Research Article

Stability Analysis of Dump Slope: Taking Zijinshan Open-Pit Mine as an Example

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1. Introduction

Zijinshan gold and copper mine is located in the territory of Shanghang County, Fujian Province, China, and is one of the newly proven mega non-ferrous metal mining bases in China. The mining area belongs to the mountainous terrain of low and medium mountain erosion, and the mountain system belongs to the southern section of Wuyi Mountain. The mountain trend is north-east, and the terrain is inclined from north-west to south-east. Due to neotectonic movement, Zijinshan mountain is in the uplifting stage, and erosion and other actions have resulted in severe terrain cutting and steep terrain, with numerous deep gullies, canyons, and cliffs reaching over 100 meters, with most slopes concentrated between 25° and 50° [1].

With the continuous expansion of the production scale of Zijinshan open-pit mine and the multi-phase technical transformation and expansion, the amount of stripping from the open-pit mine is increasing day by day, which should bring huge pressure to the waste dump. Reasonable slope form of the waste dump is the necessary foundation to ensure the safety of the mine. As a typical high steep slope waste dump in China [2], how to carry out safe production under the condition of ensuring the stability of the waste dump has become an important subject.

2. Waste Dump Model

2.1. Geological Overview of the Waste Dump. The north side dump mainly consists of ditch 1# and ditch 2#, and ditch 1# is located in the south central part of the north side dump. The natural topography is made up of a near east-west gully and a south-east gully converging into an east-west gully at the downstream, with a longitudinal extension in the shape of a “Y” and a cross section of the gully in the shape of a “V.” The slopes on both sides are covered by gravelly clay containing Quaternary deposits and residual deposits, and some of the slopes are exposed with strongly weathered bedrock, and the slopes on both sides have a slope gradient of about 20° to 40°, with relatively developed vegetation and stable natural slopes. Ditch #2 is located in the northern part of the north side dump and is a north-east oriented gully with a longitudinal extension of “~” and a cross section of “V,” its downstream gully joins with ditch #1 in Dayanli, and the slope of both sides of the gully is 20°~40°, locally up to 50°. The slopes on both sides of the gully are covered by gravelly powder clay of Quaternary deposit and residual deposit, and the thickness is generally 1.0–2.0 m as revealed by the slope of the hillside road, the local strongly weathered bedrock has exposed the hillside surface, the vegetation is more developed, and the natural slope is stable. At present, ditch 1# and
ditch 2# have been covered by the waste dump, and the waste dump is expanded downstream of the confluence trench of ditch 1# and ditch 2# [3]. The current status of the north side dump is shown in Figure 1.

The survey for the substrate of the waste dump was carried out before the operation of the dump, the waste dump is located in area A of the mine, and according to the survey data, the rock mass of the slope of the quarry consists of medium and coarse-grained granite, medium and fine-grained granite, fine-grained muscovite granite, implosion tuff, implosion conglomerate, ingenite, granite porphyry, etc., among which medium and fine-grained granite occupies the largest proportion and is the most dominant rock mass of the bedrock.

The hydrogeological conditions of the basement of the north side dump are simple, the Quaternary strata are not developed, and the strongly weathered bedrock has been basically exposed at the bottom of the gully and slope section; the groundwater is mainly bedrock weathering fracture water, and the bedrock lithology is mainly granite, implosion conglomerate phyllite, and siltstone, with poor permeability and poor water storage conditions [4].

According to the analysis of engineering survey data, the physical and mechanical parameters of different layers were obtained as shown in Table 1.

2.2. Dumping Sequence. According to the different dumping sequence, the waste dump is divided into single-bench full-stage high dumping method (Figure 2(a)), pressed slope toe multi-stage dumping method (Figure 2(b)), and covered multi-stage dumping method (Figure 2(c)).

Most mines using the single-bench full-stage high dumping method are dumping by track and the topography of the dumping is steep slopes and valleys. The high space utilization rate is achieved through the dispersal of a small and large number of dumps, which has the advantage of a simple dumping process and low dumping operating costs. However, the disadvantages are that the high height of the deposit can lead to safety accidents, resulting in high maintenance costs, and requires good mechanical properties of the bedrock and the discharged bulk rock. This method was used in the early days of the Zijinshan gold and copper mine.

Nowadays, the overburden multi-step earth dumping method is mostly used in Zijinshan, and the comprehensive multi-step earth dumping method combined with the overburden multi-step earth dumping method is used in the local area above +670 m in north side dump [5]. The characteristics of overburden multi-step dump are layered from bottom to top according to the designed step height (this design is 30 m), stacked layer by layer or several steps at the same time for overburden dump, forming the end slope of the dump. These methods are suitable for gentle ground or open hillside terrain where the slope is not too steep, and Zijinshan waste dump is ready for this method after years of development. The advantage is that the discharge of a large amount of waste material in the middle of the mine development can be achieved by stacking and discharging from bottom to top in horizontal layers according to a certain of bench height.

The minimum elevation of the overlaid multi-step earth dumping method in north side dump is +670 m. The current transport road above +670 m will be interrupted with the north-east side of the stope, and the transport road above +670 m +910 m shall be completed in the subsequent process of earth dumping to the boundary, as a road to maintain smooth communication between the upper and lower parts of the dump. The transition section between the stope and the dump will form a comprehensive slope with the lower rock and soil of the upper bulk.

For the expansion of north side dump, it is necessary to form an earth dumping transport road below +670 m. The slope foot dumping method is designed to build embankments, make full use of the road transport system within the earth dumping range below +620 m, build temporary transport roads from +620 m to +460 m, and then extend to the minimum elevation of +450 m of the dump toe pre-loading area. After the foundation treatment at the foot of the slope and the prepressure steps to prevent bottom heave are formed, the overburden multi-step dump or comprehensive multi-step dump is used to discharge soil from the bottom +460 m to +670 m elevation.

The stability of the lower first step should be ensured in the soil dumping operation, which plays an important role in the stability of the whole dump and safe production. In principle, the height of the first step should be controlled and hard rocks should be piled at the same time [6]. When multiple steps discharge soil at the same time, the safety distance of the next step ahead of the upper operation step must be no less than 50 m in the process of discharging soil, and the next platform should be set up to prevent the harm of rolling stones. As the stripping steps of the stope descend, the pile elevation of the dump rises gradually, the rock and soil transportation distance of the upper steps of the stope is far away, and the heavy truck carries the rock and soil down the slope. After entering the closed circle, the deep level rock and soil are usually transported to the dump by the heavy truck. According to the topographic conditions, appropriate dispersion method can be adopted to select a number of upper, middle, and lower scattered dumping unloading sites, so as to achieve the purpose of scattered dumping on the whole, and the end slope of the dumping site is still formed by several steps from bottom to top.

2.3. Waste Dump Design Parameters

2.3.1. Design Parameters. According to Li et al., (1) during dumping, the use of a single bench with one slope at the end is beneficial to the operation, but the height of the step is too large and the stability is lower than that of the multi-step method; (2) during dumping, a single bench with a width of 20 to 30 m will ensure the overall stability of the waste dump and maximize the discharge capacity; (3) the stability requirements of the waste dump can be guaranteed with a single-bench height of around 30 m [7]. According to the
Safety Regulations for Metal and Non-Metal Mines (GB16423-2006) [8] and other regulations, as well as relevant experimental data, the design parameters for the waste dump are as follows:

1. Final deposition elevation of the waste dump ranges from +450 m to +670 m; upper part ranges from +850 m to +910 m;
2. Final bench stacking height is 30 m;
3. Safety platform width should be 30 m for layered deposite in the waste dump;
4. Maximum possible distance is 5 m for waste rock rolling down the slope of the bench;
5. Overall slope angle is 23°, single bench slope angle is 34°.

2.3.2. Volume Calculation. This expansion design aims at the north side dump, which is used in the open-pit mining of Zijinshan gold and copper mine, to make reasonable use of the downstream and upper elevation to carry out the work. According to the calculation based on topographic map and dump planning map, the main elevation of the downstream expansion of north side dump is between +450 m and +670 m. After optimization and adjustment of parameters, the effective volume of the dump is 79.9667 million m$^3$. The elevation of the upper part of north side dump is mainly between +850 m and +910 m. After optimization and adjustment of parameters, the effective volume of soil discharge is 31.118,900 m$^3$, and the effective volume of soil discharge designed for expansion of north side dump is 110,885,600 m$^3$.

The effective volume of the dump is calculated according to the following formula:

$$V = \frac{V_0 K_p}{K_c} \times K_f,$$

where $V_0$ represents solid cubic volume of rock, m$^3$; $K_p$ represents rock looseness coefficient, $K_p = 1.358$; $K_c$ represents dumping settlement coefficient, generally 1.05~1.10.
The rock physical parameters of Zijinshan Gold Copper Mine are selected by referring to the Preliminary Design of Technical Reform Project for Comprehensive Utilization of Resources of Zijinshan Copper Mine of Zijin Mining Group Co. LTD. [9] submitted by China Ruilin Engineering Resources of Zijinshan Copper Mine of Zijin Mining Group Co. LTD. in November 2009.

In the gold mining area, for the gold ore, the weight is 2.39t/m³, Firmness Coefficient ranges from 6 to 10, Angle of Repose is 38°, Loose Coefficient is 1.358. For the surrounding rock, the weight is 2.39t/m³, Firmness Coefficient ranges from 6 to 10, Angle of Repose is 38°, Loose Coefficient is 1.496.

In the copper mining area, for the copper ore, the weight is 2.76t/m³, Firmness Coefficient ranges from 6 to 10, Angle of Repose is 38°, Loose Coefficient is 1.358. For the surrounding rock, the weight is 2.6t/m³, Firmness Coefficient ranges from 6 to 10, Angle of Repose is 38°, Loose Coefficient is 1.358.

The calculation results are shown in Table 2.

### 3. Stability Analysis of Stack Arrangement

According to Jiang and Jia, the formation of the waste dump can be regarded as a filling problem, adding several layers of material step by step and accumulating the displacements, strains, and stresses calculated at each stage to obtain a complete record of the construction loading, thus achieving a description of the deformation damage of the geological body [11]. Due to the fact that most of the existing open-pit mines in Zijinshan are nowadays using the covered multi-stage dumping method, this paper simulates the new discharge bulk model by superimposing it on the bedrock and the old discharge bulk layer according to the current situation of the Zijinshan open-pit mine, and the analysis obtained is as follows.

#### 3.1. Stress Field Analysis

##### 3.1.1. Stress Analysis in the X-Axis Direction

Figures 5(a)–5(e) show the X-axis direction stress clouds on the slopes of the waste dump with increasing sequential overburden layers. It can be seen that due to the increase of the overburden layer and the existence of settlement and shifting slip of the overburden layer, compressive stress distribution in X-axis direction is obvious at the contact surface between the overburden layer and the artificially excavated depression of bedrock, and the stress concentration phenomenon at the corner of bedrock is gradually obvious, the tensile stress of the slope of the overburden layer reaches the maximum value of 46,547.1 Pa when covering the third layer, and the compressive stress reaches the maximum value of 2.46 MPa when covering the fifth layer of soil. The compressive stress reaches a maximum value of 2.46 MPa when the fifth layer is covered.

Figure 6 shows the number of layers of covered soil versus the maximum tensile stress in the X-axis direction. As can be seen from Figure 6, the maximum tensile stress is obtained when the overburden layer reaches the third layer and then starts to decline, indicating that the tensile strength of the bulk on the slope has reached its maximum at this time, and then the phenomenon of slip shifting starts to appear.

Figure 7 shows the number of layers of overburden soil versus the maximum compressive stress in the X-axis direction. It can be seen from Figure 7 that the compressive strength increases more significantly when the overburden layer reaches the second layer, which is due to the consolidation of the soil layer, the rapid increase in compressive strength, and the phenomenon of stress concentration.

#### 3.1.2. Stress Analysis in the Y-Axis Direction

Figures 8(a)–8(e) show the stress in the Y-axis direction of the waste dump with the sequential increasing overlay. From
Figure 3: Waste dump profile.

Figure 4: Side slope modelling drawing.

Figure 5: Continued.
Figure 5: Continued.
Figure 5: Stress cloud in the X-axis direction of the overburden increase.

Figure 6: Maximum tensile stress in the X-axis direction.

Figure 7: Maximum compressive stress in the X-axis direction.
Figure 8: Continued.
the graphs, it can be seen that under the continuous addition of soil cover, a certain range of tensile areas appears from the top to bottom of the bulk slope, and the maximum compressive stress in the $Y$-axis direction is increasing due to gravity. Both tensile and compressive stresses in the overburdened soil slope reach their maximum values by the fifth layer, at 17,612.9 Pa and 4.47 MPa, respectively.

Figure 9 shows the number of layers of cover soil versus the maximum compressive stress in the $Y$-axis direction. Comparing Figures 7–9, it can be seen that the maximum compressive stress in the $X$-axis direction and the maximum compressive stress in the $Y$-axis direction both increase as the number of layers of overburden increases and reach a maximum value when the overburden reaches the fifth layer. The increasing value of compressive stress indicates that the bedrock as well as the consolidated bulk layer has a strong resistance to compression and will produce a certain amount of settlement without collapse.
Figure 10: Maximum tensile stress in the Y-axis direction.

Figure 11: Continued.
Figure 11: Displacement in X-axis direction.
Figure 12: Continued.
Figure 10 shows the number of layers of overburden versus the maximum tensile stress in the Y-axis direction. The maximum tensile stress in the Y-axis direction is much less than the maximum compressive stress, and the maximum tensile stress occurs in the surface layer of the slope of the drainage field. The tensile strength will be greatly improved when the underlying bulk layer is consolidated.

3.2. Displacement Field Analysis. According to Hu, the stability of slopes can be analyzed by comparing the maximum displacement values because the maximum horizontal and vertical displacement values inside the slope can be determined [12].

3.2.1. Displacement in X-Axis Direction. Figures 11(a)–11(e) show the displacement in the X-axis direction of the slope under the condition of continuously increasing the bulk layer. From Figures 11(b)–11(e), it can be seen that the displacement in the X-axis direction of the slope is concentrated in the middle of the slope, which indicates that this area is more likely to be the starting point of sliding, and the sliding potential of the slope gradually increases from the top to...
Table 3: Physical and mechanical parameters of the bulk under the strength reduction method.

| Strength reduction factor | Bulk mechanics parameters | New dispersion layer | Solidified bulk layer |
|--------------------------|--------------------------|----------------------|-----------------------|
|                          | Cohesion $c$ (KPa)       | Internal friction angle $\phi$ (°) | Cohesion $c$ (KPa) | Internal friction angle $\phi$ (°) |
| $F = 1$                  | 21                       | 27                   | 25                    | 28                     |
| $F = 1.2$                | 17.5                     | 23                   | 20.8                  | 24                     |
| $F = 1.4$                | 15                       | 20                   | 17.8                  | 20.8                   |
| $F = 1.6$                | 13.1                     | 17.7                 | 15.6                  | 18.4                   |
| $F = 1.8$                | 11.7                     | 15.8                 | 13.9                  | 16.5                   |
| $F = 1.9$                | 11                       | 15                   | 13.2                  | 15.6                   |

Figure 13: Continued.
the middle of the slope, while the trend from the middle to the bottom of the slope is decreasing. From Figures 11(c)–11(e), it can be found that the top of the slope moved backward due to the settlement generated by the bulk layer. The slope produced a more obvious displacement of 0.920219 m when the bulk is added to the fifth layer, while there is a maximum collapse of 0.427 m when the bulk is stacked to the fourth layer.

3.2.2. Displacement in Y-Axis Direction. Figures 12(a)–12(e) show the displacement in the Y-axis direction of the slope under the condition with increasing bulk layer. It can be seen that the displacements in Y-axis direction of the bulk slope of the waste dump all occur at the top of the slope, while the displacements in Y-axis direction of the bedrock are few, indicating that the bedrock is solid. Along with the increase of the overlying soil layer, the displacement in the Y-axis direction also increases. The collapse degree is larger when covering to the fifth soil layer, which is 6.23 m.

4. Slope Stability Analysis

4.1. Calculation Parameters. By using the method of computational non-convergence as a basis [13], the cohesion and the angle of internal friction at each strength reduction factor are obtained for strength reduction factors $F_s = 1.8–1.9$, which produce plastic strain, as shown in Table 3.

4.2. Calculation Results and Analysis

4.2.1. Displacement Field Analysis. Figures 13(a)–13(e) show the displacement in the X-axis direction of the slope under the conditions of different strength reduction factors. It can be observed from the figure that the X-axis direction displacement values of bedrock part are small, but with the continuous reduction of strength coefficient, the area of maximum X-axis direction displacement of slope gradually extends to the direction of the first layer and the second layer. When the strength discounting coefficient is $F_s = 1.8$, the obvious X-axis direction displacement appears in the first layer, the second layer, and the fifth layer, with the increase of strength reduction factor, the displacement in X-axis direction of slope also increases, and when the strength reduction factor $F_s = 1.9$ is reached, the X-axis direction displacement of the first layer increases rapidly to the maximum value and reaches 2 m.

Figures 14(a)–14(e) show the displacement in the Y-axis direction of the slope under the conditions of different strength reduction factors. From the figure, it can be
Figure 14: Continued.
Figure 14: Displacement in the Y-axis direction with different strength reduction factors.
Figure 15: Continued.
observed that the displacement in Y-axis direction is basically similar, respectively, but when the strength reduction factor \( F_s = 1.9 \), the displacement in Y-axis direction at the top of the slope changes abruptly from 6.2 m to 7.1 m, and the displacement in Y-axis direction along the slope face that was not originally present appears on the slope of the first and second bulk, respectively.

4.2.2. Plastic Deformation Analysis. Figures 15(a)–15(e) show the plastic deformation of the waste dump under different strength reduction factors. From the plastic deformation diagram when \( F_s = 1.2 \), it can be seen that the plastic deformation area is located at the foot of the slope of the first layer, the slope angle of the second layer, and the foot of the slope of the fifth layer. When the strength reduction factor \( F_s = 1.6 \) is set, it can be seen from the diagram that the arc-shaped deformation traces start to extend from the slope surface of the first, second, and fifth sides, and the plastic zone is about to penetrate the first step when the strength reduction factor is 1.8. When the strength reduction factor \( F_s \) reaches 1.9, circular plastic deformation occurs inside the slope, and the plastic zone penetrates at this time, so the strength reduction factor is between \( F_s = 1.8 \) and \( F_s = 1.9 \).

5. Security Measures

Since the bedrock is stable, the dump method can meet the demand for waste disposal and safety requirements during mine production. As the top of the slope may settle with the increase in height, compaction of the soil layer should be achieved during the construction operation, and the rule of “first light pressure, then heavy pressure, first slow pressure, then fast pressure, first on both sides, then in the middle” can be adopted, which can
further reduce the porosity of the soil and improve the compactness of the soil layer [14]. Moreover, GPS monitoring technology can be used to monitor the slope of Zijinshan waste dump, which can provide timely changes in slope trends and more detailed and accurate measurement data, so that the stability of the slope can be accurately obtained, and corresponding safety measures can be taken in time, which not only ensures the safety of the mine operation system but also provides an important basis for the in-depth study of geotechnical engineering [15].

6. Conclusion

This paper analyzes the dump method and stability of Zijinshan waste dump and derives the X-axis and Y-axis stress and displacement, X-axis and Y-axis stress, and plastic deformation of the waste dump under different numbers of layers by ANSYS software. Through the stability analysis of the strength reduction factor method, it is known that the direct deposit will cause bottom drum type circular sliding, and the pile load prepressure drainage consolidation engineering treatment measures can be taken to improve the bearing capacity and anti-slip force of the waste dump, so as to realize the safety and stability of the waste dump.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The author declares that there are no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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