Numerical Analysis of Effects of Clay on a Cut Rock Slope Deformation at an Open-pit Limestone Mine, Japan

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Abstract
Rock slope instability is one of the major challenges of rock engineering projects, including open-pit mining. In this regard, rock slope deformation due to excavation, change in temperature, and influence of rainfall and snowfall have been previously investigated to understand characteristics and causes of slope deformation observed at an open-pit limestone quarry in Japan. The results only revealed characteristics of the deformation as forward and downward displacement of the cut rock slope, but its causes were not clarified. To deduce the causes of the rock slope deformation, we employed the 2-dimensional finite element method (2-D FEM) to investigate the deterioration effect of clay found at the footwall of the rock slope in terms of reduction in Young's modulus of the clay based on experimental results. Firstly, change in distances was analysed from displacement data measured by the automated polar system (APS) over five years, which decreases gradually with time. Secondly, the simulation results were discussed and then compared with the measured displacement data, which shows similar tendencies at the middle and top of the rock slope revealing maximum displacement at the middle of the rock slope. Conclusively, deterioration of clay at the footwall of the rock slope is one of the possible causes of the deformation in the quarry.

Keywords: 2-D FEM, Deterioration effects, Rock slope deformation, Stability assessment, Young's modulus

1. Introduction

Regarding the increased demand for deep resources and minerals exploitation and environmental problems, rock engineers have become much more interested in the study of rock slope instability in order to provide the basis for deformation, stability and safety of rock engineering projects, including open-pit mining, which largely depends on the strength and deformability of rock masses [1]. These have led to numerous researches intending to cover all aspects of rock mechanics from theories to engineering practices, emphasizing on the future direction of rock engineering technologies [2]. In mining engineering, open-pits account for the major portion of the world's mineral production. However, the instability of rock slopes has been a concerning issue that commonly occurs in open-pit mines around the world. Therefore, it is essential to ensure a degree of stability for the slopes in the mines to minimize the risks related to the safety of operation and economic risks to the reserves, mainly in the complex vicinity of ore bodies where exact geological and mechanical properties of cut rock slope are uncertain [3]. These complicate the prediction of the stability of rock slopes.

In Japan, there are large reserves of limestone that have been quarried for cement productions, construction aggregates, and consumption in iron and steel industries [4]. Therefore, large-scale limestone quarries, mostly open-pit limestone quarries, are still under operation. However, most of the limestone deposits are located at steep mountainous terrain [5-6], excavation mostly progresses from either the top or side of the mountain to its foot. Sometimes, these left a huge rock slope in the quarry during operation and/or after being mined out [7]. In this regard, extensive studies have been done on mining-induced deformation of rock slopes in pit-type mines, Japan [8-11].

Previously, the elastic deformation of the cut rock slope due to excavation and backfilling, effects of change in temperature, the influence of rainfall and snowfall on the slope stability have been investigated to understand the characteristics and causes of the slope deformation observed at an open-pit limestone quarry in Japan, but these only reveal the characteristics of deformation modes as forward and downward displacement of the cut rock slope while causes of the rock slope deformation were not clarified. In that regard, the Finite Element Modelling (2D-FEM) method was employed to investigate the deterioration effect of clay found at the footwall of the rock slope in terms of reduction in Young's modulus of the clay quantified by experimental results. Finally, the deformation mechanism was discussed based on the comparison of the measurement and simulated results of the rock slope displacement.

2. Overview and displacement characteristics of the rock slope at of the studied limestone quarry

2.1. Overview of the studied limestone quarry

The studied quarry is a small-scale open-pit limestone quarry, which has been under operation for more than 100 years with an annual production of 200,000 tons [12]. The rock mass of the quarry consists of complex geological rock types of main limestone, schalstein and slate rocks. However, the schalstein and slate rocks have been weathered intensively, resulting in the formation of clay of about 70 m thick (elevations of 440-370 m) at the footwall of the rock slope, as illustrated in Fig. 1.

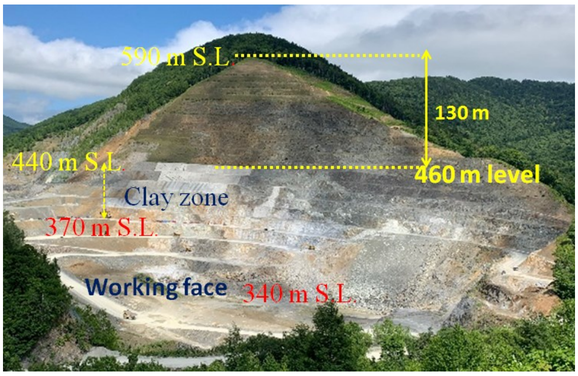

Figure 1: Plane view of the rock slope layout.

At present, mining has been undertaken at 340 m above sea level, whereas backfilling has been done on the northern side of the quarry. Initially, the quarry was designed with a bench height of 10 m at a slope angle of about 70°, as illustrated in Fig. 2. Currently, as the operation continues, the height of the rock slope has increased to about 130 m, as seen in Fig. 1. The final slope angle has been reduced to 55°.

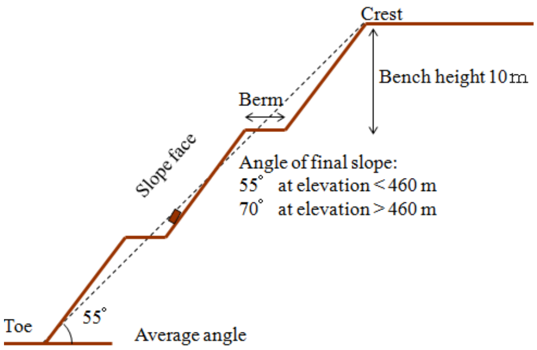

Figure 2: The bench design of the quarry.

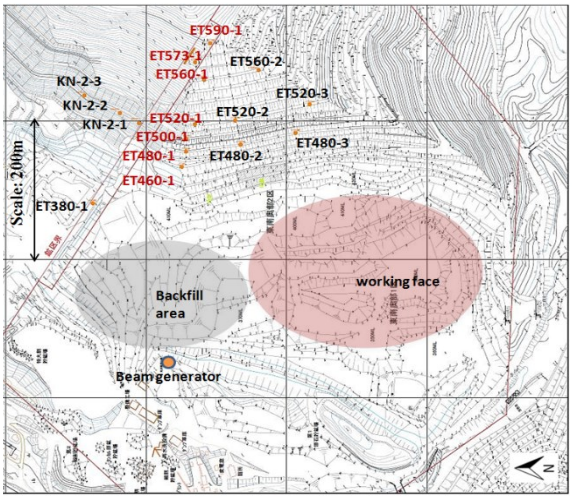

Figure 3: Map showing the APS layout. The ET represents the mirror point locations of automated polar system (APS) set along the rock slope. Each mirror point is represented with a number that indicates its level of elevation.

2.2 Rock slope displacement measurements

In order to ascertain the characteristics of rock slope deformation observed at the quarry, displacement has been measured for more than five years using an automated polar system (APS). In APS, the travelling times of laser beam from a beam generator to mirrors located at various points along the slope (Fig. 3) were measured. Thereafter, changes in distance between each of the mirror points and the beam generator point were calculated from the change in travelling time and velocity of the laser beam. The calculated change in distance from 11 APS data measured from January 2014 to April 2019 are shown in Fig. 4. The results show that change in the distance at all elevations decreases gradually with time, although its decreasing rate depends on mirror points. Total changes in distance are approximately between 20 mm and 100 mm. Fig. 5 shows the relationships between change in distance and elevations of the quarry, which revealed that maximum displacements occurred at the middle (elevation 520 m) of the rock slope. This implied that rock slope displacements depend on the elevations. The result was also used to validate the simulation results.

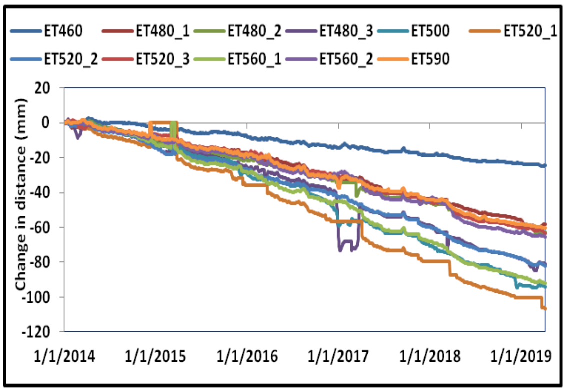

Figure 4: Change in the distance from 2014 to 2019.

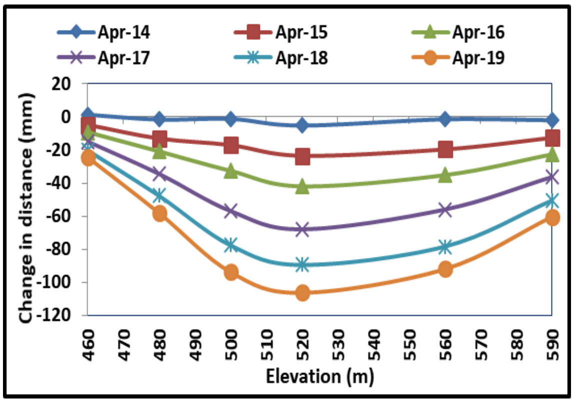

Figure 5: Relationship between change in distance from 2014 to 2019 and elevations.

3. Numerical analysis of rock slope displacement induced by deterioration effect of clay

In this section, the open-pit quarry consisting of limestone, schalstein and slate rocks as main rock types were modeled as homogeneous limestone, except within the clay zone in the vicinity of the footwall of the rock slope by using 2-D FEM in terms of reduction in Young's modulus of the clay-based on the quantitative experimentally results. This is to understand the deterioration effect of the clay on the cut rock slope deformation.

3.1 Simulation conditions

2-D FEM was undertaken using MIDAS GTS/NX 2014 (V2.1) [13] finite element code to simulate deformation induced by a reduction in Young's modulus of clay. Finite element meshes on cross-sectional areas of the quarry, as shown in Fig. 6, were generated using six-node triangular elements based on the elevations read from the regional contour map. Fig. 7 shows the entire analytical model with the dimension of 830 m and 1489 m.

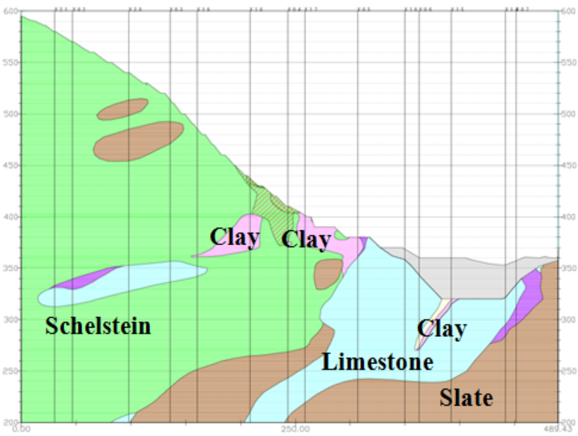

Figure 6: The cross-sectional area of the quarry.

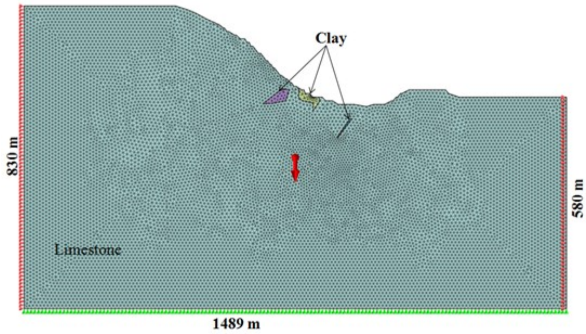

Figure 7: The entire model generated based on the elevations read from the cross-sectional area of the quarry.

The rock mass was assumed to be homogeneous limestone, except within the clay zone in the vicinity of the footwall of the rock slope. The mechanical properties of the limestone and clay zone for this simulation are presented in Tables 1 and 2. In order to clarify the deterioration effects of the clay on the slope deformation, two basic analyses were made based on experimental results, as shown in Tables 1 and 2. Firstly, Young's modulus of clay was set as 50 MPa and 20 MPa at initial stages, then it was assumed to have deteriorated to 20 MPa, and 3 MPa, defined as Case 1 and Case 2 as Young's modulus of limestone was set as 1 GPa, respectively (Table 1). Secondly, Young's modulus of limestone was increased to 5 GPa, whereas Young's modulus of clay was the same, then defined as Case 3 and Case 4, respectively, as shown in Table 1. The analyses were carried out under a plane-strain condition. The nodal displacement perpendicular to the right-left and the bottom surface of the model were fixed at zero. Nodal forces due to gravity were applied to the entire model in the vertically downward direction to generate the initial stress field. Afterward, the relative displacements induced by a reduction in Young's modulus of clay were calculated for each of the models by subtracting the displacement at initial Young's modulus from that of after deterioration.

3.2 Simulation results and discussions

The relative displacements induced by a reduction in Young's modulus of clay (50MPa → 20 MPa) and (20 MPa → 3 MPa) were shown in Fig. 8-11, where horizontal displacement (X-direction) and vertical displacement (Y-direction) are shown on the right-hand-side and left-hand-side of the figures, respectively. The positive values (in X-direction) and the negative values (in Y-direction) indicate forward and downward displacement of the rock slope, respectively. The results revealed that forward surface displacement occurred mostly at the top of the cut rock slope, whereas high downward displacement occurred below the clay zone near the footwall of the rock slope. It also shows similar tendencies of displacement but different magnitude, which increases with reduction in Young's modulus of clay, revealing that displacement depends on the deterioration of the clay. Fig. 12 shows the result of the change in distance calculated from the simulated relative displacement, revealing similar tendencies but different magnitude depending on Young's modulus of clay and limestone. To validate the simulation results, the simulated change in distances was compared with the result of the measured displacements (Fig. 5); both show similar tendencies at the middle and upper part of the cut rock slope. This suggested deterioration of clay found at the footwall of the rock slope as one of the possible causes of the rock slope deformation observed at the quarry.

4. Conclusion

In this paper, displacement measured over five years by APS was analyzed in order to understand the characteristics of rock slope deformation observed at the quarry. The measured results revealed that the distance between the beam generator and mirrors at all elevations on the rock slope gradually decreases with time. Although, the magnitude of change in distance differs at all elevations, and the maximum displacement occurs at the middle of the rock slope. Subsequently, the causes of deformation observed in the quarry were investigated numerically by considering the deterioration effect of clay deposited at the footwall of the rock slope. The results revealed that deterioration of the thick clay could be the possible cause of the slope deformation in the quarry.

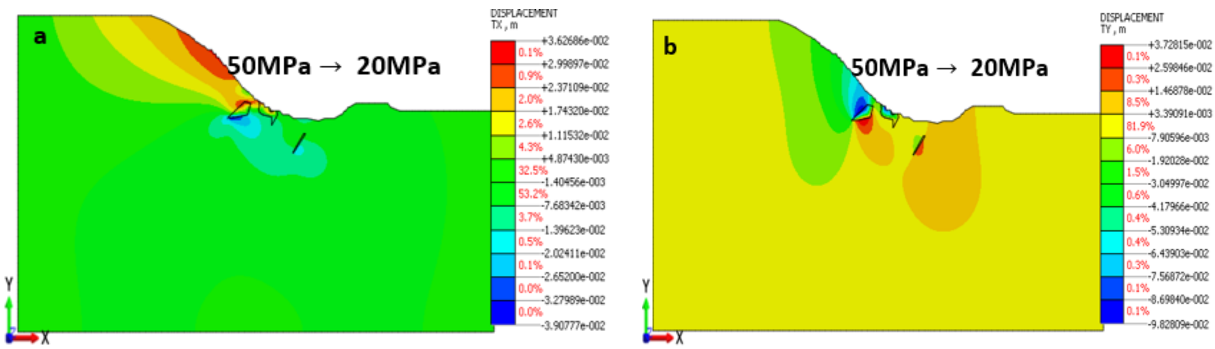

Figure 8: Relative displacement distribution in X-direction (a) and Y-direction (b) (Case 1).

Table 1: Young's modulus of limestone and clay rock.

Case	Clay (GPa)		Limestone (GPa)
	Initial	After deterioration	
Case 1	0.05	0.020	1.0
Case 2	0.02	0.003	1.0
Case 3	0.05	0.020	5.0
Case 4	0.02	0.003	5.0

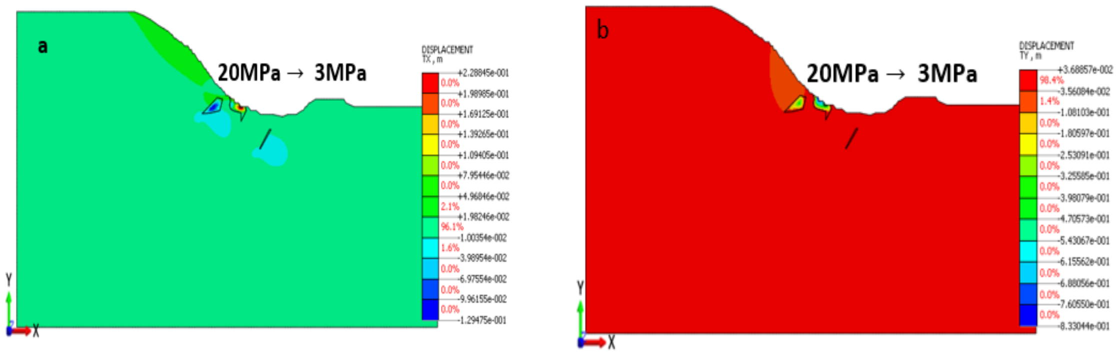

Figure 9: Relative displacement distribution in X-direction (a) and Y-direction (b) (Case 2).

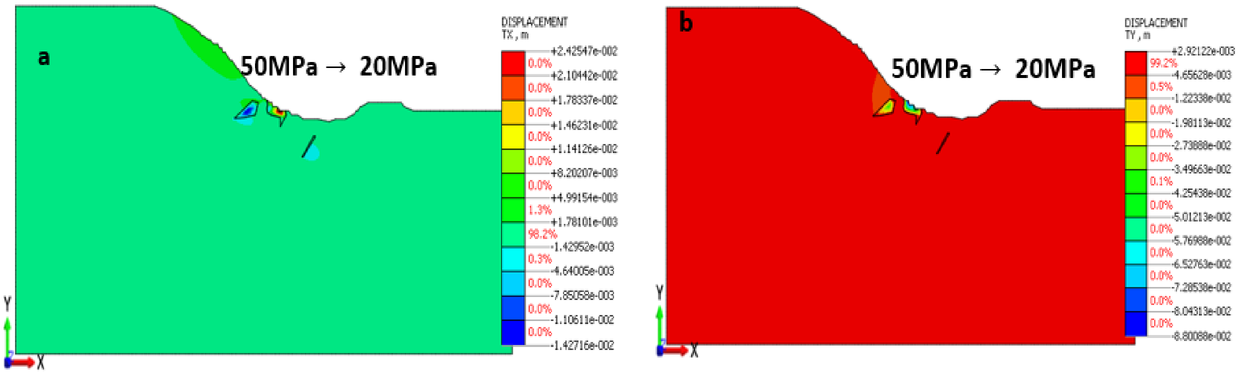

Figure 10: Relative displacement distribution in X-direction (a) and Y-direction (b) (Case 3).

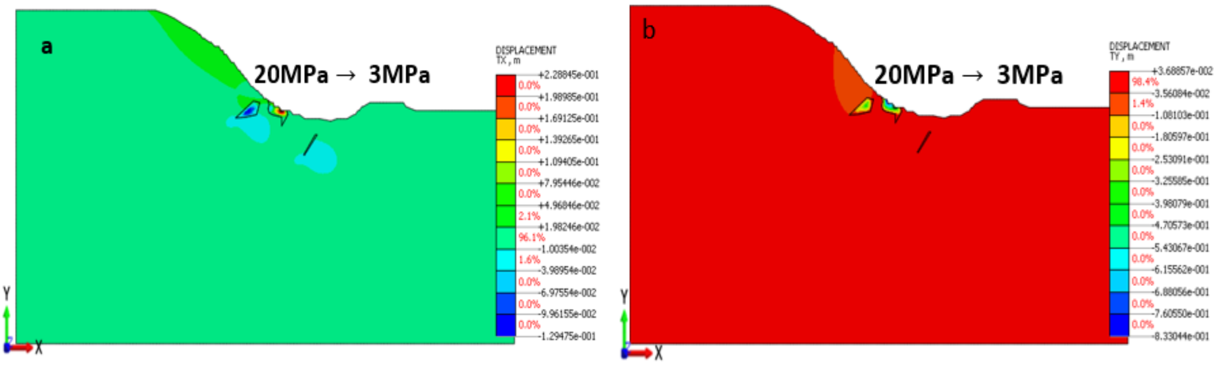

Figure 11: Relative displacement distribution in X-direction (a) and Y-direction (b) (Case 4).

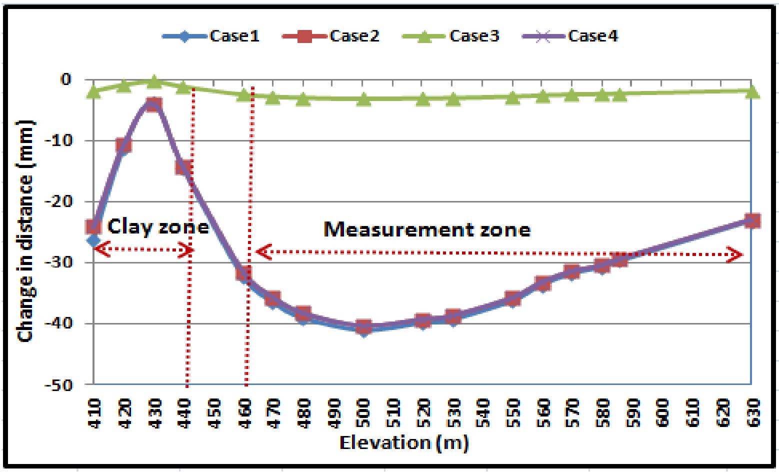

Figure 12: Change in the distance calculated from simulated relative displacements.

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