Elastic deformation of rock slopes due to excavation in open pit mines

NAJIB
Candidate for the Degree of Doctoral program
Supervisor: Jun-ichi KODAMA
Division of Sustainable Resources Engineering

Chapter 1. Introduction

Stability assessment is an important issue for rock slopes. Instability of rock slopes may result in slope failure, causing not only loss of production but also unexpected expense for rehabilitation. Furthermore, fatal accidents may occur due to rock slope failure, making slope monitoring critically important in open-pit mining. Displacement of a natural slope is usually caused by inelastic deformation; however, a cut rock slope in an open-pit mine may often result in inelastic deformation as well as elastic deformation due to excavation. For this reason, decomposing the measured displacement into elastic and inelastic components is necessary for a stability assessment. It is shown that numerical analysis is a powerful tool to estimate the elastic deformation due to excavation and that of cut rock slope in a homogeneous pit-type mine has been clarified. However, the deformation in a mountain-type mine is not investigated in detail. In the most cases, geological condition of open-pit mines is not homogeneous. For an example, limestone deposit is often found on inclined bedrock and buttress of intact limestone is often used for preventing from degradation of bedrock. Thus, understanding of impacts of the geological structure and buttress on rock slope deformation is also significant.

In this dissertation, a mining-induced elastic deformation of a cut rock slope formed in an open pit mine is investigated using a two-dimensional finite element method. The background and purpose of the study are described and the literatures related to rock slope stability of open pit mines are reviewed.

Chapter 2. Deformation of rock slopes formed in homogeneous mountain-type mines

The deformation mode and mechanism of a cut rock slope formed in a homogeneous mountain–type mine was investigated. Based on the fundamental analysis of horizontal deformation of the mountain due to both gravity and excavation of the whole mountain, it was found that the effect of the Poisson’s ratio can be further decomposed into two mechanisms: well–known Poisson’s effect (PE) and distributed load effect (DLE). The PE enhances the horizontal extension of the mountain due to gravity and dominates at larger Poisson’s ratios, and the DLE induces horizontal contraction due to gravity at the boundary between the mountain and constrained surface beneath and dominates at smaller Poisson’s ratios. It was also found that a decrease in the slope angle enhances the bending of the mountain, and intense horizontal compression near the middle of mountaintop occurs. By using a model with the slope face inclined at an angle of about 45° to the horizon, it was found that forward horizontal surface displacement of the cut rock slope occurs by the release of horizontal compressive stress due to bending around the center of the mountaintop. Asymmetric stress release due to excavation affects the horizontal deformation of mountain and induces a moment that enhances the horizontal backward displacement due to shear distortion of the mountain. The mechanism for the elastic horizontal surface displacement of a cut rock slope formed by excavation can be explained by considering these four effects. Furthermore, based on the internal displacement analysis, it was found that the magnitude of horizontal extension due to excavation was greatest at the surface of the cut rock slope and decreased with increasing horizontal depth from the surface. It was also found that the horizontal extension of rock slope increased rapidly during the early stages of excavation but that decreased in the latter stages of excavation.

Chapter 3. Deformation of rock slopes formed in mountain-type mines consisting of limestone and bedrock

The impact of difference of Young’s modulus between limestone and bedrock on deformation of a cut rock slope in a mountain–type mine was investigated with a model consisting of both the rocks. The effect of intact limestone buttress on the deformation of the rock slope was also investigated. It was found that the behavior of the rock slope depends on the ratio of Young’s modulus of both the rocks. In the case that Young’s modulus of bedrock is smaller than that of limestone, the cut rock slope tends to exhibit horizontal forward displacement and extension regardless of Poisson’s ratio. The magnitude of the horizontal forward surface displacement and extension increases with decreasing in Poisson's ratio. The extension tends to decrease with the increase in distance from the slope surface and progress of excavation. In the case that Young's modulus of the bedrock is greater than that of limestone, the cut rock slope tends to exhibit horizontal backward displacement and contraction. The contraction tends to decrease with the increase in distance from the surface and progress of excavation. The rock slopes with or without buttress exhibits extension, but the magnitude of horizontal forward surface displacement and extension decreases with the increasing in buttress thickness.
Chapter 4. Deformation of rock slopes formed in pit-type mines consisting of limestone and bedrock

The impact of difference of Young’s modulus between limestone and bedrock on a rock slope in a pit-type mine consisting of limestone and bedrock was investigated. The effect of an intact limestone buttress on a rock slope deformation in a pit-type mine was also investigated. It was found that deformation modes of rock slope formed in limestone is independent of the ratio of Young’s modulus of both the rocks. It always shows the horizontal backward surface displacement and contraction at smaller Poisson’s ratios, but it shows the horizontal forward displacement and extension around the toe of slope at larger Poisson’s ratios. In contrast, the deformation behavior of the rock slope formed in bedrock depends on the ratio of Young’s modulus of both the rocks. In the case that Young’s modulus of bedrock is smaller than that of limestone, the cut rock slope formed in bedrock tends to exhibit the horizontal backward displacement and contraction at smaller Poisson’s ratios, whereas it tends to exhibit the horizontal forward displacement and extension at large Poisson’s ratios. In the case that Young's modulus of the bedrock is greater than that of limestone, the cut rock slope formed in bedrock tends to exhibit horizontal backward displacement and contraction at all Poisson’s ratio. These results demonstrate that the elastic deformation behaviors of a rock slope formed in a pit-type mine are significantly different from those in a mountain-type mine. The contracted and extensions due to excavation tend to become larger toward the slope surface with some exceptions and the rates of extended or contractions with respect to the rock surface decreased with the progress of excavation. The effect of buttress in a pit-type mine is similar to that in a mountain-type mine. The presence of the buttress only affects the magnitude of the rock slope horizontal deformation, in which the magnitude of the deformation decreased with increasing of thickness of the buttress.

Chapter 5. Suggestions and application to rock slope

Deformation modes of rock slopes due to excavation in mountain-type and pit-type mines described in previous chapters were summarized in the lists for quick understanding of stable deformation. From the lists, it was shown that rock slope mostly shows the contraction in pit-type mines and rock slope generally extends in mountain-type mines. These results suggest that the extension is certainly a warning sign of unstable deformation of the rock slope in a pit-type mine. On the other hand, the rock slope with an extension in a mountain-type mine can be in a stable state as long as the rock slope surface is displaced backward. This means the measurement of the horizontal surface displacement is also important in stability assessment. From the internal displacement analysis, it is suggested that the following deformation behaviors are also the indication of an unstable state of rock slope; larger extension deeper inside the rock slope than near the slope surface. The rate of increase in the extension with respect to the rock surface decreases as the excavation progresses. To verify the elastic analysis approach adopted in this dissertation, rock slope deformation measured by extensometers in Shiriya limestone mine was attempted to be interpreted by applied elastic analysis. It was concluded that deformation behavior of the rock slopes can be qualitatively interpreted as being elastic deformation if Young’s modulus of bedrock is smaller than that of limestone. As mentioned above, the impact of difference of Young’s modulus between limestone and bedrock has been cleared by assuming that Poisson’s ratio of limestone was equal to that of bedrock for simplicity. However, it is highly possible that Poisson’s ratio of limestone is different from that of bedrock. Therefore, clarification of impact of difference in Poisson’s ratio between limestone and bedrock on a mining-induced rock slope deformation is one of future works. The measurement results of rock slope deformation of a pit-type mine was interpreted by elastic analysis. However, for mountain-type mine, the interpretation of deformation behavior by elastic analysis has not been conducted yet due to the lack of field measurement results, which is also future challenging work.

Chapter 6. Conclusions

The obtained results are review and some suggestions for future work are given.