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ARMA 16-346

Roof Collapse Modeling with FLAC3D

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ABSTRACT: Recently, a numerical model based approach for support analysis has been developed at the National Institute for Occupational Safety and Health (NIOSH). In this approach calibrated models are used to determine a stability factor for a supported entry. The stability factor is determined using the strength reduction method (SRM). The success of the SRM depends on the ability to accurately identify a collapsing or stable roof condition in the models. A collapse condition can be identified by considering the mechanical ratio and the velocity/acceleration of the roof grid points. It is found that during collapse, grid points of the zones within the collapsing roof move at least 50 to 100 times faster than in the remainder of the model. However, the default local damping scheme in FLAC3D attempts to arrest the collapsing roof, which may result in an incorrect assessment of roof stability. In order to solve this problem, combined damping is used. In addition, unloading of the model to simulate the excavation is controlled strictly with a relaxation algorithm to provide efficient energy dissipation.

1. INTRODUCTION

The strength reduction modeling technique has a long history in numerical model analysis in rock slope stability engineering (Lorig and Varona, 2000). This modeling technique was adapted to underground coal mine entry analysis by Esterhuizen (2015) to address the need for a method to compare the effectiveness of different support systems when designing ground support in coal mines. The SRM calculates a stability factor of the entry roof by gradually reducing the rock strength until failure is indicated. The stability factor is expressed as the inverse of the strength reduction factor. For example, if collapse occurs when the strength is reduced by a factor of 0.5, the entry stability factor will be 2.0. The stability factor can be used to assist in developing a final support design by comparing the effectiveness of various support systems and the stability of excavations under various geological and loading conditions, as demonstrated by Tulu et al. (2016).

The success of the SRM depends on the ability to accurately identify a collapsing or stable roof condition in the models. In this paper, a procedure to reliably identify the collapsing roof in a FLAC3D model is presented.

2. THE MODELLING APPROACH

The SRM stability factors are determined using the FLAC3D finite difference code (Itasca, 2014). A systematic procedure is used to estimate model inputs based on the Coal Mine Roof Rating (Esterhuizen et al., 2013a). Model calibration and validation studies were conducted to ensure that the developed modeling technique provides realistic estimates of the stability of mine entries. As part of the validation studies, model-calculated stability factors were compared to the results of the empirically based Analysis of Roof Bolt Systems (ARBS) method (Mark et al., 2001). Outcomes of the validation studies are presented by Esterhuizen et al. (2013b, 2013c).

2.1. Material Model and Properties

Similar to the “synthetic rock mass” concept, the rock matrix and discontinuities are modelled separately. This approach is necessary to capture both rock matrix failure and bedding-related slip in the sedimentary coal measure rocks (Figure 1).

The strain-softening ubiquitous joint constitutive model is used to simulate the bedded coal measure rocks. The models are run in large strain mode to incorporate the change in support capacity due to large deformation as the modeled entry approaches the point of collapse.

Support units are modelled with the built-in finite element structural components available in FLAC3D (Figure 1). Interfaces are modelled between different rock units, allowing joint opening and closing to be simulated.

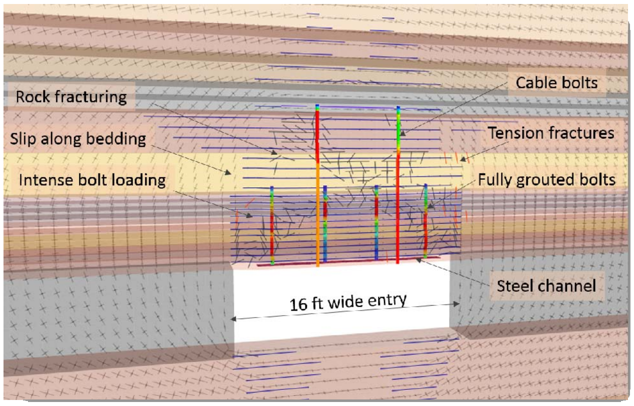

Fig. 1. Material model and roof support.

The strength of the bedded rocks can be highly anisotropic, and anisotropy has an important impact on roof stability under high horizontal stresses. The built-in script language (FISH) is used to incorporate the strength anisotropy of bedded rock (Esterhuizen et al. 2013a).

2.2. *Boundary Conditions and Model Layout*

The models are set up to simulate cross sections through coal mine entries in various geological settings encountered in the United States. The model boundaries are located at least 24 m (79 feet) from the edges of the entry and extend at least 20 m (65 feet) above and below the entries. The outer boundaries of the models are fixed against normal displacement, while allowing displacement to take place along the boundary surface (roller boundaries). The model thickness is based on the bolt spacing, which represents the typical slice of rock supported by a single row of bolts. The element (zone) sizes in the vicinity of the entry are between 0.25 and 0.35 m (10 to 14 in). In relatively thin geologic beds, the element height is constrained to the thickness of the bed with a minimum of 15 cm (6 in).

Rock bolt supports are modeled across the entry roof, located in the center of the slice. The boundary conditions cause the model to effectively simulate a long entry excavation with repeating rows of supports.

The stress within the models is initialized based on field stress measurements, where available, or using the best published data available for the geological region. When field stress measurements are not available, the horizontal stress is based on the relationships published by Dolinar (2003) in which the horizontal stress is affected by the modulus of elasticity of each rock layer.

3. DEFINITION OF COLLAPSE/FAILURE IN THE SRM

The FLAC3D software has an automated procedure to calculate the factor of safety (FOS) using the strength reduction method. In the user manual, it is indicated that the definition of failure must be established by the user (Itasca, 2014). The automated FOS procedure uses a mechanical ratio value of 10^{-5} to separate a failed model from a stable one. The mechanical ratio is the ratio of the maximum unbalanced force to the total applied forces in the model. It is found that using only the mechanical ratio to separate a failed roof from a stable one is much harder for entry stability models.

Figure 2 shows the contour plot of the vertical velocity of a collapsing roof. It is clear from this figure that grid points on the roof are moving almost 50 to 100 times faster than the remaining parts of the model. Figure 3 shows the mechanical ratio versus the number of steps for this model. The default value of 10^{-5} used in FLAC3D is indicated as a horizontal line. It is clear that the mechanical ratio of this model with a collapsing roof is much lower than the default value used in the automated FOS procedure. The small mechanical ratio would erroneously indicate a stable condition.

It is found that it is possible to observe very low mechanical ratios in models with a collapsing roof entry. This is different from slope stability models, for example, where relatively large volumes of material are mobilized which produce larger unbalanced mechanical ratios. Roof collapse in entries typically represents a much smaller portion of the total model volume which may explain why smaller mechanical ratios are indicated.

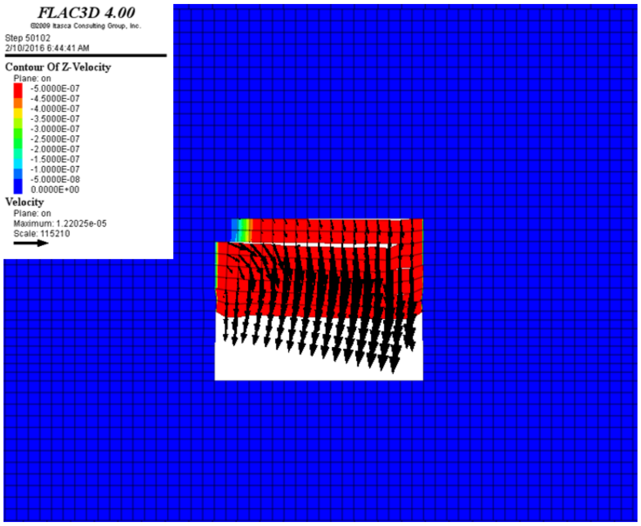

Fig. 2. Velocity contour of a collapsing entry roof.

It is found that roof collapse can be reliably identified by tracking both the velocity of the roof grid points and the mechanical ratio. The limiting value for roof velocity to define collapse was identified through the analysis of a large number of models with different geological, stress, and support conditions. The results indicated that during collapse, grid points of the zones within the collapsing roof move at least 50 to 100 times faster than the remaining part of the model. Currently a limiting roof velocity of 5×10^{-7} m/solution-cycle is used to indicate roof collapse.

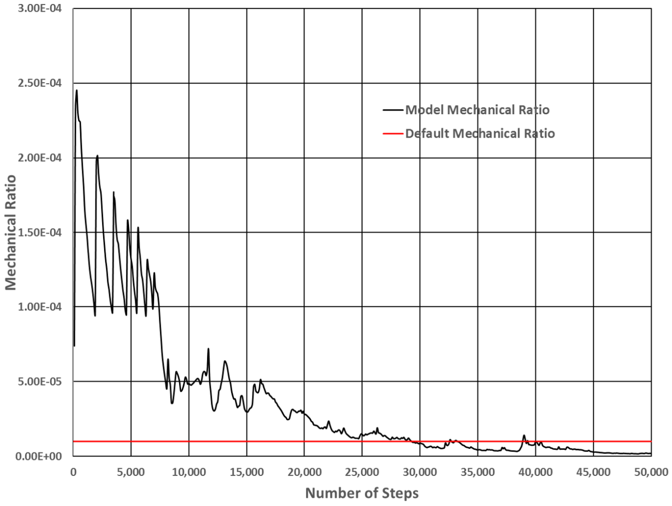

Fig. 3. Mechanical ratio of a collapsing entry roof.

4. EFFECT OF DAMPING ON A COLLAPSING ROOF

FLAC3D has several damping schemes to achieve a steady state solution. The damping scheme can have a significant impact on the interpretation of roof collapse.

4.1. Effect of Local Damping

During the analysis, it is found that the default local damping scheme in FLAC3D attempts to arrest the collapsing roof, which may result in an incorrect assessment of roof stability or unrealistically high run times to decide stability of the roof. This behavior generally occurs when strength reduction causes the models to be close to the stability limit.

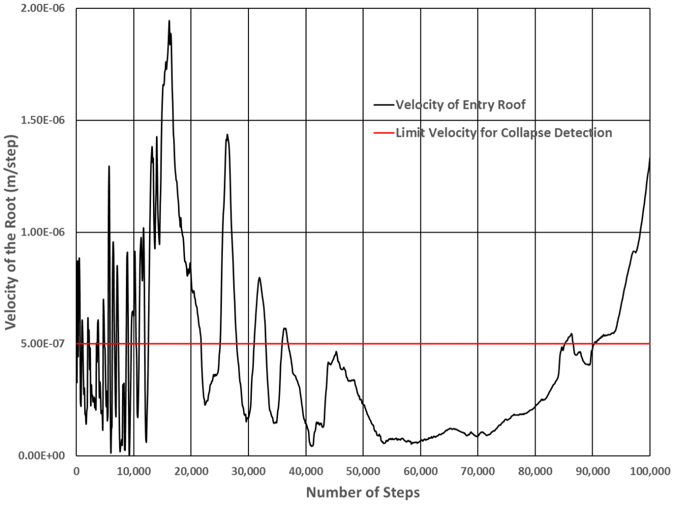

Fig. 4. Velocity history of a collapsing entry roof.

In Figure 4, the history of the vertical velocity of a collapsing entry roof is shown using local damping. During the initial 40,000 steps, the velocity history plot shows fluctuating velocities near limiting velocity (horizontal line in Figure 4). Near equilibrium, the model is in a transient condition. After 40,000 steps, velocities start to drop to lower values (up to 10 times or more). After 70,000 steps, velocities start to increase and finally the roof starts to accelerate and pass the velocity limit. In this model the mechanical ratio during roof collapse is much lower than the default mechanical ratio for static equilibrium (10^{-5}).

Near the stability limit, roof support (primary bolts or cable bolts) can resist the large roof deformations and reduce the velocity of the roof and, if capacity is adequate, stop the roof from falling. At this stage, local damping provides unrealistic resistance to the roof that may appear to indicate a stable condition. Local no-viscous damping applies damping force that opposes motion of a grid point. In general, this damping dissipates energy very efficiently. However, when there is a significant uniform motion like roof collapse in the SRM models, this damping attempts to arrest the falling roof, which is not desired. In order to solve this problem, combined damping is used instead of the default local damping.

4.2. Effect of Combined Damping

The FLAC3D manual indicates that combined damping should be used if there is significant rigid-body motion of a system in addition to oscillatory motion to be dissipated (Itasca, 2014). It is important to note that combined damping dissipates energy at a much slower rate than local damping. Therefore, it should be used with caution. In order to show what might be the problem with combined damping in the SRM model, an elastic circular entry (Figure 5) was modelled with local and with combined damping.

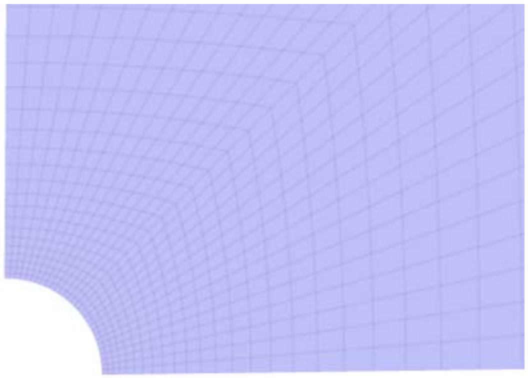

Fig. 5. Circular elastic entry in a constant stress field.

In this elastic model, the horizontal stress to vertical stress ratio is set to one. The major and minor principal stresses of zone number 423 were monitored. This zone is located in the third row from the excavation boundary at 45 degrees from the horizontal axes. Excavation is made instantaneously. Figure 6 shows the convergence of the principal stresses to the solution with two different damping methods.

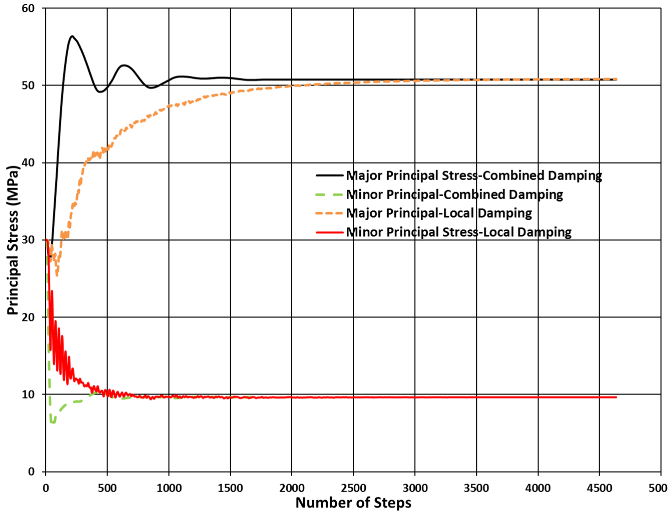

Fig. 6. Major and minor principal stresses for circular elastic entry in a constant stress field.

Figure 6 shows that the two methods follow different stress paths to the solution. Local damping dissipates energy more efficiently and it follows a more stable path.

Convergence of the solution against the Mohr-Coulomb failure envelope shows the significance of following different paths more clearly (Figure 7). The Mohr-Coulomb failure envelope is defined by Eq. 1.

$$f^s = \sigma_1 - \sigma_3 N_\phi + 2c\sqrt{N_\phi} \tag{1}$$

$$N_\phi = \frac{1+\sin(\phi)}{1-\sin(\phi)} \tag{2}$$

where

σ₁ = major principal stress.
σ₃ = minor principal stress.
c = cohesion.
φ = friction angle.

If Eq. 1 is zero or negative, this means that stress applied to element is higher than its strength. For this analysis the rock strength was selected so that the stress condition of zone 423 would plot on the Mohr-Coulomb failure envelope.

The vertical axis in Figure 7 shows the values of the function defining the Mohr-Coulomb failure envelope (Eq. 1) for zone 423. Cohesion and friction angle are selected so that the failure envelope converges to a value slightly above zero which means that the zone does not yield, as expected. Local damping converges to this point, always staying above zero, but combined damping passes below zero on more than one occasion, which would initiate failure in the early stages of the solution of an elastic-plastic model. The combined damping would therefore create an erroneous interpretation of instability.

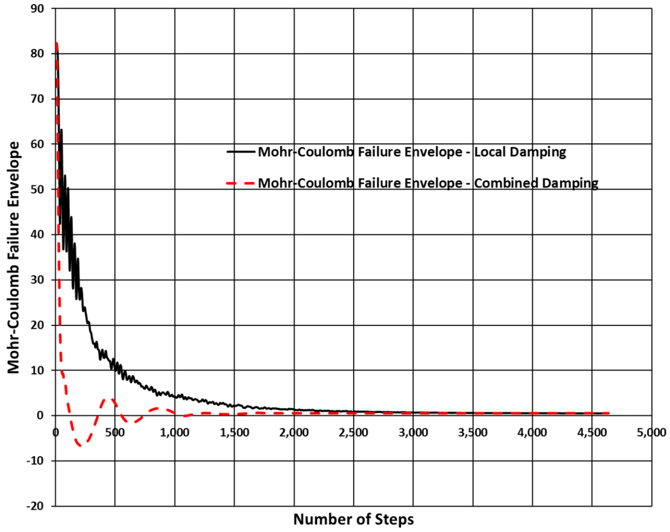

Fig. 7. Convergence of Mohr-Coulomb failure envelope to solution with different damping methods.

In order to prevent this type of problem with combined damping, the internal pressure in the excavation is relaxed in a controlled manner to prevent excessive fluctuation of the grid-point velocities. In the entry model, internal forces are applied to boundary grid points around the perimeter of the excavation. Before mining, it is checked to make sure that applied forces at the boundary grid points provide static equilibrium under in-situ stress conditions. Then the boundary forces are reduced in a servo-controlled manner based on the mechanical ratio of the model. Figure 8 shows an example where combined damping and controlled entry relaxation were used together. The Mohr-Coulomb failure envelope converges to the solution in a stable manner similar to local damping.

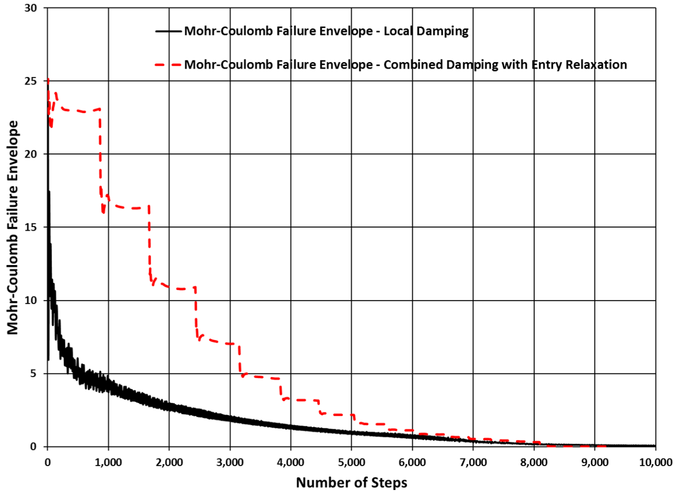

Fig. 8. Convergence of the Mohr-Coulomb failure envelope to solution with the controlled entry relaxation algorithm and combined damping method.

4.3. Decision of Collapse in SRM Model

Based on the analysis of more than 600 models using combined damping, in the SRM models the static mechanical ratio was set to 10^{-6} and the limiting velocity was set to 5×10^{-7} to define a collapsing roof.

5. CONCLUSION

The strength reduction method applied to entry roof stability requires that the collapsing roof should be reliably identified during a FLAC3D analysis. It was found that detecting a collapsing roof using both the mechanical ratio and the velocity of roof grid-points results in consistent identification of a collapse condition. In addition, it is found that a default local damping scheme in FLAC3D attempts to arrest the collapsing roof, which may result in an incorrect assessment of roof stability or unrealistically high run times to decide on the stability of the roof. This behavior generally occurs when the strength reduction causes a model to be near the equilibrium limit.

In this paper, it is shown that combined damping with strictly controlled entry relaxation can be used to model a collapsing roof of an entry in an accurate and efficient way.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and don not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mentioning and company name, product or software does not constitute endorsement by NIOSH.

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