

Wedge failure analyses of the rock slope influenced by foliations

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1 INTRODUCTION

Among the recognized failure modes worldwide, wedge failure of the rock slope results when rock mass slides along two intersecting discontinuities, both of which dip out of the cut slope at an oblique angle to the cut face. Thus, forming a wedge-shaped block. The situations governing the wedge failure mode under both static and dynamic conditions have clearly been explained in detail in various geotechnical literatures (John 1970, Hoek *et al.* 1973, Hoek & Bray 1981, Kumsar *et al.* 2000, Wyllie & Mah 2004, Aydan & Kumsar 2010, Basha *et al.* 2013). Analytical models have been applied to study the effects of several governing parameters (such as the weight of the rock mass, uplift forces due to water pressure on the weak planes, force applied by anchor system if any, and seismic forces due to the earthquake occurrence) on the factor of safety of the wedge sliding (Kumsar *et al.* 2000, Wang *et al.* 2004, Aydan & Kumsar 2010, Basha *et al.* 2013, Bowa 2019). In mining and civil engineering applications, some rock slope possesses intersecting discontinuities, which dip out of the cut slope at an oblique angle to the cut face, thus forming a wedge-shaped block. Moreover, this kind of rock slope possesses the foliations that are oriented at some angle to the original sedimentary rock mass forming the wedge. Therefore, wedge sliding failure analysis subjected to foliations oriented at some angle to the original sedimentary rock mass forming the wedge, particularly its effect on the factor of safety against the slope failure using the current analytical method, may be complex and may not yield accurate results. Although the current analytical method allows early identification of the likely failure mechanisms, it does not account for displacement along foliations and does not provide the more realistic approximations of the behavior of the real slopes and modes in which such slopes could fail.

Thus, this article examines the wedge sliding failure analysis of the rock slopes on the physical case study by building a numerical model using *3DEC* (2007) which incorporates foliation as a key geologic feature to provide the more realistic approximations of the behavior of the real slopes.

2 CASE STUDY – WEDGE FAILURE

A slope failure occurred on the North West wall of the Chingola open pit located on the west side of the Nchanga Open Pits in Chingola mining town of Zambia on 20th November 2018 as indicated in the mine plan – see Figure 1. The copper ore is hosted in an arkose rock formation, that occurs in an interbedded sequence of roan dolostone overlain by stratigraphic sedimentary rocks namely; Chingola dolomite, banded shale, upper banded sandstones, feldspathic quartzite, lower banded shale, lower banded sandstones, arkose, granite and basements formations. The basements formations occur in a series of what is traditionally described as the southwest limb of the Chingola Anticline, a complex northwest trending ridge of Lufubu Gneiss and Schist locally referred to as Basements.

The failed rock mass comprises mainly Chingola dolomite, banded shale and upper banded sandstones on the upper stack of the slope. The material along the weak planes are highly weathered and extremely weak

with an estimated rock strength of 0-2 MPa. It crumbles under firm blow with a point of a geological hammer and can be peeled by a pocketknife and indented by thumbnail. The failure affected three benches from the 75mB (1258 m elevation) to the 105mB (1228 m elevation) over a 200m strike length from 16200 mN to 16000 mN Section Lines. The volume of the failed material was approximately 912,000 bank cubic meters by manual computation. Inspection of the failed zone along the perimeter road of the pit indicated the occurrence of the hairline to about 2 cm wide cracks along the major discontinuities and foliations that propagated from 1275m to 1320m elevation leading to the failure as shown in Figures 2a & b. The site assessment indicated that the failure was structurally controlled and the failed zone was defined by at least 3 major discontinuity planes (J1: dip = 85° dip direction = 084°; J2: dip = 55° dip direction = 059°; and J3: dip 5° dip direction 185°) and foliations (dip=50° dip direction = 273° spaced at 1m) see Figures 3a & b.

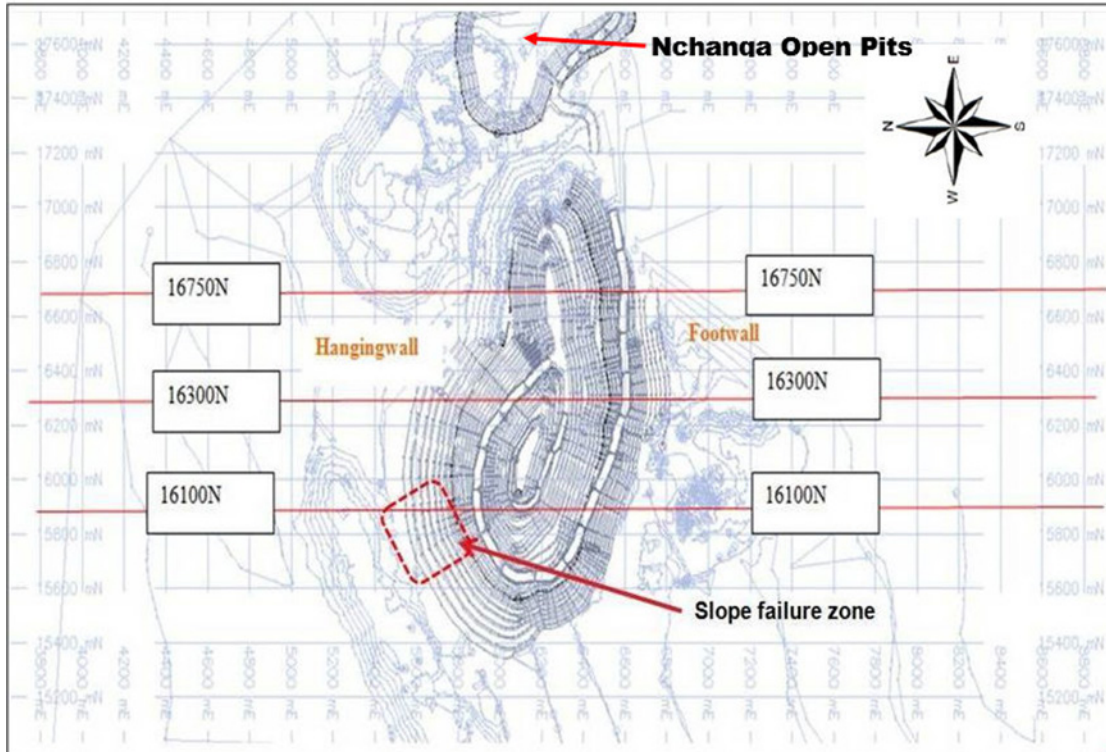


Figure 1. Mine plan indicating the slope failure zone.



(a)



(b)

Figure 2. Slope failure (a) propagations of hairline to about 2mm wide cracks along the major discontinuity and foliations prior to the slope failure on the perimeter road of the pit, and (b) Photo of the resulting slope failure on the perimeter road of the pit.

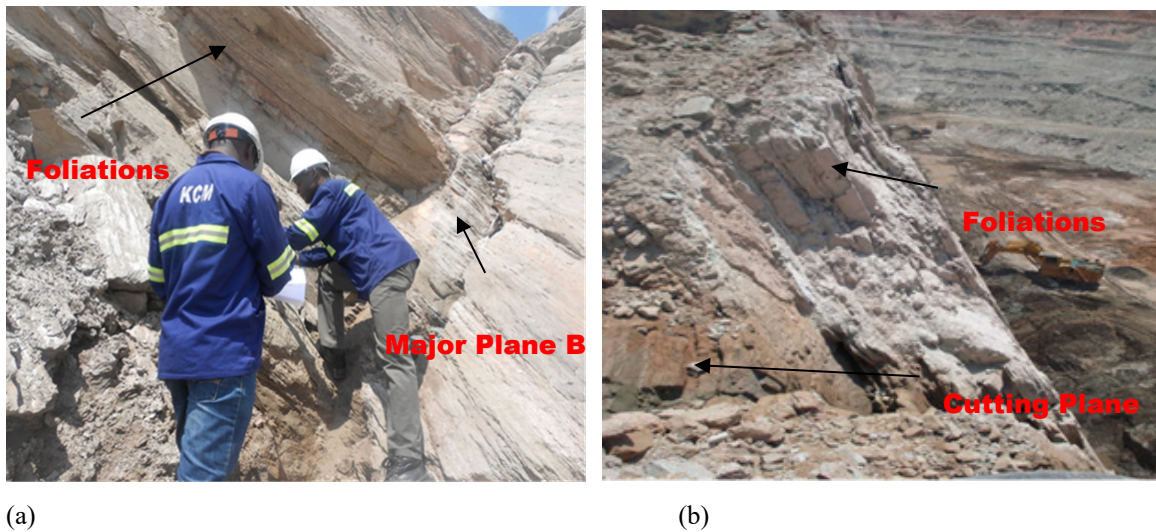


Figure 3. Geotechnical mapping of the failure slope: a) major planes, b) foliations.

3 NUMERICAL MODELLING

Stability of a wedge sliding in a rock mass, formed by three major intersecting planar surfaces and foliations under the action of gravity at COP F&D's West wall, was studied by Numerical modeling using *3DEC* software. Slope models built using *3DEC* tend to be general purpose in nature, as they are capable of solving a wide variety of problems that may not be solved using analytical models. For example, numerical model generated using *3DEC* can incorporate key geologic features such as foliations, joints, faults providing more realistic approximations of the behavior of the real slopes, particularly foliations' effects on the mixed modes of failure, displacements along foliations and provisions of actual failure.

The analytical model tends to oversimplify the existing conditions, possibly leading to overly conservative solutions. The sloping geometry at the time of failure considered for modeling are as follows: Berms width (1320 – 1258m Elevation): 5m ; Upper Stack Height-30m; Upper stack angle -37°; Batter angle –lower stack- 70°; Lower Stack Height -75m; Overall slope of the model (crest to toe): 43°; Bench height: 15m. Figure 4 shows the model set up in *3DEC* indicating the three major weak planes and foliations. The summary of rock mass properties acquired and used for the 3D model are presented in Table 1. The strain-softening model that reproduces a lower shear strength and null tensile strength as predictable after failure was embraced. In addition, the joint constitutive model with Coulomb slip was used to explain the discontinuities. In *3DEC* software, the discontinuities which bound the blocks are treated as boundary conditions along which large displacements and rotations are permitted. Discontinuities are regarded as distinct boundary interactions between these blocks and joint behavior is prescribed for these interactions.

Table 1. Rock mass properties.

Parameters	Rock Formation		
	Chingola Dolomite	Banded Shale	Banded Sandstones
Density, Kg/m ³	2000	2200	2500
Bulk Modulus, (GPa)	9.88	10.85	11.25
shear Modulus, (GPa)	8.5	7.65	8.4
Cohesion, (MPa)	360	380	405
Tension, (MPa)	0	0.2	0.45
Friction, (°)	35	37	40

It is suggested that the use of three-dimensional discontinuum techniques allows one to not only resolve the true kinematics of wedge failure mechanisms but also to better understand the three-dimensional asymmetry and wedge sliding displacement response behaviors and mixed failure modes of the high rock slopes. The edge at the back of the wedge has contact with an intersection with foliation at the rear blocks. Joint shear and normal stiffnesses of 1 MPa/m were assigned to all the contacts. Two different material numbers were assigned to joints in the model. Both material numbers have the same contact normal (K_n) and shear (K_s) stiffness, equal to 1.0×10^9 (here, Pa/m).

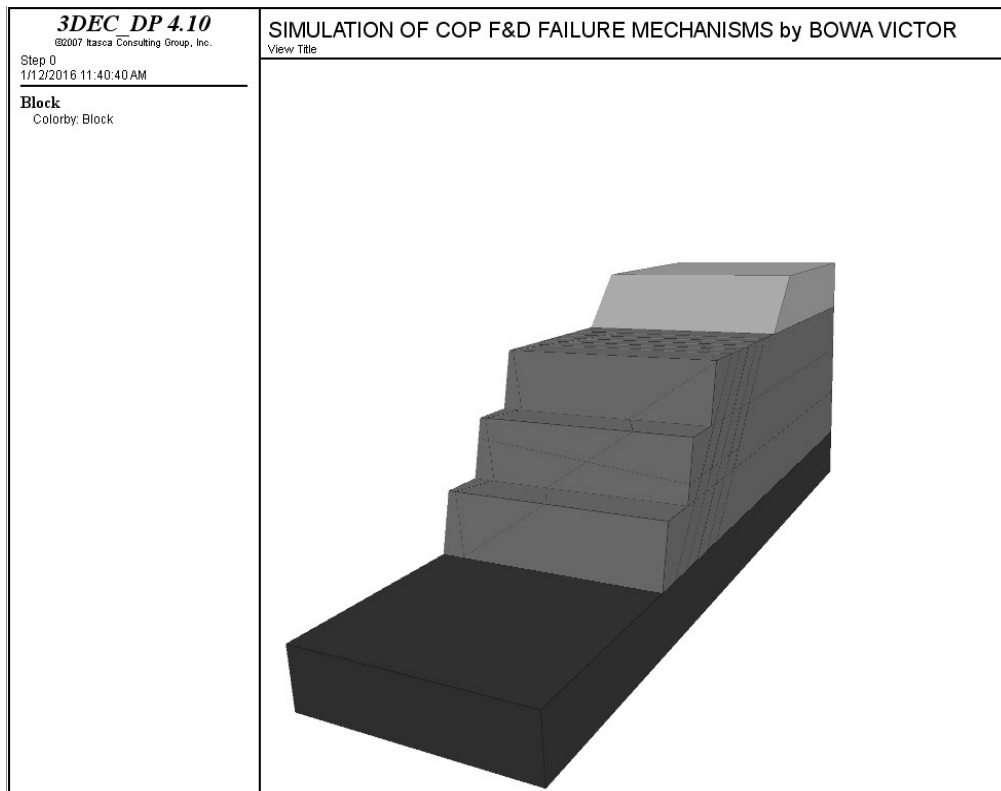


Figure 4. Model set up in 3DEC showing the 3 major planes and foliations.

4 NUMERICAL MODEL RESULTS

It is often helpful to judge the behavior of the slope (equilibrium, motion) by observing the motion of the specified points on the slope model being executed. In this problem, unbalanced forces of the specified points (30, 30, 30); (60, 30, 30); (50, 30, 50) and (70, 30, 40) were monitored on the numerical model and the program returns the information of the unbalanced force for the selected monitoring points on the numerical model. The graphical representation of this unbalanced forces behavior is obtained for each specified point e.g. (30, 30, and 30) on the numerical model as shown in Figure 5. Review of slope instability at North West Corner by Simulations using 3DEC software reveal geotechnical risks of unbalanced forces which could have led to wedge slope failures.

The magnitude of the horizontal displacement first increased and then decreased from the toe to the crest as shown in Figure 6. Simulation results reveal variations in the plastic zones predicting the mixed failure modes taking place since several blocks were formed by the intersections of the foliations and the three major weak planes. It is envisaged that sliding failure mode along the foliation planes was taking place combined with the sliding of the wedge near the toe of the slope failure. The wedge sliding near the toe of the slope took place first, initiating the sliding of multiple blocks on the upper section of the slope.

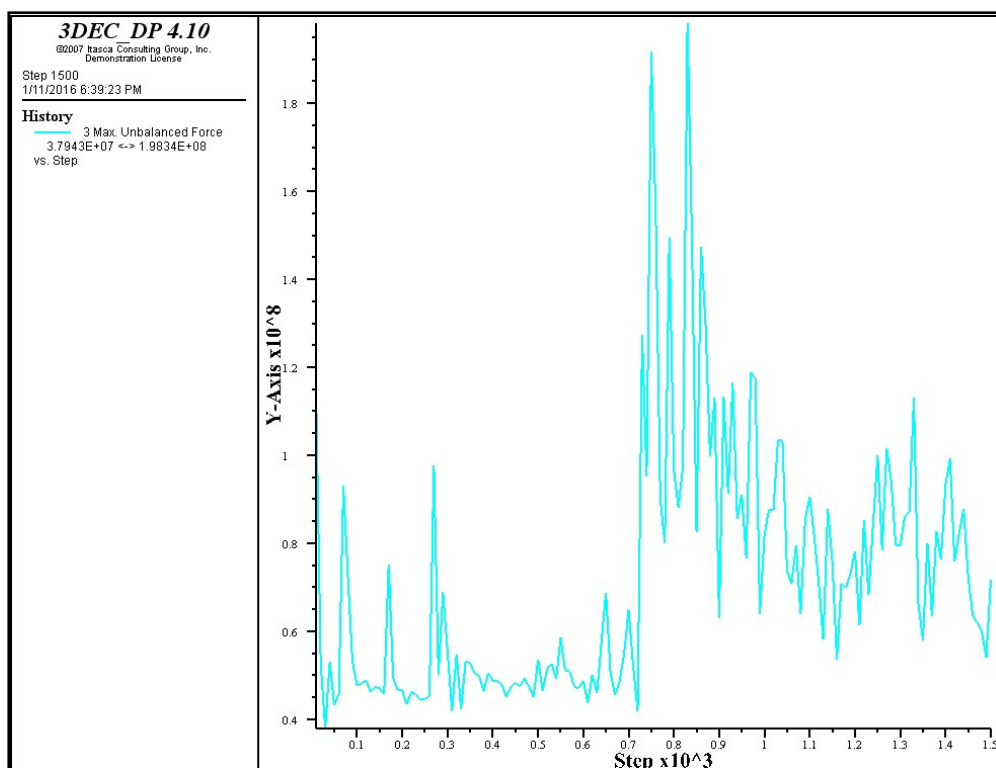


Figure 5. Simulation results – maximum unbalanced force.

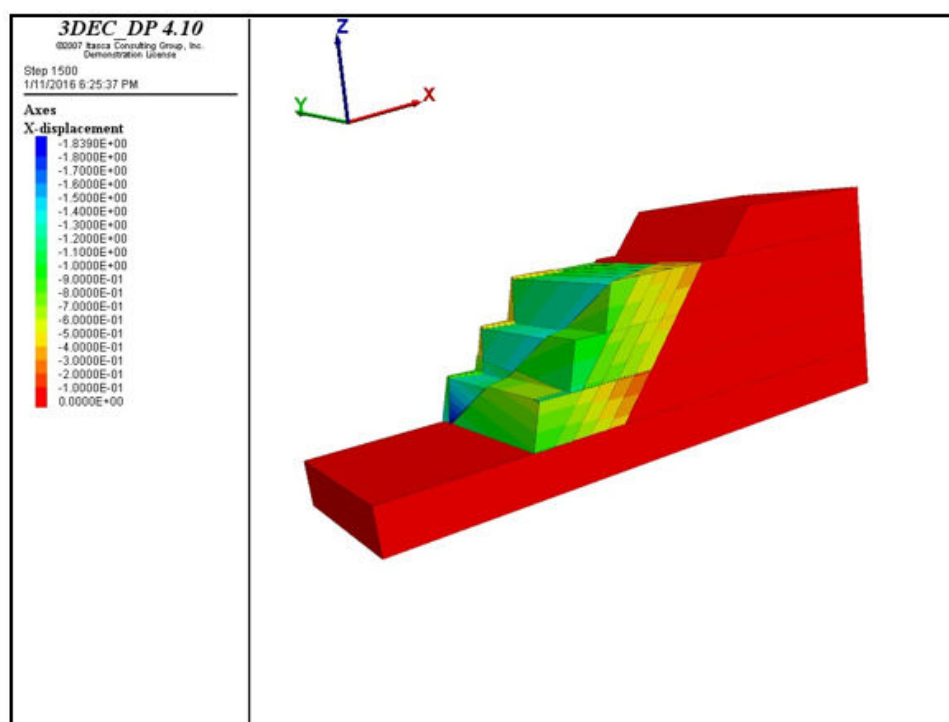


Figure 6. Rock slope failure in progress – X-displacement magnitude.

5 CONCLUSIONS

To cushion the shortfall in the analytical models that tend to oversimplify the prevailing conditions such as; the complexity of the slope's geometry, key geologic features such as numerous jointed weak planes and foliations, discontinuum numerical modelling codes such as *3DEC* tend to be general purpose in nature, for example, discontinuum numerical model can incorporate key geologic features such as faults, foliations providing more realistic approximations of the behavior of the real slopes than analytical models. In fact, discontinuum numerical analysis can help to explain the observed physical behavior than the analytical methods. Furthermore, numerical analysis can evaluate multiple possibilities of geological models and multiple failure modes in which wedge failure could occur.

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