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Comparison of Discrete element method and Finite element method of waste dump slope failure mechanism in Open Pit Mine

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Abstract
This study determines the mechanical properties, such as cohesion and internal friction angle of the soil-rock mixture waste dump slope at different consolidation pressures of 400 KPa, 800 KPa, and 1600 KPa and analysed the deformation of the slope models. The stability of the slope was analysed by the discrete element method (DEM) PFC2D and the Limit equilibrium method GEO 5. The results show that the hazardous area is not only concentrated on the surface of the waste dump's slope but also in the consolidation pressure of the soil-rock mixture slope, which has the weakest consolidation strength, making it prone to sliding.

Keywords
Waste dump slope; Discrete element method; Finite element method; Failure mechanism

Introduction

Waste dump instability problems have increased steadily worldwide during the last few decades (Hustrulid, 2013;Zevgolis, 2019). With the increased waste generated from open pit mining comes an increased risk of large-scale stability problems. A large-scale failure of the waste dump slope can be disastrous to the operation and the personnel working in the mine (Blight, 2008). Consequently, the precise design of the waste dump slope and its consolidation state has become extremely important, particularly since very small changes in slope consolidation have large economic consequences such as landslides. In 2013, a dump failure at Basundhara mines of the Mahanadi Coalfields Limited (MCL), Odisha, took 14 lives and created problems for the mining industry (Behera, 2016). Generally, failure within the unsaturated waste dump material would involve a circular failure surface (Steiakakis, 2009;Poulsen, 2014). Stability analysis against circular shear failure is typically undertaken using limit equilibrium methods, and the simplicity of such methods has led to the wide use of the technique (Azarafza, 2021). If the soil-rock mixture profile is represented with appropriate strengths, limit equilibrium methods with non-circular failure paths can also be used to study failure paths through the foundation (Chen, 2020). Therefore, the stability of waste dumps has always been a core issue in the safe production of open-pit mines. The stability of a waste dump is mainly affected by the mechanical properties of waste materials, inclination and rock soil properties of the base, dumping technology and dumping height, surface water, and groundwater (Stojadinović, 2013).

Wang summed up the causes of the deformation and settlement of the waste dump slope at the Zaha pit mine through field investigations and clarified the deformation process and failure mechanism of the waste dump slope (Wang, 2019). Li calculated the stability of a dump slope with a weak interlayer by numerical simulation and obtained the failure mode of the dump slope (Li, 2022). Slope stability analysis methods comprise the numerical simulation method, limit equilibrium method, discrete element method, model testing method, and reliability analysis method (Bertrand, 2008;Strelec, 2017;Tyulenev, 2018). The limit equilibrium method requires some basic knowledge of the sliding surface position and ignores the stress-strain relationship of the soil-rock mixture waste dump slope. The base friction test is the most commonly used model testing method (Cuomo, 2019). It can record the deformation and failure process of research Open Pit slope and display the redistributed stress state at each moment. Therefore, the discrete element method and particle flow code (PFC2D) can simulate large deformation and soil-rock mixture waste dump slope failure. Base friction test is widely used in civil engineering because it is simple, quick, intuitive, effective, and of a short experimental period (Wang, 2020).

Sarfarazi and Haeri conducted shear tests on gypsum specimens to investigate the effect of factors on the carrying capacities of discontinuities, such as the number and area of rock bridges on the bearing capacities of discontinuities (Sarfarazi, 2016). As typical discontinuous and highly heterogeneous material, rocks are seriously vulnerable to some stress and fail prematurely under chronic cyclic loading and vibrations. Yaylaci M. simulated the edge and an internal crack problem and an estimation of the stress intensity factor through the finite element method and the stress intensity factor (Yaylaci, 2022). Yalacia also used both the analytical approach and FEM to study the continuous and discontinuous contact difficulties of FG materials (Yaylaci, 2022).

Although various research conducted in this area provides insight into the waste dump stability analysis, they are limited in scope and method. For example, most of the previous research is based on the comparison between the Finite element method or Limit equilibrium method and does not consider the comparison between the Finite element method and the Discrete element method of soil-rock mixture slope at different consolidation pressures. Given this critical gap, this paper aims to investigate the failure mechanism at different consolidation pressures of the soil-rock mixture and evaluate the stability of the waste dump by using the Geo 5 Limit equilibrium method and the discrete element method for future optimization of the waste dump slope. Laboratory tests included consolidation test and direct shear test; the Finite element method (Geo 5) and Discrete element method were used to analyze the deformation of the waste dump. The internal waste dump slope of Xinjiang Tianchi Energy's South Open-pit Mine was taken as the research background to provide a reference for the mine to optimise the waste dump slope, which has essential engineering significance.

Geological Overview of South Open Pit Mine Engineering

Tianchi Energy's South Open Pit Mine is located in the western part of the Dajing Mining area, Zhundong, Coalfield, Xinjiang, China, as shown in Fig. 1(a). The climate of that mining region is dry with a straining season. It is anticipated that from 2021 to 2026, the production of the mine will reach about 30 million tons of coal. The ratio of the volume of loose rock after blasting to the volume before blasting is about 1.2. The ratio of stripping mine is 2.0 m3/t. The soil and rock samples used in this paper were acquired from the inner waste dump, as shown in Fig.1 (b). It is anticipated that after 2025, all waste materials will be accommodated by the internal waste dump. The bench height of the internal waste dump is 180 m, with a width of 30 m and a slope angle of 30°, as shown in Fig. 1(c). Under the existing parameters, the internal waste dump does not meet the dumping requirements after 2025. Therefore, this research is aimed at optimizing the consolidation strength of the internal waste dump to increase its capacity of the waste dump.

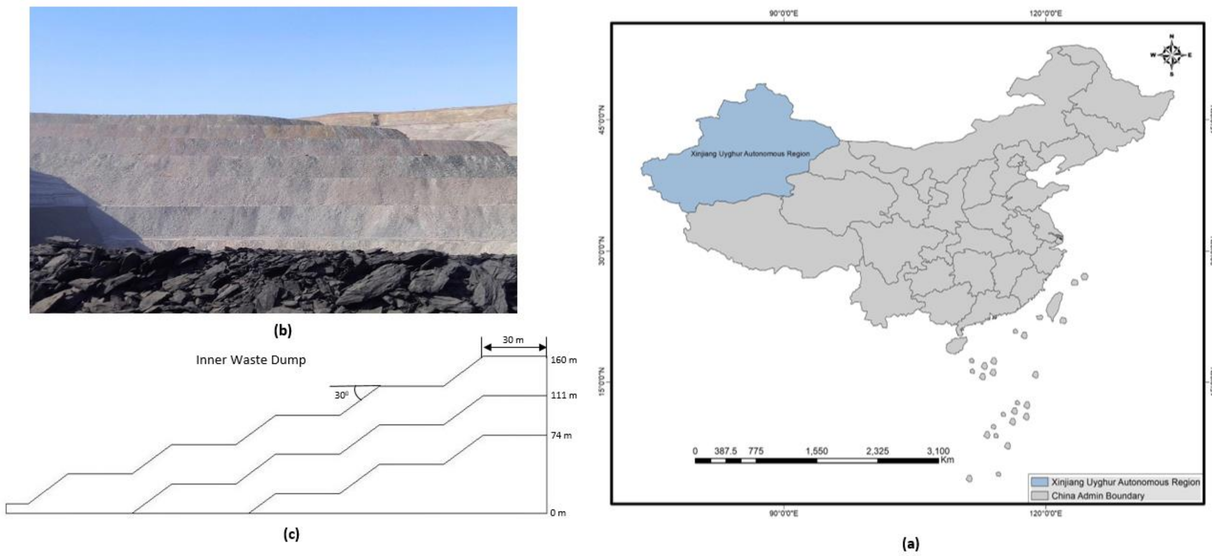

Fig 1. Overview and schematic diagram of south open pit dump (a) South Open Pit Mine Location (b) Mining design in March 2021 (c) section Inner waste dump

Material and Method

Preparation of soil and rock samples: The soil and rock samples used in this work were acquired from Xinjiang Tianchi Coal Mine. For this test, the soil and rock have the same chemical properties. The soil was divided into four different particle sizes, with a maximum particle size of 10 mm. After the soil and rock sampling, samples were packed in plastic bags (Fig. 2), sealed, and stored in the laboratory for future use.

Preparation of experimental samples: Under conditions of size and shape of the soil-rock mixture, samples with different ratios of soil and rock were prepared. In the sample preparation process, the weight of soil and rock was calculated and weighed using an electronic scale. The soil samples with different particle sizes were mixed and consolidated into a cylindrical shape. The state indexes of soil sample particle composition are shown in Tab. 1.

Tab.1. Percentage content of soil samples

Particle size (mm)	0.08	0.16	0.315	0.63	10	Total
Percentage of soil sample	14%	8.5%	11.0%	16.5%	50%	100%
Quantity(g)	84	51	66	99	300	600g

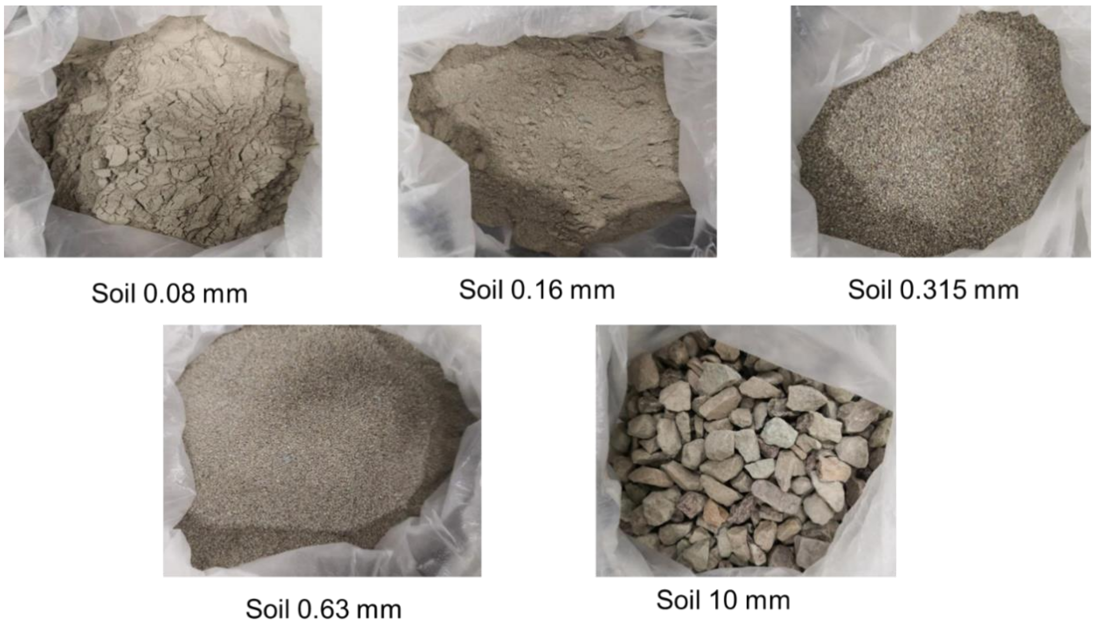

Fig. 2. Soil-rock samples

Mixing and consolidation of samples: For the preparation of soil and rock samples, according to the percentage of experimental materials, the weighed content of soil and rock was put in a bowl. Then, a 15% moisture content was added, after which it was mixed thoroughly to assume uniformity. Finally, the resultant soil-rock mixture was put into a single rod consolidation mould (A). This experiment adopts a fast consolidation method (B). As shown in Fig. 3, the consolidation stresses were found by looking at the material's pressure during the consolidation test. The pressures were C1 (400 KPa), C2 (800 KPa), and C3 (1600 KPa).

Fig. 3. Experimental steps of consolidation

Direct shear apparatus was used for the rapid direct shear test in this experiment because the strength parameters of the soil-rock mixture are completely dependent on the ratio of soil and rock in the shear plane (zone). The soil and rock were randomly distributed in the sample, and the deformation and shear parameters of the soil-rock mixture in the same group may vary greatly. Three samples were taken from each group of C_1, C_2 and C_3 for the direct shear test under the same experimental conditions to ensure reliability and reproducibility. The normal stress applied to each sample group was 50 KPa, 100 KPa, 150 KPa, and 200 KPa, respectively. Normal stress was applied to the sample at the beginning of the experiment. The horizontal thrust was applied when the sample was in a stable state under certain normal stress. The final displacement was recorded during the test when no displacement occurred for each graded load. Under certain shear stress, the test does not stop until the displacement decreases continuously. After the test, the normal stress was unloaded first before the horizontal stress. The failure surface of the soil-rock mixture was cleaned and photographed, as shown in Fig. 4. The test results were processed and analysed. The average values of cohesion and friction angle for each group of samples were determined, as shown in Tab. 2.

Fig. 4. The direct shear test

Tab. 2. The mechanical properties of soil-rock mixture

Samples	Cohesion	Internal friction angle
C1	19.31	23.95
C2	74.35	18.16
C3	46.45	26.72

The criterion of strength and basic failure form of soil-rock mixture

After the soil-rock mixture is consolidated for a long time, the internal pores are compacted due to the compression of loading stress. As the pressure increases, the air and water in the pores are gradually replaced by soil particles.

According to the consolidation theory, the porosity variation of the soil-rock mixture is as follows:

$$\frac{\partial}{\partial t}\left(\frac{e}{1+e}\right)dz = \frac{e}{1+e}\frac{\partial e}{\partial t}dz \tag{1}$$

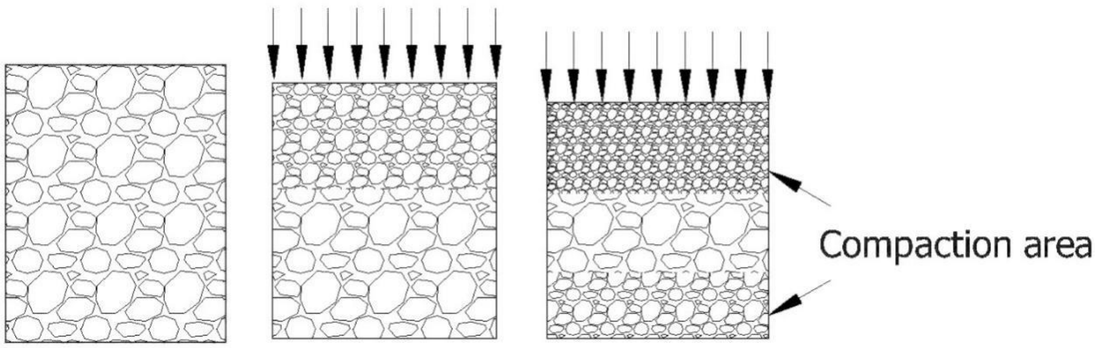

Fig. 5. Changes in meso-structure during the consolidation of soil-rock mixture

In the formula, t is the compression deformation time, e is the average void ratio of loose materials, and z is the depth of the soil-rock mixture.

The change in the void ratio in Fig. 5 shows that the original free pores are filled with dense soil particles. The failure of the soil depends on large shear strength. According to Coulomb's law, the shear strength of soil mainly comes from two aspects: cohesion and internal friction. However, the strength mechanism of soil with different properties is also different. For soil-rock mixture, its shear strength mainly comes from the frictional resistance between particles, which is usually represented by the internal friction angle. Therefore, the shear strength of the shear surface is:

$$\tau = C(1-e) + \sigma \tan\varphi \tag{2}$$

In the formula, φ is the internal friction angle of the soil-rock mixture, τ is the shear strength of KPa and σ the Normal stress.

The resistance parameters of the soil-rock mixture have obvious validity. Mechanical strength and physical parameters vary according to consolidation conditions. Many factors affect the mechanical strength of soil-rock mixture, including the consolidation of a pressurised environment, duration and water content. Therefore, the Factor of safety of the soil-rock mixture waste dump slope is determined by the cohesion and the internal friction angle.

Limit equilibrium method (LEM)

Hoek et al. stated that LEM can be considered a reliable slope design tool and has been the most popular technique used in estimating the stability of slopes in geotechnical engineering (Hoek, 1992). Furthermore, Duncan stated that LEM is used to calculate the shear strength of the ground against some factors causing the shear stresses (Duncan, 2000). In general terms, the factor of safety (FOS) of the slope is described as the ratio of strength to stress load. According to Fleurissen and Cojean, if the FOS is less than 1, the stress exceeds the strength; hence, the slope is unstable. When the FOS is equal to 1, there is an equal chance of failure or stability of the waste dump slope. However, when the FOS is greater than 1, it implies that the strength of the soil-rock mixture exceeds the stress; thus, the waste dump slope is stable. The stability conditions are presented in Tab. 3.

Tab. 3. Stability condition analysis for slope failure

Calculated FOS	Stability Condition	Recommended Action
FOS>1.5	Stable	None
1.0<FOS<1.5	Marginal	Analyze stability rigorously
FOS<1	Unstable	Revise design or stable

The LEM can be combined with the Mohr-Coulomb failure criterion to assess the initiation of the failure waste dump slope. The profile shape of the waste dump is shown in Fig. 1(c), with a slope height of 180 m and a slope Angle of 30°. The two-dimensional profiles established beforehand using AutoCAD were imported into Geo 5 software. The corresponding mechanical properties of the soil-rock mixture slope were assigned to each layer slope, and the inlets and outlets of the slip surface were assumed artificially to carry out calculations to judge the slope stability. In this approach, the FOS is defined as the shear strength of the soil-rock mixture along the potential failure zones. However, the LEM is so fast that it can make multiple calculations of FOS, while the Discrete element method takes a long time to estimate just one FOS.

Strength reduction method

Over the years, Geotechnical engineers started using high-computing software tools and computer codes to analyze waste dump slope stability. The shear strength reduction is the most widely used approach for performing FEM in slope analysis. Hammah et al. conducted a study on the principle of systematical reduction of soil-rock mixture slope by FOS until the deformation was unacceptably high (Hammah, 2005). The factor of safety was the critical state of soil-rock mixture shear strength. Duncan pointed out that the safety factor of slope can be defined as the slope state just at the critical failure of soil shear strength indexes, namely the cohesive force and internal friction angle (C and ϕ) on the degree of reduction (Duncan, 2000). The contact strength and friction coefficient were the important factors employed to determine the FOS of the waste dump slope. Therefore, the contact strength and friction coefficient were reduced at the same time until the waste dump slope reached the critical failure state, at which time the reduction coefficient was the safety coefficient of the waste dump slope. The safety factor (SF) can be defined as:

$$F_s = \frac{cb}{cb'} = \frac{\mu}{\mu'} \tag{3}$$

Where cb and μ were the contact strength and friction coefficient, respectively, between particles when the waste dump slope reached the critical failure state after reduction.

Numerical simulation

Modelling

The discrete element numerical simulation model is generated by many circular or irregular particles with the characteristics of friction coefficient, stiffness and density. When the distance between particles is less than the contact trigger condition, the particles generate contact between themselves. The mechanical properties of the contact particles are determined by the chosen contact model and the parameters of the contact between the particles (Tian Ya, 2022). The meso parameters in DEM were the parameters of particle-to-particle contact, which are different from microscopic and macroscopic parameters. The meso parameters of the contact between particles will eventually be reflected in the macroscopic mechanical properties of the model. The contact of the active state within the boundary conditions determines the macroscopic mechanical performance of the numerical simulation model.

The direct shear test model is used to calibrate the meso parameters between particles, while the slope numerical model is used to simulate progressive deformation of the waste dump slope failure, as shown in Fig. 6 (a). The minimum particle size in the numerical simulation model was set to 0.2 m, the maximum particle size was 2 m, the internal scale ratio was 8.7×10-3, the direct shear test numerical model height was 60 m, and the width was 30 m. In the slope numerical model, the bench height was 30 m, and the total height of the model was (160+H) m.

The stability of the waste dump slope was simulated by PFC 2D. The numerical simulation model is based on the geometry of the dump section. The two-dimensional profiles of waste dumps established beforehand using AutoCAD were imported into FPC2D software with a slope angle of 30º and a dump height of 180 m, as shown in Fig. 6(b). After forming the particle collection, it reached the balance under the self-weight stress. Then, the excess particles were removed according to the shape of the waste dump slope. On the condition that the computer's running speed and calculation accuracy were satisfied, about 42,083 particles were generated for the numerical analysis of the deformation of the waste dump slope model.

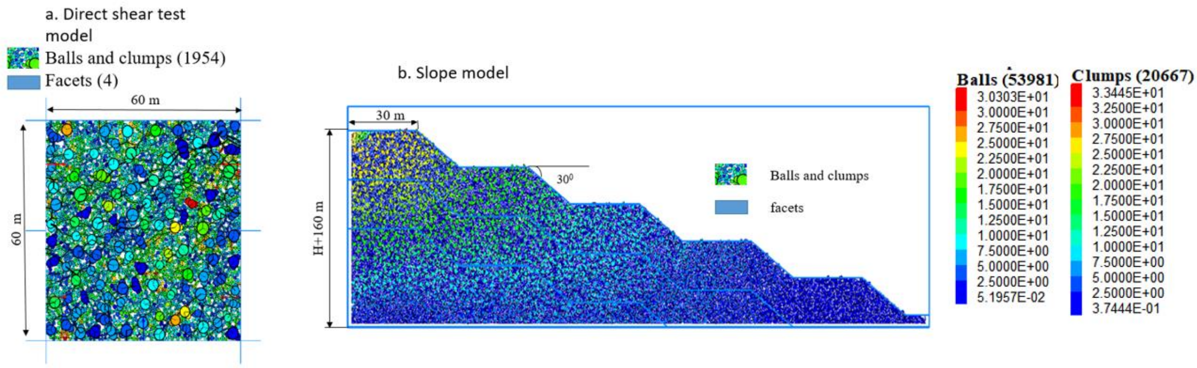

Fig. 6. PFC2D model of waste dump slope

The particle flow method was used to analyze the stability of the dump. After the simulation, the reduction multiple (or gravity increase multiple) of the contact strength and friction coefficient of the particles was the safety factor of the dump. The displacement vector chart can observe the dynamic failure process of the whole dump and the shape and position of the final sliding surface.

The strength reduction method was adopted to ensure that the slope was in a stable state at the beginning of the reduction. According to the stability of the waste dump slope, the reduction coefficient 1.0 was taken as the initial position, the contact strength and friction coefficient were divided by 0.6 at the same time, and the reduction coefficient was gradually increased until the waste dump slope was destroyed.

Relationship between granular meso-parameters and soil-rock mixture macroscopic parameters

The soil-rock mixture waste dump slope is mainly constituted of clay minerals; therefore, the linear contact bond model is selected as the contact model of this kind of rock fill. This study follows the idea of calibrating the meso parameters through the laboratory test curve of the soil-rock mixture using the discrete element method. To study the relationship between the meso-parameters and macroscopic parameters, The Mohr-Coulomb theory was used first to obtain the values of the corresponding mechanical properties of the soil c and y meso-parameters. For the soil-rock mixture direct shear test numerical simulation, the failure stress circles under each confining pressure can be obtained from the peak strength under different confining pressures, from which the cohesive force and internal friction angle of the soil can be obtained. For elastic modulus, corresponding stress-strain range of the tangent to a curve of stress-strain relationship of change over secant computation, usually desirable deviation peak stress varying from 0 to 1/2 or 1/3 that a curve of stress-strain relationship of slope value was taken as a representative of the deformation modulus of soil rock mixture, known as the average modulus of deformation.

In the linear contact bond model, Cb = 400kPa and friction angle μ = 0.5 were used as the criteria to distinguish the intergranular contact intensity. Some research results discussed that particle friction coefficient is the main factor influencing the internal friction angle, and the intensity of contact mainly influences the size of the cohesive force; thus further particle flow code (PFC) model of the slope after the determination of mesoscopic parameters provides the basis (Moussa, 2021). Through different trials and adjustments, the numerical simulation stress-strain curve is fitted with the laboratory test to obtain the meso parameters under different consolidation pressures, as shown in Fig. 7(d). The macroscopic parameters and corresponding microscopic parameters of the slope are shown in Tab. 4 and 5, respectively.

Tab. 4. Macro parameters of soil in each layer

Layer	Cohesion (KPa)	Friction angle (0)	Weight (KN/m^3)	Modulus of elasticity (MPa)	Poison ratio
First layer	19.31	24	19.5	9.5	0.7
Second layer	74.35	18	19.5	9.5	0.7
Third layer	46.46	26	19.5	9.5	0.7

Tab. 5. Microscopic parameters of the soil-rock mixture in each layer

Soil	ρ (Kg/m^3)	$R_{min}(m)$	R_{max}/R_{min}	$Cb(KPa)$	μ	$k_n(N/m)$	k_n/k_s
First layer	2300	0.045	2	400	0.5	4.18	1
Second layer	2300	0.045	2	800	0.5	4.15	1
Third layer	2300	0.045	2	1600	0.5	4.2	1

Results and Discussion

Influence of consolidation pressure

Fig.7 (a), (b) and (c) show the shear strain curve of deviatory stress under different consolidation pressures for different samples respectively (C1), (C2) and (C3), with the increase of consolidation pressure, the shear strength curve becomes steeper, the initial tangential modulus becomes larger, the peak strength continues to increase, the shear strain corresponding to the peak value also increases, and the softening characteristic of the curve becomes more obvious. It is seen that the failure pattern is almost similar under different confining pressures. For Fig. 7 (b), it can be seen that the shear stress curve of 100 KPa at the peak level crosses horizontally the shear stress curve of 150 KPa and 200 KPa, meaning some rocks were broken during the direct shear test simulation.

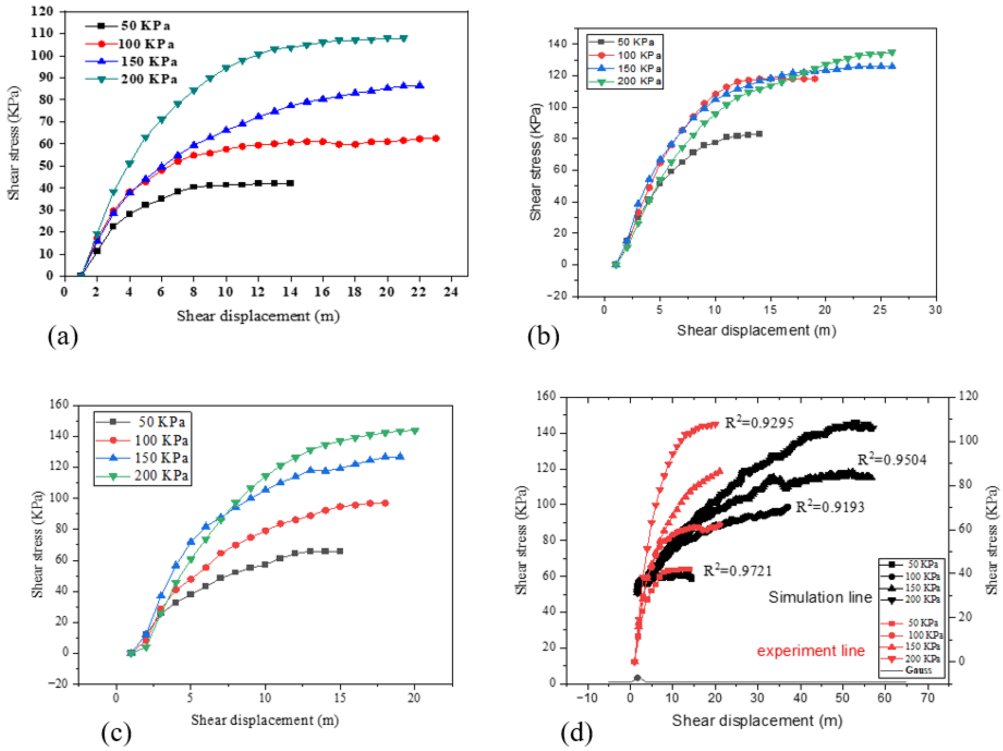

Fig. 7. The stress-shear strain curves of different confining pressures, (a) 400 KPa, (b) 800 KPa, (c) 1600 KPa, (d) laboratory test and simulation of stress-strain curves

Safety stability factor

The displacement of the waste dump slope in the X-direction is shown in Fig. 8. When the calculation time started, the slope deformation was small, then the soil reached its shear strength, the contact connection between particles was broken, and slippage occurred. In the end, the slope deformation increased sharply, and the whole slip occurred. It can be seen from the x-displacement diagram that the slope slide was quite obvious.

Fig. 8. Displacement diagram in the X-direction of dump slope

Fig. 9 shows the displacement cloud map in the Y-direction. It can be seen that the slope had obvious characteristics of bedding landslides. From the cloud map of strain increment in the y-direction, it can be found that the shear strain increment of the weak interlayer was significantly greater than that of the surrounding rock mass.

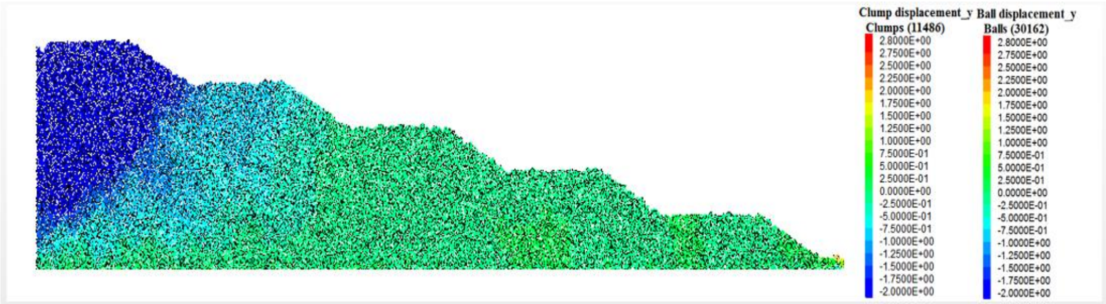

Fig. 9. Displacement diagram in the Y-direction of dump slope

According to the distribution of displacement, in comparison to the original state model of the slope, the slope soil rock mass with large displacement rises. At the same time, the weak layer shear strain concentration also increases. The weak layer appearance significantly increased the length of the shear stress effect. However, it was found that high strain values were from the bottom of the weak layer upwards, which gradually spread and eventually decayed.

Fig. 10 shows the velocity vector diagram. During calculation, the velocity vector in the whole failure of the soil-rock mixture waste dump slope was very large, with the maximum velocity reaching 1.55 m/s, indicating that the failure was in the overall sliding stage. It can be seen from the velocity vector graph that the overall velocity of the failure decreased with a velocity of 7.61×10-5 m /s, indicating that the landslide was stabilised from sliding.

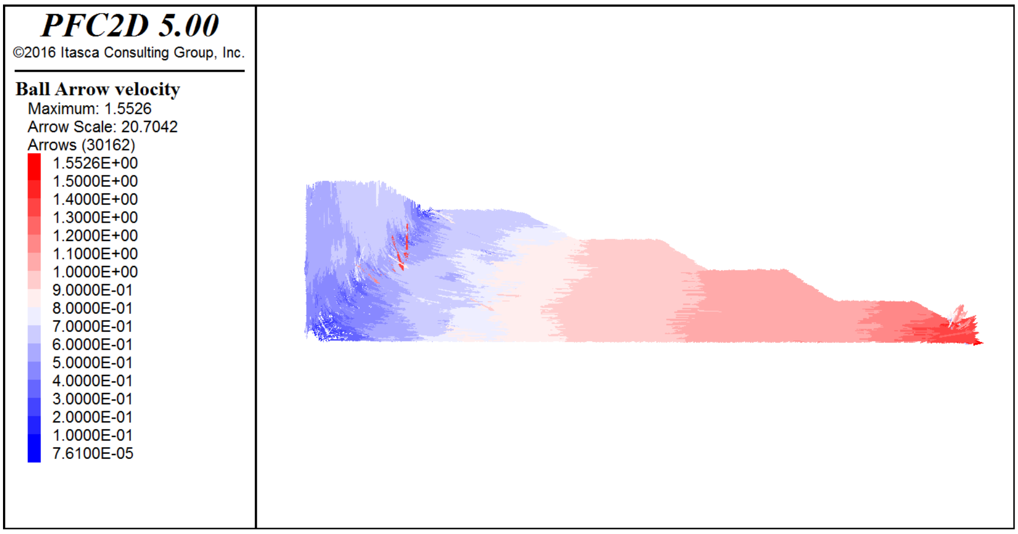

Fig. 10. Displacement velocity vector diagram of dump

When the strength reduction method was adopted, the contact strength and friction coefficient of each layer of soil were reduced simultaneously until the dump was destroyed. When the reduction coefficient was 1.78, the displacement of the dump particles in the x-direction at different steps is shown in Fig. 11.

This paper used Geo 5 for slope stability analysis; the analysis principle adopted is the limit equilibrium method. The software comprehensively reflects all the principles and methods of slope stability analysis (Fellenius-Petterson, Spencer, Janbu, and Bishop), which can better compare the analysis results, comprehensively evaluate the analysis effect of each method, and accurately determine the best stability coefficient. For the stability analysis of the special location with weak layer, fault, water content, etc., the section of the special location can be selected for targeted analysis by the bishop method. The slope stability coefficient of the waste dump is 1.53 under natural conditions, without considering rainfall conditions or seismic conditions, which conform to the safety standard. The location of the corresponding failure surface of the soil-rock mixture slope is shown in Fig. 12.

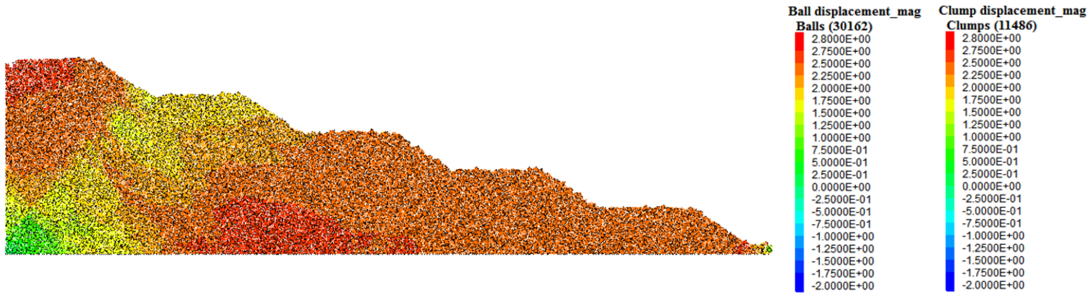

Fig. 11. Strength reduction factor versus maximum displacement

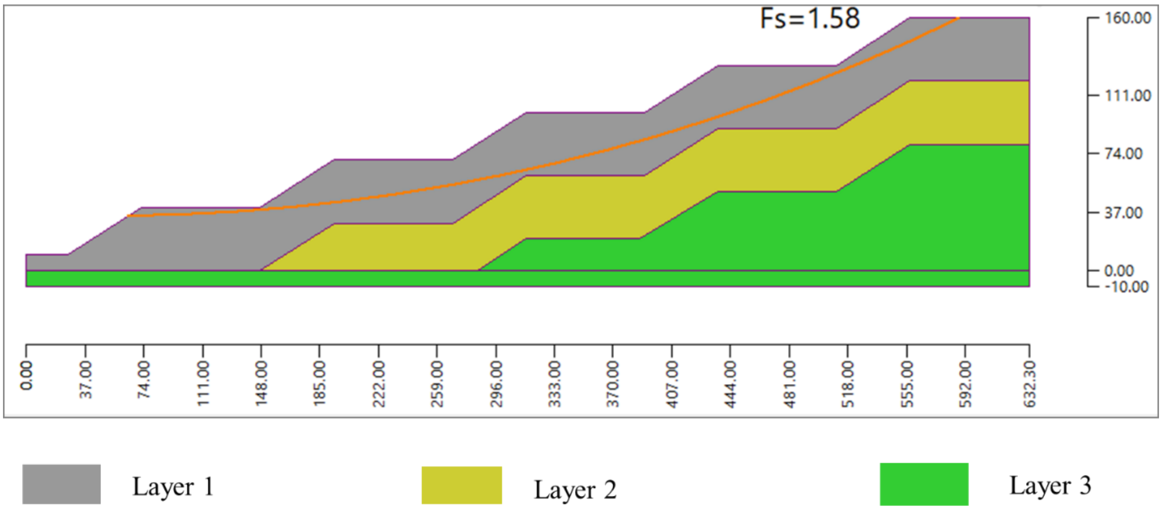

Fig. 12. Waste dump slope stability analysis by Geo 5 section scale (m)

The issue of convenient guidance for comparing Geo 5 and PFC2D slope stability analysis in the presented paper is important because of the need for widespread use. New challenges like this, which are related to slope stability methods (Meng, 2018) or the development of areas of man-made soils (Alkema, 2011), require ongoing discussion in search of optimal solutions that can be quickly applied in the evaluation of safety slope along with scientific research and engineering practice (Duncan, 2000).

It is also important to discuss the numerical simulation method used in this paper, which could have an impact on the safety factor result. The *c-ϕ* reduction method is also implemented in software other than Geo 5, which also uses the Finite Element Method or methods such as the distinct element method and finite difference method (Plaxis, FLAC, UDEC, PFC, and Midas). In certain extremely complex situations, performing calculations using two or more methods and comparing the results may be helpful. Furthermore, at different phases of the identification of geological structures, the outcomes of computations made with different techniques can be applied (e.g. initial slope stability calculations, stability calculations of individual smaller slope portions, stability calculations of the full slope model). One instance of such an approach can be found in the research article on numerical modelling of slope mining in China and worldwide (Zheng, 2022). As numerous studies have demonstrated, analytical approaches can also provide accurate slope stability analysis results in some situations involving slope stability analysis (such as slopes with typical geological characteristics) (Matthews, 2014).

Geotechnical methods are one of the most frequently proposed methods for investigating the stability analysis of waste dump slope which are proposed in the presented calculation scheme. However, the geotechnical engineer should remain prudent when using these tools, as they have their own flaws and "imperfections". For example, (Geertsema, 2006) suggests that thin, weak consolidation layers may trigger landslides. In the case of waste dump slopes, such layers may be responsible for the emergence of predisposed slip surfaces, as presented in the current paper or in (Gupta, 2021). The particle flow simulation of the multi-layer dumping site shows that the instability failure of the dumping site presents a progressive failure. For Multi-layer dumping sites, the safety factors calculated by the particle flow method were quite different from those obtained by the Bishop method. The reason was that the numerical simulation slope model considers the particle contact characteristics of each soil layer to analyse the safety factor of the waste dump slope.

Further work is required to use the PFC3D dimension to study the deformation of the waste dump slope for the optimization of the mine.

Conclusion

The particle flow code 2D (PFC2D) method and the finite element method (Geo 5) were used to analyze the multi-layer waste dump slope stability. The following conclusions were drawn: (1) With the increase of consolidation pressure of soil-rock mixture and contact strength (i.e., viscous waste dump slope), the failure form of the waste dump slope gradually changed to brittle failure. The specific failure form was tensile at the top, shear at the middle, and compressed at the bottom. (2) The safety factor of the waste dump obtained using the discrete element method was higher than the factor of safety given by the simplified Bishop method, which used the method of slices to discretize the soil mass. The waste dump slope was stable both in Geo 5 and PFC2D. (3) The relationship between the cohesion and the consolidation pressure of the soil-rock mixture implies that the cohesion increased exponentially with the consolidation pressure. (4) Based on the stability coefficient of the dumping schemes in the dynamic dumping process, the waste dump discharges layer by layer from the bottom to the upper layer. The dangerous sliding surface is mainly concentrated on the surface of the dump slope. Therefore, in the process of dynamic dumping, attention should be paid to the deformation, settlement, and even slip of surface slope.

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