Numerical analysis of ground support systems subjected to dynamic loading

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Abstract. Herein, a new numerical approach is proposed to simulate the dynamic loading processes in mines. To present a realistic seismic phenomenon, a parallel two-dimensional seismic source is introduced by adjusting the classic point seismic source. The seismic source can be easily integrated into the universal distinct element code numerical model, and it can adjust its bearings and strength. The numerical model assumes an elastic rock mass with potential fractures because the dynamic-related bulking surrounding excavations is mainly caused by the separation and sliding of fracture planes; cable bolts are installed on the sides of roadways. The numerical simulations can accurately reproduce the full dynamic loading process. After axial forces build up, numerical results from a case analysis show that cable bolts considerably restrict the movement of the surrounding rock mass towards the roadway, preventing potential fractures from developing into the large opening cracks. The cable bolts do not considerably change the local stresses, although they can maintain local horizontal stress compressive near the roadway surface. The monitored cable element experiences multiple loading and unloading processes; it is found that cable bolts initially cause rapid attenuation of seismic velocities and then dissipate dynamic energy in a fluctuating manner.

Keywords: Numerical analysis, ground support system, dynamic loading, two-dimensional seismic source, potential fractures.

1 Introduction

Mining-induced seismic events often cause severe damage around excavations, threatening the safety of personnel and equipment and disrupting production. In mines, seismic events are generally associated with the sudden failure of highly stressed areas in the rock mass, which is referred to as a seismic source. The seismic source may be close to or far away from the excavations. The seismic strength of the limited areas around the excavations when the seismic waves propagate through them, as well as the strength of the local rock mass, determines whether or not the seismic events cause severe damage.

Applying a reasonable support system is one of the practical approaches to relieving seismic damages. Great effort has been made to relate the performance of ground support systems to the strength of dynamic loading through in-situ tests [1,2], in which blasting-induced seismic events are popular due to the difficulty of triggering a violent
failure in the rock mass in a controlled manner. Simulating the performance of the ground support system under dynamic loading using numerical models is an alternative method that reduces costs and laborious undertakings.

A numerical simulation method is suggested here to evaluate dynamic loading effects on excavations and ground support systems. The main advantage of this method is that it provides a full scenario to understand the seismic initiation, development, and interaction among the seismic wave, excavations, and ground support systems.

2 Simulation strategy

To realistically reproduce the dynamic interactions among seismic waves, excavations, and ground support systems, representation of seismic sources, failure modes of rock mass, and seismicity-resistant mechanisms of reinforcing components are factors that should be considered.

2.1 Representation of seismic sources

Micro-seismic monitoring data in longwall mining coal mines show that seismic events are mainly caused by shear failures in front of the face [3]. Considering that the fault slip phenomenon is characterized by shear failure, incorporating the fault slip seismic source model into the mining dynamic analysis appears to be a suitable choice. A two-dimensional seismic source is introduced by adapting the classic point seismic source, which is a three-dimensional fault slip model for earthquake research. The coordinate arrangement follows the convention for describing a point seismic source, and coordinates \((x, y, z)\) belong to a local coordinate system based on the fault bearings (see Fig. 1 (a)). The point source is located at the origin of coordinates, the fault lies at the \((x, y)\) plane, and the direction of fault slip is parallel to the x-axis. A two-dimensional seismic source is obtained by first extending the point source along the y-axis to create a line source with infinite length, and then symmetrically expanding the line source inside the \((x, y)\) plane to create a strip source with a width of 2B. Fig. 1 (b) shows a two-dimensional fault with a dip angle, \(\theta\), in the plane strain numerical model.

Assuming the fault is embedded in an infinite homogeneous, isotropic elastic medium, with known constants, rock density, \(\rho\), bulk modulus, \(K\), and shear modulus, \(\mu\). Speed of P wave, \(\alpha\), and speed of S wave, \(\beta\), are two constants obtained by applying equations \(\alpha = \sqrt{(K + 4\mu/3)/\rho}\) and \(\beta = \sqrt{\mu/\rho}\).

The displacement field is obtained by

\[
\begin{align*}
    u^A(x,z) &= \frac{\bar{u}\mu}{4\pi\rho} \left( \frac{2}{\beta^2} - \frac{2}{\alpha^2} \right) \frac{z(pn - qm)}{mn} + \frac{2}{\beta^2} \left( \frac{\arctan \frac{q}{z} - \arctan \frac{p}{z}}{z} \right) \hat{x} \\
    &+ \left( \frac{2}{\beta^2} - \frac{2}{\alpha^2} \right) \frac{z^2(n - m)}{mn} + \frac{1}{\alpha^2} \ln \left( \frac{n}{m} \right) \hat{z}
\end{align*}
\]

(1)

where \(\bar{u}\) is the average shear displacement of the fault; \(\hat{x}\) and \(\hat{z}\) are unit vectors; \(m = z^2 + (x - B)^2\), \(n = z^2 + (x + B)^2\), \(p = x - B\), and \(q = x + B\).
The combined parameter, \( \bar{u}\mu \), represents the seismic moment per area, representing the strength of seismicity; the parameter, \( B \), determines the shape of the displacement field. It can be inferred that the energy radiation patterns of the two-dimensional seismic source in the far-field are fully consistent with those of the point seismic source in the \((x, z)\) plane [4], i.e. S waves dominate in the directions parallel and normal to the fault plane, while P waves dominate in the directions with an angle 45° relative to the fault plane.

![Diagram](image1)

**Fig. 1.** Representation of seismic sources: (a) the local coordinate system for seismic sources and (b) a two-dimensional fault in the \((x, y)\) coordination system.

The bearings and strength of the two-dimensional seismic source can be easily changed, and the seismic source could be initiated anywhere in the numerical model.

### 2.2 Failure modes of rock mass

Rock fracturing and disintegration cause severe dynamic damages, such as bulking and ejection of the rock mass around the excavations. The dynamic bulking effect is mostly caused by separation and slip of fracture planes, as opposed to the relatively slight volume dilation caused by rock yield. Therefore, the rock mass is assumed to be an elastic medium, and potential fractures of varying strengths are arranged around excavations. The combination of the elastic rock mass and potential fractures reflects the strength properties of the weakened area around the excavations. The presence of potential fractures will not affect the propagation of seismic waves through the adjustment of the joint properties.

### 2.3 Seismicity-resistant mechanism of reinforcing components

Rock or cable bolts are the essential reinforce components to resist dynamic loading. One of the seismicity-resistant mechanisms is the extension of tendons to dissipate the dynamic energy in the rock mass around the excavations. An alternative seismicity-resistant mechanism is a support system that improves the integrity of the rock mass, restrains the velocity enlargement effect, and allows for smooth energy propagation through the excavations.

### 3 Numerical analysis

#### 3.1 Numerical model description

Considering the seismic events that occur in coal mines, the geometry of the numerical model is shown in Fig. 2 (a). The seismic source, which is a fault with a dip angle of...
about 60°, has a depth of 600 m. To meet the simulation precision, the square area (50 m × 50 m) is divided into fine zones with an average edge length of 0.5 m, and the other part of the model is divided into zones with an average edge length of 5 m. The left and right boundaries of the model are fixed in the horizontal direction, while the bottom boundary is fixed in the vertical direction and the top boundary is the free surface.

Two 5 m × 5 m cross-section roadways were driven symmetrically across the y-axis. The range of potential fractures may comprise multi-circle zones with varied strengths around roadways. The least width of potential fractures must be greater than the extent of opening cracks induced by the seismic event, which can be determined through trial and error. For a clear observation of seismic waves in this simulation, potential fractures with single strength are only arranged on the sides of the roadways, in an area of 2 m (width) by 5 m (height) (see Fig. 2 (b)). The stress conditions on the sides of roadways, where the vertical compressive stress prevails should be taken into account when determining the direction of potential fractures. Compress-induced fractures may be parallel to the maximum compressive stress in the case of tension failure, or have an angle of \((45^\circ + \Phi/2)\) with the horizontal plane in the case of shear failure [5,6], where \(\Phi\) is the friction angle.

Three monitoring sites are indicated with the numbers 1, 2, and 3 in Fig. 2 (c), which are located near the left roadway and are supported by five cable bolts. Site 1 is a surface point where varying velocity and displacement are tracked. Site 2 is an inner point of the rock mass where the local stresses can be observed. Site 3 is a point on the fracture plane that is used to monitor the opening and relative slip between two sides of the fracture. One cable element in the black rectangle is selected to observe axial force development.

Table 1 shows the rock properties, which are typical of coal-measure rocks [7]. Table 2 shows three types of joint properties: auxiliary lines have high strength, faults experience a sudden strength change to induce a seismic event, and potential fractures have low strength. Table 3 lists the cable properties.

The numerical models use seismic sources of two sizes: \(B = 2\) m (for a trial simulation) and \(B = 23.5\) m (for a realistic simulation). According to the history of fault slip velocity at the center of the faults, the corresponding fault slip times are about 3.2 ms and 30 ms respectively, as shown in Fig. 2 (d).

![Fig. 2. Outlines of numerical model: (a) model specifications (unit in meter), (b) two roadways with potential fractures, (c) monitoring sites near the left roadway, and (d) fault-slip time.](image)
Numerical simulations include two stages. First, the model is brought into an initial equilibrium state; secondly, joint parameters are changed to induce fault slip movements. Displacements are reset before the dynamic analysis.

Table 1 Rock properties

| K (GPa) | μ (GPa) | ρ (kg/m³) | α (m/s) | β (m/s) |
|---------|---------|-----------|---------|---------|
| 5       | 3       | 2500      | 1890    | 1095    |

Table 2 Joint mechanical parameters

| Property                        | Auxiliary line | Fracture | Fault     |
|---------------------------------|----------------|----------|-----------|
| Normal stiffness (GPa/m)        | 100            | 100      | 100       |
| Shear stiffness (GPa/m)         | 100            | 100      | 100       |
| Friction (°)                    | 30°            | 30°      | 30° → 5°  |
| Cohesion (MPa)                  | 10000          | 1        | 10000 → 0 |
| Tensile strength (MPa)          | 10000          | 0.5      | 10000 → 0 |

Table 3 Cable properties

| Area (mm²) | Density (kg/m³) | Yield (kN) | Khond (MN/m/m) | Sbond (kN/m) | Ymod (GPa) | S (m) |
|------------|-----------------|------------|----------------|--------------|------------|-------|
| 380        | 7800            | 200        | 10000          | 300          | 200        | 1     |

3.2 Results

In a trial simulation, the roadways are not driven, and a small fault slip over a width of 4 m (i.e. B = 2 m) is triggered to demonstrate the far-field behaviors of the seismic waves. The initiation and development of a velocity vector field are shown in Fig. 3. Shear waves propagating normally to the fault plane dominate the onset phase of the seismic waves. As the dynamic time increases, the velocity vectors first deviate along the rim of the fault, then gradually develops from the rim to the center area. At the time of 100 ms, nearly cylindrical wave-fronts were detected, P waves and S waves separate due to differences in velocities, and the energy radiation patterns correspond with the theoretical estimation in the far-field. The displacement fields from numerical and analytical results are sufficiently similar in the shape and magnitude between (see Fig. 4 (a) and (b)), despite a vertical offset of about 0.5 m in the numerical result during the initial balance phase. The two-dimensional seismic source works properly.

The realistic dynamic analyses were performed after roadways and cable bolts had been installed. A fault slip over a width of about 47 m (B = 23.5 m) was triggered to produce strong dynamic loading. The damages and displacements around roadways are shown in Fig. 5. In contrast to the case with cable bolts, when t = 100 ms, there were large opening cracks developed in the areas of potential fractures without support. Large displacements occurred around both roadways without support, the displacements reduced greatly around the left roadway but remained the same around the right roadway when only the left roadway was supported using cable bolts.
Fig. 3. Development of the velocity vector field: (a) dynamic time, $t = 0.5$ ms, with a peak velocity, $V_p = 0.89$ m/s; (b) $t = 1$ ms, $V_p = 1.52$ m/s; (c) $t = 2$ ms, $V_p = 0.59$ m/s; (d) $t = 100$ ms, $V_p = 0.007$ m/s.

Fig. 4. Displacement fields: (a) numerical results and (b) analytical results from Eq. (1).

The horizontal velocity, $V_x$, vertical velocity, $V_y$, horizontal displacement, $D_x$, and vertical displacement, $D_y$, were monitored at site 1 during dynamic loading as shown in Fig. 6, where moving toward the roadway or downwards shows a negative value. Regardless of whether using cable bolts, the initial segments for any pair of curves coincide, implying that cable bolts are passive during the onset phase of dynamic loading; however, the subsequent segments of curves show that the existence of cable bolts greatly changes the movement trends at site 1, particularly for horizontal velocity and displacement. Fig. 6 (a) shows how the presence of cable bolts results in a change in movement direction and fast velocity attenuation; Fig. 6 (c) shows how cable bolts can control the horizontal displacement at a low level.

Fig. 5. Damage and displacement around roadways when $t = 100$ ms: (a) damages around the left roadway with and without support and (b) displacements around both roadways without support and with support only on the left side.
The horizontal stress, $\sigma_{xx}$, and the vertical stress, $\sigma_{yy}$, are monitored at site 2 during dynamic loading, as shown in Fig. 7, where compressive stresses are negative. Although the presence of cable bolts causes some changes between the pairs of stress curves, there is no considerable change in stress trends. A similar trend in stress change implies that the cable bolts do not considerably change the local stresses. However, the certain advantage of using cable bolts is that the horizontal stress remains compressive after $t = 63$ ms, as shown in Fig. 7 (a).

The normal displacement (fracture opening) and shear displacement (relative slip along the fracture plane) were monitored at site 3 during dynamic loading as shown in Fig. 8. The presence of cable bolts fundamentally inhibits the development of the fractures, as opposed to the lasting trends of fracture opening and slipping when no cable bolt is applied. The local contact stresses on the fracture show that failure had occurred before dynamic loading.

The axial force of the cable element was monitored during dynamic loading as shown in Fig. 9. The monitored cable element had experienced multiple loading and unloading. The high axial force that lasts from 13 ms to 28 ms can dissipate most of the
dynamic energy, with the rest dissipating in a fluctuating manner. This estimation can be validated by the curve of the horizontal velocity in Fig. 6 (a).

Fig. 8. Displacement on the fracture at the site 3: (a) normal displacement and (b) shear displacement.

Fig. 9. Axial force in the monitored cable element.

4 Conclusion

The proposed numerical analytical method is a promising tool for investigating the response of ground support systems to mining-induced seismic activities.

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