Stability and parameter sensitivity of a large-scale waste dump in China

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Abstract. Waste dump stability has long been a major concern in open-pit mine production. This paper describes the landslide morphology in detail, based on a summary of the geological conditions of the Dagushan Waste Dump. The modified Mohr–Coulomb strength criterion, which is more suitable for the deformation and failure behavior of waste materials, was adopted based on the limit equilibrium theory to study waste dump stability under complex working conditions such as dumping, vibration, and basement softening, as well as the parameter sensitivity of the main influencing factors. The test results revealed that: (1) the safety factor of the Dagushan Waste Dump first decreased from 1.343 to 1.238 when the waste dump increased from +150 m to +201 m. Thereafter, it decreased from 1.238 to 1.129 because of the weakened basement of silty clay. Afterward, it decreased from 1.129 to 1.029 because of the toe excavation of the waste dump. Finally, the mechanical vibration at the slope toe made the safety factor of the waste dump change periodically every 6 s. The lowest safety factor of the waste dump under mechanical vibration was 0.747, which can eventually result in landslides. (2) The dump stability was moderately sensitive to the third-grade slope angle, basement cohesion, and mechanical vibration strength; however, it was highly sensitive to the third-grade slope height, basement friction angle, basement moisture content, and first-grade slope excavation angle. The dump stability decreased with an increase in the third-grade slope height and angle, basement moisture content, first-grade slope excavation angle, and mechanical vibration strength. The dump stability increased as the basement friction angle and basement cohesion increased. (3) Slope reshaping is proposed as a remedial measure because it was discovered to be effective in maintaining slope stability. These results can be used as a reference point for further dump stability studies.

Keywords: Stability; parameter sensitivity; landslide; waste dump; limit equilibrium theory
1 Introduction

Mineral resource development has contributed significantly to national economic development and the improvement of people’s living standards. At the same time, mining wastes will inevitably be produced, resulting in waste dumps \cite{1, 2}. A waste dump is a large, loose man-made slope that is used for storing stripping topsoil and mining waste rocks \cite{3, 4}. Since waste dumps are made up of loose topsoil and waste rocks, their shear strength is relatively low, making landslides a common occurrence \cite{5, 6}. In recent years, landslides of different scales have occurred in many open-pit mine waste dumps, such as Dagushan iron ore \cite{7}, Basundhara coal mine \cite{8}, and “South Field” lignite mine \cite{9}, resulting in various economic losses and even casualties. Waste dump stability has always been a major concern in open-pit mines.

Many scholars have conducted extensive research on the deformation characteristics, landslide mechanism, and stability of dumps under complex conditions using model tests and numerical simulations, with positive results \cite{10, 11}. J. Adamczyk used the waste dump of the Osilik II mining area as a research subject, designed the final geometry of the waste dump in combination with the current state, and verified its stability \cite{12}. I. Ogbonnaya and C. Chidinma used laboratory tests to analyze the material composition, permeability, shear strength, and stability of the Enyigba mine dump and proposed corresponding preventive and control measures \cite{13}. P. K. Behera used the limit equilibrium method to analyze the stability of the dump in the Talcher Coalfield, concluding that rainfall infiltration is the main cause of the dump landslide and proposing a series of disposal plans \cite{14}. S. W. Sloan used numerical simulation to determine the stability and failure of a dump slope with a weak interlayer \cite{15}. L. Han investigated the relationship between waste dump stability and the mechanical structure of the waste dump base, obtaining the criteria for self-locking and unlocking the waste dump base and proposing an optimization scheme for the waste dump structure and stability \cite{16}. J. Wang analyzed the influence of groundwater infiltration into the soft loess layer on dump stability and concluded that the dump deformation mode was the integral sliding along the interface between the muddy and natural loess \cite{17}. G. H. Huang used the Fast Lagrangian Analysis of Continua in three dimensions (FLAC3D) fluid-structure coupling module to analyze the stability of dump slopes under four different types of heavy rainfall conditions and obtained the rainfall intensity and duration of the dump critical landslides \cite{18}. J. C. Wang and C. Chen concluded that double-wedge failure occurred along the internal cracks of soft waste soil foundation using three-dimensional numerical inversion model tests \cite{19}.

Currently, limit equilibrium, numerical simulation, and geomechanical model test methods are widely used to determine dump stability \cite{20-24}. The Mohr–Coulomb
strength criterion is generally used in the limit equilibrium method to determine dump stability, and it states the ultimate shear stress of the material increases linearly as the normal stress increases, with no upper limit \[25\]. In practical engineering, when the normal stress increases to a certain extent, the ultimate shear stress growth rate of waste dumps becomes slow or even stops, indicating that the deformation behavior of waste dumps does not completely obey the Mohr–Coulomb strength criterion. The normal stress of the upper and lower elements of waste dumps is quite different, particularly for large and high dumps, and thus, there are great limitations in using the Mohr–Coulomb strength criterion to calculate the safety factor of dumps.

Herein, a large-scale landslide of an abandoned waste dump at the Dagushan iron mine is described. The modified Mohr–Coulomb strength criterion, which is more suitable for the deformation and failure behavior of waste materials, was adopted based on the limit equilibrium theory to study the stability of waste dumps under complex working conditions such as dumping, vibration, and basement softening, as well as the parameter sensitivity of the main influencing factors. Thereafter, the appropriate remedial scheme for the Dagushan Waste Dump and the stabilization of the sliding area is described. The following are the objectives of this paper: (1) to provide a brief introduction of the landslide and geological conditions of the study area, (2) to reveal the stability and parameter sensitivity of waste dumps under complex working conditions, and (3) to recommend appropriate remedial measures for landslide stabilization.

2 Landslide and engineering geology

2.1 Description of the landslide

The Dagushan iron mine is one of the largest open-pit mines in China, and it is operated by ANSTEEL (China Metallurgical Mine Corporation). Operations at the Dagushan iron mine first commenced in 1916. A total of 255 Mt of iron ore was produced, and 447 Mt of overburden and interbedded waste materials was excavated with an average stripping ratio of 1.753 until the end of 2005. The mine currently covers an area of 10.6 km² and reaches a depth of more than 400 m. It produces 7 Mt of iron ore annually. The ore is exposed by removing the overburden using the semicontinuous mining method. The Dagushan Waste Dump is an external waste dump of the Dagushan iron mine, and it is located in Dagushan town, 12 km southeast of Anshan city in Liaoning Province, as shown in Fig. 1. The slope height is between 113 and 137 m. The usage of the external waste dump in the Dagushan iron mine began in the 1950s, and railway dumping ceased in the 1970s. The external waste dump was abandoned and reclaimed after the upper car dumping ceased operations in 2007.
At 7:50 a.m. on November 12, 2014, a small-scale failure occurred at the plant beneath the waste dump. The ground surface shifted upward and moved toward the northwest. Thereafter, a large-scale failure occurred, and it was accompanied by a flow of materials outside the dump boundary, which resulted in the burying of trees and the inclination of telegraph poles. The sliding mass is about 550 m long and 890 m wide, with an overall volume of about 7 million cubic meters and a plane area of about 338000 m². It is a large-scale landslide. The elevation of the front edge of the landslide is about 64–80 m, the elevation of the back edge is about 193–201 m, and the slope height is about 113–137 m. The landslide characteristics are shown in Fig. 2. (1) The entire landslide body is shaped like a round chair, the front and back of the landslide form platforms, the slope is gentle with an angle of 10°–12°, the middle part is slightly steep with a slope angle of about 18°–25°, and the back wall is steep with a slope angle of 35°–51°. The main sliding direction of the landslide differs on the east and west sides; it is northwest on the west side and northeast 15°–30° on the east side. The landslide surface is uneven, various cracks are developed, the distribution characteristics are visible, and the front and rear edges have concentrated cracks because of the topography of the dump basement and the multiple sequences of the landslide. (2) The back wall of the landslide is arc-shaped, with circular tensile cracks developing at the back edge and 162-m-long cracks at the top of the slope. Dump gravels make up the majority of the back wall stratum, which has gneiss, granite, lean ore, and a small amount of weathering stripping material as the primary material sources. Two steps are formed on the back wall, the main step is about 175–200 m in elevation, the inclination angle is about 35°–51°, and the length is about 710 m. The secondary step is on the southeast side of the main step, with an elevation of 188–200 m, an inclination angle of 36°–42°, and a length of about 250 m. The back wall of the landslide has a steep slope. The west wall of the landslide is affected by traction, and
there is no noticeable steep wall. The east side wall of the landslide is about 280 m long, and it is higher in the south and lower in the north, with an elevation difference of 21 m. The shape of the east side wall is affected by the steps of the dump, and the upper part is a zigzag line with a slope angle of about 33°–45°. (3) The landslide tongue is serrated. The main material compositions of the landslide tongue include the original dump gravel, silty clay and sand layers at the base, and buildings on the ground. The shear outlet of the landslide is 15–30 m away from the slope toe of the original dump. The shear outlet is uplifted, the overturning phenomenon is visible, and the surface is noticeably higher than the original ground elevation. At the shear outlet, there is spalling cohesive soil and gravel sand. After the landslide is sheared out, there is a secondary northward movement, and the horizontal movement distance of the front edge is more than 100 m. (4) There are three types of cracks in the landslide area based on the different stress and deformation characteristics: tension cracks, shear cracks, and bulging cracks. The most common fracture type in this area is the tension fracture. It is mainly located on the top of the 124–134 m platform and the back edge of the dump, roughly parallel to the landslide wall and along the landslide boundary. Shear cracks are generally located in the middle and lower parts of landslides. They have high density and short extension lengths. The visible opening on the surface is generally about 0.2–0.5 m, the spacing is generally about 1.1–3.5 m, and the local sections are dense. The extension length is generally about 5–38 m. The fractures generally strike straight and parallel to the main sliding direction, and they intersect. Most of the bulging cracks are located on the front edge of the landslide and are caused by internal compression of the rock and soil. The number of visible bulging cracks on the surface is small, and the opening is about 1.6 m, which is in the form of continuous extension. There are many secondary pinnate or small branched fractures on both sides of the main cracks.
Fig. 2. Landslide characteristics: (a) landslide panoramic view, (b) tension cracks, (c) posterior wall, (d) transverse cracks, (e) ruined railway sleeper, (f) broken track, (g) fallen trees, (h) buried equipment and factory, and (i) landslide tongue.

2.2 Engineering geology

The Dagushan dump is located in the south wing of the Huanglingzi–Wujiaoyao syncline, which is composed of Middle Lower Cambrian, Sinian, Qingbaikou Nanfen, and Diaoyutai formations. There are many north-northeast (NNE)- and north-northwest (NNW)-trending faults in the south wing of the syncline. The terrain is high in the south and low in the north, with round gravel and silty clay deposited in the north piedmont plain. The height difference between the north and the south is 100 m, creating favorable conditions for the development of the landslide. On the south side of the waste dump, there is a tailing pond, and on the north side, from west to east, there are many small industrial plants, the Huanglingzi village, cement plants, high voltage lines, and other facilities.

The stratum of the site is mainly composed of gravel, silty clay, gravel sand, and bedrock, and the bedrock is composed of limestone, sandstone, and granite. The upper dump gravel has the following characteristics: variegated, angular, uneven, loose, slightly wet, and various particle sizes. The maximum particle size is greater than 25 cm, and the original rock is mainly composed of granite, gneiss, phyllite, pore filling gneiss, and phyllite weathering debris. This layer is thick and loose, and it mainly forms the
The lower original stratum mainly includes a silty clay layer, gravel sand layer, and bedrock. The silty clay has the following characteristics: yellowish-brown color, saturated, plastic state, and a small amount of iron-manganese nodules. The round gravel has the following characteristics: yellowish-brown color, slightly to moderately dense, saturated, subangular, a general particle size of 2–20 mm, accounting for about 60% of the total, and a maximum particle size of about 45 mm. It is interbedded with medium-coarse sand and cohesive soil, which is mainly composed of sandstone and granite. The limestone has the following characteristics: gray color, a cryptocrystalline structure, a massive structure, hard rock, and a columnar core. The sandstone has the following characteristics: gray-white to flesh red color, a clastic structure, a thick-layered structure, siliceous cementation, tight cementation, and a columnar core. The grain mineral composition is mainly quartz and feldspar. The rock fracture is developed, and part of the fracture surface is attached with iron.

The rock–soil body of the Dagushan Concentrator is mainly composed of silty clay and a thin layer of round gravel, according to the quaternary system distribution. The landslide area is composed of upper silty clay and lower round gravel layers. The central part of the Huanglingzi village is mainly composed of round gravels. Silty clay is distributed on the east and west sides of the Huanglingzi village. In terms of bedrock and structural factors, the landslide area and the Huanglingzi village are composed of sandstone, limestone, shale, and other sedimentary rocks, whereas the Dagushan Concentrator is mainly composed of granite. Similar to the south wing of the syncline, the south side of the Huanglingzi village was eroded, forming Qianshan alluvial deposits and groundwater outlets.

3 Stability analysis

3.1 Calculation method

(1) Limit equilibrium theory

The limit equilibrium theory is one of the most classical methods for calculating slope stability. It is a method for determining the stability of the current state by comparing the stress parameters of the current state to those of the limit equilibrium state. The rigid body limit equilibrium method is the most commonly used. As shown in Fig. 3, the polygon, \(ABDEGH\), represents a waste dump slope, and the circular arc \((CF)\) represents a potential sliding surface inside the waste dump.
This method has the following assumptions: (I) the material obeys the Mohr–Coulomb shear strength criterion, (II) the failure of the slope is assumed to be the circular arc, (III) there is no interaction force between each strip, and (IV) the safety factor is calculated using the balance of force or moment in the horizontal direction. The specific calculation formula is as follows:

\[
F_s = \frac{M_c + M_f}{M_o} = \frac{cL + \sum_{i=1}^{n} w_i \cos \alpha_i}{\sum_{i=1}^{n} w_i \sin \alpha_i},
\]

where \( \alpha_i \) is the angle between the sliding surface and the horizontal direction of block \( i \), \( W_i \) is the weight of each block, and \( L \) is the arc length of the shear plane.

(2) Improved limit equilibrium method

In the traditional limit equilibrium method, the material is assumed to obey the Mohr–Coulomb shear strength criterion. According to a large number of field tests and numerical simulation tests, the shear strength of bulk materials in the waste dump does not completely follow the Mohr–Coulomb strength criterion. When the maximum principal stress is low, the shear stress increases linearly as the maximum principal stress increases, and it obeys the Mohr–Coulomb strength criterion. When the maximum principal stress is high, the growth rate of the shear stress becomes slow or even stops. The normal stress of the upper and lower elements of waste dumps is quite different, particularly for large and high dumps; therefore, there are great limitations in using the Mohr–Coulomb strength criterion to calculate the safety factor of dumps. For the above reasons, the exponential strength criterion is proposed to study waste dump stability under complex working conditions. This criterion is more suitable for the deformation and failure behavior of waste materials (see formula 2).

\[
\tau = A(\sigma)^B + C,
\]

where \( \tau \) is the shearing stress, \( \sigma \) is the maximum principal stress, and \( A \) and \( B \) are
the material constants. Therefore, the safety factor calculation formula in formula 2 can be improved to the following formula (see formula 3).

\[
F_s = \frac{M}{M_o} = \frac{cL + \sum_{i=1}^{n} A(w_i \cos \alpha_i)^n}{\sum_{i=1}^{n} w_i \sin \alpha_i}, \quad (3)
\]

The stability analysis was carried out using the GeoStudio software, which is based on the limit equilibrium theory. The software can calculate the safety factor of slopes using common strength models, such as Mohr–Coulomb, Hoek–Brown, and strain–softening, and also by customizing the strength model, which can match the stability and parameter sensitivity analyses.

3.2 Model and parameters

As shown in Fig. 4, the representative geological section before the landslide was selected as the research object based on the research results of the rock and soil partition characteristics of the dump. The total slope is about 201.2 m high, and it contains three slopes with different elevations: the first-grade slope is 29.6 m high with a slope angle of 37°, the second-grade slope is 48.6 m high with a slope angle of 32°, and the third-grade slope is 41.8 m high with a slope angle of 35°. The geomaterials include waste materials, silty clay, rounded gravels, limestone, and tailings.

According to the analysis results of the slope instability factors, combined with the dumping process and landslide sequence of the Dagushan dump, the dump stability analysis can be divided into the following six different working conditions based on the time sequence (Fig. 5). C1 is the working condition when the second platform dumping is completed, C2 is the working condition when the dumping reaches an elevation of +175 m, C3 is the working condition when the dump is completed, C4 is the working condition when the silty clay of the dump base is softened, C5 is the working condition when the dump slope toe is excavated, and C6 is the working condition corresponding to the mechanical vibration at the slope foot.
In this calculation, the Auto Locate method of the slope/W software was used to search for the most dangerous sliding surface, and the Morgenstern price method was used to calculate the safety factor. According to the mechanical test and the previous numerical simulation, the shear strength expression of the bulk is

\[
\tau = 1.28 \sigma^{0.27} + 0.56 \quad \text{(unit: MPa)}
\]

because the dump bulk meets the exponential strength criterion. The mechanical parameters of other geotechnical materials in the model that uses the Mohr–Coulomb strength criterion are shown in Tab. 1. Since there is no geological structure on the dump slope generated by artificial dumping in the later stage, the influence of tectonic stress was not considered in the calculation, and only the influence of the gravity field was considered.

**Tab. 1 Physical and mechanical parameters of the materials**

| Geomaterials | Bulk density \( \gamma \) (kN/m\(^3\)) | Cohesion \( c \) (kPa) | Friction angle \( \phi \) (°) |
|---------------|------------------------------------------|------------------------|-----------------------------|
| Round gravel  | 20                                       | 5                      | 33                          |
| Bedrock       | 26                                       | 3000                   | 39                          |
| Tailings      | 23                                       | 0.1                    | 26                          |
| Silty clay    | 22                                       | 33.52                  | 11.43                       |

To study the influence of mechanical vibrations on slope stability, dynamic loading is required. Considering the research background of this study, the
acceleration–time curve of the vibration wave in the concrete batching plant was selected in this study. Additionally, as required in a subsequent study, the reduction was conducted based on the peak acceleration of corresponding intensities to generate the acceleration–time curve. Figure 6 shows the transverse component of the time history curve of the vibration wave, which is calibrated by the filter and baseline to ensure that the integral of the vibration velocity time history is zero. The vibration used in the analysis had a total duration of 6 s, with a time step of 0.02 s, and a value of 0.1 g.

![acceleration curve](image1.png) ![velocity curve](image2.png) ![displacement curve](image3.png)

Fig. 6 Vibration wave used in the analysis

3.3 Stability under complex conditions

Figure 7 shows the change curve of the safety factor of the dump slope under C1–C5 conditions, and $F_S$ is the safety factor. As shown in the figure, the safety factor of the dump slope is reduced by the stacking load at the slope top, the base softening, and the slope toe excavation. The base softening has the highest effect on the dump stability (reducing the safety factor by 0.109), followed by the slope toe excavation (reducing the safety factor by 0.1), and the stacking load at the slope top, which has the smallest effect on the dump stability (reducing the safety factor by 0.066 and 0.039). The above three factors have different mechanisms for reducing dump stability. The stacking load at the slope top reduces the dump slope stability by increasing the sliding force, the base softening reduces the dump slope stability by reducing the shear strength of the base, and the slope toe excavation reduces the dump slope stability by reducing the anti-sliding force.

![Safety factor of the Dagushan Waste Dump](image4.png)

Fig. 7 Safety factor of the Dagushan Waste Dump under different working conditions
To analyze the influence of slope toe vibration on slope stability, the parent term analysis was conducted using the QUAKE software, and the vibration wave was inputted. Figure 8 shows the QUAKE analysis model and displacement boundary conditions adopted in the model. The displacement in the x-direction is fixed on the left and right sides of the model, while the displacements in the x and y directions are fixed on the bottom of the model. The horizontal seismic wave is input as a boundary condition in the blue area at the slope foot.

Figure 9 (a) shows the specific method of setting the displacement boundary conditions. The red and green boundary conditions indicate the fixed displacement in the x, y, or xy directions, and the blue boundary conditions indicate the horizontal seismic wave boundary. As shown in Fig. 9 (b), the “acceleration–time” method was used to input the vibration wave into the model.

Figure 10 shows the variation curve of the dump safety factor at different times of mechanical vibration. The waste dump is at the limit equilibrium state at the start of vibration, and the safety factor is 1.029. In this study, the safety factor of 1.05 was taken as the criterion for slope stability. After the mechanical vibrations lasted for 2.26 s, the waste dump entered a critically unstable state for the first time, with a safety factor of 1.05. The safety factor fell below 1.05 twice, and the corresponding times
were 2.26–3.92 s and 5.2–6.0 s. The minimum safety factor of the waste dump was 0.747, and the corresponding time was 3.06 s.

![Fig. 10 Safety factor of the Dagushan Waste Dump under vibration conditions](image)

As explained in the above C1–C6 analysis, the landslide of the Dagushan Waste Dump was caused by many factors, including top loading, basement softening, toe excavation, and mechanical vibration. First, the safety factor decreased from 1.343 to 1.238 as the waste dump increased from +150 m to +201 m. Thereafter, the weakened basement of silty clay decreased the safety factor from 1.238 to 1.129. Afterward, the toe excavation of the waste dump decreased the safety factor from 1.129 to 1.029. Finally, the mechanical vibration at the slope toe caused the safety factor of the waste dump to change periodically every 6 s. Under mechanical vibration conditions, the minimum safety factor of the waste dump was 0.747, which can eventually result in landslides.

4 Parameter sensitivity analysis

4.1 Geometric factors of the third-grade slope

The height of the third-grade slope ranges from +150 m to +201 m, and the stability analysis was conducted once per 10 m of surcharge load. Assuming all other parameters remained constant, the analysis nodes of the third-grade slope height are +150 m, +160 m, +170 m, +180 m, +190 m, and +201 m. As shown in Fig. 11, when the height of the third-grade slope increases from +150 m to +201 m, the safety factor of the dump slope decreases from 1.343 to 1.238. The dump safety factor is linearly related to the height of the third-grade slope, and the dump safety factor decreases linearly with the height of the third-grade slope. The dump safety factor is indicated by \( y \), and the height of the third-grade slope is indicated by \( x \). The functional relationship between \( y \) and \( x \) is \( y = -0.0021x + 1.6655 \), and the correlation coefficient is \( R^2 = 0.984 \). As the stacking height of the third-grade slope increases by 1 m, the safety factor of the dump decreases by 0.0021.
The third-grade slope angle is 32°, and the sensitivity calculation range in this section is 20°–40°; the interval is 4°. As shown in Fig. 12, as the third-grade slope angle increases from 24° to 32°, the dump safety factor increases from 1.22 to 1.238. As the third-grade slope angle increases from 32° to 40°, the dump safety factor decreases from 1.238 to 1.205. As the third-grade slope angle increases, the dump safety factor increases and subsequently decreases. When the third-grade slope angle is 32°, the dump safety factor has the highest value of 1.238.

4.2 Basement strength

As shown in Fig. 13, when the cohesion of the silty clay increases from 28.5 kPa to 38.5 kPa, the dump safety factor increases from 1.224 to 1.252, and the dump safety factor increases linearly as the cohesion of the silty clay increases. The dump safety factor is indicated by y, and the cohesion of the silty clay is indicated by x. The functional relationship between y and x is $y = 0.0028x + 1.1442$, and the correlation coefficient is $R^2 = 0.998$. 

![Diagram](image-url)
As shown in Fig. 14, when the friction angle of the silty clay increases from 5.5°–17.5°, the dump safety factor increases from 1.045 to 1.433, and the dump safety factor increases linearly with the friction angle of the silty clay. The dump safety factor is indicated by $y$ and the friction angle of the silty clay is indicated by $x$. The functional relationship between $y$ and $x$ is $y = 0.0324x + 0.8665$, and the correlation coefficient is $R^2 = 0.9999$.

In summary, the relationship between the dump safety factor and the base shear strength is shown in Fig. 15. The dump safety factor increases linearly as the cohesion and internal friction angle of the silty clay increase, with increasing rates of 0.0028 kPa and 0.0324°, respectively. They both improve the waste dump stability significantly. From the viewpoint of the slope stress state, an increase in the base strength causes an increase in the friction force of slope sliding along the bottom surface, improving the anti-sliding force of slope sliding and thereby increasing the safety factor.
The increase in the water content of the silty clay due to rainfall is a direct factor of the decrease in the dump base strength. Therefore, it is necessary to study the influence of the water content of silty clay on the dump safety factor. As shown in Fig. 16, when the water content of the silty clay increases from 18% to 28%, the dump safety factor decreases from 1.347 to 1.035. The water content of the dry silty clay is 18%, and the water content of the saturated silty clay is 28%; the water content of the silty clay corresponding to the landslide is 25% following rainfall softening. The dump safety factor decreases as the water content of the silty clay increases. The dump safety factor is indicated by y, and the water content of the silty clay is indicated by x. The functional relationship between y and x is 

\[ y = -8.1165x^2 + 0.5448x + 1.5143 \]

and the correlation coefficient is \( R^2 = 0.9932 \).

4.3 Slope angle of the first-grade dump

The first-grade slope angle of the Dagushan dump before excavation and after
excavation is 22° and 35°, respectively. Therefore, the sensitivity calculation range is within 22°–36°, and the interval is 4°. As shown in Fig. 17, when the first-grade slope angle increases from 22° to 36°, the dump safety factor decreases from 1.238 to 1.126. The dump safety factor decreases as the first-grade slope angle increases, and the relationship between them is an approximate quadratic function. The dump safety factor is indicated by y, and the first-grade slope angle is indicated by x. The functional relationship between y and x is 
\[ y = 0.0004x^2 - 0.0299x + 1.7131 \]
and the correlation coefficient is \( R^2 = 0.9997 \).

![Fig. 17 Safety factor varying curve](image)

### 4.4 Mechanical vibration intensity

To enhance the comparability of the calculation results, the shear strength of the natural silty clay is used in this calculation. Figure 18 shows the dump safety factor variation curve at different times of mechanical vibration. It can be observed that the waste dump is stable at the start of vibration, and the safety factor is 1.238. In this study, the safety factor of 1.05 was used as the criterion for slope stability. The waste dump entered critical instability for the first time with a safety factor of 1.05 after 2.6 s of mechanical vibration. The safety factor fell below 1.05 once, and the corresponding time was 2.6–3.6 s. The minimum safety factor of the waste dump is 0.875, and the corresponding time is 3.04 s.
In this study, the average vibration acceleration was used as an index to measure the mechanical vibration intensity. Figure 19 shows the relationship between the safety factor and the average vibration acceleration of the waste dump. The safety factors of the waste dump decrease rapidly as the average acceleration increases. When the average acceleration reaches 0.041, the waste dump will be at risk of a landslide with a safety factor of 1.05. The dump safety factor is indicated by $y$, and the average vibration acceleration is indicated by $x$. The functional relationship between $y$ and $x$ is $y = 14.42x^2 - 5.15x + 1.2379$, and the correlation coefficient is $R^2 = 0.9997$.

### 4.5 Parameter sensitivity

Multiple factors influence the dump safety factor, and each factor has its individual dimension. The dimensionless treatment of these factors allows for a comprehensive evaluation of the influence of various factors on the slope stability of the dump. The sensitivity coefficient ($I$) is defined as the ratio of the change ratio of stability to that of the influencing factors. The sketch map is shown in Fig. 20, and the calculation formulas are formulas 4–7. A high sensitivity factor indicates that the stability of the dump is greatly affected by the influencing factors, i.e., the degree of
sensitivity is high. The sensitivity coefficient is positive, indicating that an increase in
the influencing factors will enhance the stability of the dump.

\[ y(x) = (y_2 - y_1)/2\Delta x, \]

\[ x_1 = x_0 - \Delta x, \]

\[ x_2 = x_0 + \Delta x, \]

\[ I = \frac{(y_2 - y_1)/y_0}{2\Delta x/x_0} = \frac{x_0(y_2 - y_1)}{y_0(x_2 - x_1)}. \]

When there is a definite functional relationship between the safety factor and the
influencing factors, formula 8 can be used for calculation. Where \( f(x) \) represents the
functional relationship between the influencing factors and the dump safety factor, and
\( x_0 \) represents the value of the influencing factors when the waste dump fails.

\[ I = \frac{x_0}{f(x_0)} \cdot \frac{f(1.05x_0) - f(0.95x_0)}{1.05x_0 - 0.95x_0}. \]

The sensitivity coefficient is classified in Tab. 2 according to its absolute value,
which is divided into four levels: very high, high, medium, and low.

| classification | sensitivity coefficient \(I\) | Sensitivity   |
|----------------|--------------------------------|---------------|
| I              | \(|I| \geq 1\)                  | very high     |
| II             | \(0.2 \leq |I| \leq 1\)               | high          |
| III            | \(0.05 \leq |I| \leq 0.2\)             | moderate      |
| V              | \(0 \leq |I| \leq 0.05\)             | low           |
Tab. 3 shows the sensitivity calculation results of each influencing factor. The dump stability is moderately sensitive to the third-grade slope angle, basement cohesion, the mechanical vibration strength; however, it is highly sensitive to the third-grade slope height, basement friction angle, basement moisture content, and first-grade slope excavation angle. The dump stability decreases with an increase in the third-grade slope height and angle, basement moisture content, first-grade slope excavation angle, and mechanical vibration strength. The dump stability increases as the basement friction angle and basement cohesion increase.

| NO. | Influence factor                  | $x_2 - x_1$ | $y_2 - y_1$ | $x_0$   | $y_0$   | $I$       | Sensitivity |
|-----|----------------------------------|-------------|-------------|---------|---------|-----------|-------------|
| 1   | Height of third-grade slope      | 20.1        | 0.04221     | 201     | 1.238   | -0.341    | high        |
| 2   | Angle of third-grade slope       | 2           | -0.004      | 32      | 1.238   | -0.052    | moderate    |
| 3   | Basement strength                | 3.352       | 0.009       | 33.52   | 1.238   | 0.076     | moderate    |
|     | Cohesion                         | 1.143       | 0.037       | 11.43   | 1.238   | 0.299     | high        |
|     | Friction angle                   | 2.25%       | -0.07       | 22.5%   | 1.238   | -0.565    | high        |
| 4   | Angle of first-grade slope       | 2.2         | -0.027      | 22      | 1.238   | -0.219    | high        |
| 5   | Mechanical vibration intensity   | 0.01        | -0.023      | 0.1     | 1.238   | -0.183    | moderate    |

4.6 Remediation

After the landslide at the Dagushan Waste Dump occurred, the sliding mass migrated to the slope foot, the overall dump slope angle decreased, and the stability improved. A landslide slope under gravity influence is fundamentally a process of localized high ground stress release. During the stress release process, the slope changes from an unstable state to a stable state, and the waste dump following the landslide occurrence is in a stable state. Therefore, slope cutting and shaping measures can meet the stability requirements.

The slope is cut and reshaped from the top to bottom along the landslide boundary, starting from the trailing edge, and the specific implementation measures over the representative geological section are shown in Fig. 21. The slope angle remains less than 35°, and the width of the platform is preserved and suited for mechanical operation. The slope is shaped into three platforms at the trailing edge of the landslide, with elevations of +155 m, +180 m, and +200 m and a width of 12 m. The slope angle
from the +130 m platform to the +200 m platform is 33°. The slope below the +130 m platform and above the +100 m train track platform was 15°–20° originally, and there was lush vegetation on the slope; therefore, no treatment was required.

Fig. 21. Slope reshaping over the slope section

Overall, the slope below the +100 m train track platform slipped. The clay on the slope toe is hunched and shored out. The clay layer pushed architectural structures, vehicles, and building materials 50–100 m northward at the slope toe. A cleanup of the domestic garbage and construction waste at the slope is required. The slope is cut and shaped to maintain a 30° angle and a 20-m-wide train track platform. The current terrain is trimmed to a platform with a high elevation in the middle and a low elevation on both the east and west sides, and the slope is trimmed to a reverse slope with a slope ratio of 2%–3%. A gabion retaining wall with a height of 2 m, a thickness of 2 m, and a burial depth of 1 m are provided at the slope toe.

5 Conclusions

The following conclusions are presented based on the research:

(1) The landslide characteristics and engineering geology of the Dagushan Waste Dump area are described in detail. The leading edge of the landslide in the Dagushan Waste Dump is attached to the silty clay layer at the slope toe, while the trailing edge of the landslide is located at the middle part of the third-grade slope with an elevation of +200 m. The geomaterials in the landslide area mainly include waste materials, silty clay, rounded gravel, limestone, and tailings.

(2) The landslide mechanism of the Dagushan Waste Dump was discovered. First, the safety factor of the Dagushan Waste Dump decreased from 1.343 to 1.238 as the
waste dump increased from +150 m to +201 m. Thereafter, the weakened basement of the silty clay reduced the safety factor from 1.238 to 1.129. Afterward, the toe excavation of the waste dump reduced the safety factor from 1.129 to 1.029. Finally, the mechanical vibration at the slope toe caused the safety factor of the waste dump to change periodically every 6 s. Under mechanical vibration conditions, the minimum safety factor of the waste dump was 0.747, which can eventually result in landslides.

(3) The stability and parameter sensitivity of the waste dump under complex working conditions were analyzed. The dump stability was moderately sensitive to the third-grade slope angle, basement cohesion, and mechanical vibration strength; however, it was highly sensitive to the third-grade slope height, basement friction angle, basement moisture content, and first-grade slope excavation angle. The dump stability decreases with an increase in the third-grade slope height and angle, basement moisture content, first-grade slope excavation angle, and mechanical vibration strength. The dump stability increases as the basement friction angle and basement cohesion increase.

(4) A corresponding remedial measure of dump landslide is proposed. Since the waste dump has basically been stable after landslide occurrence, the remedial measure of slope cutting and reshaping is because it proved to be effective for maintaining slope stability.

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