Dynamic Stability Evaluation of Underground Caverns in Jointed Rock Mass using Friction Energy Generated by Joint Sliding

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Abstract: General seismic damage surrounding underground excavations of jointed rock masses is closely associated with the presence and response of discrete fracture networks. As the failure of rock masses is mainly controlled by joints, energy dissipated through slippage along joints is proposed as an evaluation index for dynamic stability analysis of underground caverns. Energy dissipated in slippage is represented as a product of the shear stress and plastic shear displacement. The method was demonstrated through dynamic analysis of an underground cavern containing joints of varying dip friction angle and location. The results show that the proposed index can record the failure history and damage of rock structures surrounding an underground cavern subjected to dynamic loading. The effects of four types of joint sets on the dynamic stability of a cavern in the DaGangshan hydropower project were assessed using the friction energy of the joints. The combination of steep and non-steep joint sets was found to be much more unfavorable to large caverns than joints sets of only steep dip angle or non-steep dip angle.

Keyword: friction energy; dynamic analysis; joint; underground cavern

1. Introduction
With the progress of social and economic development in western China, a large number of large-scale hydropower projects have been constructed or are in planning. Most are designed with large underground caverns containing major hydraulics structures. The size of underground powerhouses have reached, for example (length × width × height):
- 436 m × 33.8 m × 78.2 m XiLuo-Du
- 439 m × 32.2 m × 78.5 m BeiHeTan
- 284.8 m × 25.5 m × 66.7 m JinPing I
- 309.75 m × 30.0 m × 73.84 m LaXiWa
- 226.5 m × 30.8 m × 73.78 m DaGangshan

The above projects are not only related to specific geology and rock structures but also located in strong earthquake areas in southwest China. For example, the degree of seismic intensity at BeiHeTan and XiLuoDu is VIII, with peak ground accelerations of 168 and 180 gal respectively [1]. Tunnels that cut across faults are subjected to serious damage during large earthquakes, as seen in the 1994 California earthquake [2], the 1995 Kobe earthquake [3], and the Wenchuan earthquake [4]. The dynamic stability of large underground caverns that are much larger than ordinary tunnels is a key technical issue for the design and safe operation of hydropower projects.

The current main stability evaluation method for underground caverns is based on continuous medium analysis under static conditions, such as the displacement discrimination method [5], the plastic zone discrimination method [6], and the strength reduction method [7]. These methods all have some
deficiency in dynamic analysis. For example, a monitoring point at the boundary cannot always be accurately representative due to the heterogeneity of rock masses. The strength reduction method requires many trials leading to long dynamic analysis computational times. The plastic method is not applicable to block rock masses where stability is predominantly controlled by joints. While block theory [8] can be used to study a variety of complex joint conditions it cannot consider changes in rock stress during earthquakes.

In this study, friction energy of slip joints is proposed as a dynamic stability evaluation index for rock structures. The applicability of this index is first demonstrated by dynamic analysis of an underground cavern intersected by joints of varying dips, friction angle and location. Numerical simulations are then performed for the large underground cavern in the Dagangshan hydropower project using the distinct element method. Finally, the effects of four different joint sets on the dynamic stability of the cavern are evaluated by friction energy of the joints.

2. Formula of Friction Energy of Joint

The total energy balance can be expressed in terms of the released energy \( W_r \), which is the difference between the work done at the boundary of the model and the total stored and dissipated strain energies [9]:

\[
W_r = W - (U_e + U_b + W_f + W_p)
\]

where:

- \( W_r \) = released energy
- \( W \) = total boundary loading work supplied to the system
- \( U_e \) = total stored strain energy in material
- \( U_b \) = total change in potential energy of the system
- \( W_f \) = total dissipated energy in joint shear and
- \( W_p \) = total dissipated work in plastic deformation of intact rock

\( W_f \) and \( W_p \) reflect shear failure of the joints and plastic damage of the blocks, respectively, caused by external force. \( U_e, U_b, \) and \( W \) describe the energy of the whole system. Since rock structures mainly slip along joints, \( W_f \) is proposed as an evaluation index for the dynamic stability of rock structures. In the Mohr–Coulomb model, the joint shear stiffness is linear. The energy is determined for each contact along all joints in the model. The friction loss is calculated as follows:

If \( f_s > f_{\text{umax}} \),

\[
usf = \left( f_{s1} + f_{s2} \right) us / 2
\]

where:

- \( usf \) = friction energy at a contact during a time step
- \( f_{s1} \) = previous shear force at a contact
- \( f_{s2} \) = current shear force at a contact
- \( us \) = increment in shear displacement

The total dissipated friction energy \( W_j \) is summed over all time steps and contacts:

\[
W_j = \sum_1^{n_t} \sum_1^{n_j} usf
\]

where \( n_t \) is the number of time steps and \( n_j \) is the number of contacts.

3. Verification of Friction Energy as Evaluation Index

3.1 Udec Model Configuration

The model shown in Figure 1 was chosen to evaluate the applicability of friction energy for the stability evaluation of an underground cavern. The cavern in the model has an arch-profile crown shape. It is 30 m wide, 74 m high and located at a depth of 400 m. The scale of the model is ten times that of the cavern in order to eliminate boundary effects on the results.

Joints were assumed to intersect the underground cavern in three locations respectively, i.e., case 1, 2, and 3 shown in Figure 1. Joint dips and friction angles were assigned representative values as listed in Table 1. A total of 36 cases were generated by random combinations of these factors.
Two sets of artificial joints dipping at 45° with 10 m spacing were introduced into the model for more precise evaluation. These artificial joints were in the same location for each of the 36 cases. They were assigned very large strength parameters to ensure that they would not break. Intact rock in the present model is considered to be an ideal elastoplastic material that follows the Mohr Coulomb criterion. Mass density $\rho = 2650$ kg/m$^3$, elasticity modulus $E = 20$ GPa and Poisson’s ratio $\nu = 0.25$. Slip failure of the joint is also governed by the Mohr–Coulomb criterion. The normal stiffness of the joint $K_n = 20$ GPa/m and the shear stiffness $K_s = 2$ GPa/m. The vertical stress varies linearly with depth and the horizontal stress is calculated by $v_x = k_0 v_z$, where $k_0$ is assumed to be 0.6.

### 3.2 Modeling Procedure

Numerical calculations involve static and dynamic stages, including:

1. Equilibrium at the in situ stress state and excavation of the cavern
2. Application of the dynamic load

During the static calculation stage, a zero-velocity boundary condition was specified at the lateral boundary in the horizontal direction and the base of the model in the vertical direction. The model was initially run to reach equilibrium and find the in situ stress under the specified boundary conditions. The entire cavern was then mined in three steps. Numerical calculation was terminated in each case once the specified equilibrium criterion was satisfied.

During the dynamic calculation stage a viscous boundary condition was applied to the base of the model and free field boundary applied to the sides. The seismic input is a simplified artificial wave with a frequency of 4 Hz and acceleration of $a_{\text{max}} = 0.25$ g. The amplitude of the wave gradually approaches maximum over 2 s and is constant for 1 s, gradually decreasing to zero over 1 s (Figure 2). The seismic record was transformed into a stress record and applied to the quiet boundary. The applied stress is doubled to overcome the effect of the viscous boundary. Rayleigh damping at 0.05% of 4 Hz frequency was applied to simulate the actual material damping. Simultaneously, the friction energy was counted and recorded at each time step.

![Figure 1. Sketch of underground cavern model](image)

![Figure 2. Time history of seismic wave](image)
3.3 Numerical Results and Discussion

Parametric analyses focused on the friction energy associated with the joint dips, location, and shear strength. Figure 3 shows a plot of the time history of friction energy of the joints intersecting the bottom of the sidewall at different joint dips under friction angle of 35°.

Figure 3. Time history of the friction energy of joint at varying dips

Figure 3 shows that joint dipping at 60° generated the greatest friction energy, which means the cavern suffered maximum damage after dynamic loading. Liu gang’s model tests also showed that an opening intersected by joints dipping at 60° receives a greater damaged area compared to those intersected by joints dipping at 75° and 45° after axial loading [9]. The friction energy of the steep joints dipping at 60° and 75° grows faster than that of the gently dipping joints, and reaches its maximum within 1.5 s, before the seismic wave reaches its peak, which indicates that the steep joint intersecting the bottom of the sidewall is prone to slip.

Figure 4 summarizes the relationship between friction energy increment and joint dips for different friction angles and joint locations after dynamic loading. Friction energy of the joints intersecting the upper sidewall is small, which suggests relative stability of the rock structure. This is mainly because stress concentration in the arch increases the normal stress and shear strength of the joint after excavation. When the joint intersects the middle and lower part of the sidewall, stress relaxation caused by excavation can affect the joints in a larger range and reduce their strength. These affected joints are prone to sliding during dynamic loading and generate more friction energy.

In summary, the friction energy of the joints was able to record failure history and is an effective index for the dynamic stability evaluation of rock structures around an underground cavern.

Figure 4. The friction energy of the joints with different friction angles, joint angles, and cutting positions after dynamic loading

4. Dynamic Stability Analysis of Dagangshan Underground Hydropower House

The DaGangshan underground powerhouse is located at a depth of 390–520 m on the left bank of the DaDuHe river. The axial direction of the powerhouse is N55°E. It has an arch-profile crown and tall side wall with dimensions of 30 m width and 74 m height. Four different combinations of unfavorable
geological structures around the cavern were set up respectively, including a combination of gently and moderately dipping joints in Case 1, gently and steeply dipping joints in Case 2, moderately and steeply dipping joints in case 3, and two steeply dipping joints in Case 4. Figure 5 shows the model configuration. The joint sets are only created within a limited region around the cavern which is sufficient to encompass the extent of joint failure. The artificial joints mentioned above are distributed in other areas. All joints have a constant spacing of 10 meters.

Figure 5. Model of underground cavern for numerical analysis.

In this analysis, the blocks are set as elastic material with properties:
- \( P = 2650 \, \text{kg/m}^2 \)
- \( E = 20 \, \text{GPa} \)
- \( V = 0.25 \)

and joint properties:
- \( K_v = 20 \, \text{GPa/m} \)
- \( k = 2 \, \text{GPa/m} \)
- Friction angle = 30°

The modeling procedures and in situ stress are generally the same as discussed before, except that the excavation is divided into nine stages (Figure 5). The system was subjected to a longer artificial seismic wave similar to Figure 3 but vibrating with maximum amplitude for 3 s. Figure 6 shows a plot of the collapsed block and slip joints after dynamic loading. The thickness of the black line plotted on the slip joints is proportional to the shear displacement of slip joints. The movable blocks with steeply inclined sliding surfaces in Case 2, Case 3, and Case 4 collapse to the bottom. The movable blocks with moderately inclined sliding surfaces only partially collapse in Case 1 and detach from the parent rock over the entire right-side wall in Case 3. The movable blocks with gently inclined sliding surfaces in Case 2 are relatively stable and do not collapse. There is a wider distribution of sliding joints on the side wall in Case 4 than in the previous three cases. Overall, each of the four types of structures have collapsed blocks and sliding joints. It is difficult to judge which one is the most unfavorable.

Figure 6. Shear displacement of joints for different joint sets after dynamic loading.

The slippage process can be better understood by considering the time history curve of the friction energy of joints as shown in Figure 7. The process of collapse and friction energy growth in Case 2 has the following two different stages. When the seismic wave reaches its maximum amplitude within 3.5 s, the blocks on the left wall with a steeply inclined sliding surface collapse first, and the friction energy
increases rapidly. In the subsequent loading, the friction energy tends to converge, indicating that the blocks on the right wall do not collapse with a gently inclined sliding surface. Case 3 differs in the following three stages. First, the friction energy increases rapidly as the blocks on the left wall collapse, like in Case 2. In the following 3.5–5 s, there is little growth in friction energy and no block collapse. As the seismic wave decays at the end, the friction energy increases at an increasing rate, indicating the blocks with a moderately inclined sliding surface on the right wall can no longer stabilize themselves. The friction energy in Case 1 and 4 increases slightly before the seismic wave weakens, and then tends to converge, indicating a relatively small number of collapsed blocks.

![Figure 7. Time history of friction energy of the different joint sets during dynamic loading.](image)

By comparing the friction energy, the rock mass structure that is most unfavorable for the cavern is the steeply and moderately dipping joint sets in Case 3, followed by the steeply and gently dipping joint sets in Case 2, two steeply dipping joint sets in Case 4, and finally gently and moderately dipping joint sets in Case 1.

In addition, the shape of the block also affects the stability of the rock structures. The right wall in Case 1 and 3 has blocks with different shapes and the same middle-inclined slip surface. When the blocks on the right wall collapse, the friction energy increases by 38 MN•m from 5 to 7 s in Case 3, and up to 10 MN•m in Case 1 including full load time. The shape of the block on the right wall in Case 3 is more unfavorable according to friction energy. This is related to the mechanics of excavations and earthquakes. The center of the movable blocks on the right wall in Case 3 are closer to the excavation surface than in Case 1. The stress and strength of the block surface will decrease significantly after excavation. The steep trailing edge of blocks in Case 3 which is approximately perpendicular to the horizontal ground motion easily opens and loses resistance during dynamic loading.

5. Conclusions

As the failure of jointed rock masses is mainly controlled by its joints, the energy dissipated through friction in the joints was proposed as an evaluation index for dynamic stability analysis of underground caverns in jointed rock masses. The applicability was verified through dynamic analysis of an underground cavern with varying joint parameters (dip, friction angle, and location). The effects of four types of joint sets on the dynamic stability of cavern in the DaGangshan hydropower project were assessed according to the friction energy of the joints.

In summary, this study identified the following points:

- Friction energy of joints can record the failure history and damage to rock structure surrounding an underground cavern under dynamic loading.
- Friction energy of joints can be used to evaluate the stability of rock structure due to shear failure.
- Joints dipping at 60° are more unfavorable for large caverns compared with joints dipping at 75° and 45°.
- A combination of steeply and non-steeply dipping joint sets is much more unfavorable to large caverns than joints sets of only steep dip angle or only non-steep dip angle.
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