Case Study

UDEC-based stability analysis of jointed bedding slope and slope parameter optimization suggestions: a case study

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Abstract

The major hazard in open pit mining is ground movement resulting from the instability of the mining slopes. Among the factors that influence slope instability, external loads from earthquake and rainfall are of serious concern. In this paper, the conventional and numerical methods of slope stability study have been used to investigate the stability of the designed mining slopes and subsequent optimization of the slope parameters at Tanjiashan mine in P.R. China. The mine is on a rugged terrain with complex geology having bedded rock strata with highly developed joints. The simulation to understand the stability of the overall slope (before and after mining) was explored using UDEC software by considering four working conditions: natural, natural + earthquake, heavy rainfall, and heavy rainfall + earthquake. Rocscience DIPS software was used for the kinematic feasibility study to determine the failure mechanisms in the slope forming rock masses. SLIDE and SWEDGE software were used to determine the factor of safety for expected sliding and wedge sliding blocks and subsequent optimization of step slope angles in the different slope forming rock masses. It was established that the overall natural slope is stable. However, the overall mining slope is not stable due to the steepness of the step slopes which allow for the bedding planes (planes of weakness) to daylight on the slope faces. The compression shear bi-planar sliding is the potential failure mechanism. The optimization of the step slopes angles by rock formation resolved the instability problem on the overall mining slope.

Keywords Open pit mine · Bedding slope · Slope stability · Slope parameter optimization · UDEC

1 Introduction

Mined slopes in mountainous terrains are usually liable to instability owing to variation in the geology of the slope forming material and external factors induced by the environment such as seismic activities and rain water into the slope. The strength parameters of the slope material and the presence of discontinuities play a significant role in the instability of the mined slopes. Additionally, the geometrical characteristics of mined slopes such as face angle and slope height have also a controlling role in the stability of mined slopes [1].

Several methods of evaluating the stability of slopes have been devised over the years. There are basically four categories of methods that can be applied on slope stability study. The categories include the following: kinematic analysis, limit equilibrium, empirical, and numerical simulation methods.

The reliability of the results of any slope stability study is highly dependent on the choice of the analysis method as well as the software used. Each of the methods available for slope stability analysis has certain merits and demerits; hence, the governing parameters involved in the analysis are key to the selection of these methods [2–4]. Some of the governing parameters include the complexity of

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geological conditions, hydrologic and geometric parameters, purpose of analyzing the stability of the slope, computational capacity and evaluator capabilities. The slope stability analysis methods are briefly described below.

Kinematic analysis uses stereographic projection to predict potential structural failure mechanisms, i.e., planar, wedge, and toppling failures. Kinematic methods have an advantage of being relatively simple in application. However, they only suggest the potential for failure, but do not provide slope stability condition in quantitative terms [5]. Although, these methods are cardinal prior to application of other quantitative methods.

Limit equilibrium methods evaluate the stability of the slope in quantitative terms by factor of safety (FOS) means. The FOS is the ratio of the driving force/moment to the resisting force/moment that act along the sliding planes [6]. This method is used in determining slope structural stability. The results may not be realistic when dealing with complex slopes owing to over simplification due to assumptions made in limit equilibrium methods.

Empirical methods, on the other hand, are often used for preliminary assessment of the engineering behaviors of the rock mass. These methods can be applied over a large area in order to scrutinize the general slope stability condition. For simple uniform planar discontinuity cases, these methods can be directly applied. Although cases which involve variations in the slope geological conditions, such methods cannot be applied [7].

Further, for stability assessment for slopes having complex geology with potential non-planar failure surfaces, *numerical simulation methods* can be applied [4, 8, 9]. Numerical simulation gives insight into the effect of stress distribution in the slope and displacements on its behavior [10]. There are three types of numerical simulation methods which can be applied depending on the complexity of the slope. These methods include the following: continuum, discontinuum, and hybrid methods.

The continuum modeling is applied to rock slopes defined by rock mass which is relatively uniform, such as heavily disintegrated rock mass which may be continuous throughout the slope. The variations in the governing parameters for slope stability analysis can be simulated for static and dynamic conditions. The continuum modeling technique is based on finite element, finite difference, and boundary element methods. The constitutive model, in situ stress, shear strength parameters for surfaces, and groundwater are some of the basic input data required for continuum modeling approach. These methods are suitable for application in weak rock masses where the failure is due to intact rock deformation or due to the discrete stratified discontinuities [4]. Simplifications are needed in defining rock mass as a continuum material, and this

proves to be a major limitation as the final results are highly influenced by such simplifications [11].

Discontinuum modeling technique is mostly suitable for slope stability analysis involving slopes defined by discontinuous rock mass and having a failure mechanism that is controlled by preexisting discontinuities. The movement of intact rock blocks bounded within discontinuities and the deformation of intact rock in discontinuum modeling can be addressed for both dynamic and static conditions [4]. The modeling process input data required include slope geometry, characteristics of discontinuity, shear strength of discontinuity and stiffness, in situ stress and groundwater. Distinct element method and discontinuous deformation analysis are commonly used for discontinuum modeling. The discontinuum method is quite effective in simulating discontinuity behavior and also in the assessment of rock slope stability for given conditions.

The hybrid modeling approach uses both capabilities of continuum and discontinuum methods. The combined effect of strength along the rock joints and the strength of the intact rock between the joints applies to strength of the rock mass in this approach [5]. Complex slope and discontinuity geometry can be considered in hybrid modeling approach. Step-path geometries can be simulated by hybrid finite-discrete element method with fracture propagation approach [4].

Therefore, in this paper, three categories of slope stability analysis from the described four have been used to investigate the stability of the mining slope presented in the design plan for Tanjiashan mine. The techniques used include the numerical simulation method by discontinuum modeling using UDEC software to determine the overall stability of the natural slope before mining and the overall stability of the mining slope (after mining); the kinematic analysis by DIPS software to determine the possible failure mechanisms in the two slope forming rock masses (Qixia and Maokou and Wujiaping); and the limit equilibrium method by means of SLIDE and SWEDGE software to determine the FOS for the expected planar sliding blocks and wedge sliding blocks on step slopes.

UDEC was used in numerical slope stability analysis due to the nature of the slope forming material at Tanjiashan mine which is bedded and highly jointed. This software considers the characteristics and behavior of joints rather than just the physical and mechanical properties of rock mass [12]. Slope failures involving jointed rock mass are controlled by the discontinuities as they tend to reduce the rock mass strength. The orientation of these discontinuities (Strike and Dip) influence the failure modes and potency of sliding [13, 14]. UDEC is also effective in the assessment of rock slope stability analysis under the prevailing conditions (susceptibility to earthquake and high rainfall) at Tanjiashan mine. Further, assumption is needed

in defining rock mass as a continuum material in continuum modeling, but this is not the case in discontinuum modeling with UDEC; intact rock properties and discontinuity properties are input as measured in the laboratory tests [11]. Hence, the stability results from UDEC are highly reliable.

On the other hand, the kinematic analysis by DIPS software and limit equilibrium methods by SLIDE and SWEDGE software were used for the core purpose of establishing the triggering parameters for the slope instability and subsequently rectifying the problem. The kinematic analysis aided the determination of the potential slope failure mechanisms in each slope forming rock formation. Knowing the failure mechanisms helped to identify the triggering parameter for the slope instability (through the general conditions for a particular failure mechanism). The instability was rectified through remodeling of step slopes at various slope angles and calculating the FOS using SLIDE and SWEDGE software for planar and wedge sliding failures, respectively. The subsequent comparison of analysis results was done to choose optimized slope parameters for the proposed design on a more reasonable and reliable quantitative basis. The structure of this article is summarized in Fig. 1 flowchart.

2 Overview of Tanjiashan mine

2.1 Location

Tanjiashan mine is located in Nanjiang County, Bazhong City, Sichuan Province, P.R. China, between north latitudes $32^{\circ}25'15''$ and $32^{\circ}26'30''$ and east longitudes $106^{\circ}43'45''$ and $106^{\circ}46'57''$. The mine sits on Tanjia

mountain and covers an area of 5.69 km^2 . Figures 2 and 3 show the location and topographic maps for Tanjiashan Mine.

2.2 Physiography, rainfall and earthquake intensity

The mining area is located at Tanjia mountain which has a highly rugged topography. This type of topography can be categorized as steep terrain. The elevation ranges from 758 to 1508 m.

There is a small river called Daijia river with water level elevation of 775 m on the north-western end of

Fig. 2 Tanjiashan mine location

Fig. 1 Structure of the article

Fig. 3 Topographic map for Tanjiashan mine

the mining area. The river eventually merges with the Nanjiang river. According to statistics at the mine, during the dry season, the water flow rate in the Daijia river is 0.2 and 0.8 L/s during the wet season. The minimum estimated resource level of the limestone deposit is 800 m, which is higher than the local minimum erosion reference surface of the Daijia river. According to the geotechnical drilling data at the mine, the orebody does not contain any groundwater within the scope of resources.

Further, the topography of the mining area is conducive to the natural excretion of atmospheric precipitation. Based on historical rainfall data at the mine, the maximum daily precipitation is 224.6 mm.

According to the China Earthquake Parameter Zoning Map (GB18306-2001), the peak acceleration of ground motion in the mining area is 0.05g, and the seismic intensity is zone VI [15].

2.3 Geology

The host mountain for the mine is composed of three rock formations of the Paleozoic era; Wujiaping limestone and Qixia and Maokou limestone formations of the Permian period and the Luojiaping Mudstone formation of the Silurian period. The Ore bearing strata include the Qixia and

Maokou limestone formations and the Wujiaping limestone formation. The two formations are steeply inverted, striking between 326° and 349°, and the dip angles range from 44° to 74°. The Qixia and Maokou limestone has a thickness range between 97.39 and 246.09 m, and Wujiaping limestone between 173.0 and 296.7 m. The ore bearing strata are also highly jointed. The stratigraphy for Tanjia mountain in Fig. 4 further describes the rock formations at Tanjiashan mine. Figure 5 shows the section of the natural slope cut at A–A which clearly shows how the rock formations are oriented in respect to the natural slope.

3 Existing problem and objectives

In order to speed up the development of the cement industry, the Nanjiang County Government introduced investment and brought in Bazhong Conch Cement Co., Ltd., for the purpose of producing limestone (for cement production) at the rate of 4 million tons/year at Tanjiashan Mine. The mining of limestone at Tanjiashan mine is done by open pit mining principles. The design parameters being followed in the mining process are as shown in Table 1.

Era	Period	Rock Formation	Code Name	Stratigraphic Column	Thickness (m)	Lithology Description
Paleozoic	Permian	Wujiaping	P ₂ w		173.0 to 296.7	Dark gray to gray thin layers of flint limestone with a small amount of gray medium-thick layer of limestone.
		Qixia and Maokou	P ₁ ^{q+m}		97.39 to 246.09	Light gray to dark gray medium-thick layer to massive limestone (thickness of layers (4–14m)). Upper part is composed of dark gray thick layered limestone intercalated with dolomitic and argillaceous limestone. Middle section is gray thick layered limestone with a small amount of dolomitic limestone and carbonaceous shale. Lower part is dark gray thick layered, intercalated with dolomitic limestone with small amount of argillaceous limestone.
	Silurian	Luojaping	S ₂ ^{Lr}		>173.9	The upper part is light greenish-gray mudstone, the middle and lower part is gray to yellowish-gray silty mudstone

Fig. 4 Stratigraphy of Tanjia mountain

The major problem being faced during the mining process is the instability of the step slopes on the first two benches after commencement of the mining. The instabilities on the step slopes on the two benches do not guarantee continuation of the mining process at Tanjiashan mine, especially with the current design parameters. Step slope failures have continued to happen on first two top benches that have been mined using the current design. This implies that the overall mining slope is also expected to be unstable if mining continues downward with the current design parameters.

Further, the Tanjiashan mining area has a large design scale and is hosted on a mountain that is steep with complex engineering geology. The rock strata are bedded and dips toward and daylight on the slope face, the

joints and fractures are developed, and the cumulative damage effect of production blasting is obvious.

In order to ensure stability of mining slopes in the production process, it is necessary to analyze the stability of mining slopes provided in the existing design and put forward optimization suggestions for the mining slope parameters that guarantee safety during and after the mining process.

Therefore, the main objectives of this research are to remodel the Tanjia slopes in UDEC software, determine the stability status of the overall slope, before and after mining by considering four working conditions (natural, heavy rainfall, natural + earthquake, and heavy rainfall + earthquake), and then determine the reliability of the existing mine design. The second objective is to establish

Fig. 5 Section A–A showing the occurrence of rock formations in respect to the slope

Table 1 Design specifications for slope parameters

Excavation parameters	
Minimum mining elevation	850 m
Bench height	15 m
Step slope angle	60°
Safety berm width	4 m
Clearing platform width	6 m (set every after 1 safety berm)
Overall slope height	230–320 m
Overall slope angle	41.9°

the causes for the slope instabilities under the current design and further propose new optimized slope structure parameters (bench height, berm width, step slope angle, and the overall slope angle) that could guarantee safety during and after the mining of limestone at Tanjiashan mine.

Figure 6 shows step slope failures on the top two benches of Tanjiashan mine that have been mined using the existing design parameters, and Table 1 shows the design specifications of mine slope parameters.

4 Data collection

The data used in this research were collected through; on-site engineering geology supplementary survey and in-door mechanical properties test for rock and rock joint material.

4.1 On-site engineering geology supplementary survey

The on-site survey was limited to engineering geology supplementary survey of slope forming rock masses (Qixia and Maokou and Wujiaping limestone formations). This process involved identifying various factors affecting the stability of high-steep slope in the field, carrying out a detailed investigation of the rock types, material composition and mapping of structural discontinuities. The analysis of mapped data was done with DIPS software. The details of the orientation for the natural slope and dominant joint sets orientations and spacing in the two slope forming rock masses are provided in Table 2.

4.2 Mechanical properties tests for rock and rock joints

The main purpose for these tests was to determine the physical and mechanical indexes of rock mass including

Fig. 6 Instability of mined step slopes at Tanjiashan mine

Table 2 Dominant joint sets orientations and spacing of the studied slope

Formation	Type	Joint set	Dip angle (°)	Dip direction (°)	Spacing (m)
Qixia and Maokou and Wujiaping	Slope	Natural slope	38	044	
Wujiaping	Bedding	J1	49	046	0.5
Qixia and Maokou	Bedding	J2	45	051	6
	Joints	J3	80	076	6
	Joints	J4	75	226	6

density, water absorption rate, saturation coefficient, uniaxial compressive strength, shear strength, cohesive force, internal friction angle, tensile strength, elastic modulus, Poisson's ratio, and cohesive force and internal friction angle of joint material. These indexes provided necessary parameters and conditions for the subsequent slope stability demonstration and numerical simulation calculations. The experiments conducted include rock density and water absorption test, rock uniaxial compression test, rock triaxial strength test and rock joint direct shear test. In order to understand the differences in physical and mechanical properties of rocks under different climatic conditions, the tests were carried out in three states: natural, dry and saturated conditions.

4.2.1 Rock density and water absorption test

The purpose of the rock density and water absorption test was to obtain the basic physical parameters including rock density, water absorption rate and saturation coefficient by determining the volume and weight of the rock in different states. The instruments and equipment used were dryer, scale, Vernier caliper and a suction device.

4.2.2 Rock mechanical properties test

For the rock mechanical properties, two tests including rock uniaxial compression test and triaxial compression test were carried out. Both tests were conducted by means of the Universal Testing Machine (UTM).

The purpose of the uniaxial compression test of rock blocks was to determine the axial and radial strain values of rock specimens under uniaxial compressive stress and obtain the stress-strain relationship, deformation modulus and Poisson's ratio of the rock mass. The tensile strength was calculated as 1/10 of the UCS of rock.

On the other hand, the triaxial test was carried out to find the basis for the shear strength parameters, i.e., internal friction angle and cohesion. The results from the triaxial test were analyzed by RocData software to obtain the friction angle and cohesion.

Based on the experiments carried out, the mechanical properties of the current rock mass are as shown in Table 3.

4.2.3 Direct shear box test

The structural surface plays an important controlling role in the deformation and failure of slopes. A direct shear box test was conducted on the rock joint material samples that

Table 3 Rock strength input parameters

Rock type	State	Density (kg/m ³)	Elastic modulus (GPa)	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Poisson's ratio	Cohesion (MPa)	Internal friction angle
Limestone	Natural	2680	36.3	118.5	5.74	0.263	20.77	47.79
	Saturated	2690	33.3	103.4	4.12	0.267	18.41	46.66

were collected from the site. The test was done under different normal stress state in order to determine the rock structure damage limit shear stress. The shear stress at failure is the shear strength of the rock joint material. Based on Mohr-Coulomb criterion [16], the rock joint material shear strength parameters (angle of internal friction ϕ and cohesion C) were determined.

The assignment of stiffnesses to an interface depends on the way the interface is used. In this case, it is a real joint interface that is soft enough to influence the behavior of the rock mass (i.e., a thin layer of argillaceous limestone). The values for normal and shear stiffnesses for rock joints typically range from roughly 10 to 100 MPa/m for joints with soft material in-filling, to over 100 GPa/m for tight joints in granite and basalt. Published data on stiffness properties for rock joints are limited. However, the summary for the normal and shear stiffness value range for various rock types is found in Bandis et al. (1983) [17]. The joint material normal and shear stiffness values in this paper were determined according to Eq. (1) [18] and Eq. (2) [19], respectively. The calculated joint stiffness values are within the ranges of stiffness for limestone presented in Bandis et al. (1983) [17].

$$K_n = \left[10 \times \max \left[K + \left(\frac{4}{3} \right) G \right] \right] / (\Delta z)_{\min} \quad (1)$$

$$K_s = \frac{K_n}{2(1 + \mu)} \quad (2)$$

where μ , K and G are the Poisson's ratio, bulk and shear moduli, respectively; $(\Delta z)_{\min}$ is the smallest width of an adjoining zone in the normal direction (see Fig. 7), which is 1.0 m for this case.

The max[] notation indicates that the maximum value over all zones adjacent to the joint is to be used (e.g., there may be several materials adjoining the joint).

In UDEC, material models assume an isotropic material behavior in the elastic range described by two elastic constants: bulk modulus, K , and shear modulus, G , which correspond to more fundamental aspects of material behavior. The conversions from Young's modulus, E , and Poisson's ratio to bulk and shear moduli are as shown in Eqs. (3) and (4), respectively [18].

Fig. 7 Zone dimension used in stiffness calculation

$$K = \frac{E}{3(1 - 2\mu)} \quad (3)$$

$$G = \frac{E}{2(1 + \mu)} \quad (4)$$

The mechanical properties for rock joint material are as shown in Table 4.

5 Stability analysis and optimization of mining slope parameters

Having established rock mass mechanical parameters, the stability analysis and optimization of mining slope parameters were carried in four (4) steps.

The first step was to analyze the stability conditions of the overall slope in its natural state and after simulated mining using the design specifications. UDEC software was used to analyze the stability of the slope on three (3) sections (A–A, B–B, C–C) that were cut at 600-m intervals and considering four working conditions. These working conditions include natural, natural + earthquake, heavy rainfall, and heavy rainfall + earthquake.

Table 4 Rock joint material strength input parameters

Material type	State	Density (kg/m ³)	Normal joint stiffness, K_n (GPa)	Shear joint stiffness, K_s (GPa)	Poisson's ratio	Cohesion (MPa)	Internal friction angle
Argillaceous limestone	Natural	1920	40	15	0.263	0.1155	26.74
	Saturated	2040	37	14	0.267	0.304	24.21

The second step was to establish the causes for the slope instability through the kinematic analysis of determining the possible failure mechanisms in the two slope forming material. The kinematic analysis was carried out using DIPS software.

The third step was to establish the stability of the expected sliding blocks and wedge sliding blocks in relation to step slope angles by limit equilibrium methods using SLIDE and SWEDGE software, respectively. The suggestion of optimized slope parameters was done by performing this analysis with different step slope angles till the FOS of 1.2 [10] for open pit mining was met.

The final step was to remodel the overall mining slope with the suggested slope parameters and determine the overall stability of the mining slope.

5.1 UDEC stability analysis of the designed overall mining slope

The three slope sections (A–A, B–B, C–C) were modeled in UDEC version 6.0, and the stability of the natural slope was studied based on the four working conditions. The orebody portion was then mined out using original design parameters, and the stability of the overall mining slope was studied under same four working conditions.

During the modeling, the material model for the deformable blocks adopted the Mohr–Coulomb plasticity model, and the material model of joints was Mohr–Coulomb joints surface contact.

For natural and heavy rainfall conditions, the models were subjected to static boundary conditions (by constraining the two vertical sides of the model with zero velocity in the x-direction (x velocity = 0) and bottom part of the model made fixed with both x and y velocities being equal to zero). The slope was then solved to equilibrium state under gravity loading, and the displacement vectors were noted. The FOS was also calculated under same boundary conditions.

For earthquake simulation, the models were subjected to different boundary conditions after equilibrating the model. This analysis started from the end of static analysis. The viscous dynamic boundary conditions ($xvis$) were input on the two vertical sides of the model to prevent the effect of reflecting waves back into the model. The base of the model was subjected to a velocity time history earthquake wave. The practical 8.0 Wenchuan earthquake [20] record having peak acceleration of 0.05g based on seismic fortification intensity of the mining area was used as input, lasting a period of 5 s. Figures 8, 9, and 10 show the models for the three slope sections (A–A, B–B, C–C) highlighting simulated original design excavation limits, rock formations and orebody limits.

Based on the discrete element software UDEC, the overall stability of the natural slope under the four working conditions of natural, natural + earthquake, heavy rainfall and heavy rainfall + earthquake was analyzed, and the instability mechanism of the bedding rock slope composed of Qixia and Maokou and Wujiaping limestone formations was evaluated. The dip angle of the natural slope ranges between 34° and 38°. After the stability analysis with UDEC, it was established that the natural slope is in an overall stable state. The stability of the natural slope was physically verified during on-site survey, and it was found to be stable.

The orebody was then excavated with the original design parameters (4 m berm width, 6 m cleaning platform, 15 m step height and 60° step slope angle), and the final mining slope formed was mainly located in Wujiaping limestone formation, with a small part of Qixia and Maokou limestone layer at lower elevations. Under the same four working conditions as the natural slope, the stability of the overall mining slope was analyzed in UDEC software. It was established from the analysis results that the overall mining slope would collapse when under the conditions of heavy rainfall and heavy rainfall + earthquake using the existing design parameters. This is because displacement vector results from UDEC show

Fig. 8 Model for section A–A showing simulated original design excavation limit, rock formations and orebody limit

instability of the entire slope region, and the FOS requirement of 1.2 for open pit mining is not met under the two working conditions.

The displacement vector analysis of UDEC gives the magnitude and direction of the displacements of each point in the rock slope. The direction of the displacement vector is a precursor to the development of slope deformation. The direction of displacement vectors for the points in the natural slope is vertically downwards, implying that the natural slope is in a compression stable state. However, the direction of displacement vectors for the points in the mining slope points downwards but tilted toward the slope face. The tilting toward the slope face increases down the slope and toward the overall slope toe. This implies that deformation in the slope is happening and is high near the overall slope toe. Hence, once the slope forming materials reach yield points, failure is expected.

The displacement vector directions of points in the mining slopes create two directions defining the nature of expected failure, which is compression-shear-biplanar sliding. The results of the analysis for the three sections are shown in Figs. 11, 12, 13 and Table 5.

Additionally, the design is unreliable for reasons that, after modeling the slope in UDEC with the prescribed slope parameters as outlined in the design, it was established that the overall mining slope is 48.2° instead of the design specification of 41.9° . The other reason is that the 60° slope angle of the step slopes specified in this design makes the slopes to cut through the Wujiaping bedding planes. The bedding planes daylight on the slope face, satisfying the condition for planar failure to occur, because the exposed layers would become a potential sliding surface.

Fig. 9 Model for section B–B showing simulated original design excavation limit, rock formations and orebody limit

5.2 Kinematic analysis

Since the original design is not reliable, and the overall mining slope exhibit instabilities across the entire slope when under the conditions of heavy rainfall and heavy rainfall + earthquake, it is necessary to establish the real causes for that instability. In doing so, the kinematic analysis was done using DIPS software in order to determine the possible failure mechanisms in the two slope forming material. Knowing the possible failure mechanisms helps in backtracking the real causes for the slope instability.

Having done the kinematic analysis, it was established that the possible failure mechanisms in the two slope forming rock formations are wedge sliding and planar sliding failures for the Qixia and Maokou limestone formation and Wujiaping limestone formation, respectively. The kinematic analysis results of DIPS software are as shown in Figs. 14 and 15.

Based on the kinematic analysis results, in Fig. 14, the zone outside the pit slope, but enclosed by the friction cone represents the zone of wedge sliding. Any plane intersections highlighted by blue dots falling within this zone are unstable. It can be seen from the figure that two wedges formed by J2–J4 and J3–J4 intersections are unstable and have the potential to slide, and therefore, wedge sliding is a problem in Qixia and Maokou rock formation. In Fig. 15, it can be seen that the bigger portion of J1 joint set is overlaid by the daylight envelope; therefore, the risk of planar sliding is high in the Wujiaping rock formation.

The common condition that contribute to the occurrence of wedge sliding failure is that of the dip of the line of intersection for the two discontinuities that make up a wedge, daylighting on the slope face and that it is less than dip of the slope face [21]. The same condition also applies to planar sliding, where failure plane must daylight on the slope face, and its dip must be smaller than the slope face [21].

Fig. 10 Model for section C–C showing simulated original design excavation limit, rock formations and orebody limit

Therefore, it is clear that the Wujiaping formation step slope failures happening at the mine are necessitated by the bedding planes (weakness planes) daylighting on the slope face. Likewise, the wedge failures expected in the Qixia and Maokou formations are due to the discontinuity intersection plane daylighting on the slope face. This was confirmed in the field as the bedding planes were seen daylighting on the slope face and the model in UDEC also confirms the same as shown in Figs. 8, 9 and 10. Hence, the instability problem can be resolved through optimization of the step slope angles in the two slope forming rock masses.

5.3 Optimization of step slope angles

The optimization of step slope angle was done with the aid of limit equilibrium methods of SWEDGE and SLIDE

software programs. The stability of the expected wedge sliding blocks and that of the planar sliding blocks were analyzed with SWEDGE and SLIDE, respectively, in relation to the designed step slope angles. This analysis was done based on the four working conditions including natural, natural + earthquake, heavy rainfall, and heavy rainfall + earthquake. The factor of safety for the sliding blocks in relation to the design step slope angles was recorded.

This analysis was repeated with different step slope angles, and based on comparison of the safety factors that met open pit mining safety factor requirement of 1.2, the optimum step slope angles of Wujiaping limestone and Qixia and Maokou limestone were determined as 51° and 70°, respectively.

For Qixia and Maokou, the stability analysis of expected wedges was done with SWEDGE software, and in the Wujiaping formation, stability analysis was

Fig. 11 Displacement vector analysis results for section A–A with simulated original design excavation under heavy rainfall + earthquake conditions

performed with SLIDE software by taking the dominant bedding plane of 49° dip angle (daylighting on the step slope face) as the potential sliding surface. The results of the two analysis are shown in Fig. 16, Table 6, Fig. 17 and Table 7.

5.4 UDEC stability analysis of the proposed overall mining slope

With the optimized step slope angles of 51° and 70° in the Wujiaping and Qixia and Maokou formations, respectively, but maintaining all the other parameters of the original design, the overall slope angle of the optimized final mining slope is 42.4° . UDEC software was used to analyze the stability of the optimized overall mining slope, and the results show that the stability of

the overall mining slope meets the FOS requirements of open pit mining, and the instability previously seen on the slope surface has been eliminated as direction of displacement vectors for the points in the optimized overall slope are vertically downwards, implying that the optimized overall mining slope is in a compression stable state. The results of the analysis are shown in Figs. 18, 19, 20 and Table 8.

6 Conclusions

The instability of step slopes at Tanjiashan mine was confirmed through analysis as being structurally controlled. Slope failures are expected if the mining of limestone is to continue through implementation of the existing design parameters. The current design is unreliable and

Fig. 12 Displacement vector analysis results for section B–B with simulated original design excavation under heavy rainfall + earthquake conditions

would lead to serious slope instability problems as the mining continues downward. This is because step slope instability is already happening at the mine, and simulation in UDEC also shows that instability of the overall mining slope is expected, with compression shear bi-planar sliding as the failure mechanism.

It has been established in this research that before attempting to optimize the slope structure parameters, it is important to identify the triggering factors for the instability on the particular slope and slope parameter that need to be corrected in order to resolve the instability situation. Therefore, the steepness of the step slopes are the major causes for the instability of the overall mining slope. It has also been concluded that the stability of step slopes have a controlling influence on the stability situation of the overall mining slopes.

Hence, the optimization of step slopes resolved the instability challenges for both step slopes and overall mining slope.

The 60° step slope angle provided in the original design was generalized across the entire slope, regardless of rock formation. This could cause instability of the overall slope across the entire slope region when under the conditions of heavy rainfall and heavy rainfall + earthquake. Hence, optimized step slope angles have been proposed based on lithology as 51° and 70° for Wujiaping and Qixia and Maokou formations, respectively. The optimized overall slope angle is 42.4°. The stability of the optimized overall slope was analyzed in UDEC, and the slope was found to be stable and it guarantees safety of the mining process. Table 9 shows the original and proposed optimized mining slope parameters.

Fig. 13 Displacement vector analysis results for section C–C with simulated original design excavation under heavy rainfall + earthquake conditions

Table 5 Summary of displacements and FOS values for the design mine slope in the three analysis sections under different working conditions

Slope type	Profile section →	A–A		B–B		C–C	
	Parameter →	Max displace-	FOS	Max displace-	FOS	Max displace-	FOS
	State ↓	ment (cm)		ment (cm)		ment (cm)	
Natural slope	Natural	1.1	1.55	1.3	1.42	0.9	1.48
	Natural + earthquake	1.3	1.49	1.4	1.37	1.1	1.42
	Heavy rainfall	2.5	1.31	2.8	1.28	2.1	1.31
	Heavy rainfall + earthquake	3.2	1.23	3.5	1.19*	2.7	1.22
Original design slope	Natural	5.2	1.47	10.5	1.36	6.6	1.40
	Natural + earthquake	5.2	1.40	10.5	1.31	6.6	1.34
	Heavy rainfall	8.4	1.26	11.7	1.15*	8.6	1.20
	Heavy rainfall + earthquake	11.4	1.19*	11.7	1.10*	10.8	1.13*

*FOS values do not meet open pit mining FOS requirements of 1.2

Fig. 14 Kinematic analysis results for wedge sliding analysis in Qixia and Maokou limestone formation

Fig. 15 Kinematic analysis results for planar sliding analysis in the Wujiaping formation

Fig. 16 SWEDGE stability analysis of wedge 1 and wedge 2 in the Qixia and Maokou limestone formation

Table 6 SWEDGE stability analysis results of wedge 1 and wedge 2 in the Qixia and Maokou limestone formation

Slope angle	Wedge 1 FOS				Wedge 2 FOS			
	Natural	Natural + earthquake	Rainfall	Rainfall + earthquake	Natural	Natural + earthquake	Rainfall	Rainfall + earthquake
75°	1.57	1.32	1.19	1.12	1.83	1.67	1.46	1.34
70°*	1.72	1.53	1.36	1.28	1.93	1.76	1.52	1.39
65°	1.88	1.54	1.50	1.42	2.05	1.69	1.59	1.45

*70° is the steepest possible slope angle in Qixia and Maokou formation meeting open pit mining FOS requirement of 1.2

Fig. 17 Stability analysis results at 60° and 51° step slope angles under heavy rainfall + earthquake conditions in the Wujiaping limestone formation in SLIDE software

Table 7 Step slope stability analysis results in the Wujiaping limestone formation in SLIDE software

Slope angle	Factor of safety			
	Natural	Natural + earthquake	Rainfall	Rainfall + earthquake
75°	1.259	1.181	0.84	0.794
70°	1.331	1.245	0.91	0.856
65°	1.442	1.343	1.015	0.953
60°	1.549	1.431	1.122	1.045
55°	1.662	1.529	1.242	1.148
51°*	1.762	1.613	1.334	1.227
50°	1.792	1.637	1.354	1.242

*51° is the steepest possible slope angle in Wujiaping formation meeting open pit mining FOS requirement of 1.2

Fig. 18 Displacement vector analysis of section A–A with simulated optimized design excavation under heavy rainfall + earthquake conditions

Fig. 19 Displacement vector analysis of section B–B with simulated optimized design excavation under heavy rainfall + earthquake conditions

Fig. 20 Displacement vector analysis of section B–B with simulated optimized design excavation under heavy rainfall + earthquake conditions

Table 8 Summary of displacements and FOS values for the optimized design mine slope in the three analysis sections under the four working conditions

Slope type	Profile section →	A–A		B–B		C–C	
	Parameter →	Max displace-	FOS	Max displace-	FOS	Max displace-	FOS
	State ↓	ment (cm)		ment (cm)		ment (cm)	
Optimized design slope	Natural	5.0	1.5*	10.0	1.4*	6.0	1.5*
	Natural + earthquake	5.0	1.5*	10.0	1.4*	6.7	1.4*
	Heavy rainfall	5.5	1.3*	11.0	1.3*	6.8	1.3*
	Heavy rainfall + earthquake	5.5	1.3*	11.0	1.2*	7.8	1.2*

*All FOS values meet open pit mining FOS requirement of 1.2

Table 9 Original and proposed mining slope parameters

Excavation parameter category	Original design slope parameters	Proposed optimized slope parameters
Minimum mining elevation	850 m	Endorsed
Bench height	15 m	Endorsed
Step slope angle	60°	51° Wujiaping 70° Qixia and Maokou
Overall slope height	230–320 m	Endorsed
Overall slope angle	48.4°	42.4°
Safety berm width	4 m	Endorsed
Cleaning platform width	6 m	Endorsed

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Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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