Numerical Investigation of the Instability on Rock Slopes with Wedge Block

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Abstract. The wedge blocks on rock slope generally wide-range spread varying in occurrence condition, geometry, and dimension, resulting in complex instability mechanism and difficult stability evaluation. A series of slope models with wedge blocks including both symmetry and asymmetry are studied to reveal the instability mechanisms. The results indicate that the intersecting joints with narrow included angles can cause clamping effects on wedge blocks, resulting in significant enhancement of the stability of wedge block and the loss of joint domination on the failure mode. As the expansion of included angle, the rock slope models exhibit typical wedge failures in symmetric situations. While in asymmetric situations, the instability of wedge blocks suffers rotational kinematic characteristics, resulting further influence on the evaluation of the stability.

Keywords: rock slope; joint; wedge failure; failure mode; kinematic characteristic

1 Introduction

Since Wittke first proposed the limit equilibrium method against wedge failure[1], the study of wedge stability had been an important component of rock slope engineering. It is generally believed that the wedge failure was dominated by joints, exhibiting a translational sliding along the intersection of joints. While the instability of rock slope with rock wedge block do not always develop according to the consensus in practical projects[2]. In many cases, wedge blocks controlled by joints may not have a controlling effect on the global slope failure. The wedge block itself may also have different kinematic characteristics over unevenly distributed friction or rock bridges, and even disintegrate during the failure process under the influence of internal secondary weak surfaces. In this paper, a series of numerical models of rock slopes with symmetry and asymmetry wedges were conducted to investigate the instability characteristics. The research results have certain reference value for relevant engineers and scientists.

Y. Zhang et al. (eds.), *Proceedings of the 2024 10th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2024)*, Advances in Engineering Research 259,
https://doi.org/10.2991/978-94-6463-658-1_68

2 Materials & Methods

2.1 Experiment Scheme

The rock slope studied in the paper is considered an ideal 'step' shape with vertical slope surface and horizontal crest. This is because steep rock slopes are very common, especially in open-pit mines and cliffs, and considering the convenience of calculation and modeling. Single tetrahedron rock wedge resides on the slope with two more intersecting joints. The rock wedges considered in the paper shares the same line of intersection with the only variation of the occurrence of joints. The joint spatial configuration is referred to the combination of the included angel (ξ) and the angle of tilt (β) in the view of the line of intersection (Fig. 1). Symmetry (β=90°) and asymmetry wedges (β=60°) with series of included angel (ξ) were conducted to reveal the instability of rock slopes with various wedge blocks.

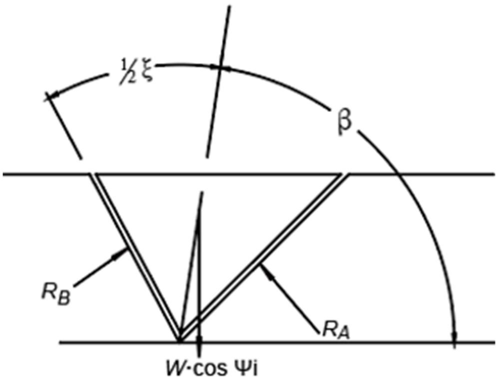


Fig. 1. Schematic diagram of spatial configuration of wedge blocks modified from Hoek et al[4].

2.2 Materials

Table 1. Physical and mechanical parameters for discontinuities and host rock.

Material	Parameter	Value
Discontinuity	Normal Stiffness, kn (GPa/m)	1
	Shear Stiffness, ks (GPa/m)	1
	Cohesion (MPa)	0
	Friction Angle (°)	45
	Tensile Strength (MPa)	0
Host Rock	Density (kg/m3)	2800
	Young's Modulus (Gpa)	25
	Poission's Radio	0.3
	Cohesion (MPa)	0.5
	Friction Angle (°)	45
	Tensile Strength (MPa)	0.5

The host rock refers to the strength chart provided by Hoek[3] and is chosen to represent ideal rock mass with the maximum shear strength property in natural condition. Accordingly, the host rock is described with both 'undisturbed hard rock masses with no major structural patterns dipping out of face' and 'rock masses or filling containing hard clean angular interlocking papers and blocks.' The discontinuities between blocks are carried out with Mohr-Coulomb model. As a convention built into the model, shear failure is perfectly plastic, with no strain softening. The strength of discontinuities is simply considered based upon friction with no cohesion and tensile strength acting as the form of 'residual strength' commonly used for back analysis. The stiffness and strength parameters are shown in Table 1.

On this basis, strength reduction method (SRM) is carried out to calculate the factor of safety (FS). Shear-strength reduction method is popular in researchers. Because the method does not require prior assumptions about the failure mode. During the step-by-step reduction of strength, the slope gradually approaches the limit equilibrium state to unveil the failure mode. The method can intuitively observe the failure mode of the rock slope, and therefore the result can be compared and analyzed with the default failure mode. The shear strength parameters of the structural plane are reduced according to the formula

$$N_r = \frac{c}{c_n} = \frac{tan\varphi}{tan\varphi_n} \tag{1}$$

where c and φ are actual cohesion and internal friction angle of the slope materials, respectively; c_n and φ_n are the trial cohesion and internal friction angle after reduction, respectively; and Nr corresponding to the limit equilibrium state of the slope and could be taken as the factor of safety of slopes. A termination criterion, stipulating whether the slope reach limit equilibrium state is also required.

2.3 Model Procedures

The discrete element code 3DEC is utilized for its obvious advantages in blocky computing and joints establishing[5].

1. A step-shaped slope model with a rock wedge in certain geometric is first established and meshed. Once the block is meshed, it is transferred to deformable block. A zone size of 0.7 m is introduced to all blocks to balance efficiency and accuracy. All blocks are treated as finite difference continuous medium with elastic perfectly plastic behavior and Mohr-Column strength criterion.

2. The model is constrained by lateral constraints in the left, right, and rear surfaces and fixed in all three directions at the base. All deformation and strength parameters were set to high values to gain the initial equilibrium state under gravity.

3. The shear-strength reduction is conducted to both rock mass and discontinuous until the terminate criterion is meet. The criterion for slope instability is the convergence of the program for the convenience of calculation.

4. Displacement contour can be used to characterize the failure mode of rock slopes. The sliding surface can generally be represented by the area of maximum shear strain increment, but the contour will suffer interruptions at joints. The shearing of a slip

surface can be characterized by the relative displacement on both sides of the discontinuous surface.

3 Results

The factor of safety results of both 3DEC and LE method are conducted in Table 2. According to the analysis of Table 2, the factor of safety results of symmetry and asymmetry are visualized shown in Fig. 2 and Fig. 3, respectively. For slopes with symmetrical wedge, there is a significant difference in the results calculated by the two methods when the wedge block is narrow in the included angle (ξ). Similar situation is also found in asymmetric wedges. It is worth noting that the results of symmetric wedges show good consistency in the case of ξ>15°, while evident inconsistency occurs in asymmetric wedges when the included angle greater than 60° (ξ>60°). The results of 3DEC abnormally exceed those of the limit equilibrium method.

To further investigate the reasons, a series of failure characteristic diagram of displacement contour and vectors are listed for both symmetry and asymmetry cases in Fig. 4 and Fig. 5, respectively. According to Fig.4, the slope exhibits a typical wedge failure as the included angle greater than 15° (ξ>15°). The slip surface is fully controlled by joints. But as the internal angle shrinks, the instability characteristic synchronously evolves from typical wedge sliding to global circular failure. The results indicate that the intersecting joints with narrow included angles would cause clamping effects on wedge blocks, resulting in significant enhancement of the stability of wedge block and the loss of joint domination on the failure mode.

Table 2. Factor of safety results.

Included angle-ξ	FS			
	90		60	
	3DEC	LE	3DEC	LE
2	7.03	57.30	6.91	49.62
4	6.95	28.65	6.84	24.81
6	6.91	19.11	6.83	16.55
15	6.66	7.66	6.81	6.63
30	3.97	3.86	3.45	3.35
45	2.66	2.61	2.3	2.26
60	2.02	2.00	1.73	1.73
75	1.66	1.64	1.33	1.42
90	1.42	1.41	1.1	1.22

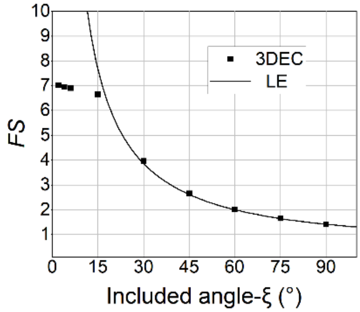


Fig. 2. FS results of symmetry wedge

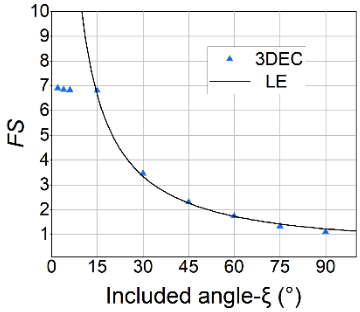
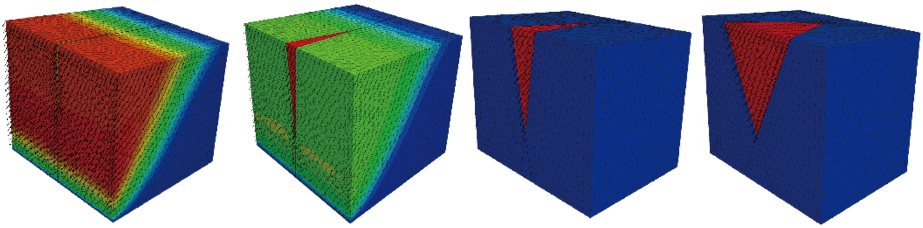
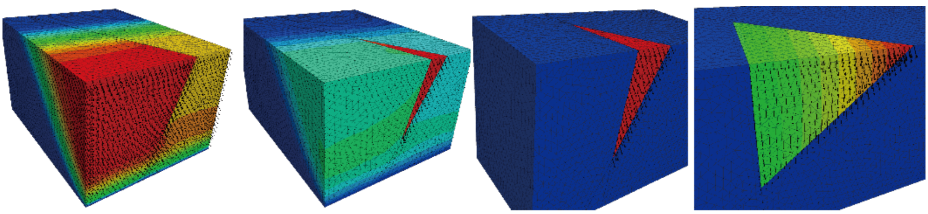


Fig. 3. FS results of asymmetry wedge



(a) $\beta = 90° \; \xi = 2°$ (b) $\beta = 90° \; \xi = 15°$ (c) $\beta = 90° \; \xi = 30°$ (d) $\beta = 90° \; \xi = 75°$

Fig. 4. Displacement contour and victors of rock slope with symmetrical wedge block.



(a) $\beta = 60° \; \xi = 2°$ (b) $\beta = 60° \; \xi = 15°$ (c) $\beta = 60° \; \xi = 30°$ (d) $\beta = 60° \; \xi = 75°$

Fig. 5. Displacement contour and victors of rock slope with asymmetrical wedge block.

The similar transformation of failure modes also witnessed in asymmetric situations with two exceptions different to symmetric situations.

1., When the internal angle is narrow, there is a significant difference on the displacement between rock masses on both sides of the adjacent joints. This implies that adjacent inclined joints with similar orientations will act as a weak interlayer leading to enhancement on the displacement of the rock mass above.

2., When the internal angle is greater than 60° (ξ>60°), significant difference of displacement inside the wedge block is observed which indicates a certain rotation.

Synchronous alienation occurred on the factor of safety results which is further proof of the correspondence between stability evaluation and failure modes[6,7,8].

4 Conclusions

In this paper, the stability evaluation and failure characteristics of rock slopes with symmetry and asymmetry wedge blocks are introduced to study the instability mechanisms. A general failure characteristics transformation to localized is witnessed for both symmetrical and asymmetrical as the included angle expanding, in which the intersecting joints gradually acquire a dominate role in the failure mode. Adjacent joints with narrow included angles will act as a weak interlayer especially in inclined cases lead to enhancement on the displacement of the rock masses above. The rock slope models with a large included angle exhibit typical wedge failures in symmetric situations. While the asymmetry wedge blocks will suffer certain rotational kinematic characteristics, leading to transition on the instability mechanism, and thus resulting in further influence on the evaluation of the stability. The research results have certain reference value for relevant engineers and scientists.

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