Numerical analysis of impact of fault and weak rock formation on mining-induced deformation of rock slope

C Zhang¹, C A Amagu¹, J. Kodama¹, A Sainoki², S Ogawa³, C Umeda³, Y Fujii¹ and D Fukuda¹

¹Faculty of Engineering, Hokkaido University, 060-8628, Japan
²Faculty of Advanced Science and Technology, Kumamoto University, 860-8555, Japan
³Ryoko Lime Industry Co., Ltd., Une Mine 357-1 Yokoze Town, Saitama, 368-0072, Japan

Abstract. Geological structures, such as fault, geological discontinuity, and weak rock formation are likely to play a critical role in the stability and behaviour of rock slopes. However, the impact of such geological structures on the mining-induced deformation of rock slopes in an open-pit mine remains unclear. This study takes an open-pit limestone quarry in Japan as an example to discuss the mechanical interaction between specific geological structures. In this quarry, below the mining area is a vertical fault intersecting with a weak rock formation almost parallel to the slope surface. Based on these unique geological structures, numerical simulations are conducted in the framework of discrete element method while considering different geological situations to elucidate the impact of each geological structure. The analysis results show that the vertical fault and weak rock formation significantly impact the deformation of the rock slope during mining progression. In the case of a fault-only model, no slip occurs. However, in the case of the fault and weak rock formation model, as the mining face is crossing the fault, apparent slip occurs along the weak rock formation. In this model, although the vertical fault constrains the sliding of the upper discontinuities at the early stage, the normal stress of the weak rock formation decreases gradually as the mining progresses, and local shear failure occurs at the intersection of the weak rock formation and fault, which leads to the slip. However, rock slope displacement due to the slip gradually decreases and eventually stabilizes as the working face gets away from the vertical fault. This study provides new insight into the deformation mechanism of the rock slope and serves as a reference for future mining and slope prevention work.

1. Introduction
Assessing slope stability is a critical part of mining and civil engineering projects. This is especially important for large open-pit mines and rock slope engineering because slope failure results in a delay in production and may cause fatalty and equipment loss. In this regard, it is common to evaluate the stability of an open-pit mine based on the deformation behaviour of the rock mass (Kodama et al. 2009). Among factors affecting open-pit mine deformation including excavation (Najib et al. 2015), geological structures are significant due to their unique mechanical characteristics. Therefore, a number of studies on the influence of geological structures have been undertaken in recent years. Such studies indicate that geological discontinuities such as faults, and their properties, including shear strength, slope face angle (α), and friction angle, determine the failure mechanism. For example, if a potential failure plane daylights on the slope face at an angle smaller than the slope face angle and greater than the angle of friction, the kinematic condition is satisfied, and failure can take place (Raghuvanshi 2019). In the study, the impact of weak rock formation has been examined as a unique rock material. Zhao et al. (2020) also indicate that a weak rock formation often affects the stability of the rock slope because of its creep behaviour.
As described above, geological structures can play a pivotal role in the stability of rock slopes. In this paper, the effect of geological structures observed in a case study mine on deformation behaviours of the rock slope is examined. In particular, the combined impact of a vertical fault and a weak rock formation on excavation-induced rock slope deformation is investigated as a fundamental study for rock slope stability assessment with discrete element method.

2. Numerical method

2.1. Numerical models
We have constructed the following models to study the effects of the fault and the weak rock formation: (a) Homogeneous model (H model), (b) Model with both fault and weak rock formation (F-W model), (c) Model with a fault (F model), and (d) Model with a weak rock formation (W model). In all models, the rock slope is 500 meters in height and 800 meters in width. The excavation area is set on the upper left side of the slope, 150 meters in height and 50 meters in width. The slope angle is 45 degrees.

As seen in Figure 1(b), the vertical fault and the weak rock formation were incorporated in the F-W model to represent the geological conditions of the B open-pit mine. The width of the vertical fault is approximately 5 meters. The width of the weak rock formation, which is parallel to the slope surface, is 5 meters. F Model and W model were intended to investigate each effect of the fault and weak rock formation. The homogeneous model was prepared to clarify the effect of discontinuities.

Figure 1. Numerical models: (a) Homogeneous (H model), (b) With fault and weak rock formation (F-W model), (c) With fault (F model), (d) With weak rock formation (W model).

2.2. Mechanical properties of rock mass and discontinuities.
In this study, it is assumed that shear failure (slip) takes place only at the contact between the geological structures and the surrounding rock mass, i.e., the contact is modeled as a discontinuity plane in the framework of DEM, while elastic, deformable zones are used to model the rock mass composing the geological structures (Figure 2). Literature review was then performed to determine the normal and shear stiffnesses of the discontinuity, and the result is summarized in Table 1. As shown in the table, the range of $K_n/K_s$ is roughly between 1.0 and 3.0. Accordingly, in this study, parameters shown in Table 2 are employed assuming $K_n/K_s$ is 2.0.
2.3. Analysis conditions and procedure.

The numerical analysis process can be divided into the gravity balance stage and the excavation stage. In the gravity stage, gravity was applied to each model by fixing displacement on the left, right, and bottom surfaces of the model at zero. In the excavation stage, zones shown as excavation stages I to IX in Figure 3 are removed from the model step by step. The zone height of each excavation stage is 20 meters. In the F-W model, note that the excavation zone passes the fault in the fifth excavation stage. According to this feature, we can divide the model state into two: pre-fault state (the first to the fourth excavation stages) and post-fault state (the fifth to the ninth excavation stages).

Table 1. Discontinuities parameters of different rock types

| Rock Type  | $K_n$ (GPa m$^{-1}$) | $K_s$ (GPa m$^{-1}$) | $K_n/K_s$ | Friction (°) | Young’s modulus (GPa) | Resource                   |
|------------|----------------------|----------------------|-----------|--------------|-----------------------|---------------------------|
| Sandstone  | 2                    | 0.8                  | 2.5       | 25           |                       | Chen Gang et al.(2014)    |
| Limestone  | 2                    | 0.2                  | 10        | 30           | 20                    | Guo Ran et al.(2013)      |
| Limestone  | 10                   | 4.8                  | 2.1       | 30           |                       | D.C.P Peacock et al.(1994) |
| Sandstone  | 11.7                 | 5                    | 2.3       | 30           |                       |                           |
| Shale      | 4.4                  | 1.5                  | 2.9       | 25           |                       |                           |
| Tuff       | 1.68                 | 1.49                 | 1.1       | 4.4          |                       | Yujing JIANG et al.(2008) |
| Tuff       | 0.785                | 0.637                | 1.2       | 2.9          |                       | Senro Kuraoka et al.(2000) |

Table 2. Mechanical properties of rock mass and discontinuities

| Rock mass         | Discontinuity |
|-------------------|---------------|
| Properties        | Fault         | Weak rock formation | Limestone | Fault-limestone contact | Weak rock formation -limestone contact |
| Density (kg m$^{-3}$) | 2700         | 2700                | 2700      | 1                        | 1                                      |
| Modulus of elasticity (GPa) | 0.1           | 1                    | 1         | 0.5                      | 0.5                                    |
| Poisson’s ratio   | 0.2           | 0.2                  | 0.2       | 30                       | 30                                     |

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A series of measuring points are set as Figure 3 to analyze displacement and stress change owing to excavation. Displacement increment at Points 1 to 8 on the slope surface and stress change at Points A to C along the weak rock formation are analyzed.

**Figure 3. Excavation stage and observation points.**

3. Numerical simulation results and discussion

3.1 Displacement of the model with both fault and weak rock formation

**Figure 4.** Displacement vectors of H model induced by the excavation of 1-7 stages.

**Figure 5.** Displacement vectors of the F-W model: (a) Before excavation level reaches fault level, (b) After excavation level reaches fault level.
Figure 4 shows that in the H model, the slope surface deforms backward in the upper-right direction. On the other hand, for the F-W model with the fault and the weak rock formation, the mining-induced deformation trend changes, as shown in Figure 5. More specifically, for the pre-fault state, the deformation trend is the same as the H-model on the upper side of the fault, while the deformation direction changes to forward in the post-fault state. On the lower side of the fault, the surface moves in the upper-right direction in the H model, while in the F-W model, the surface moves in the upper-left direction.

As for the vertical deformation, all the points in the H model continuously move upward (Figure 6a), while in the F-W model, the deformation trend is different among the points; at points 1-5 on the upper side of the fault, the surface deformation in the vertical direction increases firstly and then decreases in the post-fault state; at points 6-8 on the lower side of the fault, the vertical deformation of the F-W model monotonically increases upward and is identical with the H model (Figure 7a).

As for the horizontal deformation, the slope surface of the H model deforms backward in the pre-fault state and moves forward when the fault zone is excavated, and deforms backward again in the post-fault state (Figure 6b). The horizontal deformation pattern of the F-W model differs among the points; at points 1-5 on the upper side of the fault, the deformation pattern has the same characteristics as the H model in the pre-fault state, but it changes to forward movement in the post-fault state; at points 6-8 on the lower side of the fault, although the displacement magnitude is small, the characteristics are identical with the H model (Figure 7b).

Figure 6. Displacement of H model at Points 1 to 8 induced by excavation: (a) Vertical direction, (b) Horizontal direction.

Figure 7. Displacement of F-W model at Points 1 to 8 induced by excavation: (a) Vertical direction, (b) Horizontal direction.
Combining the above results and considering the effects of the fault and the weak rock formation, it is speculated that the slip occurs only on the upper side of the fault after the excavation zone passes the fault. The rock mass on the upper side of the weak rock formation slides along the discontinuity surface, resulting in the downward and forward movement of the slope surface in the F-W model. The fault is also pushed by slip, deforming leftward due to the lower Young’s modulus. For slip itself, the slip displacement increment tends to decrease with excavation progress. Hence, the slope eventually stabilizes. In addition, based on the results of the analysis and from a long-term perspective, some suggestions are given in mining:

1. Deformation monitoring like APS or GPS should be set at different heights of the mining surface to monitor the slope surface deformation.
2. Slow down the excavation progress when excavation through the fault, and take protective measures when the deformation is large.

### 3.2. Each effect of fault and weak rock formation on rock slope displacement.
To understand each effect of the fault and the weak rock formation on mining-induced deformation, we compared the results of the four models at points 5 and 6 (Figure 3). Figures 8 and 9 show vertical and horizontal displacements, respectively. Points 5 and 6 are located on the upper and lower sides of the fault.

![Figure 8. Vertical displacement comparison: (a) Point 5, (b) Point 6.](image)

![Figure 9. Horizontal displacement comparison: (a) Point 5, (b) Point 6.](image)

At point 5 on the upper side of the fault, the vertical displacement of the F-W model decreases in the post-fault state, while for the W model and F model, the vertical displacement monotonically increases.
For the horizontal direction, the F-W model also shows that the displacement decreases in the post-fault state, while the changes in the W model and the F model are almost negligible. At point 6 on the lower side of the fault, although all models have a slight difference in the displacement magnitude, the deformation trends in the vertical and horizontal directions are identical. These results suggest that no slip occurs in the case of only a single weak rock formation or a single fault. Slip only occurs when both are present, and it is located on the upper side of the fault.

At the same time, comparing the results of the W model and the H model, the mining-induced deformation is the same at points 5 and 6. That is, a single weak formation has almost no effect on mining-induced deformation of the surface. Comparing the F and H model results, especially in the vertical direction, the fault increases the mining-induced deformation. This is considered that the fault has changed the stress field during the excavation stages.

3.3 Stress change on weak rock formation by excavation.

To understand the cause and mechanism of slip, we recorded the stress changes in the F-W model at points A-C (Figure 10) and noticed that the shear failure occurs two times in each measuring point. The stress change was found to have the following characteristics. First of all, before the excavation stage, due to the weak strength, shear failure has occurred at the interface between the weak rock formation and the rock mass. In addition, as the excavation progresses, the shear and normal stresses gradually decrease, especially for the normal stress, and shear failure occurs at all three measurement points repeatedly, which eventually caused the upper rock mass to slip forward together with the weak rock formation. Finally, the failure progresses from the upper part of the slope to the lower part; specifically, failure is initiated at the 2nd excavation, the 4th excavation, and the 5th excavation at points A, B, and C, respectively.

![Figure 10. Changes in stress and shear stress on the weak rock formation in the F-W model by excavation.](image)

4. Conclusions

This paper reveals the effect of a vertical fault and a weak rock formation parallel to a rock slope on the slope deformation, using discrete element method, as a fundamental study for the stability assessment of a case study mine. The main results are as follows.

1. When either the fault or the weak rock formation exists, the slope surface moves backward and upward under the effect of excavation, which is the same as that of the homogeneous model without the geological structures. However, in the case of the model including both the vertical fault and weak rock formation intersecting at 45 degrees, slip occurs along with the weak rock formation, and the surface deforms forward and downward.

2. The slip is caused by the significant decrease in the normal stress on the weak rock formation due to the excavation, and the slip is initiated at the upper part of the weak rock formation, extending downward.
3. The deformation caused by the slip along the weak rock formation tends to reduce and stabilizes as the working face gets away from the fault.
4. Combining conclusions 1, 2 and 3 indicates the necessity of considering these particular geological structures in evaluating the slope stability of the case study mine.

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