Coal Operators' Conference

Faculty of Engineering and Information Sciences

2014

New fracture models for the progressive failure of rock slopes

Gaetano Venticinque
University of Wollongong

Jan Nemcik
University of Wollongong, jnemcik@uow.edu.au

NEW FRACTURE MODEL FOR THE PROGRESSIVE FAILURE OF ROCK SLOPES

Gaetano Venticinque and Jan Nemcik

ABSTRACT: An improvement to previously developed constitutive FISH User-Defined-Model subroutine by Venticinque (2013) is demonstrated here to simulate the initiation and progressive propagation of fractures through rock structures. This model is based on the amalgamating failure and fracture mechanics theory applied to the finite difference FLAC code. The prior validation of fracture propagation in isotropic rock has been modified to simulate fracture propagation in anisotropic rock. It is shown that the model is capable to accurately simulate fracture distributions in both isotropic and anisotropic rock mass. Furthermore, application of the model to study rock slope stability highlights several characteristics relevant to the progressive failure process of hard rock dry wall slopes. Moreover the model introduces new potential insight towards the effectiveness of rock and cable bolt supports. This work contributes towards improving safety in mines through an increased understanding of key fracture and progressive failure characteristics within geological structures.

INTRODUCTION

In open cut mines the failure of high wall rock slopes is regarded as a non-simultaneous occurrence. Instead massive shear failure events are recognised as being a progressive consequence of local fracture propagation from one area to another within the slope, (Bertoldi, 1988). The knowledge of when fractures initiate and how they may propagate through a rock mass is fundamental to the safety and efficiency of stable mine design. During simulation it is often useful to determine if and more importantly how a structure will fail. This paper presents an example to further demonstrate the capability of the recently developed model by Venticinque (2013).

The fracture model is a constitutive FISH subroutine driving the FLAC 2D geotechnical software by Itasca (2005). It offers independent simulation of rock fracture initiation and propagation behaviour. This model has been previously verified for isotropic rocks where it was proved to offer more realistic solution of the brittle fracture propagation and post failure response of rock as illustrated in Figure 1. The modelled fractures exactly matched the fracture geometry that developed in the isotropic marble rock tested in the laboratory. It also shows the difference between the brittle fracture propagation and the unrealistic plastic-like failure akin to rock at critical stress modelled without the FISH subroutine.

Furthermore in its current form, the model incorporates all three combinations of fractures described by: Mode I tensile, Mixed Mode I-II and Mode II pure shear. This was verified through simulated application over the entire brittle-to-ductile transitional failure range of rock and shown in Table 1.

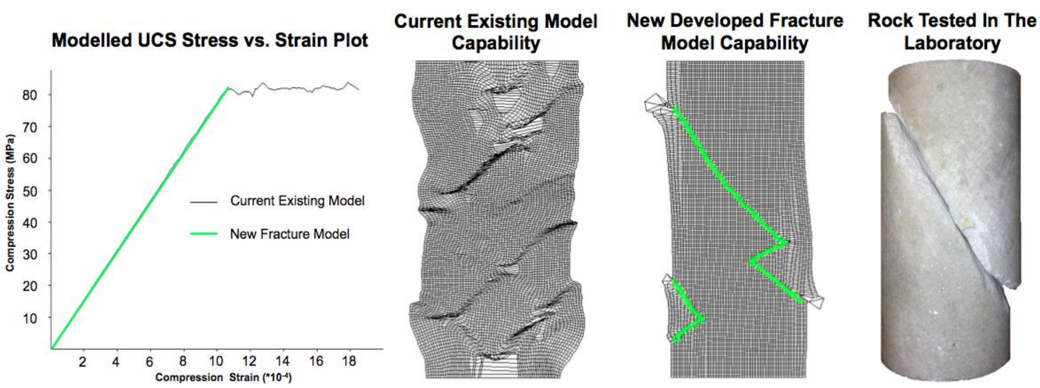
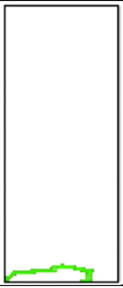
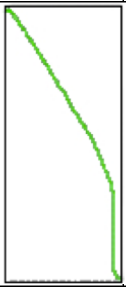
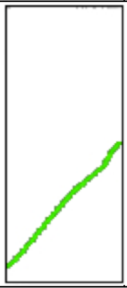
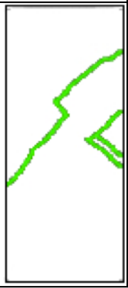
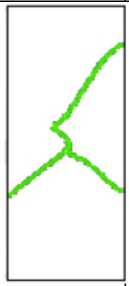
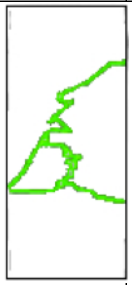


Figure 1 - Comparison of current existing and newly developed modelled failure against real isotropic marble rock tested in the laboratory (Venticinque, *et al.,* 2013)

School of Civil Mining and Environmental Engineering, University of Wollongong, NSW. E-mail: jnemcik@uow.edu.au, M: 0408 711 280

Table 1 - Simulated brittle-to-ductile transitional failure range of isotropic marble rock (Venticinque, *et al.*, 2013)

Confining Pressure	0 MPa*	0 MPa	3 MPa	5 MPa	10 MPa	25 MPa	50 MPa
$\sigma 1$ *Theory*	-3.5 MPa	80 MPa	99 MPa	111 MPa	137 MPa	199 MPa	283 MPa
β ° *Theory*	0°	64°	-	-	-	-	-
$\sigma 1$ *Modelled*	-3.3 MPa	80 MPa	99 MPa	115 MPa	138 MPa	202 MPa	283 MPa
β ° *Modelled*	0°	64°	55°	55°	50°	50°	45°
Fracture Distribution							

**Under Tensile Loading Condition*

VALIDATION OF FRACTURE MODEL FOR ANISOTROPIC ROCK

A FLAC model driven by the FISH fracture subroutine was constructed to simulate uniaxial compression failure in anisotropic marble rock. In FLAC anisotropic rocks are modelled with an isotropic continuum exhibiting reduced strength properties in the direction of existing joints. Simulated results have been validated against theoretical failure criteria for anisotropic rock by Jaeger and Cook (1971).

Validation model

The model used identical model geometry, intact rock properties and loading procedure as in previous verification reported in Venticinque *et al.* (2013) for isotropic rock. The anisotropy was introduced by altering FLAC joint properties to include weakly oriented joints at 40° to the sample vertical axis. The geometry of the modelled cylindrical rock core and the rock properties are shown in Figure 2 and Table 2 respectively.

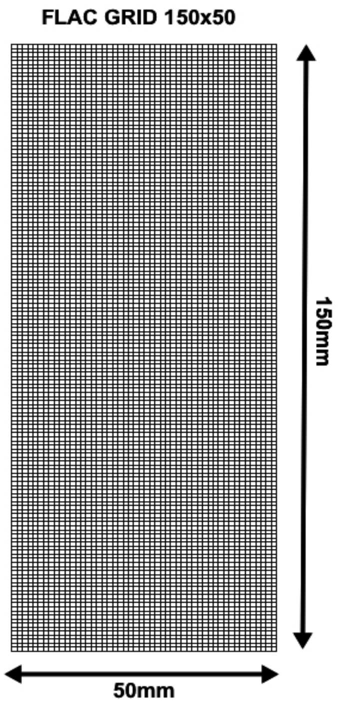


Figure 2 - FLAC model geometry for cylindrical rock

Table 2 - Anisotropic modelled rock properties

Isotropic Marble Rock	Properties	Introduced Anisotropic Marble Rock Properties	
Bulk Modulus (GPa)	58.5	Joint Angle (°)	40
Shear Modulus (GPa)	27	Joint Friction (°)	32
Cohesion (MPa)	19.3	Joint Cohesion (MPa)	1
Tension (MPa)	3.5	Joint Tension (MPa)	3.5
Internal Friction (°)	38.5		
Density (kg/m^3)	2700		

Validation results

The modelled fracture distribution presented in Figure 3 closely aligned expected slip failure along weakly bound joints oriented at 40°. In addition from the respective stress-strain plot, compressive strength was indicated at 8MPa. This value is identical to the theoretical derived value from Jaeger and Cook (1971) equations for anisotropic rock strength, Figure 4. In this way predicted fracture distributions of anisotropic rock in the fracture model are verified.

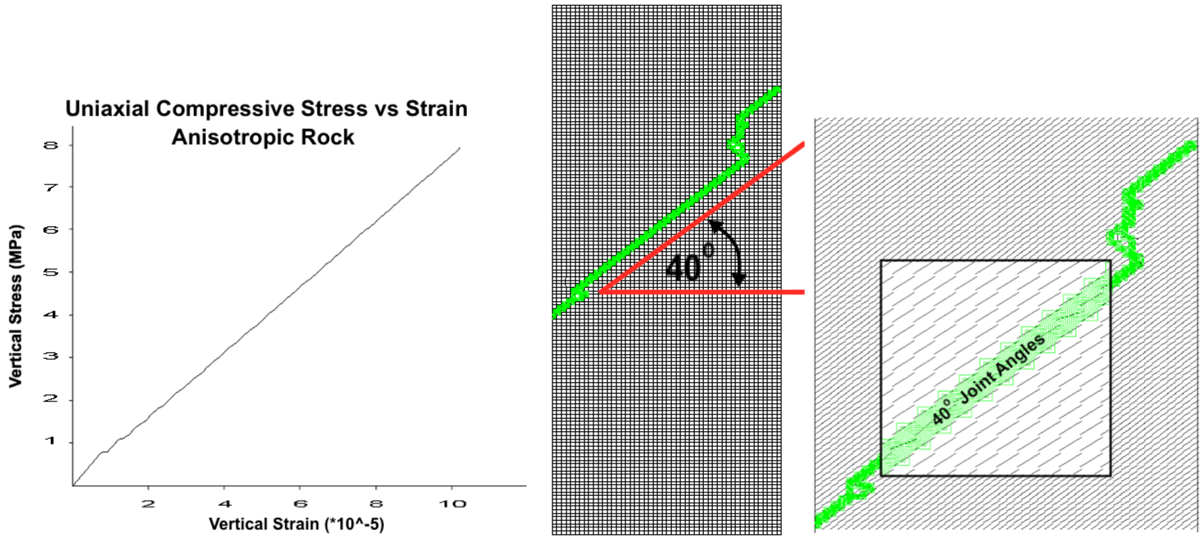


Figure 3 - Interpretation of simulated failure plane produced for anisotropic rock

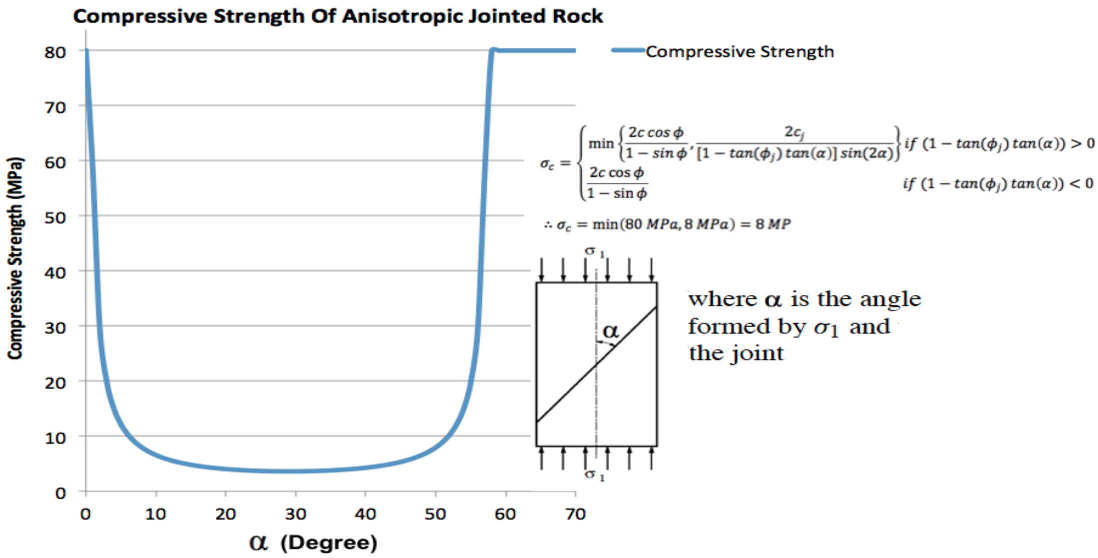


Figure 4 - Comparison of uniaxial compressive strength values for anisotropic rock

SIMULATION OF ROCK SLOPE FAILURE

The application of the FISH subroutine fracture model for progressive failure simulation of hard rock slopes is demonstrated here. Two examples make the advantages of this developed model apparent, in particular the ability to perform comparative analysis between both fracture distribution and progressive failure of unsupported or supported rock slope designs.

Rock slope model

The FLAC model used in these simulations reflected a hypothetical layered rock slope mined at 60° batter angle. In-situ stresses were equalised in models and progressive mining simulation undertaken through incremental excavations of 1m strips. Fractures and localised failures were produced independently throughout this entire process. Geological section of the model had a simple stratigraphy illustrated in Figure 5. The strata consisted of two coal seams overlain by claystone and weathered sandstone unit. Rock properties applied to this geology are listed in Table 3. Mechanical properties of rock and cable bolts can also be found in Table 4 representing the typical values experienced in the field.

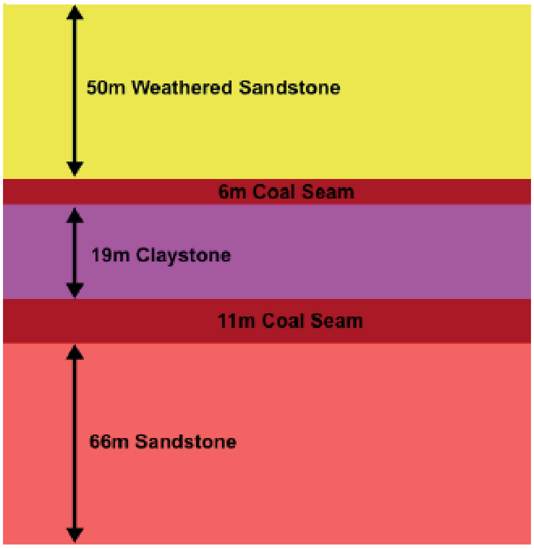


Figure 5 - Geologic stratigraphy of modelled rock units

Table 3 - Modelled rock unit properties

Property	Weathered Sandstone	Coal Seam	Claystone	Sandstone
Bulk Modulus (GPa)	6	2.5	4	6.7
Shear Modulus (GPa)	3	1.1	4.8	4
Cohesion (MPa)	.1	.1	.25	2
Tension (MPa)	.1	.1	.5	1
Internal Friction (°)	32	25	30	35
Density (kg/m3)	2500	1380	2500	2500

Table 4 - Modelled rock bolt and cable bolt properties

Property	Rock Bolt	Cable Bolt
Youngs' Modulus (GPa)	200	200
Yield Strength (MPa)	340	1380
Cross Sectional Area (mm^2)	370	380
Installed Length (m)	2	10-20m
Tensioned Force (kN)	-	100

Example 1 - Simulation of unsupported rock slope

The FLAC results plotted in Figure 6 reveals the dominating fracture produced at failure for the 60-degree batter design. Maximum depth following failure for the unsupported slope is reported as 49m.

Following all fracture initiation and propagation the FLAC model was iterated once again to establish the effect that newly formed fractures would have on the overall model structure. For the FLAC model with the FISH subroutine an immediate failure was simulated through increasing rotational displacement shown in Figure 7. This is compared to FLAC model without application of the FISH subroutine with negligible unchanged displacement. In this way the FISH subroutine demonstrates ability to simulate failure initiated through multiple fracturing that previous FLAC modelling was incapable performing.

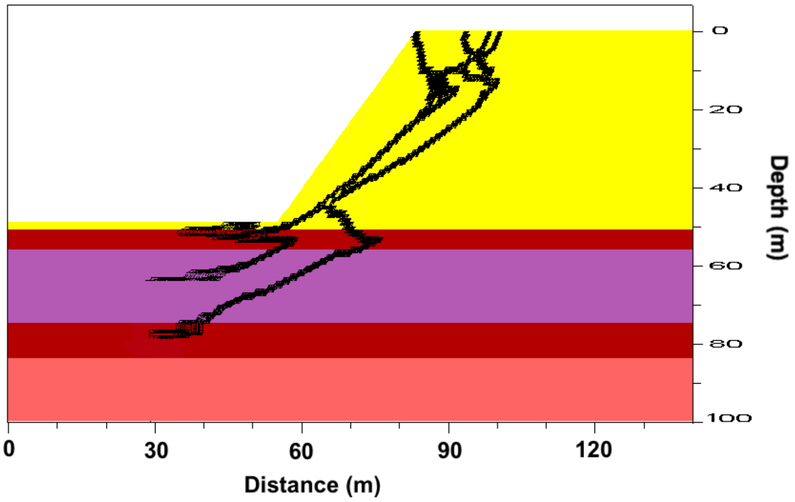


Figure 6 - Simulated failure in unsupported rock slope

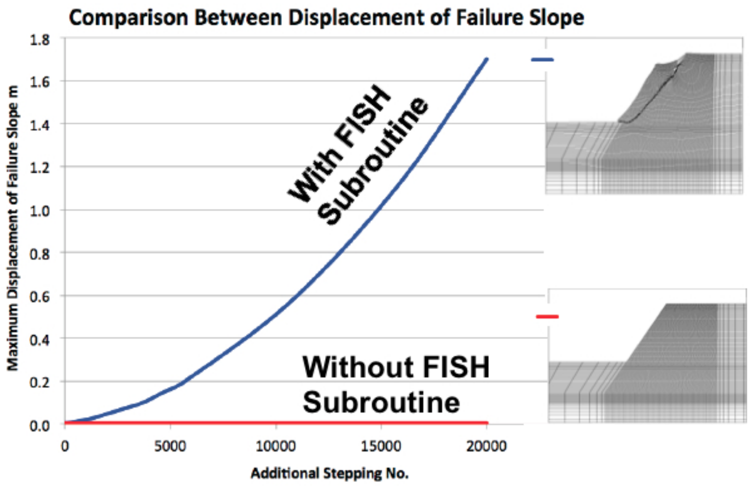


Figure 7 - Comparison between slope displacement at failure for FLAC model with and without application of FISH subroutine

Example 2 - Simulation of supported rock slope

The progressive failure and fracture distribution of rock slope designs reinforced with rockbolts and cable bolts are presented in Figure 8.

In the case of rock slope reinforced with 2m rockbolts at 3m depth intervals, slope failure propagated at 49m. Whilst this may seem indifferent to the previous unsupported result, comparison between fracture distributions reveals otherwise. It is shown that application of rock bolts produced a reinforced capping over the slope face increasing the existing rock strength close to the slope surface. During progressive failure large bulky rock pieces remained intact generating a resistance to material flow. This effectively reduced the large rotational failure size with combination of rotation and plane failure. This was further observed to change from an initially occurring circular failure plane into a non-circular one.

In contrast to rock bolts, 10m-20m cable bolts tensioned to 100kN at 4m depth intervals proved to be significantly more effective, reinforcing an 82m high slope before failure was observed. Reason for this was a deeper penetration by the cable bolts.

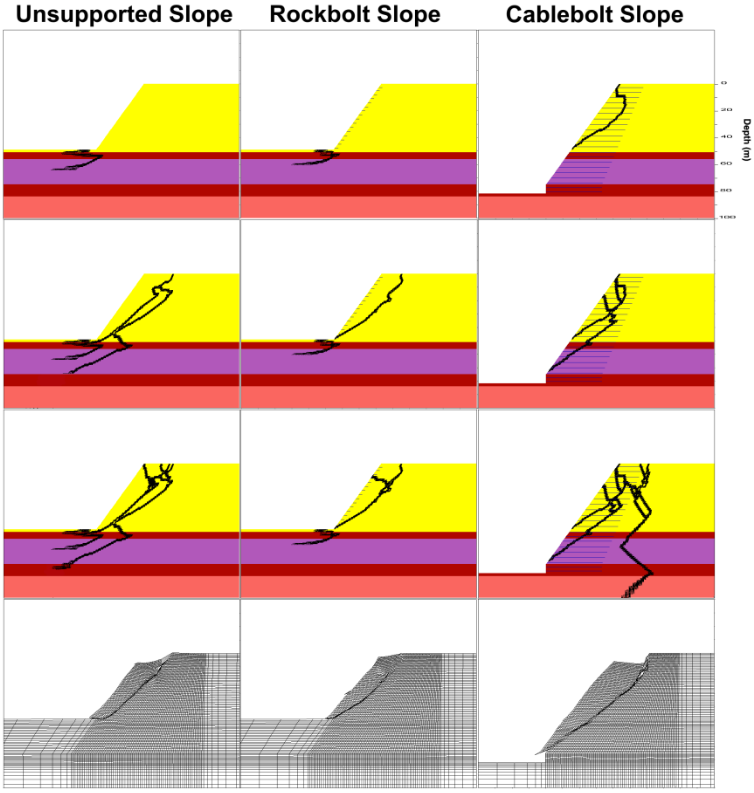


Figure 8 - Comparison of simulated rock slope progressive failure

Through assessing the progressive failure between supported and unsupported rock slope designs several important observations became apparent:

- New fractures that daylight from slope faces are active signs of continuing failure and fracturing deeper into the slope. Fracturing and heaving at the base of the slope toe are signal of a major failure formation.
- Additional signs of progressive slope failure activity is spall like fracture or failure of rock at the slope face. In mining communication of any such observation from haul truck drivers is both first and most important potential warning of a larger potential event and should be inspected accordingly. This reflects already encouraged practice in training haul truck drivers to be able to identify and report suspect out-of-place debris.
- Following any major slope failure event, further fractures behind the failed slope face should not be discounted from triggering additional failure events. As both models have shown, formation of large loose wedges behind the rubble is commonly generated during the progressive failure and relief process. This highlights an active risk of secondary slope failure during the removal of failed debris confining concealed failures.

In summary, the newly developed fracture model is offering new approach to simulate progressive fracture zones within geological structures.

CONCLUSIONS

This study extends verification of a recently developed fracture model to anisotropic rocks. As demonstrated through the analysis of different rock slope controls, such analysis would not have been possible using any previous conventional modelling approach. Through continued validation of other complex problems the new model is envisaged to offer safer and more realistic predictions of rock slope failure for the mining and wider geotechnical industries.

REFERENCES

Bertoldi, C E, 1988. Computer simulation of progressive failure in soil slopes, Doctor of Philosophy thesis, Department of Civil and Mining Engineering, University of Wollongong.

Itasca Consulting Group, I., 2005. FLAC - Fast Lagrangian Analysis of Continua. *Version 5.0, User Manual*. Minneapolis.

Jaeger, J.C. and N.G.W. Cook, 1971. Fundamentals of Rock Mechanics, Chapman and Hall, London.

Venticinque, G A, 2013. Advanced Numerical Modelling of Fracture Propagation in Rock, Honours Thesis, Department of Engineering, School of Mining Engineering, University of Wollongong.

Venticinque, G A, Nemcik, J A and Ren, T, 2013. New fracture model For the prediction of longwall caving characteristics, *6th International Symposium on Green Mining* (ISGM), 2013. University of Wollongong, pp 63-68.