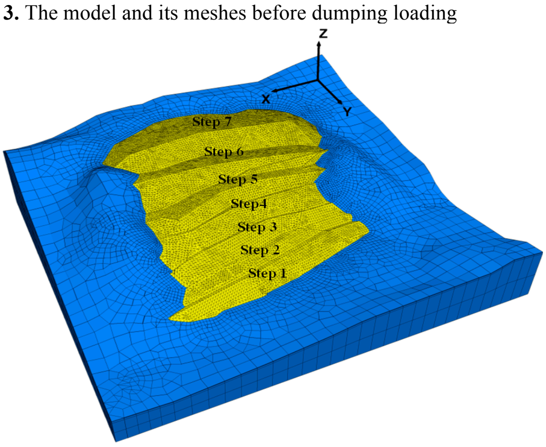


Fig. 4. The model and its meshes after dumping loading

3.3 Calculating Factor of Safety

When the shear strength parameters are reduced to the critical state of the slope, the corresponding parameter reduction degree is the safety factor defined by the strength reduction method.

When using the Mohr-Coulomb criterion to judge the slope state, the cohesion strength c and the internal friction angle φ of the materials are the main factors affecting the slope stability. The initial shear strength parameters c^0 and φ^0 of the materials are reduced according to a certain rule, and the shear strength parameter reduction degree increased. The stability state of the slope under different shear strength parameters is calculated and analysed repeatedly until the slope reached the critical state. Set the shear strength parameters of geomaterials c^{cr} and φ^{cr} in this critical state and define the safety factor $F^{cr}=1$ of the slope under the critical state. Then, the calculation method of the safety factor F of the slope under natural conditions is shown in formula (1).

$$F=\frac{c^0}{c^{cr}}=\frac{\tan\varphi^0}{\tan\varphi^{cr}} \tag{1}$$

4. Results and Discussion

4.1 Failure Characteristics and Location of Slip Surface

To determine the location of the potential slip surface, the characteristics of the slope failure and the development trend during the step-by-step dumping loading process, the FISH language built into the FLAC3D software is used to automatically identify the unit where shear failure and tensile failure occur, as shown in Fig. 5.

During the step-by-step loading of the dumping materials, the units of tensile failure and shear failure gradually increase. The tensile failure units occur at the surface of the slope and interface between the adjacent steps dumping slope, and its distribution rule coincides with the maximum shear strain increment concentration area of the slope, and increases with the volume of the dumping materials. The shear failure units are concentrated on the interface between the slope and the bedrock, and which in Steps 3 to 5 of the slope grow faster during the dumping process. The shear failure units in Step 1, Step 2, Step 6 and Step 7 are growing slower during the stacking process. This is because the slope is gentle and the shear force caused by the dumping materials is small. The two platforms between the Step 5 and Step 7 have a large width, which effectively reduces the load on the lower part of the platform.

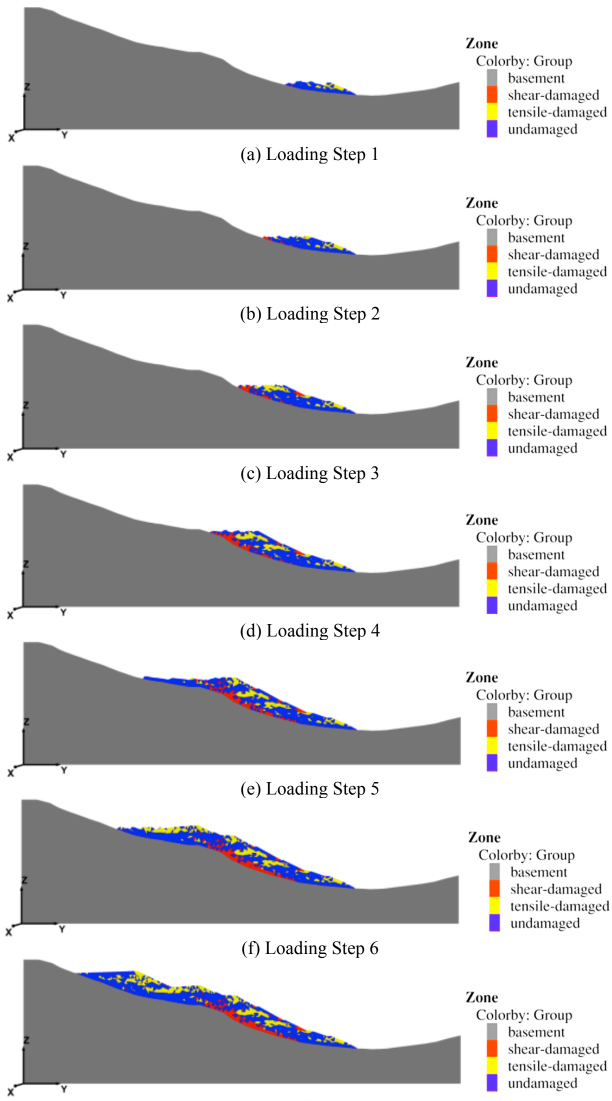


Fig. 5. Plastic zones in slope during the step-by-step dumping loading

The incremental distribution of shear strain during the step-by-step loading of the dumping slope is shown in Fig. 6. As the dumping volume increases, the shear strain increment increases, and the concentrated area gradually changes from the internal to the surface of the slope, and it transfer and develop upward along the interface between slope and the bedrock.

The increment trends of the maximum shear strain are shown in Fig. 7. During the Step 1 to Step 3 dumping process, the shear strain increment in the slope is small. During the Step 4 to Step 5 dumping process, the shear strain increment in the slope is significantly increased and the growth rate is faster. After the Step 5 dumping, the development of the shear strain zone in the slope tends to be stable. After completion of all the dumping loading, the shear strain concentration zone between the bedrock and the slope and that at the top of the Step 4 slope are penetrated, which shows the stability of the dumping slope is poor.

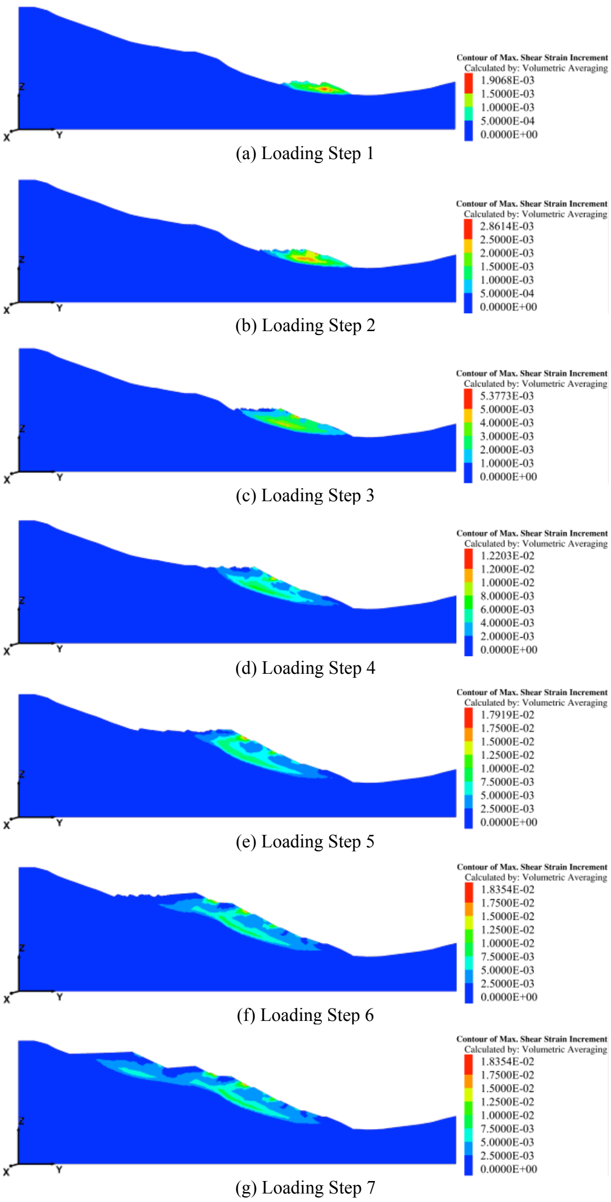


Fig. 6. Increment contours of maximum shear strain in slope during the step-by-step dumping loading

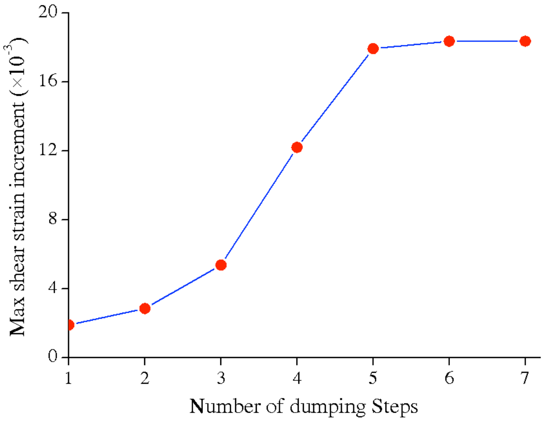


Fig. 7. Variation curve of maximum shear strain increment during the step-by-step dumping loading

4.2 Deformation Characteristics and Stability Analysis

The maximum displacement variation of the slope during the step-by-step dumping loading is shown in Fig. 8. The variation trend of the displacement and displacement horizontal component values is consistent. During the Step 1 to Step 3 dumping loading of the slope, the maximum displacement growth rate is small, but the maximum displacement growth rate of the Step 4 to Step 5 dumping loading is large. The maximum displacement of the Step 6 to Step 7 dumping loading is gradually stabilized. The variation rule of the displacement field during the step-by-step dumping loading of the slope indicates that the Step 4 to Step 5 are the key locations that affecting the stability of the slope. From the morphology analysis of the slope, the Step 4 to Step 5 of the slope are steep, and the width of the safety platform reserved at the foot of the slope is small, which causing excessive shear stress and easily causing the slope damage.

To quantitatively evaluate the stability state of the slope during the step-by-step dumping process, the finite difference method is used to calculate the safety factor of the dumping slope at each dumping loading, as shown in Fig. 9.

During the dumping process of the Step 1 to Step 3 of the slope, the overall safety factor of the slope is large, and that of the slope at these steps does not decrease significantly with the increase of the number of dumping loading. After the completion of the Step 4 to Step 5 dumping loading, the overall safety factor of the slope is suddenly reduced, while the loading of the Step 6 to Step 7 has little effect on the overall safety factor of the slope. The change trend of the safety factor is consistent with the trend of the shear failure units during the step-by-step dumping process. It can be seen that the Step 4 to Step 5 of the slope are the key parts to reduce the overall stability of the dumping slope.

4.3 Instability mechanism of dumping slope

To analyze the landslide instability mode of the dumping slope, the potential instability evolution process of the dumping slope is simulated by weakening the shear strength parameters of the dumping materials. The distribution of the plastic zones in the slope during the weakening of the shear strength parameters are shown in Fig. 10.

When c=8.33 kPa and φ=26°, the shear failure zones appear close to the interface between the slope and the bedrock at Step 4 to Step 5 of the slope. The slip interface is connected with the top of Step 6 and the tensile failure zones in Step 3 of the slope. The overall safety factor of the slope under this condition is 1.41. When c=7.14 kPa, φ=22°, the shear failure zones extend down to the Step 2 of the slope, and that also appear at the interface between the Step 7 bedrock and the slope, but it is not running through the lower shear failure zones, the overall safety factor of the slope under this condition is 1.21. When c=6.25 kPa and φ=20°, the potential shear failure surface of the whole slope is completely penetrated, and the slope faces the overall instability.

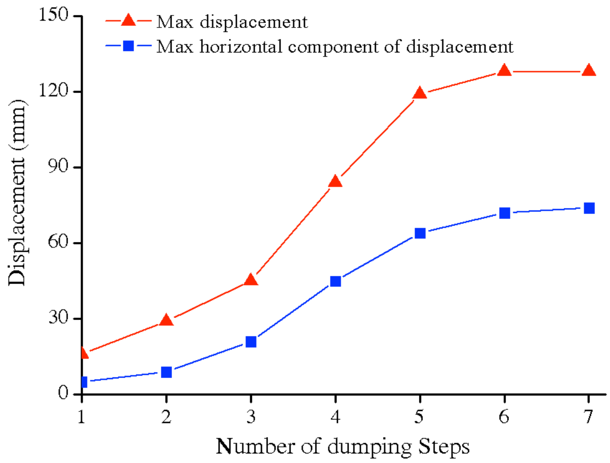


Fig. 8. Variation curve of maximum dispalcement during the step-by-step dumping loading

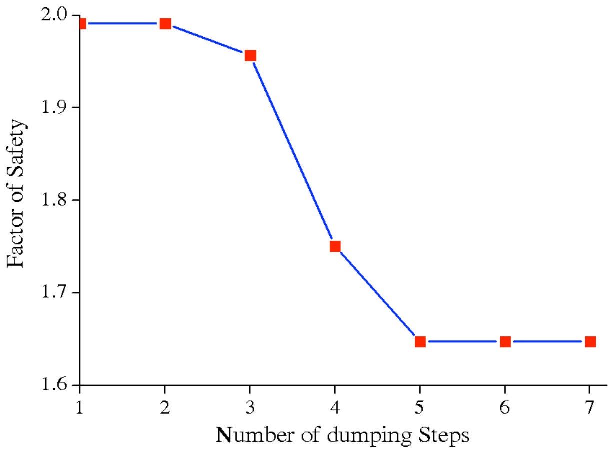


Fig. 9. Variation curve of safety factor during the step-by-step dumping loading

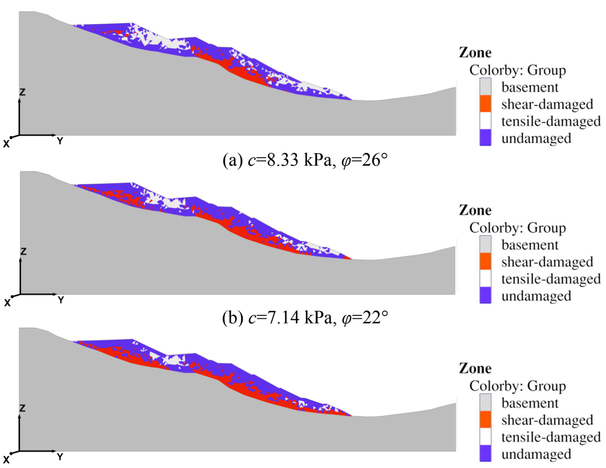


Fig. 10. Plastic zone evolution in slope during shear parameters weakening

According to the displacement vector distribution in the slope, the slope can be divided into four areas: A, B, C and D, as shown in Fig. 11.

Among the four areas, area A is a pushing potential sliding area including Step 5 and a small amount of the leading edge of Step 6 of the slope. The displacement in area A is larger, and the displacement vector inclines downward of the slope face. The area B includes the Step 3 and Step 4 of the slope, and the displacement in area B is large, which vector direction gradually increases from the top to the bottom parallel to the horizontal Y direction. The area C includes the Step 1 and Step 2 of the slope, and the displacement vector in area C is small. The area D includes the Step 6 and Step 7 of the slope, the displacement in area D is small, and the displacement vector is mainly vertical downward.

Combined with the development of shear failure and tensile failure zones in the slope during the weakening process of the shear parameters, the area A has a steep slope and a small safety platform, which is the first part to cause shear failure and pull a small amount of slope in the lower part of the area D, and it will induce tensile damage in area D. As the strength of the slope decreases, the shear failure units in the area D increases. However, due to the large safety platform, the slope of the bedrock is small and it does not penetrate with the shear zones of the area A.

When the slope is unstable, the area A is the first to lose its stability, which is the starting area of the slope landslide. Under the driving effect of the area A, the upper part of the area B is displaced along the slope. The lower part is subjected to extrusion to produce large deformation to the free side, which is the main sliding area of the slope. The area C at the slope foot is flat due to the gentle slope of the lower rock and the dumping height is small. Due to the displacement in area C is small under the action of the upper dumping force, which is the main anti-sliding area of the dumping slope. The sliding area of the dumping slope is caused by the tension of the upper slope and the complete shearing of the lower slope, so the landslide instability mode of the dumping slope is “pull-up and push down” type initiated by the area A.

Under the pushing action of the starting area A, the main sliding area B is displaced downward along the slope, and the lower slope is displaced toward the free direction. However, the displacement vector of the area C is small, which is the blocking area of the potential sliding body of the dumping slope. Therefore, the potential landslide instability path of the dump slope will be a progressive landslide instability starting from the area A, and passing through the main sliding area B, and gradually extending to the blocking area C.

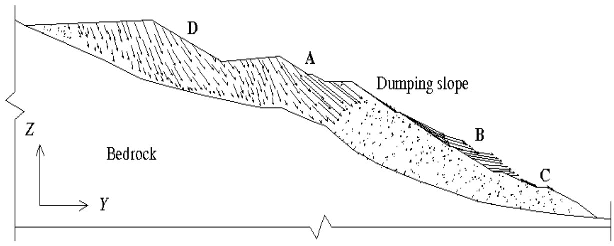


Fig. 11. Displacement vector in each potential sliding area

4.4 Schemes Optimization Analysis of Anti-slide Piles

According to the stability analysis of the step-by-step dumping process and the instability mechanism of the slope, the Step 4 and Step 5 of the slope are the key areas affecting the overall stability of the slope. Therefore, the slope foot of

Step 5 and half of Step 4 are used as the reinforcement positions of the anti-slide piles, as shown in Figs. 12 and 13.

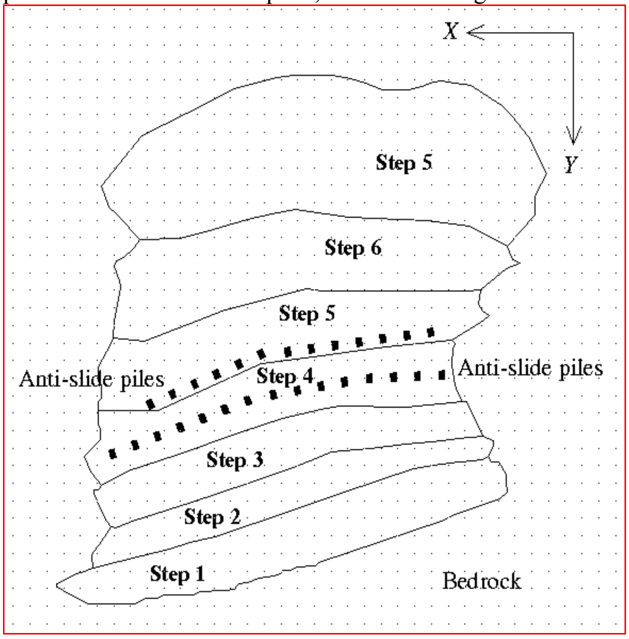


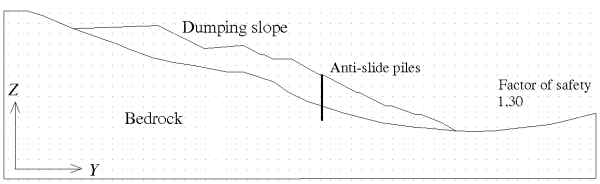
Fig. 12. Schematic diagram of anti-slide pile positions

Considering the project cost, three kinds of reinforcement schemes are proposed and the positions optimization for the anti-slide piles is carried out.

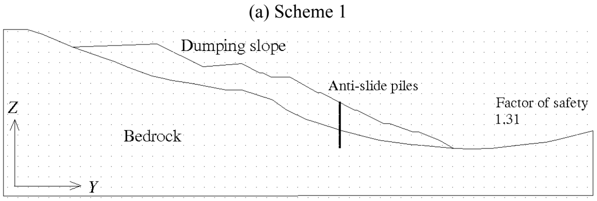
Scheme 1, a row of anti-slide piles are arranged at the foot of Step 5 of the slope; Scheme 2, a row of anti-slide piles are arranged half of Step 4 of the slope; Scheme 3, a row of anti-slide piles are arranged at the foot of Step 5 of the slope , and a row of anti-slide piles are arranged half of Step 4 of the slope, respectively. The anti-slide pile has a rectangular cross section with height of 3 m, width of 2 m, and pile spacing of 6 m. The average length of the pile is 24 m, and the embedded part in the bedrock is 1/3 of the length of the pile. The concrete strength grade of the anti-slide pile is C20. The material parameters of the anti-slide pile in the numerical calculation are listed in Table 2.

Table 2. Calculating parameters of the anti-slide pile

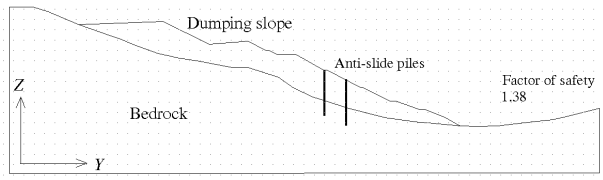
Name	unit weight (kN/m^3)	Elastic modulus (MPa)	Poisson's ratio	Frictional angle (°)	Cohesion (kPa)
Dumping materials	19.8	70	0.35	22	7.1
Bedrock	26.5	120	0.22	50	7000
Anti-slide pile	24.0	22000	0.22	-	-



(a) Scheme 1



(b) Scheme 2



(c) Scheme 3

Fig. 13. Three kinds of schemes for anti-slide piles reinforcement

The overall safety factor, maximum horizontal displacement and maximum shear strain increment of the slope under natural state after anti-slide pile reinforcement are shown in Table 3.

Table 3. Calculating parameters of the anti-slide pile

Scheme	Safety factor	Maximum horizontal displacement (mm)	Maximum shear strain increment (1.0×10^{-2})
No piles	1.21	160	1.84
Scheme 1	1.30	63	1.08
Scheme 2	1.31	107	1.61
Scheme 3	1.38	85	1.13

According to the different schemes in Table 3, comparison of the overall safety factor, the maximum horizontal displacement, and the maximum shear strain increment of the slope after reinforcement of the anti-slide piles, the scheme 3 is used to set up the anti-slide piles to strengthen the dumping slope.

The safety factor increases the most, and the deformation of the dumping slope is relatively small, and the reinforcement effect is the best. It is shown that when the anti-slide piles are used for the slope with the potential landslide mode as the pushing type, in order to obtain the ideal reinforcement effect, it should be considered to set the anti-sliding part of the slope and the main part of the sliding section. The sliding piles not only restrain the occurrence of landslide instability at the source, but also directly constrain the deformation of the dumping slope.

5. Conclusions

To reveal the landslide mechanism and failue mode, the numerical simulation of the step-by-step loading process of the dumping slope in Jinhaili mine was carried out. According to the variation rule of the displacement field and plastic zones in the dumping slope, the stability of the step-shaped slope was analyzed and the reinforcement scheme of the anti-slide piles for the potential sliding part was proposed. The major conclusions are summarized as follows:

(1) During the Step 1 to Step 3 of the slope dumping, the slope deformation is small. But the slope deformation is large and the displacement rate of the slope is faster during the Step 4 to Step 5. After that, the slope deformation tends to be stable. So the Step 5 of the slope is the key part of the potential slip of the slope.

(2) The landslide instability of the dumping slope begins with area D being tension damaged and ends with area C shear failure, forming a load-caused landslide instability mode initiated by area A. The potential landslide path of the slope will be a progressive instability starting from area A, passing through the main sliding area B, and gradually extending to the blocking area C.

(3) The reinforcement effect of the anti-slide piles show that when the slope with the potential landslide mode is the load-caused landslide, the anti-slide piles should be set at the

main sliding area. It not only restrains the occurrence of landslide from the source, but also directly constrains the deformation of the slope.

For the dumping slope in mines, considering the influence factors such as rainfall, earthquake and weak base, the potential slip of the slope during the step-by-step loading process will be further studied in the future.

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