Meaningfulness of the Stable Range of Factor of Safety for Deep Pits – A Numerical Modelling Assessment

Mahdi Zoorabadi[1,2](✉) and Mojtaba Mousakhani[3]

[1] Technical Principal-Tunnels and Geotechnics, SMEC, Melbourne, Australia
Mahdi.zoorabadi@smec.com
[2] Adjunct Associate Professor-UNSW, Sydney, Australia
[3] Senior Tunnel Engineer, Aurecon, Australia

Abstract. Limit Equilibrium (LE) methods have been used as the main tool to assess rock mass failure mechanisms at inter-ramp and overall slope scales in open pit mines. Rock mass shear strength parameters are determined by reducing the intact strength using Geological Strength Index (GSI), Damage factor (D), and a material constant (mi) to account for discontinuity properties when using Hoek-Brown strength criterion. Rock mass shear strength parameters have been used as typical input parameters for LE methods to calculate Factor of Safety (FoS) as ratio of resisting to driving forces. The calculated FoS are compared with design acceptance criteria to evaluate the stability of the pit wall. FoS of 1.3–1.5 is typical industry accepted minimum value for overall slope scale mechanisms. LE methods and calculated FoS does not provide any information about the stress induced rock fracturing and complex internal deformations happening in the deep open pits. The distributed rock stress behind the highwall in deep pits can be high enough to initiate stress induced rock fracturing for low to medium strength rocks. In this research, numerical modelling simulation using FLAC was used to assess the stress induced fracturing states for three typical cross section with depth of 250 m, 400 m, and 600 m. The input parameters including GSI values were derived using a constant mi to achieve shear strength parameters that results in FoS $\approx$ 1.5 using LE methods. The GSI based formulations are then used to estimate the deformation modulus required for the numerical modellings. Then numerical modelling was used to assess the stress induced fracturing and stability of the selected cross sections.

Keywords: limit equilibrium · factor of safety · stress induced fracturing

1 Introduction

Open cut mining is one of the most common mining methods to extract ore from the ground. In this mining method, slopes are often excavated in rock of varying quality and strength posing various challenges in stability analysis and design. The overall steepness of the slope has a major impact on the amount of waste that must be removed. As a rule of thumb, steeper the slopes less waste to access which results in more favorable strip ratios.

S. Javankhoshdel and Y. Abolfazlzadeh (Eds.): TMIC 2022, AHE 13, pp. 83–91, 2023.
https://doi.org/10.2991/978-94-6463-104-3_9

Table 1. Typical FoS and PoF acceptance criteria values for a high consequence of failure (Read and Stacey, 2009)

Slope Scale	Acceptance Criteria	
	FoS (Static)	PoF (P[FoS $\leq$ 1])
Bench	1.1	25%
Inter-ramp	1.2	20%
Overall	1.3–1.5	$\leq$5%

Thus, for a mining company to make the best of its mineral resource, the final slopes should be as steep as possible. However, with increased slope angles come an increased risk of slope failure. Instabilities in rock slopes cause disruption to the operation/project with significant financial and safety consequences.

As a common practice, LE methods are used to calculate the FoS and support Probability of Failure (PoF) for inter-ramp and overall slope scales. These methods use strength parameters of the rock mass estimated by using GSI classification-based approach. The calculated FoS and PoF are compared with design acceptance criteria such as the range suggested by Read & Stacey (2009) (Table 1). FoS of 1.3–1.5 are typical industry accepted values for overall slope scale mechanisms with a high consequence of failure. LE methods have been commonly be used to back analyse the failed slopes to determine the rock mass shear strength parameters.

Sjöberg (1999) discussed the differences between stability analysis of deep pits and moderate height (up to 100 m). He stated that in deep slopes the "*differences in scale and potential failure modes, as well as the implications of a large-scale failure, calls for a different design methodology for overall slope angles. Failure of the deep slopes involve complex internal deformation and fracturing which bears little resemblance to the assumptions required by most limit equilibrium methods.*"

Unlike moderate scale slopes, the level of rock stress concentration around the slope might be enough to cause rock fracturing. The research by Stacey (1973), Coulthard et al. (1992), Hustrulid and Kuchta (1995) showed that stress concentration happens in the toe region and tensile stress is developed at the crest of the slopes in deep pits. The rock failure is initiated when the newly distributed stresses exceed the strength of the rocks. The stress induced fracturing causes a complex internal deformation which is not being considered in the most limit equilibrium methods. This raises the following two questions below which challenge current practice for stability assessment of deep slopes:

1. Are LE methods and FoS enough to assess the stability of deep rock slopes? Or is a deep slope with FoS $\approx$ 1.5 stable against progressive failure?
2. Do we underestimate the rock mass strength too much for deep slope? Where using low GSI values or high disturbance factors are adopted to achieve a FoS just above the acceptable range of FoS?

These two questions were the main reason for the research presented in this paper. In this brief research, numerical modelling was used to assess the stress induced fracturing mechanism in three typical cross sections with depths of 250 m, 400 m, and 600 m. The FoS calculated by LE methods for these cross sections is approximately 1.5.

2 Methodology

All the selected cross sections for this research have an overall slope angle of 40o and are dry. The rock density is assumed to be 23 KN/m^3. The LE method used (Rocscience Slide 2018) software to determine the shear strength parameters of cohesion and friction for Mohr-Coulomb criterion required to achieve a FoS $\approx$ 1.5. Figures 1, 2 and 3 show the results of LE method assessment.

The back-analysis results showed that the rock mass cohesion and friction angle need to be increased by only 36 kPa and 3 respectively to maintain FoS $\approx$ 1.5 when the slope height increases from 250 m to 400 m. For 600 m deep slope, the cohesion must be only 98 kPa higher compare with the 250 m deep slope to maintain of FoS $\approx$ 1.5.

The cohesion and friction angle determined from LE method have been used to back calculate the GSI value for the rock mass by adopting a constant $m_i = 10$ and damage factor of D = 0 for all three cases. Uniaxial Compressive Strength (UCS) of intact rock must be relatively small considering the range of the estimated cohesion and friction angle values. Adopted UCS values are 20 MPa, 30 MPa and 36 MPa for 250 m, 400 m, and 600 m slopes respectively. The back calculated GSI values and the deformation modulus for each case are listed in Table 2. Relatively low values of GSI and UCS are required to calculate the cohesion and friction angles required to achieve FoS $\approx$ 1.5 from LE method. This is the point where rock mass parameters such as GSI or D are sometimes downgraded to deliver results just above the required design acceptance criteria minimum.

The shear strength parameters and deformation modulus determined from LE method and back calculation were used as input data for 2D numerical modelling using Itasca's

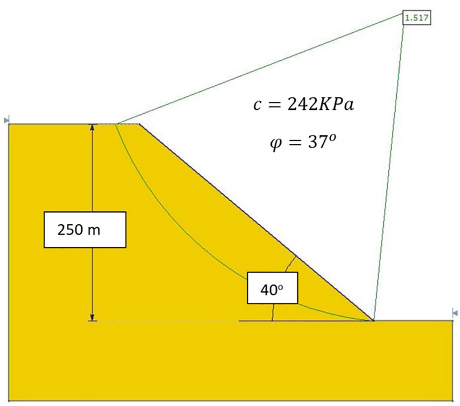

Fig. 1. LE method results for 250 m depth pit slope

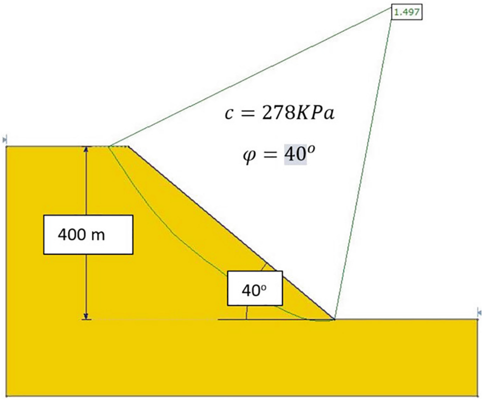

Fig. 2. LE method results for 400 m depth pit slope

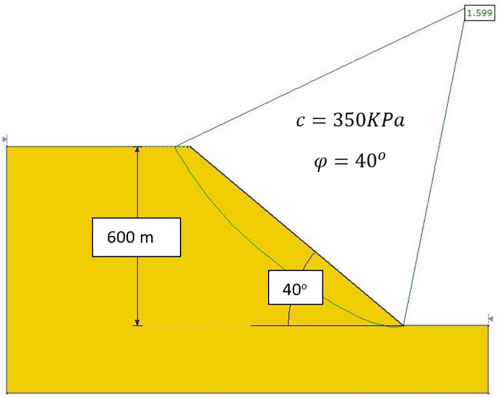

Fig. 3. LE method results for 600 m depth pit slope

Table 2. GSI and deformation modulus back calculated from each case

Slope Depth [m]	D	mi	Estimated UCS [MPa]	Back Calculated GSI	Deformation Modulus [GPa]
250	0	10	20	30	0.651
400	0	10	30	30	0.977
600	0	10	36	35	1.63

FLAC software. FLAC provides an option to develop a user-defined constitutive model to simulate the stress induced fracturing. A constitutive model developed by authors uses the Mohr-Coulomb bi-linear failure criterion (Fig. 4) to assess failure of each model. The constitutive model compares the distributed stress in each zone with the triaxial and tensile strengths of the intact rock and with shear strength of the discontinuities. If the

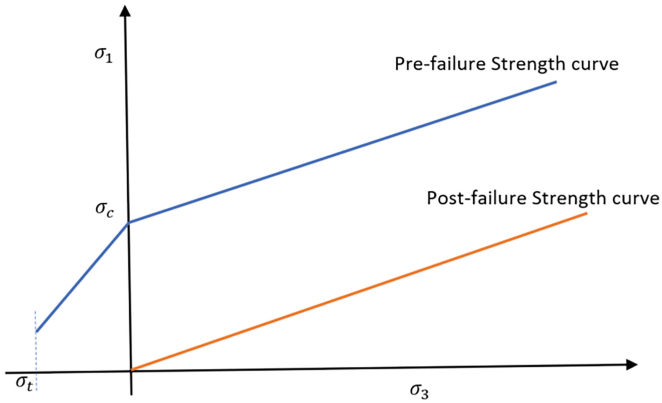

Fig. 4. Mohr-Coulomb bi-linear failure criterion used for the stress induced fracturing assessment

stress exceeds the strength, the constitutive model of the zone is changes from elastic to Mohr-Coulomb and strength is reduced from the pre-failure state to its post failure level (Fig. 4).

It should be noted that the horizontal to vertical stress ratio of 1.5 was considered for all numerical models.

3 Numerical Modelling Results

Figure 5, 6 and 7 present major failure extension (maximum shear strain increment > 0.03 contour) obtained from the numerical modelling. The numerical modelling showed that an intensive stress induced fracturing occurs at the toe for all three cross sections due to higher stress concentration in this area.

For 250 m deep cross-section, two unstable zones were formed one in the crest and one close to the toe. The rock mass between these two unstable sections was damages but remains stable. The crest instability was formed by tensile failure while shear failure is the controlling failure modes at the toe.

The stress induced fracturing is greater for the 400 m and 600 m deep cases and has formed instabilities across the cross sections. The progressive failure initiation and propagation for the 600 m deep cross section are shown in Fig. 8. As can be seen, the major stress induced fracturing started from the toe and then grew upward. The fracture propagation changes the stress distribution and initiates new instabilities in the upper zones. This process continues till a certain area behind the slopes lose its resistance against movement and a slope failure occurs.

It should be noted that the stress concentration at the crest and toe is dependent on stress ratio. Therefore, if the stress ratio changes the progressive failure can have another initiation and propagation mechanism.

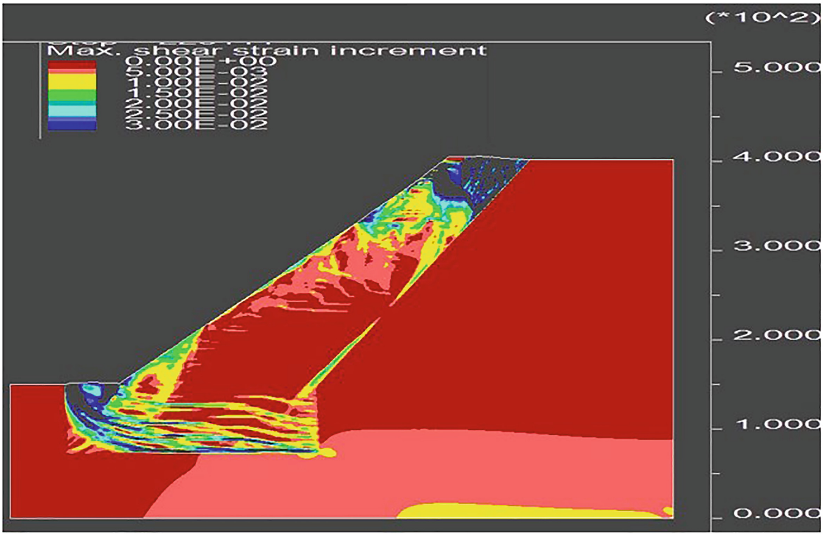

Fig. 5. Shear strain increment contour > 0.03 representing major stress induced fracturing – 250 m pit

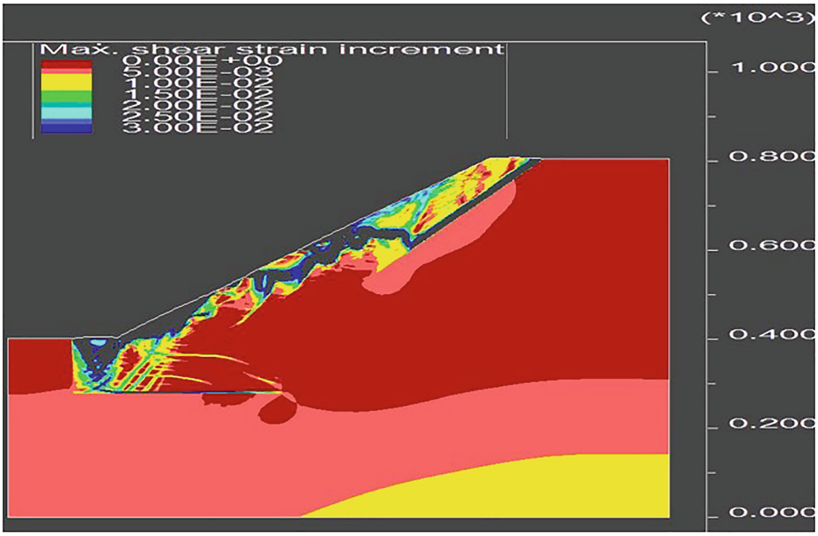

Fig. 6. Shear strain increment contour > 0.03 representing major stress induced fracturing – 400 m pit

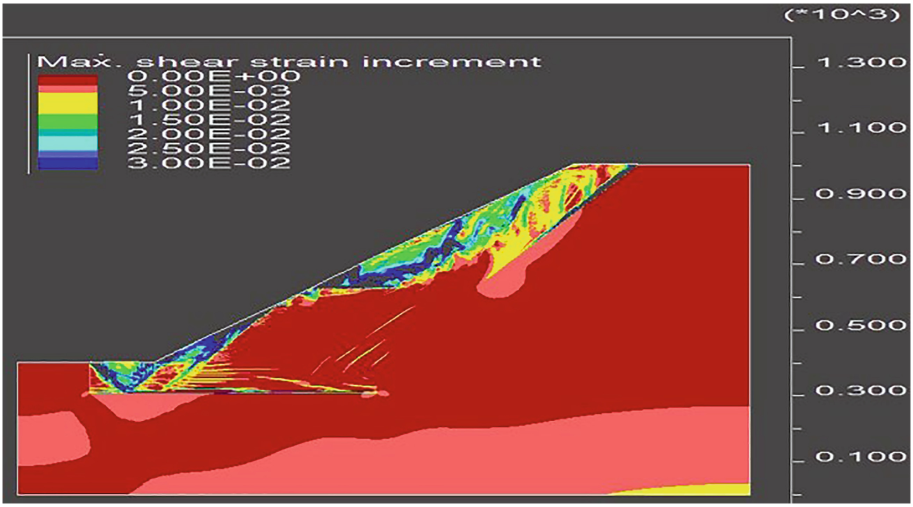

Fig. 7. Shear strain increment contour > 0.03 representing major stress induced fracturing – 600 m pit

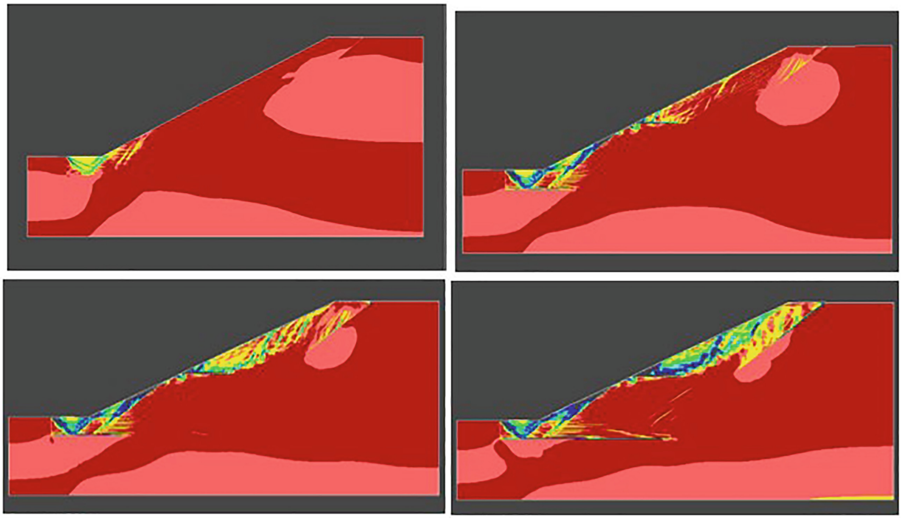

Fig. 8. Progressive failure initiation and propagation –600 m pit

4 Discussion and Conclusions

The concept of FoS calculated using LE method were originally developed to assess stability of soil mechanics related problems where progressive failure caused by stress induced fracturing were not the dominant failure mechanism. LE methods assume that a mass of ground material above a slipping surface, either circular or non-circular, act as a rigid body and the slipping surface forms across the slope instantaneously (Law and Lumb, 1977). This assumption is completely different where the slope instability is due to progressive failure induced by stress in the rocks. The concept behind LE method may work for moderate height rock slopes where the stress levels are not high enough to cause progressive failure.

Back analysis results show that the rock mass shear strength parameters required to satisfy the acceptable stable rang are not very high even for 600 m deep slope. When these strength parameters are used in numerical model capable of simulating progressive failure, the distributed stress components both tensile and compression are high enough to initiate progressive failure and form instability. Therefore, the stable range of FoS may lose their meaningfulness for deep slopes where progressive failure can form and is the critical failure mechanism. This study raises the following two questions below which challenge current practice for stability assessment of deep slopes:

1. Are LE methods and FoS enough to assess the stability of deep rock slopes? Or is a deep slope with FoS ≈ 1.5 stable against progressive failure?
2. Do we underestimate the rock mass strength too much for deep slope? Where using low GSI values or high disturbance factors are adopted to achieve a FoS just above the acceptable range of FoS?

References

Coulthard M.A., Journet N.C., Swindells C.F., 1992. Integration of stress analysis into mine excavation design. In rock mechanics, proceedings of the 33rd U.S. symposium, pp. 451–460.

Hustrulid W., Kuchta M., 1995., Open pit mine planning and design. Vol. 1 – Fundamentals. RotherdamL A. A. Balkema, 636P.

Law K.T., Lumb P., 1977. A limit equilibrium analysis of progressive failure in stability of slopes. 29th Canadian geotechnical conference, 113–122.

Read J., Stacey P., 2009. Guidelines for open pit slope design. CRC Press.

Sjöberg J., 99. Analysis of large-scale rock slopes. PhD thesis. Lulea University of Technology, Sweden.

Stacey T. R., 1973. Stability of rock slopes in mining and civil engineering situations. National mechanical engineering research institute. Council for scientific and industrial research, CSIR report ME 1202, Pretoria, South Africa, 217P.