

## Stability Analysis of Underground Excavations in Limestone Under Dynamic Loading

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### ABSTRACT

Fault-slip bursts induced by mining activities can result in severe damage to nearby mine development. In general, engineers designing rock support in burst-prone mines not only need to consider stress redistribution resulting from excavation, but also dynamic loading that results from seismic waves generated by large mining-induced fault-slip events. In this study, we simulated dynamic waves in sedimentary rock from a blasting source and from a mining-induced-seismicity source using a Universal Distinct Element Code (UDEC) model with Discrete Fracture Networks (DFNs). Our purpose was to investigate the stability of openings and the adequacy of existing support systems at an underground limestone mine in South Korea. A baseline model with only static loading was also simulated, which verified observed stability under such conditions. The results indicate that the current support system of shotcrete lining is likely to work well under dynamic loading caused by blasting. However, when the dynamic source was a far-field fault-slip event, the dynamic loading exceeded the support capacity of the shotcrete lining. Thus, if a mine is operating in ground with an elevated risk of mining-induced fault slip, mine engineers should consider seismic wave propagation and ground motion distribution from a remote, mining-induced fault-slip event to determine a suitable support design.

### INTRODUCTION

Dynamic rock support plays a critical role in ensuring underground mine safety and its design in burst-prone conditions. Although the support system can hold and retain the roof from collapsing because of nearby blasting, the rock support system might be compromised by dynamic loading caused by fault-slip-induced seismicity because the support system design considered only (quasi-) static loads. This study aims to achieve a better understanding of conventional support systems responding to static and dynamic loads.

Because the rockburst occurrences relate closely to dynamic instability of surrounding rock in higher static stress concentration states, the static stress associated with shock wave interference is commonly used to investigate rockburst mechanisms and its influencing factors, and an interesting result can be found in many papers in the literature. For example, Qin and Mao (2008) simulated rockburst induced by disturbing stress waves and analyzed the influence of depth and peak of stress wave on rockburst by using UDEC. Gao et al. (2007) found that the energy attenuation index  $\eta$  was considerably small in the rock and soil media but apparently much larger in weak or soft media. Zhao et al. (2008) calibrated UDEC models of P-wave propagation across single linearly and nonlinearly deformable fractures.

Rock support systems are designed initially considering only quasi-static loads. Dynamic loading sometimes is considered empirically through design charts or experience. Modern instrumentation permits characterization of dynamic wave forms from various event types, and some numerical modeling codes have the capability of simulating wave propagation in jointed ground. Ground-control engineers need to understand the capabilities of support systems to protect miners from ground falls caused by dynamic loading. In this study, we use a numerical model to investigate wave propagation from two likely sources to achieve a better understanding of the response of support systems subject to realistic dynamic loading.

This study focuses on the numerical analyses of a support system for an underground limestone mine in South Korea under both static and dynamic loading conditions. The support system consists of systematic rock bolting and shotcrete liner, which is proposed by an empirical classification method based on rock mass quality.

The objectives of the numerical modeling are to examine how the support system designed by an empirical classification method to conform to a static loading condition responds when a dynamic loading, such as blasting or mining-induced seismic loading, is applied. For the purpose of the analyses conducted, various parameters, such as geological structures, mining and blasting sequence, and geometry of the mine, were simplified to yield insights into how such parameters affect the behavior of the support system.

In the next section, rock mass properties and conditions, including joint system spatial characteristics, are described. Afterward, bolting and shotcrete liner behavior in the limestone excavation under static loading using UDEC (Itasca Consulting Group, 2022) is presented. Afterward, we explain methods used for creating input parameters to UDEC that appropriately characterize blasting and mining-induced seismic loading. Finally, the bolting and shotcrete liner behavior in the limestone excavation under dynamic loading conditions is investigated using UDEC, and then these results are compared to the results of the static loading condition.

## UDEC MODEL DESCRIPTIONS

### Geology and rock mass conditions

The geology around the limestone mine in South Korea consists of granite gneiss from the Precambrian period, unknown lava mountain layers, Seolok-ri layers, intruding late Mesozoic Cretaceous dykes, and alluvial layers. The limestone mine is extracting limestone by a room-and-pillar method that is deposited in the lower part of the Seolok-ri Formation. The Seolok-ri Formation is mainly composed of dark green/dark brown/dark gray mica schist and light gray/light brown/gray crystalline limestone. Crystalline limestone is mainly dense or fine-grained, with sparse minerals scattered in some places, and light gray to milky white coarse-grained dolomites are irregularly distributed (Kim et al., 2022).

Figure 1 shows a typical condition of the limestone recovered by drilling cores.



**Figure 1. Example of rock core condition**

Table 1 shows the average engineering properties of the limestone.

**Table 1. Average intact rock engineering properties and Geological Strength Index (Kim et al., 2022)**

Unit weight (MN/m <sup>3</sup> )	UCS (MPa)	Elastic modulus (MPa)	Poisson's ratio	Hoek-Brown constant, mi	Geological Strength Index
0.0027	100	59,000	0.22	9	62

These parameter amounts are the basic information needed to prepare input data for the rock blocks of the UDEC model in this study.

### Realization of joints system in the limestone using discrete fracture networks (DFNs)

The built-in DFN technique in UDEC (Itasca Consulting Group, 2022) is performed to explicitly realize the spatial characteristics of the joints system observed from the underground limestone mine. The spatial characteristics of the joints system are estimated based on the results of the field observations and then are prepared as input to the UDEC model.

Figure 2(a) presents three representative joints orientations that are W69W/88SW, N26E/69NW, and N28E/80SE, all measured underground. The range of Rock Quality Design (RQD) measured by a scanline underground is from 50% to 80%. The range of joint sets spacing observed underground is from 0.06 to 0.6 cm, and the range of joints trace length acquired underground is from 1 to 10 m, respectively (Kim et al., 2022).

The Fisher distribution based on these orientations is used to generate the DFNs. The Power-law distribution based on these trace lengths is chosen to determine the sizes of the joints. The generated DFNs are illustrated in Figure 2(b).

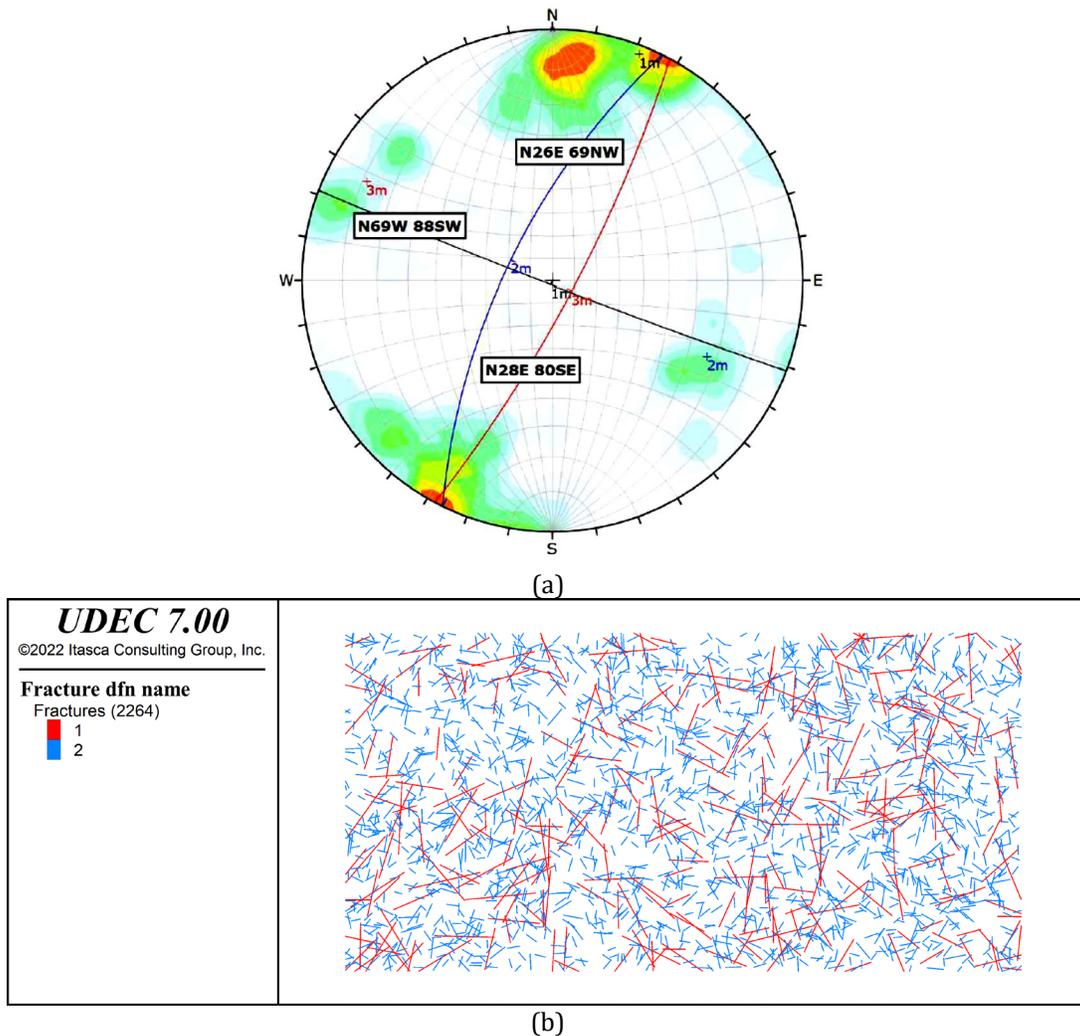


Figure 2. (a) Representative joint sets orientations; (b) reproduced joint sets in UDEC using discrete fracture network (DFN).

### Preparation of a UDEC model

A model with dimensions of 88(W) × 60(H) m was constructed as illustrated in Figure 3.

To optimize computing time, the joint sets are explicitly generated by the DFNs only in a window of 88(W) × 25(H) m in the vicinity of the underground excavations in the model. The depth of the top boundary of the model from the surface was assumed to be 60 m. A surcharge of vertical stress was applied on the top boundary of the model to account for the weight of overburden not represented in the model. The horizontal stresses were considered to be greater than the vertical stress. It was presumed that the major principal stress ( $\sigma_H$ ) had a magnitude (MPa) of  $1.69 \times$  overburden stress in the y-direction of the model. The minor principal stress ( $\sigma_v$ ) had a magnitude (MPa) of the unit weight  $\times$  depth.

For the boundary conditions, both sides of the model were fixed in the x-direction, and the bottom of the model was fixed in the y-direction. The geometries of the excavations and pillar were simplified so that the excavations' entries were 16-m wide and 5-m high, leaving a pillar which was 16-m wide, located between the excavations. The equivalent zone size of the individual mesh element in the model was 10 m for both the top and bottom layer of rock mass (with no DFNs) and as 2 m for the area where DFNs were generated.

Figure 3(a) and Figure 3(b) show before and after underground excavations in the model, respectively. All blocks in the UDEC model are built as deformable, elastic blocks. The joints realized by the DFNs cut the blocks in the model. The amounts representing joint strength are 400 kPa for cohesion, 35 degrees for friction angle, and zero tensile strength.

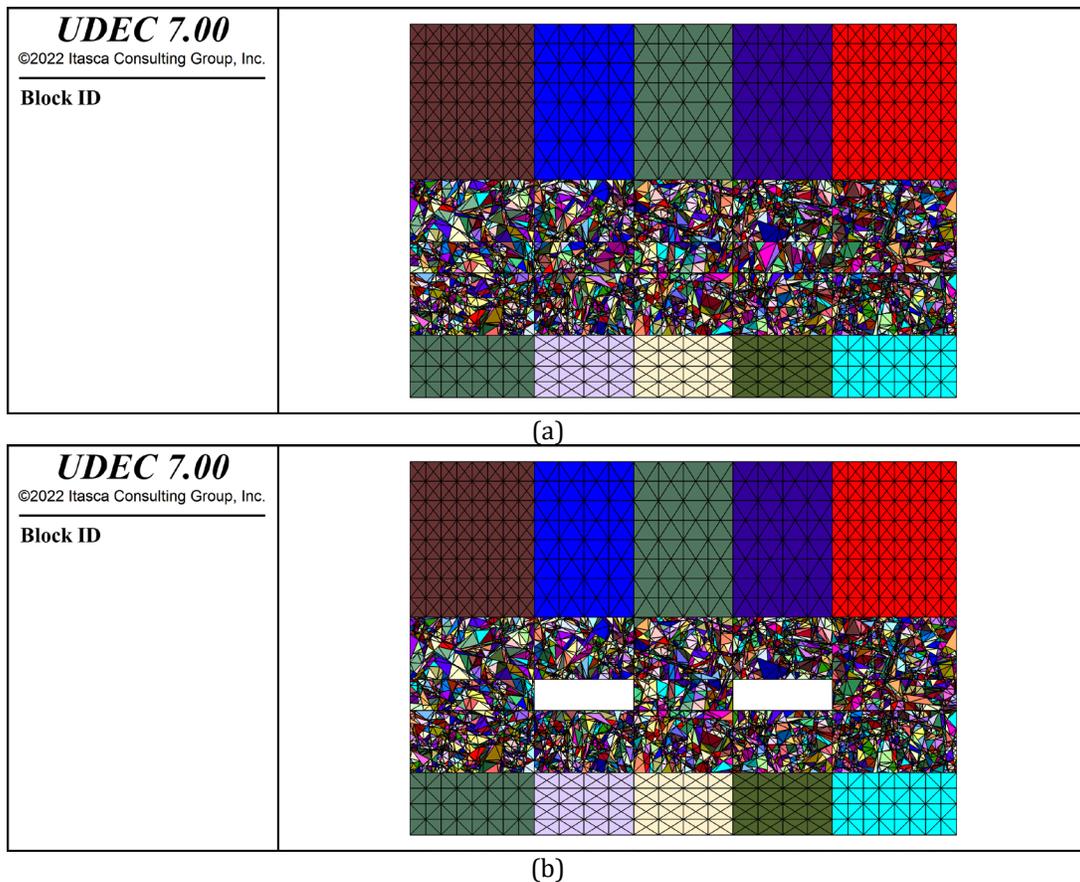


Figure 3. Block and mesh discretization in UDEC model: (a) before excavations; (b) after excavations.

### Determination of a dynamic loading

A blasting loading was monitored and measured in the underground limestone mine in South Korea (Kim et al., 2022). The field-measured blasting loading is presented as a solid curve in Figure 4(a). After the field measurement, the blasting loading was simplified by fitting the equation (1) proposed by Duvall (1953) to the field data.

$$P = P_0[e^{-\alpha t} - e^{-\beta t}] \quad (1)$$

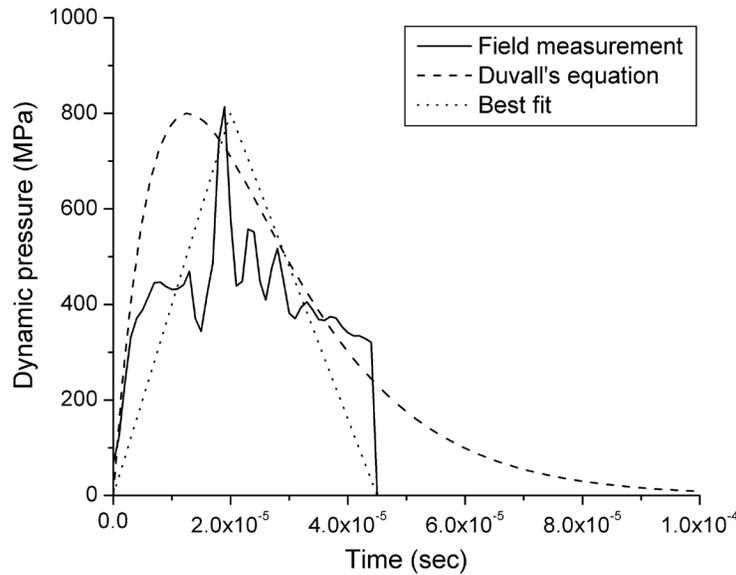
where,  $P_0$ : peak pressure value,  $\alpha$  and  $\beta$ : constants.

To fit the monitored blasting loading in the field to Equation (1), we determined the rising time ( $t_0$ ) by means of a simplification using Equation (2) which was explained in several papers in the literature (Cho and Kaneko, 2004; Ma and An, 2008; Zhu et al., 2013)

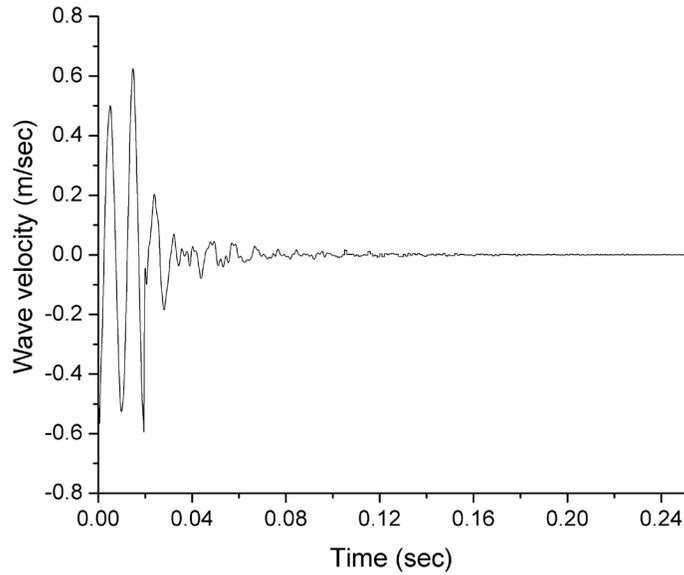
$$\begin{aligned} P &= P_0 \xi [e^{-\alpha t} - e^{-\beta t}] \\ \xi &= 1/(e^{-\alpha t_0} - e^{-\beta t_0}) \\ t_0 &= \{1/(\beta - \alpha)\} \ln(\beta/\alpha) \end{aligned} \quad (2)$$

In this study, we considered  $P_0 = 800$  MPa,  $t_0 = 12.5 \mu s$ , and  $\beta/\alpha = 1.5$  to generate a best-fit curve of the field measurement. A simplified blasting loading using Equation (1) is indicated by a dashed curve and a best-fit for the blasting loading using Equation (2) is shown as a dot-triangle curve in Figure 4(a), respectively. This best-fit curve is considered as the blasting loading condition in the UDEC model.

Although there was no significant mining-induced seismicity observed in the underground limestone mine in South Korea, we chose a stress wave with peak stress of 12.5 MPa (Itasca Consulting Group, 2022) to be applied to the UDEC model for this study. A wave velocity was applied to the UDEC model to represent the mining-induced seismic loading, as illustrated in Figure 4(b).



(a)



(b)

**Figure 4. Dynamic loading as input: (a) blasting loading (b) mining-induced seismic loading.**

## RESULTS AND DISCUSSION

The UDEC model was initially performed to reach an equilibrium state before the underground excavations followed by an elastic modulus softening process to remove the material from the excavations in the model. Once the model with the excavations reached an equilibrium state, systematic bolting and shotcrete liner elements were installed in the model to simulate the underground support system. The support system elements in the UDEC model were simplified to simulate the standard support system presently used in the underground limestone mine in South Korea. The limestone mine operation established the standard for their ground support system based on an empirical classification system (e.g., Rock Mass Rating (RMR) or Q-system). A 2.5-m long mechanically anchored rockbolt in 2-m spacing is installed in the roof of the underground excavation. A 4-cm thick shotcrete liner is applied to both of the side walls and the roof of the underground excavation (Kim et al., 2022). To best represent the standard support system, we prepared a rockbolt and a liner element with material properties (Kim et al., 2022) and then applied them to the UDEC model. The results from the UDEC model are discussed as follows.

### Static loading condition

Figure 5 shows the displacement contours after the openings were excavated under the static loading condition in the model. Figure 5(a) presents the displacement contours prior to installing the rockbolts or the shotcrete liner. The maximum displacement indicated as the red contour shows 2.5 cm which is 1% of the height of the underground excavation. Although a localized wedge fall occurred in the immediate roof of the excavation on the left-hand side in the model, the overall displacements appeared to be stabilized by forming an arch in the back of the excavations. Figure 5(b) shows the displacement contours after installing the rockbolts or the shotcrete liner (bold black lines). The displacement contours scale and interval in the figure are the same as in Figure 5(a) for easier comparison. The displacements due to the mining excavation were decreased and constrained by as much as approximately 1.4 cm by the ground support system —about 60% of the maximum displacement observed in the no-support case in the model. This behavior agreed well with the field measurement using a laser convergence meter (Kim et al., 2022). As a result, the standard ground support system designed by the empirical classification that is used in the underground limestone mine performed appropriately for the static ground condition.

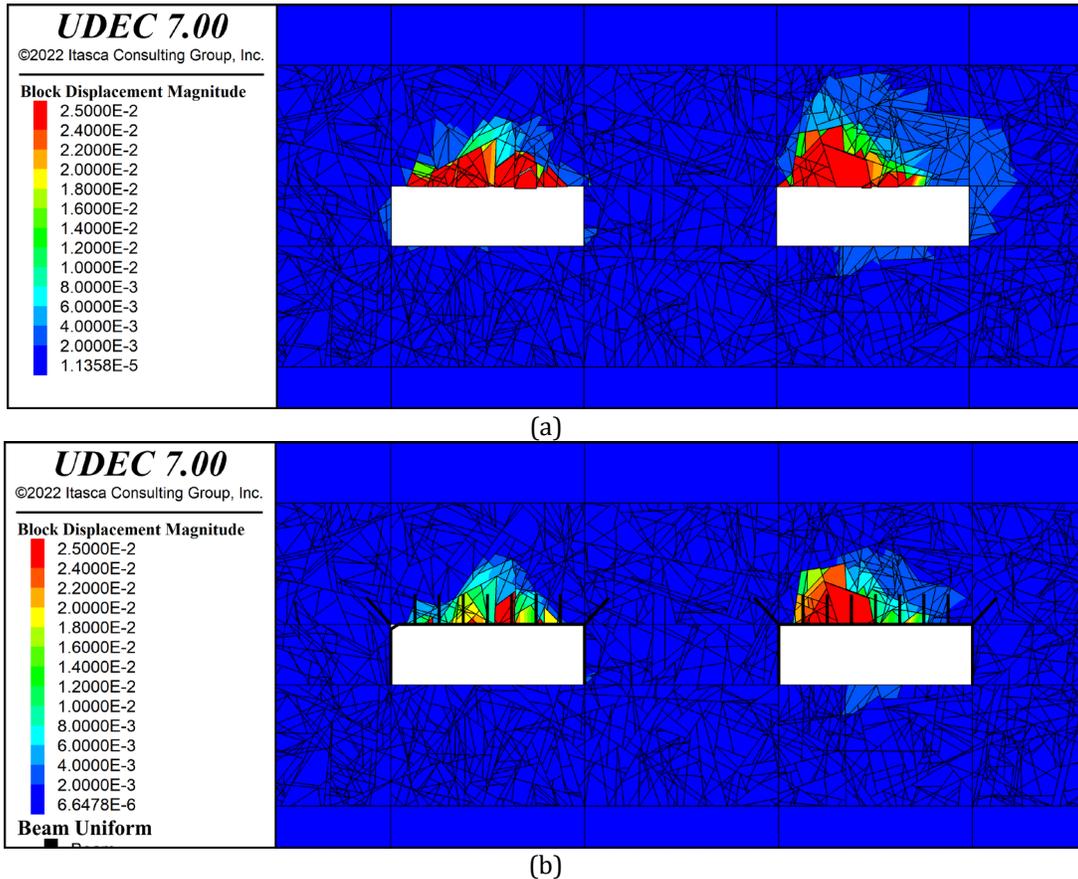


Figure 5. Roof deformation under static loading condition: (a) no support; (b) after supports installation.

### Dynamic loading condition

#### *Blasting loading condition*

As the UDEC model reached an initial stress equilibrium state, a blasting loading, as indicated in Figure 4(a), was applied to the boundary of the UDEC model to investigate a response of the ground support system under the blasting loading.

Figure 6 shows the displacement contours after the underground excavations under the blasting loading condition in the model. Figure 6(a) presents the displacement contours prior to installing the rockbolts and the shotcrete liner. The maximum displacement indicated as the red contour shows 2.5 cm which is 1% of the height of the underground excavation. Figure 6(b) shows the displacement contours after installing the rockbolts and the shotcrete liner (bold black lines). The displacement contours scale and interval in the figure are as same as in Figure 5. The overall displacement appears to be like the displacements observed in the static loading condition, as shown in Figure 5.

Even though the overall displacements under the blasting loading condition in the back of the mining excavations look like the results of the static model, we look into the behavior of the shotcrete liner more closely using a shear-moment diagram. The shear-moment diagram (Itasca Consulting Group, 2022) illustrates the inelastic material behavior of the liner and compares the shear force and moment response of the liner to a failure envelope presented in a shear-moment diagram, as shown in Figure 7.

The internal shear force and bending moment along the whole shotcrete liners calculated in the UDEC model are plotted as a square in the figure. Based on the given material properties of the shotcrete liner simulated in the UDEC, three different safety factors, 1.0, 1.2, and 1.4, are drawn as the diamonds in the figure. Depending on where the calculated internal shear force and bending moment are placed in the diagram, we can estimate the safety factor of the shotcrete liner.

All the squares indicating the internal shear force and bending moment along the whole shotcrete liners calculated in the UDEC model are located inside the dotted diamond that represents the safety factor 1.4, as shown in Figure 7. This means that all the shotcrete liner elements in the model had a sufficient bearing capacity with no yielding against the blasting loading. In other words, the standard ground support system currently used in the underground limestone mine performed appropriately not only for the static loading condition but also for the blasting loading condition. This outcome agreed well with the field-monitoring result that there was no immediate hazard potential on the ground support system regarding the blasting observed underground (Kim et al., 2022).

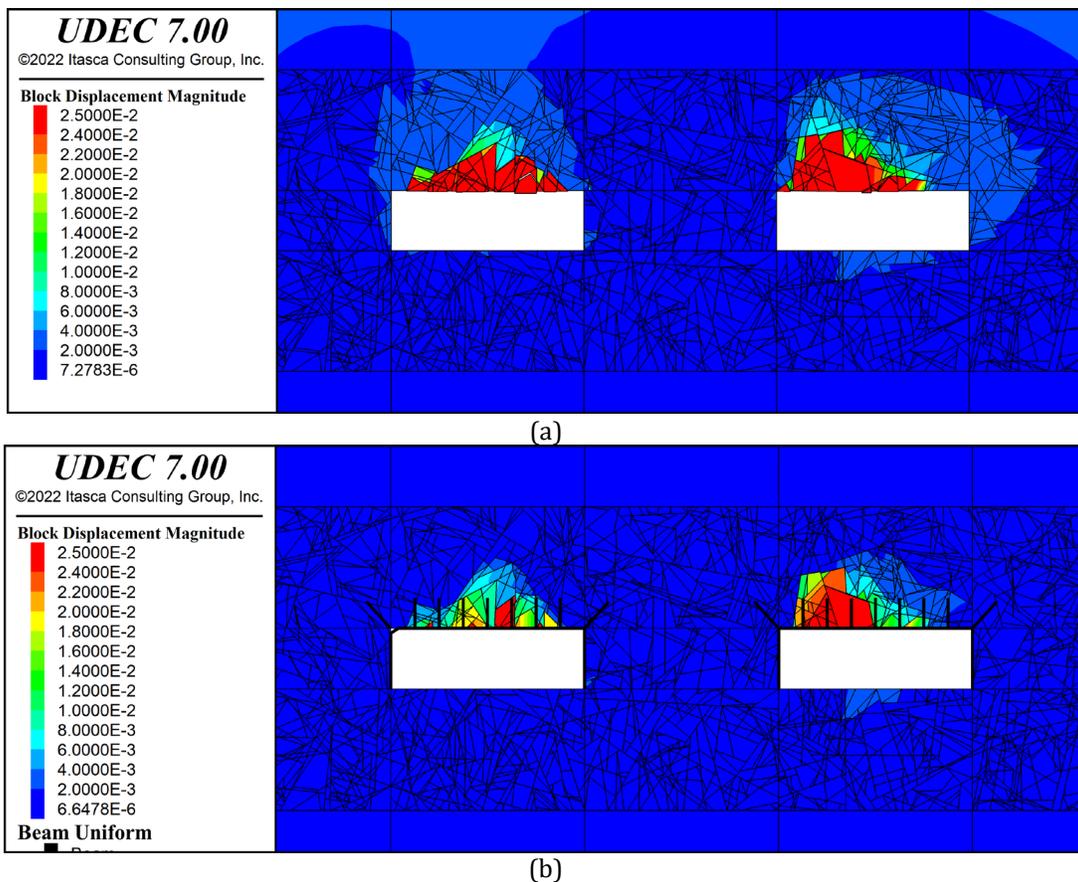
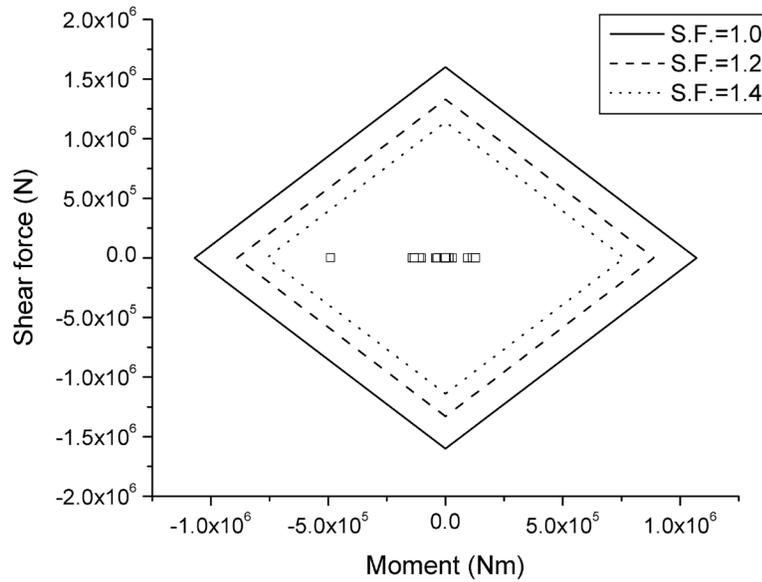


Figure 6. Roof deformation under blasting loading condition: (a) no support; (b) after supports installation.



**Figure 7. Shotcrete liners shear-moment diagram under blasting loading condition.**

#### ***Mining-induced seismic loading condition***

Once the UDEC model reached a very first stress equilibrium state, a mining-induced seismic loading, as indicated in Figure 4(b) was applied to the boundary of the UDEC model to investigate a response of the ground support system under the mining-induced seismic loading.

Figure 8 shows the displacement contours after the underground excavations under the blasting loading condition in the model. Figure 8 (a) presents the displacement contours prior to installing the rockbolts or the shotcrete liner. As shown in the figure, completely different from the static and the blasting loading conditions, the maximum displacement indicated as the red contour shows 2.5 cm of displacement occurs in the entire back of the mining excavations. Even the displacement in the side wall of the mining excavation looks unraveling under the mining-induced seismic loading. Figure 8(b) shows the displacement contours after installing the rockbolts or the shotcrete liner (bold black lines). The displacement contours scale and interval in the figure are the same as in Figure 5 and Figure 6. After the ground support system installation, the overall displacement appears somehow as being constrained; however, the reduction of the displacement is not as much as we observed in other cases as presented in Figure 5 and Figure 6.

To closely examine the ground support system performance under the mining-induced seismic loading, we generated a shear-moment diagram once again. Figure 9 presents the results of the shear force and moment response of the liner to a failure envelope. We found that the calculated results from the model indicated as squares showed a much more dispersed distribution as compared to the blasting loading condition. Some of the squares lie outside the safety factor of 1.2 and 1.4, and even outside the safety factor of 1.0. This means that the current ground support system used in the underground limestone mine could have been compromised if a mining-induced seismic loading was applied to the underground mining excavations. Consequently, conventional ground support designs that only consider static or blasting loading are not adequate to safely maintain underground excavations under mining-induced seismic loading.

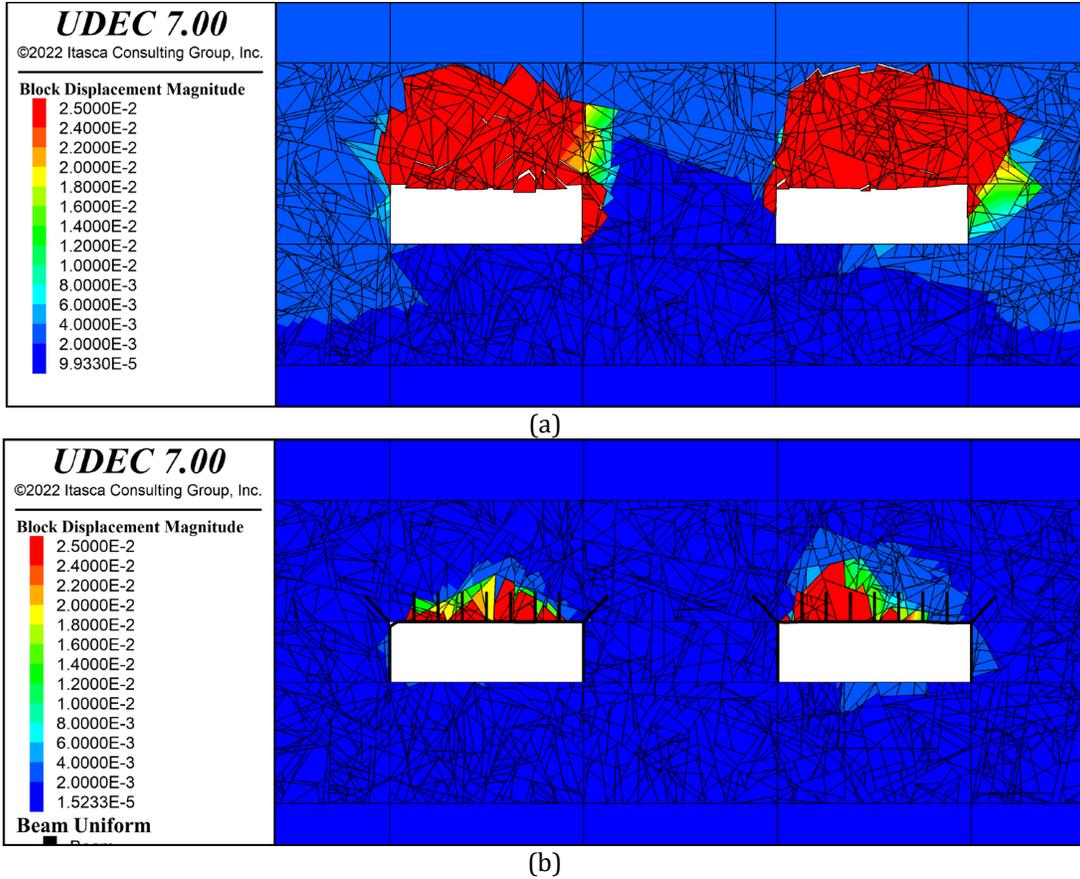


Figure 8. Roof deformation under seismic loading condition: (a) no support; (b) after supports installation.

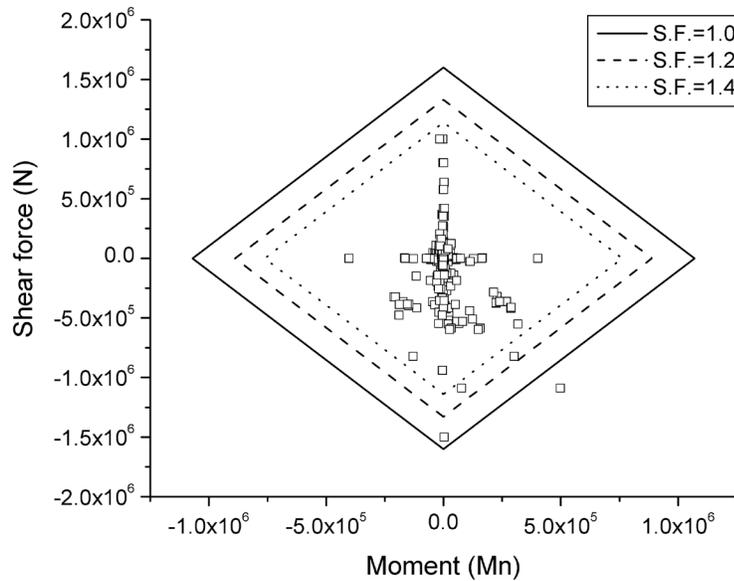


Figure 9. Shotcrete liners shear-moment diagram under mining-induced seismic loading condition.

## CONCLUSION

Researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted a numerical simulation for the purpose of understanding how the support system designed by an empirical classification method to conform to a static loading condition responds when a dynamic loading, such as blasting or mining-induced seismic loading, is applied. The field case was chosen from an underground limestone mine in South Korea.

This study focused on achieving a better understanding of the conventional support system responding to static and dynamic loads using the UDEC modeling techniques. As a result, the ground support system currently used in the underground limestone mine as a standard could have been inadequate under the mining-induced seismic loading condition even if the standard ground support design considered it appropriate to the static or the blasting loading conditions. Therefore, understanding the ground support system behavior under dynamic loading conditions is necessary to improve the design of support systems in underground mines, nearly all of which are subject to dynamic loading, i.e., mining-induced seismic loading.

Future studies might be conducted to evaluate whether this finding holds for other cases that exhibit a different magnitude of mining-induced seismicity than from this study, as well as to evaluate the influences of factors not explicitly considered in this study (such as mining sequence) on ground support system behavior under strainburst conditions.

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## DISCLAIMER

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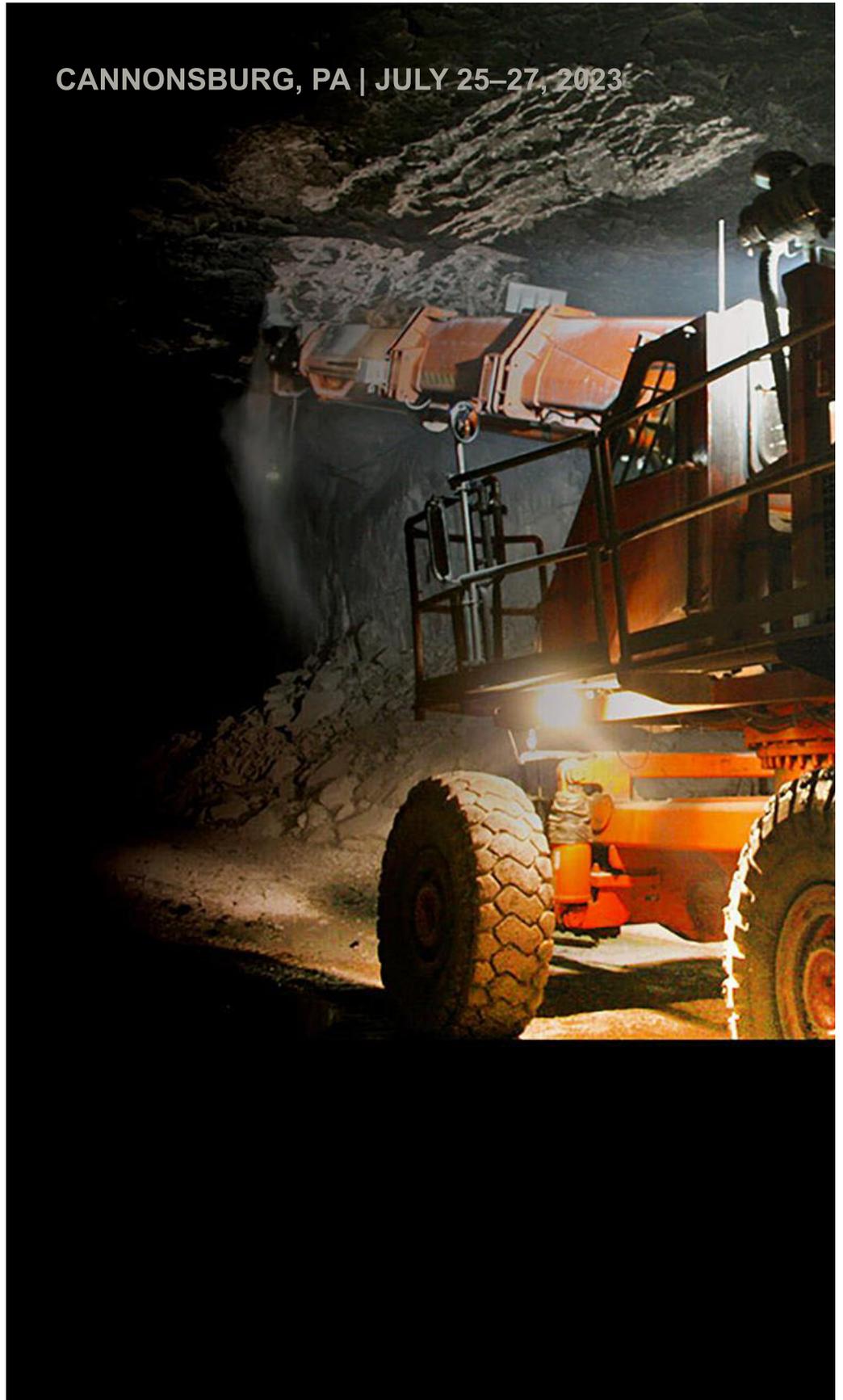
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