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|                     |                                                                                                 |
|---------------------|-------------------------------------------------------------------------------------------------|
| Title               | Elastic deformation of rock slopes due to excavation in open pit mines                          |
| Author(s)           | Najib                                                                                           |
| Degree Grantor      | 北海道大学                                                                                           |
| Degree Name         | 博士(工学)                                                                                          |
| Dissertation Number | 甲第12032号                                                                                        |
| Issue Date          | 2015-09-25                                                                                      |
| DOI                 | <a href="https://doi.org/10.14943/doctoral.k12032">https://doi.org/10.14943/doctoral.k12032</a> |
| Doc URL             | <a href="https://hdl.handle.net/2115/60000">https://hdl.handle.net/2115/60000</a>               |
| Type                | doctoral thesis                                                                                 |
| File Information    | Najib.pdf                                                                                       |



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

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2015

学位論文内容の要旨

## DISSERTATION ABSTRACT

博士の専攻分野の名称      博士（工学）

氏名    Najib

Title of dissertation submitted for the degree

学位論文題名

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

(掘削に伴う露天掘り鉱山の残壁の弾性変形の解析)

<Abstract>

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 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 dissertation consists of six chapters.

In chapter 1, the background and purpose of the study are described and the literatures related to rock slope stability of open pit mines are reviewed.

In chapter 2, the basic deformation modes and its mechanism of homogeneous mountain-type mine were discussed, including the effects of the Poisson's ratio, slope angle and progression of the excavation. The results show four effects contribute to the deformation mechanism in a mountain-type mine: the Poisson effect (PE), the distributed load effect (DLE), bending effects and shear distortion. Forward surface displacement of the cut rock slope was found to occur during the early stages of excavation due to the release of horizontal compressive stresses due to bending effects. As the excavation progresses, forward or backward horizontal surface displacement was found to occur due to PE or DLE, respectively, which depends on the Poisson's ratio. Asymmetric stress release due to excavation affects the horizontal deformation of the mountain, and induces a moment enhancing the backward displacement due to shear distortion.

In chapter 3, the effects of Young's modulus ratio of limestone and bedrock in a mountain-type mine as well as the effects of buttress were investigated and the results were compared. The obtained results indicated that deformation modes of mountain-type mine depended on ratio of Young's modulus, Poisson's ratio and progress of excavation. It was apparent that deformation modes in a mountain-type mine showed extension although contraction was also found only in the case of Young's modulus of limestone was smaller than that of bedrock. Additionally, significant impacts could not be found with or without buttress above bedrock to the rock slope deformation. However, the magnitude of deformation increased with decreasing buttress thickness and that was greatest at the surface of the cut rock slope, and decreased with increasing depth from the surface.

In chapter 4, the effects of Young's modulus ratio of limestone and bedrock in a pit-type mine as well as the impacts of buttress were studied and the obtained results were compared. Similar to a mountain-type mine, the results show that deformation modes of pit-type mine

depended on the ratio of Young's modulus, Poisson's ratio and progress of excavation. However, a clear dependence of deformation modes on Poisson's ratio was observed, in which contraction was found for a smaller  $\nu$  and extension for a larger  $\nu$ , even though an extension was found in the case of the smaller limestone Young's modulus. The impacts of buttress in a pit-type mine were also similar with a mountain type mine; there were no significant impacts of buttress unless the increasing buttress thickness affects increasing of deformation magnitude. In addition, the magnitude of deformation was greatest at the surface of cut rock slope and decrease by following the depth.

In chapter 5, summary of deformation modes of open pit mine was classified and suggestions of rock slope monitoring were given. The direction of both the surface displacement and internal displacement of the cut rock slope in open-pit mine could change with the excavation progresses, even for a stable rock slope. This is significant in interpreting surface displacement monitoring using the Automated Polar System (APS) and/or Global Positioning System (GPS) and internal surface displacement monitoring using extensometers. The qualitative comparison of analytical results and measured results showed a good agreement. Hence, rock slope stability assessment by analytical result can be qualitatively considered for rock slope monitoring.

In chapter 6, the obtained results are review and some suggestions for future work are given.

**Keywords:** excavation, finite element method, mountain-type mine, pit-type mine, rock slope monitoring, rock slope deformation.

## ACKNOWLEDGEMENTS

Foremost, I give thanks to God for protection and ability to do work. I would like to express my sincere gratitude to my advisor Assoc. Prof. Jun-ichi KODAMA for the continuous support of my Ph.D study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study.

Besides my advisor, I would like to thank the rest of my thesis committee: Prof. Yoshiaki FUJII, Prof. Satoru KAWASAKI, and Prof. Tatsuya ISHIKAWA, for their encouragement, insightful comments, and hard questions.

My sincere thanks also go to Dr. Daisuke FUKUDA for his support, advices and his kind help during my graduate studies.

I thank my fellow lab mates in Hokkaido University: Mr. A.K.M Badrul Alam, Mr. Yoshitaka MITSUI, Ms. Anjula Buddhika Nayomi Dassanayake, Mr. kenta ANDO, Mr. Ryota MORIYA and other graduate and undergraduate students for the stimulating discussions and for all the fun we have had in the last three years.

Furthermore, I would like to thank my many Indonesian friends, both in Indonesia and in Hokkaido, for their support and encouragement. I also owe a great deal to new friends I have met during activities in Hokkaido; they have welcomed me into an international circle.

My study at the graduate level was undertaken within the E3 program (English Engineering Education program) at Hokkaido University. I would like to thank the Ministry of Education and Culture of Indonesia and Higher Education Department for awarding me a Beasiswa Luar Negeri (BLN) scholarship supporting me in my graduate study.

My deepest thanks are due to my family, for their constant support and for giving me a wonderful start in life. This dissertation is dedicated to them. Last but not the least, and most importantly, I would like to thank my wife, Mrs. Etika Ratna Noer, for her dedicated support. My sincere and grateful thoughts are also extended to my son, Abdurrahman Azmi Naka Arsyad and my daughter, Tazkiyanafsi Nara Mufida.

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# CHAPTER 1

## INTRODUCTION

### 1.1. Background

Stability assessment is an important issue for rock slopes. Instability of rock slopes may result in slope failure, causing not only loss of production (Yamaguchi and Shimotani, 1986; Willie and Mah, 2004) but also unexpected expense for rehabilitation (Willie and Mah, 2004). Furthermore, fatal accidents may occur due to rock slope failure, making slope monitoring critically important in open-pit mining. The stability of rock slopes has been assessed using limit equilibrium analysis (e.g. Yamaguchi and Shimotani, 1986; Singh and Baliga, 1994; Bye and Bell, 2010), numerical analysis (e.g. Obara et al., 2000; Jing, 2003, Ataei and Bodaghabadi, 2008) and field measurements (e.g. Maffei, 2004; Kodama et al., 2009). Recently, the automated polar system (APS) and global positioning system (GPS) (e.g. Wang et al., 2010; Ma et al., 2012) have been introduced to measure regional displacements. Extensometers have also been installed in rock slopes to measure the internal displacement (Kaneko et al., 1997; Deng and Lee, 2001), and based on these measurements, the deformation behavior of cut rock slopes in open-pit mines has been investigated. 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 elastic deformation due to excavation (Kaneko et al., 1997; Kodama et al., 2009) as well as inelastic deformation. For this reason, decomposing the measured deformation into elastic and inelastic components is necessary for a stability assessment. Once the elastic deformation of rock slopes has been calculated, inelastic deformation can then be inferred from a comparison between the measured data and analyzed elastic deformation (Fig. 1.1).

Kaneko et al. (1997) and Kodama et al. (2009) investigated the deformation of cut rock slopes formed in “pit-type mines” (Fig. 1.2 (a)). The deformation of cut rock slopes formed in “mountain-type mines”, however, (Fig. 1.2 (b)) has not been investigated in detail. There are several large mountain-type mines in Japan, including Bukoh limestone mine (Study committee on slope stability and environmental

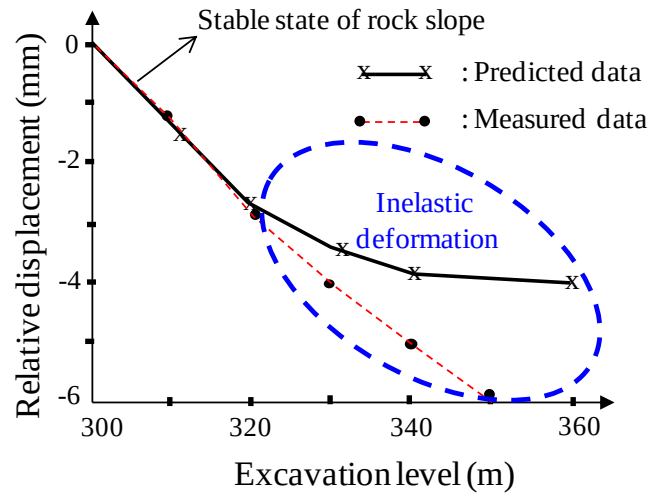


Fig. 1.1. Example of a comparison between predicted data by numerical analysis and measured data.

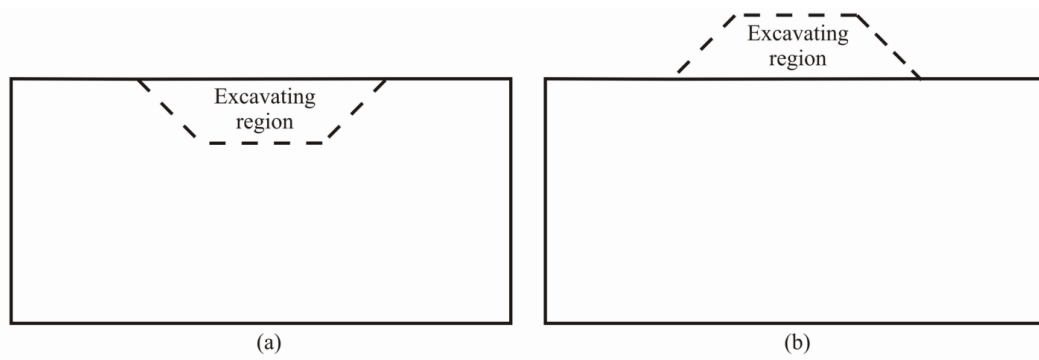


Fig. 1.2. Schematic illustration of (a) a pit-type mine and (b) a mountain-type mine.

preservation in Chichibu area, 1996) and Torigatayama limestone mine (Kodama et al., 2013). The expected slope height in these mines at the stage of mine closure will be more than 500 m. Therefore, an understanding of the modes and mechanisms of mining-induced elastic deformation of the rock slopes in mountain-type mines is important. In Japan, limestone deposit is often found on inclined bedrock and a part of limestone deposit is left on the bedrock as a buttress to prevent the bedrock from weathering. Thus, understanding effects of both geological structure such as the inclined bedrock and buttress on mining-induced rock slope deformation is also significant.

## 1.2. Literature review

Various researchers have focused on the stability assessment of rock slope (Hoek and Bray, 1981; Goodman, 1989; Willie and Mah, 2004). However, the problem of rock slope stability still presents a significant challenge to designers. Thus, as frequently used methods for stability assessment of rock slopes, limit equilibrium analysis, numerical analysis and deformation monitoring are reviewed below. Combination of the deformation monitoring with elastic deformation analysis, which has been recently developed, is also reviewed.

### 1.2.1. Limit equilibrium analysis

The most popular method widely used by engineers and researchers for slope stability analysis is limit equilibrium method (LEM). The assumption that the internal force distribution is required to evaluate the factor of safety is well known from classical two-dimensional (2-D) method of slices in LEM (Bishop, 1955; Janbu, 1973; Morgenstern and Price, 1965; Spencer, 1967; Hoek and Bray, 1977). In the method of slices, the failure mass is divided into a number of columns with vertical interfaces and the static equilibrium state is assumed to find the factor of safety. Sarma (1979) employed slices with inclined interfaces to simulate structural discontinuities. Sigh and Baliga (1994) investigated the slope stability of an open-pit copper mine by LEM. Ataei and Bodaghabadi (2008) identified the possible failure of Chador-Malu iron ore mine by comparing numerical analysis and LEM. Granon and Hadjigeorgiou (2010) compared both kinematic analysis and limit equilibrium stability analysis for bench and inter-ramp design.

The extensions of LEM to the three-dimension were also studied (Hung, 1987; Hung et al, 1989; Chen and Chameau, 1983; Lam and Fredlund, 1993). They extended Bishop's simplified, Spencer's and Morgenstern and Price's methods from two to three dimensions. However, reports on the application of these methods have been hardly documented. Stark and Eid (1998) reviewed three commercially available computer programs in their attempts to analyze the case histories of several landslides. They concluded that the precision of estimated factor of safety was poor by using commercially the three software because of their limitations in describing geometry of model, material properties and/or the analytical methods. Chen et al. (2001) developed a

3-D LEM as an extension of Donald and Chen's 2-D approach (1997). They used the upper-bound theory and therefore avoided introducing a large number of assumptions. The failure mass was divided into a number of prisms with inclined interfaces.

Kinematic conditions and stability analyses of wedges (John, 1968; Londe et al., 1969; Jaeger, 1971; Warburton, 1981; Hendron et al., 1980; Chan and Einstein, 1981; Ghosh and Haupt, 1989; Goodman, 1995; Tonon, 1998; Kumsar et al., 2000; Wanwen and Caoping, 2004; Willie and Mah, 2004; Rose and Hungr, 2007; Grenon and Hadjigeorgiou, 2008; Grenon and Hadjigeorgiou, 2010; Rasheed et al., 2011; Jiang et al., 2013), toppling (Liu et al., 2008; Mohtarami et al., 2014) and rotational stability (Hungr and Amann, 2011) have been studied extensively in geotechnical literature. Most of these analyses are based on the LEM, in which only sliding modes are considered. Chan and Einstein (1981), Mauldon and Goodman (1996), and Tonon (1998) considered special cases of rotation and discussed the rotational stability of a rock block. Although LEM can be a useful method for preliminary analysis and may be adequate for slope failure with simple mechanisms, it only considers forces or moments and does not take slope displacements into account. As such, it is unable to fully capture complex slope failure mechanisms (Stead and Wolter, 2015).

#### 1.2.2. Numerical Analysis

Numerical analysis has been widely used for rock engineering design and construction. Jing and Hudson (2002) and Jing (2003) reviewed the techniques, advances, problems and possible directions of future development in numerical modeling for rock mechanics and rock engineering. They categorized the numerical modeling into the eight modeling and design methods. In the case of inelastic deformation of rock slopes, numerical discontinuum techniques have become increasingly popular for the investigation of the influence of joints on complex rock slope deformation (Stead et al., 2004). However, these techniques have inherent limitations because failure is frequently either preceded or followed by creep deformation or extensive internal fracturing. The factors controlling initiation and eventual sliding may be complex and are not easily allowed for in a simple static analysis. Therefore, Stead et al. (2004) suggested the use of a combination of limit equilibrium analysis and numerical modeling techniques to maximize the advantages of

both. Corkum and Martin (2004) simulated the displacement of rock blocks and a toe–berm using the discrete element method (DEM). They reported that the simulated displacement of the blocks and the berm were in good agreement with the observed displacement. However, they noted that detailed information on the location of each discontinuity is required for the DEM analysis. It appears that it is not straightforward to identify such a distribution of discontinuities.

Yeung et al. (2003) developed a three–dimensional (3–D) discontinuous deformation analysis (DDA) procedure for the analysis of wedge stability. This method was found to be capable of simultaneously handling general modes of sliding and rotation. In addition, orientation of discontinuities is an important parameter affecting rock slope stability, because failure type and kinematic instability are influenced mainly by this feature. In practice, the mean value orientations of pair of discontinuity sets are commonly considered representative in the calculation of the safety factors of random wedges (Park and West, 2001).

Eberhardt et al. (2004) discussed about the concept of progressive failure and numerical modeling of rock mass strength degradation in natural rock slopes using the Randa rockslide as a working example. They used combination of continuum (i.e., finite element method (FEM)) and discontinuum (i.e., DEM) methods to model fracture propagation. He et al. (2008) evaluated the stability of Antaibao open–pit coal slope and presented a scheme of relatively steep excavation which has successfully been put in practice on the site of the coal mine, thereby allowing the mine to produce additional income. To maximize the results, the combined use of limit equilibrium and numerical modeling technique such as finite difference method (FDM) or FEM is also of very importance. Bohme et al. (2013) investigated complex rock slope deformation by combination of both kinematic and numerical discontinuum modeling. They mentioned that integrating different data sources and analysis methods is urgently required in order to understand the deformation mechanism of a complex and unstable rock slope. However, they reported that the unstable slope indicated by numerical discontinuum modeling could not be confirmed by field observations, due to thick scree deposits covering the entire lower part of the slope. Xu et al. (2004) assessed the long–term stability of a rock slope in the Three Gorges Dam Project, China, using a 2–D viscoelastic analysis, and analytically showed that the vertical and horizontal

displacements of the slopes was in good agreement with observed displacements. However, there were non-negligible differences between the analyzed results and observations. They attributed these differences to difficulties in modeling the ground water, disturbances due to blasting, and shotcrete support. Stability assessment based on inelastic analysis is thus useful but also difficult because the fracture process of rock masses is complex, and the choice of optimum parameters for an inelastic analysis is not a straightforward task. Therefore, the development of simple assessment method is desirable from an engineering point of view.

#### 1.2.3. Deformation monitoring and its combination with elastic deformation analysis

Recently, the deformation monitoring and elastic deformation due to excavation in open-pit mines has been investigated (Commission on Standardization of Laboratory and Field Tests of ISRM, 1978; Deng and Li, 2001; Sheng et al., 2002; Matsuda et al., 2003; Xu et al., 2004; Wang et al., 2010; Osasan and Afeni, 2010; Fleurisson, 2012; Ma et al., 2012; Yu et al., 2014). In addition, a method of stability assessment for rock slopes based on the combination of elastic analysis and field measurement was proposed (Kaneko et al., 1997; Kodama et al., 2009). Sheng et al. (2002) investigated the cut rock slope by installing multiple extensometers in horizontal drill holes to measure the displacement of the rock between the vertical sidewalls and drainage tunnels in the two cut slopes. Surface wire extensometers were also installed in the monitoring adits to monitor the deformation of the disturbed zones during excavation. Matsuda et al. (2003) developed a displacement monitoring system of large slope using GPS. They discussed about availability of long-term monitoring and monitoring under the condition of the high height difference between the measurement points. Wang et al. (2010) proposed integration of GPS/Pseudolites positioning technology which can increase the number of satellites, strengthen the geometric intensity of satellites and provide a precise solution for slope deformation monitoring. They also reviewed the importance of slope monitoring with these techniques in surface mine excavations such as open-pit or open-cast mines. Ma et al. (2012) investigated the potential hazards of open-pit slope in Longshou mine by applying GPS to monitoring ground movement and deformation. The GPS monitoring results basically agreed with the practical deformation state of open-pit slope in Longshou mine.

Nakamura et al. (2003) analyzed results of field measurement in open cut limestone mine. Using multi-channel extensometers, they measured deformation behavior of two kinds of rock slopes. One rock slope was formed in slate protected by a buttress of intact limestone. Another rock slope was formed in limestone. It was found that the deformation of the rock slope formed in slate differs remarkably with that in limestone. Kaneko et al. (1997) investigated the effects of the initial stress on the deformation mode of a rock slope using a 2-D elastic analysis. They found that the rock slope shows contraction when the ratio of horizontal stress to vertical stress is small, but it shows extended deformation when the ratio is larger. Kodama et al. (2009) investigated the causes of long-term deformation of a rock slope observed at the Ikura limestone quarry using a 3-D elastic analysis with various Poisson's ratios. They found that the rock slope tended to extend following excavation with a large Poisson's ratio, but to contract with a smaller Poisson's ratio. They predicted the elastic deformation of a rock slope using the Young's modulus and Poisson's ratio estimated by back analysis, and concluded that the long-term deformation observed over more than 7 years can be interpreted as elastic deformation due to excavation at the working face, which was 400 m horizontally away from the toe of the rock slope.

The above results indicate that the combination of elastic analysis and field measurements is a powerful tool in the stability assessment of a cut rock slopes in open-pit mines. Therefore, once the elastic deformation of rock slopes is estimated by a back analysis, inelastic deformation can then be inferred from a comparison between the measured data and calculated elastic deformation (Kaneko et al., 1997).

### **1.3. Objectives of dissertation**

As described above, understanding elastic deformation of a cut rock slope due to excavation in open-pit mines is important for interpreting monitoring results. However, as also described above, elastic deformation of rock slopes formed in mountain-type mines and influence of geological structure such as presence of bedrock on rock slope deformation in open-pit mines has not been investigated in detail. In this dissertation, open-pit mines consisting of limestone and bedrock as well as homogeneous mines are modeled, and characteristics of elastic deformation of cut rock slopes formed by excavation in mountain-type and pit-type mines are cleared using 2-D FEM. First, the

characteristics of deformation of a cut rock slope formed in a homogeneous mountain-type mine are clarified, and the deformation mechanism of the rock slope is discussed in terms of the Poisson's ratio, slope angle and progression of the excavation. Next, for open-pit mines consisting of limestone and bedrock, the influence of difference in Young's modulus of both rocks on mining-induced elastic deformation of cut rock slopes is cleared. The mechanical effect of a buttress of intact limestone left over bedrock on the rock slope deformation is also cleared by varying its thickness. Then effective methods of rock slope monitoring for stability assessment are suggested based on the characteristics of estimated elastic deformation after deformation modes obtained from all the analyses are summarized in lists. Finally, results of field measurement in open-pit mine is attempted to be interpreted by elastic analysis.

#### **1.4. Synopsis of dissertation**

This dissertation consists of six chapters:

In chapter 1, the background and purpose of this study are described and the literatures related to stability assessment of rock slopes in open-pit mines are reviewed.

In chapter 2, the fundamental deformation modes and its mechanism of homogeneous mountain-type mine are discussed in terms of the effects of the Poisson's ratio, slope angle and progression of the excavation.

In chapter 3, by focusing on mountain-type mines consisting of limestone and bedrock, the influence of difference in Young's modulus between limestone and bedrock on rock slope deformation is investigated. The effect of buttress of intact limestone left over bedrock is also investigated.

In chapter 4, by focusing on pit-type mines consisting of limestone and bedrock, the influence of difference in Young's modulus between limestone and bedrock on rock slope deformation is investigated. The effect of buttress of intact limestone left over bedrock is also investigated.

In chapter 5, deformation modes of rock slopes in both mountain-type and pit-type mines are summarized in lists for quick reference. Then, effective rock slope monitoring for stability assessment is considered based on the characteristics of estimated elastic deformation. Finally, rock slope deformation measured by

extensometers in a pit-type limestone mine is attempted to be interpreted by elastic analysis.

In chapter 6, the obtained results are summarized and some future challenges are shown.

## CHAPTER 2

### DEFORMATION MODES OF ROCK SLOPES FORMED IN HOMOGENEOUS MOUNTAIN-TYPE MINES

#### 2.1 Introduction

As mentioned in chapter 1, the mining-induced elastic deformation of a rock slope in pit-type mines has been cleared (Kaneko et al., 1997; Kodama et al., 2009), but, that formed in mountain-type mines has not been investigated in detail.

The deformation of rock mass due to excavation is caused by the release of an initial stress owing to the gravitational forces. This means that the deformation due to excavation is certainly affected by the deformation of the mountain due to gravity. The main objective in this chapter is to clarify the elastic deformation of cut rock slopes formed in homogeneous mountain-type mines using 2-D FEM. First, the deformations of a mountain due to both gravity and excavation were analyzed to clear fundamental deformation mechanisms. Then, the characteristics elastic of deformation of a cut rock slope formed by excavation along the mountainside were investigated in terms of Poisson's ratio, slope angle and progress of the excavation. The deformation mechanism was also discussed based on the characteristics of the deformation behavior of the mountain and rock slope.

#### 2.2 Displacement and deformation of a mountain due to gravity

##### 2.3.1. Analytical Method

Figure 2.1 shows diagrams that illustrate the analytical model of mountain-type mine. The target slope angles of the mountain were 90° and 45°. The slope angle of 90° was chosen because the deformation mode was easier to be understood. The rock mass was assumed to be a homogeneous, isotropic elastic body with a Young's modulus of  $E = 5 \text{ GPa}$  and a unit weight of  $\gamma = 27 \text{ kN/m}^3$ . The Poisson's ratio was varied through  $\nu = 0.1, 0.2, 0.3$  and  $0.4$ , because the deformation modes (i.e., extension, contraction or shear distortion) of rock mass depend on the Poisson's ratio (Kodama et al., 2009; Kodama et al., 2013; Gercek, 2007). The nodal displacements perpendicular to the right,

left and the bottom surfaces 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. All analyses were carried out under plane-strain conditions using six-node triangular elements. For example, the total number of elements in the  $45^\circ$  model before excavation was 170,713, and there were 86,028 nodes. Here, only the horizontal displacement is discussed because the magnitude of vertical displacement was strongly dependent on the vertical dimensions of the analytical model (Obara et al., 2000).

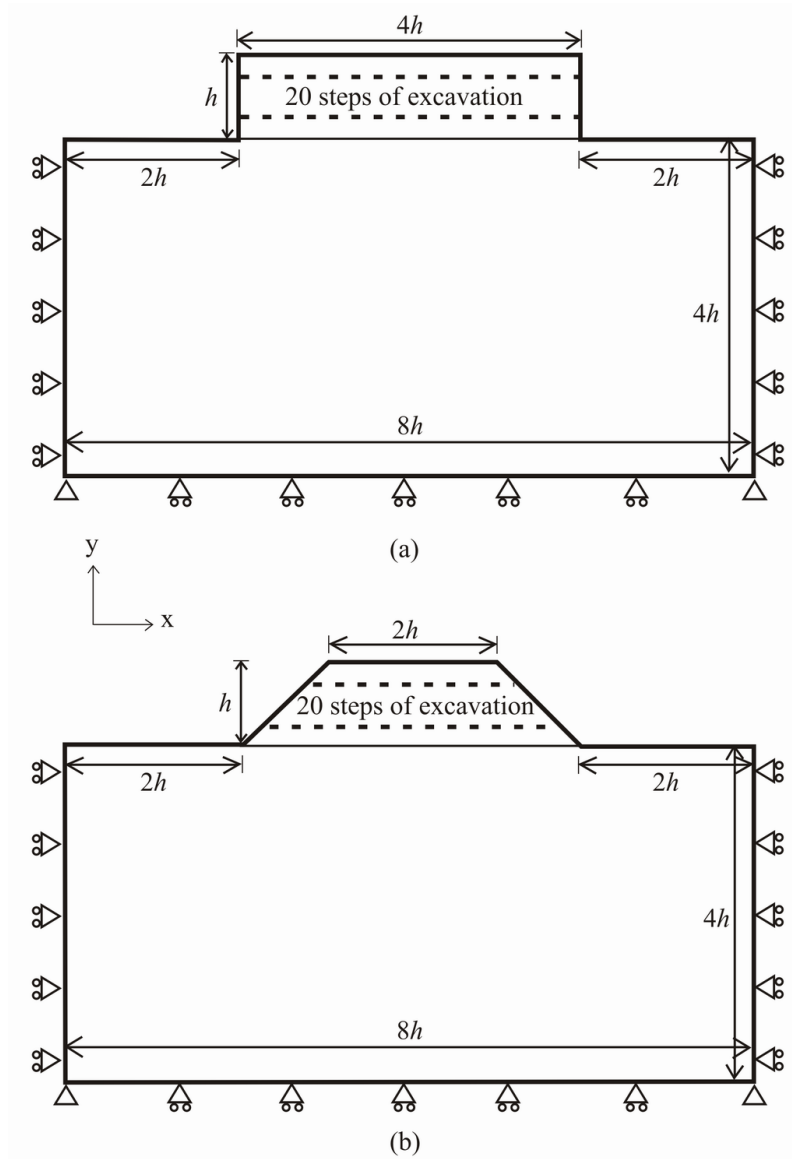


Fig. 2.1 Configuration of the two analytical models. Slope angles are (a)  $90^\circ$  and (b)  $45^\circ$ . The dashed lines indicate the progress of the excavation.

### 2.3.2. Analytical results and discussion

The horizontal surface displacements at four Poisson's ratios are shown in Fig. 2.2. In these figures, only the left side of the mountain in the model is shown because of the geometrical symmetry. For a slope angle of  $90^\circ$  as shown in Fig. 2.2 (a), forward surface displacement, i.e. horizontal extension can be observed for larger  $\nu$ , and backward surface displacement, i.e. horizontal contraction at smaller  $\nu$ . If horizontal deformation is caused by the Poisson effect (PE) only, it may expect horizontal extension is independent of distance from the surface on horizontal line and no compressive strain is seen. To investigate PE quantitatively, horizontal displacement was analyzed using a symmetric model shown by the rectangular block in Fig. 2.3. The gravity force was applied to the model under a boundary condition in which vertical displacement in the basal plane was fixed at zero. In this analysis, no constraint was made on the horizontal displacement. Figure 2.3 presents the analytical results corresponds to 0.1, 0.2, 0.3 and 0.4. The horizontal displacements shown are normalized by slope height  $h$ . Horizontal extension can be observed from the top to the foot of the model, and the magnitude of extension tends to increases approaching the foot. These results were found regardless of the values of  $\nu$ , although the magnitude of the extension depends on  $\nu$ . However, the analytical results shown in Fig. 2.2 differ from those in Fig. 2.3, suggesting that other mechanisms should be considered in the interpretation. Note that Fig. 2.2 shows relatively inward displacement around the toe of the mountain part. This horizontal displacement of the loaded region was induced because, by regarding the overburden due to the self-weight of the mountain as a distributed load, and the ground under the mountain as a semi-infinite medium, the horizontal inward movement of ground surface is expected. The exact solution was obtained for the deformation due to a distributed load with constant magnitude applied normally to the lower surface throughout an isotropic, homogeneous and elastic semi-infinite medium (Johnson, 1985; Timoshenko and Goodier, 1951). The amount of horizontal surface displacement at a point S inside the loaded region (see Fig. 2.4) can be calculated with the following Eq. (2.1) (Johnson, 1985)

$$\bar{u}_x = -\frac{(1-2\nu)(1+\nu)}{E} px \quad (-a \leq x \leq 0) \quad (2.1)$$

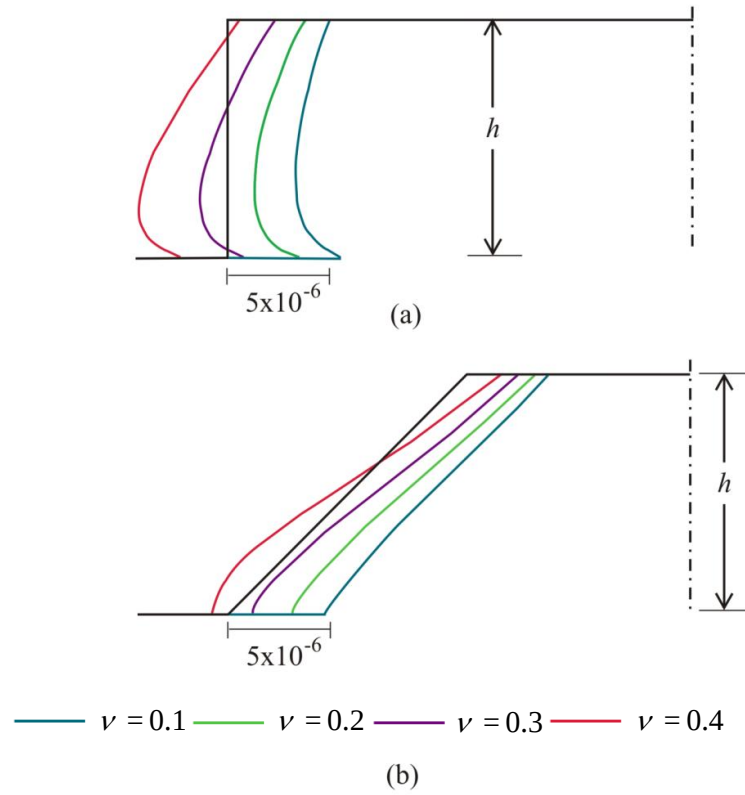


Fig. 2.2 Horizontal surface displacement of a mountain-type mine due to gravity for a slope angles of (a)  $90^\circ$  and (b)  $45^\circ$ . Only the left half of the mountain is shown. The displacement normalized by  $h$  and magnified by a factor of 500.

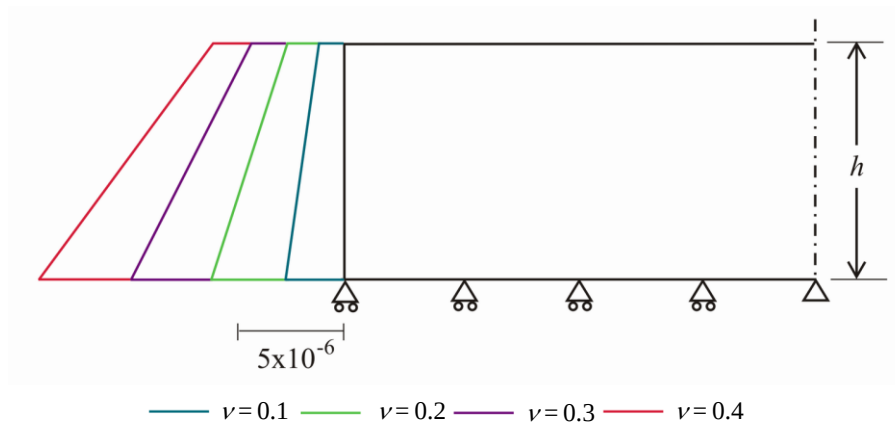


Fig. 2.3 Horizontal surface displacement of mountain-type mine with slope angles of  $90^\circ$  due to gravity without constraint in the horizontal displacement. Only the left side of

the model is shown because of its geometrical symmetry. The displacement normalized by  $h$  and magnified by a factor of 500.

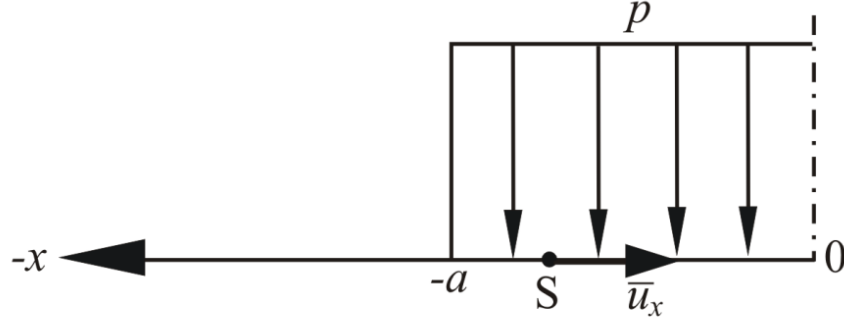


Fig. 2.4 Schematic illustration of horizontal displacement due to distributed load effect (DLE):  $p$  is a constant distributed load normally acting on the elastic semi-infinite medium,  $\bar{u}_x$  is the horizontal displacement of a point S on the ground surface, and  $a$  is half the length of the loaded region (modified from Johnson, 1985).

where  $\bar{u}_x$  is the horizontal displacement at the point S on the ground surface,  $\nu$  is Poisson's ratio,  $E$  is Young's modulus,  $p$  is the distributed load, normally acting on the elastic semi-infinite medium, and  $x$  is the distance from the center of the loaded region. Equation (2.1) shows that the ground under the mountain part in Fig. 2.2 (a) can be displaced inward from initial configuration by the distributed load effect (DLE).

To clarify the contribution of PE and DLE to deformation of the mountain part, Fig. 2.5 plots each horizontal displacement at the toe of the rock slope due to PE, normally DLE and superposition of both displacements. The displacement due to PE is estimated by the displacement at the toe in Fig. 2.3 and normalized by Young's modulus ( $E$ ), overburden ( $\gamma h$ ), and slope height ( $h$ ). The displacement due to DLE is estimated by substituting  $x = a$  into Eq. (2.1). The displacement due to PE is only shown for 0.0-0.4 because analytical results at  $\nu$  more than 0.4 are unreliable due to locking effects in the FEM approximation of elasticity problems (Bathe, 2006). Positive and negative signs indicate displacements causing contraction and extension, respectively. It can be seen that extension due to PE increases but contraction due to DLE decreases with an increased  $\nu$ . The superposition of the normalized displacements due to PE and DLE reveals that contraction occurs at roughly  $\nu < 0.3$  because the contribution of DLE is

greater while the extension occurs at roughly  $\nu > 0.3$  because the contribution of PE is greater. The effect of Poisson's ratio on the superposition of the normalized displacements due to PE and DLE was found to be in good agreement with the displacement found at the toe in Fig. 2.2 (a).

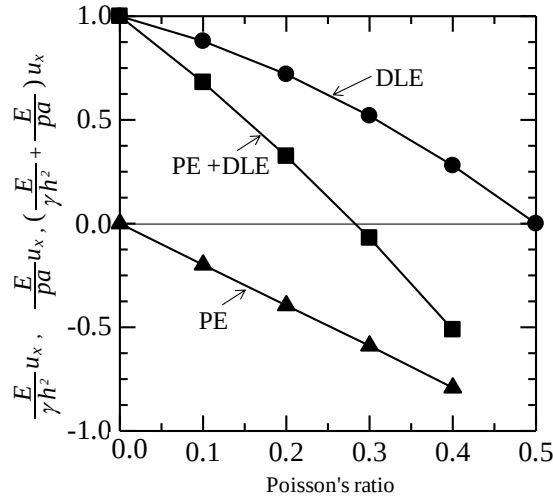


Fig. 2.5 Estimated horizontal displacements due to PE and DLE, and superposition of both displacements. The displacement due to PE is normalized by Young's modulus ( $E$ ), overburden ( $\gamma h$ ), and height of the mountain ( $h$ ). The displacement due to DLE is normalized by Young's modulus ( $E$ ), distributed load ( $p$ ), and half length of the loaded region ( $a$ ).

From above results, horizontal deformation shown in Fig. 2.2 (a) can be interpreted as the superposition of horizontal extension due to the PE and contraction due to the DLE. Horizontal contraction was observed with a smaller  $\nu$  since the PE is less significant and the DLE is the dominant effect; with a larger  $\nu$ , however, horizontal extension was observed because the PE is more significant than the DLE.

With a slope angle of  $45^\circ$ , the characteristics of the horizontal deformation were similar to that with a slope angle of  $90^\circ$ , with horizontal extension at larger  $\nu$  and contraction at smaller  $\nu$ . In addition to these competing effects of the PE and DLE, the mountain can also bend due to gravity, as shown in Fig. 2.6 , because the downward

displacement due to the self-weight increases toward the center of the mountain. This results in bending near the top of the mountain with a slope angle of  $45^\circ$ , and is less significant with a slope angle of  $90^\circ$ . To investigate this effect (hereafter, termed the bending effect), the distributions of horizontal strain ( $\epsilon_{xx}$ ) and stress ( $\sigma_{xx}$ ), as shown in Figs. 2.7 and 2.8, respectively, in the mountain at heights greater than  $h/4$ , where  $h$  is the height of the mountain, were studied for slope angles of  $45^\circ$  and  $90^\circ$ , and with Poisson's ratios of  $\nu = 0.1$  and  $0.4$ . The results for  $\epsilon_{xx}$  and  $\sigma_{xx}$  in the mountain at heights less than  $h/4$  are not shown because displaying the concentrations of  $\epsilon_{xx}$  and  $\sigma_{xx}$  around the toe of the slope results blurs the characteristics that are particular to the bending effect at the mountaintop. As is evident from the comparison between the distributions of  $\epsilon_{xx}$  and  $\sigma_{xx}$ , with a slope angle of  $45^\circ$ , more contraction occurs at the center of the mountain near the top, resulting in more horizontal compressive stress than in the surrounding parts; furthermore, these contraction and compression were greater with a smaller  $\nu$ . With a slope angle of  $90^\circ$ , the contraction was less significant at the center of the mountain near the top resulting in less horizontal compressive stress due to the bending effect. These results show that horizontal deformation in mountain-type mines increases with decreasing slope angles, which indicates that bending effects result in compressive deformation near the top of the mountain due to the effects of gravity.

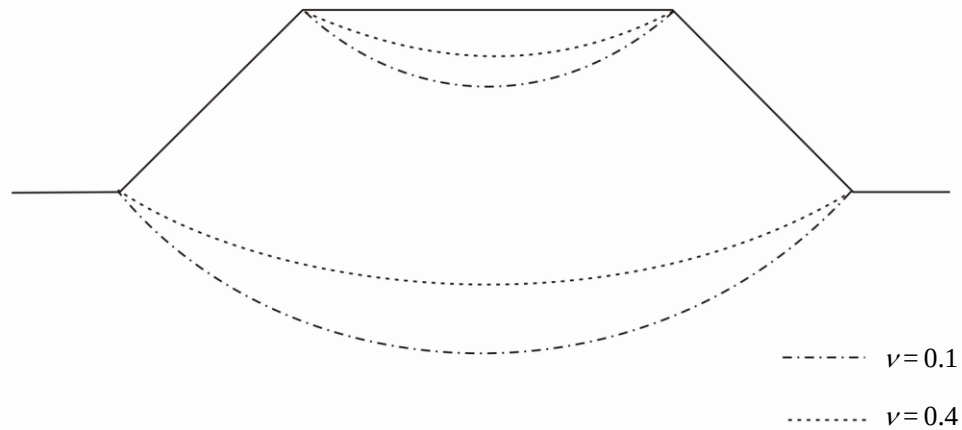


Fig. 2.6 Schematic diagram showing the bending effect observed in the model with a slope angle of  $45^\circ$ .

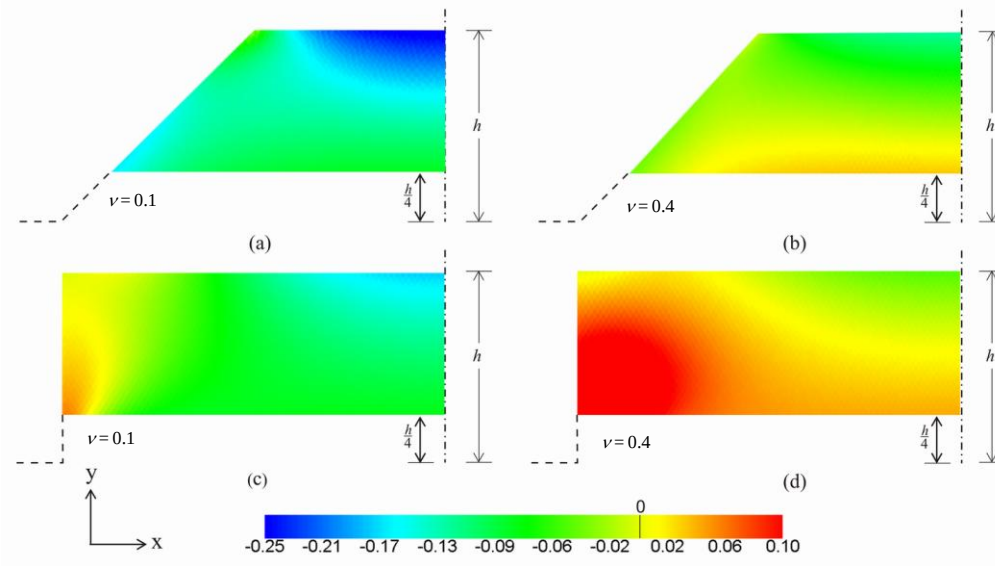


Fig. 2.7 Distribution of horizontal strain ( $\epsilon_{xx}$ ) in the mountain above  $h/4$  for slope angles of (a–b) 45° at  $\nu = 0.1$  and 0.4, respectively, and (c–d) 90° at  $\nu = 0.1$  and 0.4, respectively. Only the left side of the model is shown because of the geometrical symmetry. Here, a negative value of  $\epsilon_{xx}$  corresponds to compressive strain.

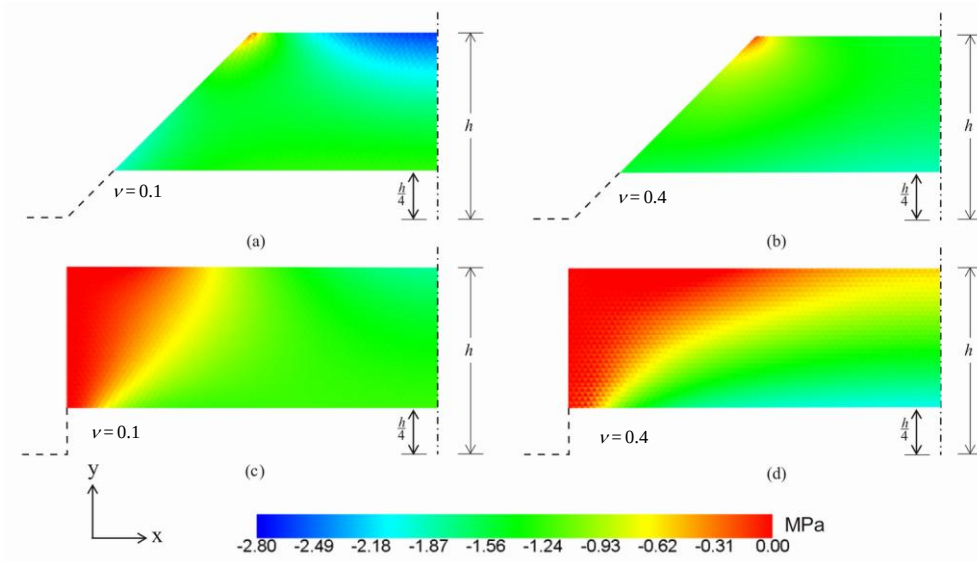


Fig. 2.8 Distribution of horizontal stress ( $\sigma_{xx}$ ) in the mountain above  $h/4$  for slope angles of (a–b) 45° at  $\nu = 0.1$  and 0.4, respectively, and (c–d) 90° at  $\nu = 0.1$  and 0.4, respectively. Only the left side of the model is shown because of the geometrical symmetry. Here, a negative value of  $\sigma_{xx}$  corresponds to compressive stress.

## 2.3 Displacement and deformation of a mountain due to excavation of mountaintop

### 2.3.1. Analytical method

Deformation of a mountain due to excavation of the entire mountaintop with height  $h$  (hereafter referred to as total excavation) was analyzed to understand the deformation of a cut rock slope formed by excavation along the mountainside from top to the bottom in mountain-type mine (hereafter, partial excavation) although a rock slope was not formed in the total excavation. The initial configuration of the total excavation model is same as shown in Fig. 2.1; i.e., the height of the mountain is  $h$ , and the excavation proceeded in 20 steps from the top to the bottom, with an excavation depth per step of  $h/20$ . The deformation due to excavation was calculated by applying the nodal forces  $\mathbf{f}_{ex}$ , equivalent to the release of both the initial stress and self-weight of the excavating region (Smith et al., 2014) ; i.e.,

$$\mathbf{f}_{ex} = \int_V \mathbf{B}^T \boldsymbol{\sigma}_o dV + \gamma \int_V \mathbf{N}^T dV \quad (2.2)$$

where  $\mathbf{B}$  is the strain–displacement matrix (Smith et al., 2014),  $\boldsymbol{\sigma}_o$  is the initial stress due to gravity,  $V$  is the excavated volume,  $\mathbf{N}$  is a matrix determined by shape functions and  $\gamma$  is the unit weight of the rock mass. The Young’s modulus of excavated the elements was set to zero.

### 2.3.2. Analytical results and discussion

The horizontal surface displacements of the rock slope due to total excavation with slope angle of  $90^\circ$  are shown in Fig. 2.9. In this figure, only the left side of the model is shown because of the geometrical symmetry. Figures 2.9(a) and 2.9(b) show results when the depth of the excavation from the initial mountaintop was  $h/4$  and  $3h/4$  due to the excavation, respectively. The backward surface displacement of the slope can be observed at  $\nu = 0.3$  and  $0.4$  with a slope angle  $90^\circ$ . At  $\nu = 0.1$ , the forward surface displacement was observed from the toe to the top of the slope when the depth of the excavation from the initial mountaintop was  $3h/4$  (Fig. 2.9b). It follows that in the case of slope angle of  $90^\circ$  the remaining mountain contracts at larger  $\nu$ , and extends at smaller  $\nu$  due to excavation. As discussed in sub chapter 2.2, the deformation due to PE increases with increasing  $\nu$  (see PE in Fig. 2.5), and that due to DLE decreases with

increasing  $\nu$  (see DLE in Fig. 2.5). The deformation that results from PE and DLE is released by excavation resulting in the opposite direction of horizontal displacements due to gravity. Thus, the contraction was seen because the PE was greater than DLE; at smaller  $\nu$ , extension was seen since DLE was greater.

The horizontal surface displacement is shown in Fig. 2.10. In this figure, only the left side of the model is shown because of the geometrical symmetry. Fig. 2.10(a) and Fig. 2.10(b) show results when the depth of the excavation from the initial mountaintop was  $h/4$  and  $3h/4$  due to the excavation, respectively.

The direction of horizontal displacement for the  $45^\circ$  slope was similar to that for the  $90^\circ$  slope. When the depth of the excavation from the initial mountaintop was  $3h/4$ , forward surface displacement occurred with a smaller  $\nu$ ; however, backward surface displacement occurred with a larger  $\nu$ , as shown in Fig. 2.10b. It follows that the PE and DLE are the dominant mechanisms in the  $45^\circ$  slope. In addition, bending effects became less significant as the depth of the excavation from the initial mountaintop increased due to excavation.

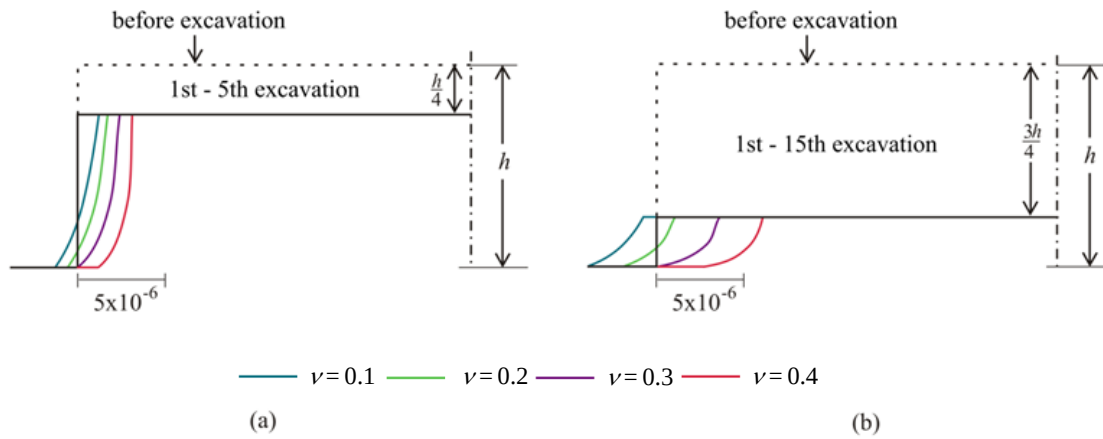


Fig. 2.9 Surface displacement of the mountain due to total excavation with a slope angle of  $90^\circ$ . The horizontal displacement is shown normalized by  $h$  and magnified by a factor of 500. Only the left half is shown because of the geometrical symmetry. The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps) and (b)  $3h/4$  (15th to 20th excavation steps).

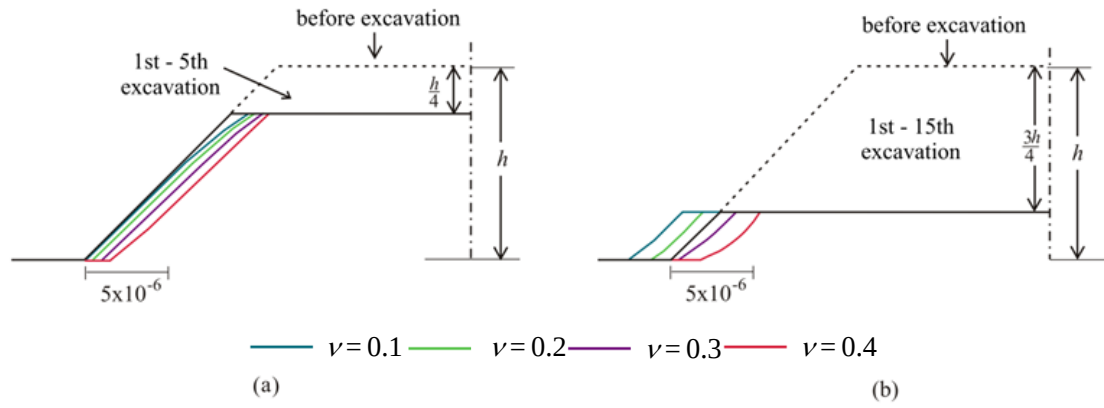


Fig. 2.10 Surface displacement of the mountain due to total excavation with a slope angle of  $45^\circ$ . The horizontal displacement is shown normalized by  $h$  and magnified by a factor of 500. Only the left half is shown because of the geometrical symmetry. The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps) and (b)  $3h/4$  (15th to 20th excavation steps).

## 2.4 Displacement and deformation of a mountain due to excavation along the mountainside

The internal displacement of rock slopes is useful as it can be measured using extensometers. In this section, the internal horizontal displacement of a cut rock slope formed by partial excavation of a mountain-type mine, as well as the surface displacement was analyzed.

### 2.4.1. Analytical method

Partial excavation of the left-hand side of the mountain from the top to bottom was modeled, as shown in Fig. 2.11. The initial configuration of the models was the same as the models shown in Fig. 2.1. The width of the excavation with a cut rock slope angle of  $90^\circ$  was  $2h$ , and that with cut rock slope angle of  $45^\circ$  was  $h$ . The excavation was successively completed in 20 steps with an excavated depth per step of  $h/20$ . The angles of the mountain slope and cut rock slope were assumed to be identical, and are simply denoted as the slope angle. The displacement due to the excavation was calculated by applying the nodal forces in the same manner as for the total excavation model; i.e., using Eq. (2.2).

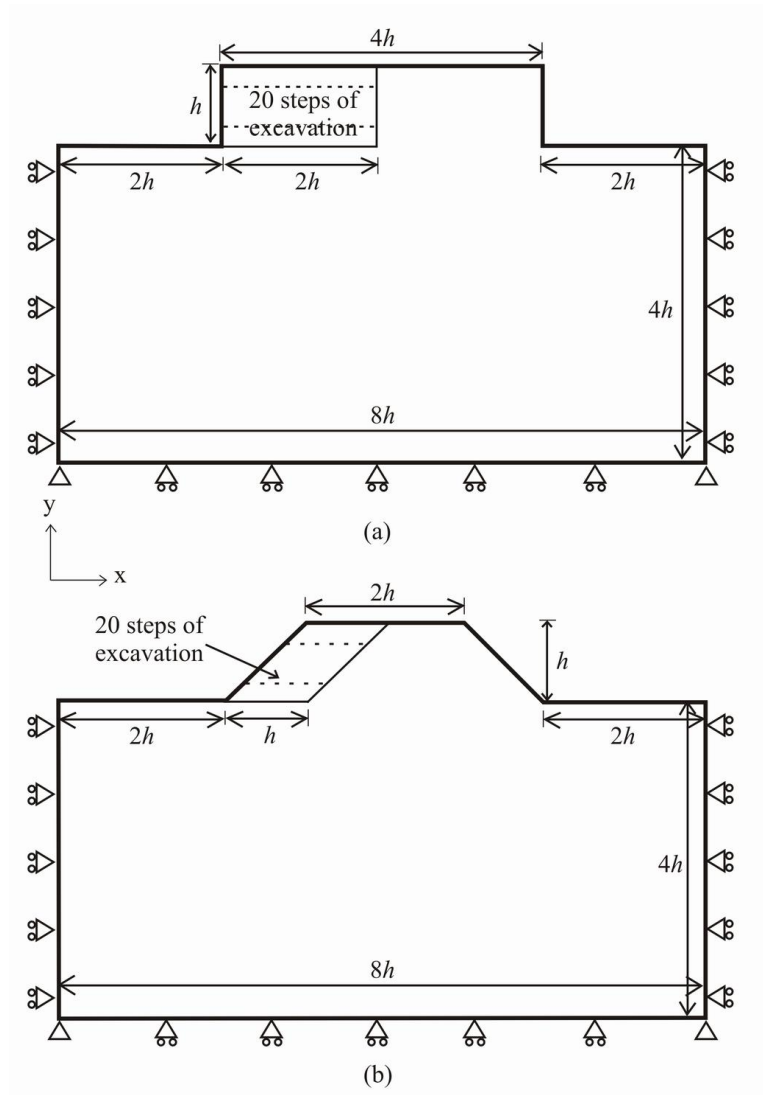


Fig. 2.11 Initial conditions of the two partial excavation models. Slope angles of (a)  $90^\circ$  and (b)  $45^\circ$ . The dashed lines indicate the progress of the excavation.

#### 2.4.2. Surface displacement and deformation

Figure 2.12 shows the horizontal surface displacement of the rock slope in the partial excavation model with slope angle of  $90^\circ$ . Figs. 12a and 12b show results for an excavated depth of  $h/4$  and  $h$  from the initial mountaintop (i.e., the 5th and 20th excavation steps), respectively. Up to the fifth step of excavation (see Fig. 2.12a), the cut rock slope formed by the excavation exhibited backward surface displacement with all four Poisson's ratios. Thereafter, up to the 20th (final) step of the excavation (see Fig. 2.12b), the cut rock slope exhibited forward displacement at  $\nu = 0.4$ , and exhibited backward displacement at  $\nu = 0.1$ . These results clearly show that the horizontal

deformation of the cut rock slope with the partial excavation model depended on both the Poisson's ratio and the stage of excavation. The stress release due to excavation was asymmetric because only the left part was excavated. As a consequence, the mountain became distorted, with clockwise shear distortion due to the asymmetric stress release moment, as shown in Fig. 2.13a. In addition, the part of the mountain in the Region A shown in Fig. 2.13b can act as distributed load over the Region B which is the whole part of the mountain under Region A; hence, backward displacement at the toe of Region A resulting from DLE increased with decreasing  $\nu$  (see DLE in Fig. 2.5). In contrast, a smaller backward displacement occurred with a larger  $\nu$  because horizontal stress release led to forward displacement in Region A. Via excavation, the DLE and the clockwise shear distortion were dominant, resulting in a larger rightward displacement with a smaller  $\nu$  (see Fig. 2.12b). With a larger  $\nu$ , however, the release of horizontal stress resulting from the reduction in the constraint at the toe of slope due to excavation becomes dominant, resulting in a larger forward displacement (see Fig. 2.12b). This can be considered as the PE in the partial excavation.

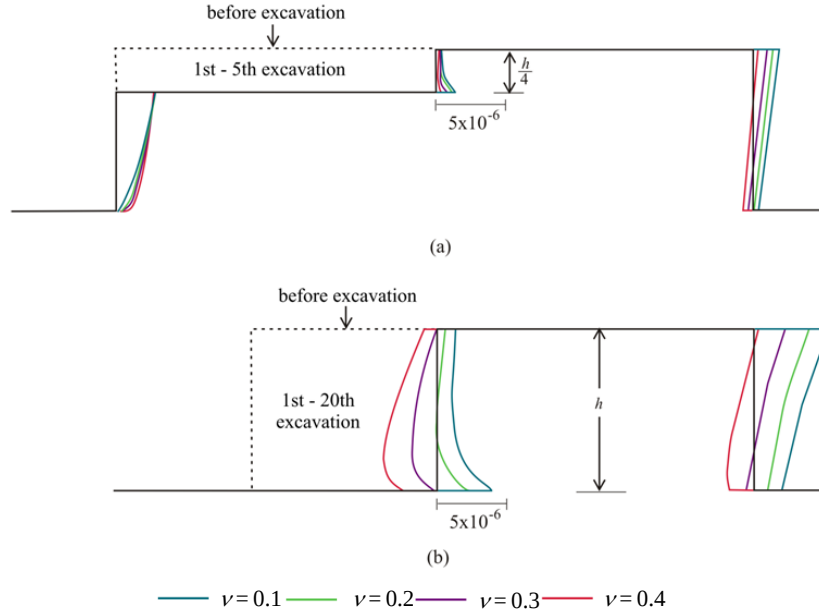


Fig. 2.12 Surface displacement of the mountain due to partial excavation with a  $90^\circ$  slope. The excavated region is shown by the dashed lines. The horizontal displacement is shown normalized by  $h$  and magnified by a factor of 500. The excavation depth was (a)  $h/4$  (1st to 5th excavation steps) and (b)  $h$  (1st to 20th excavation steps).

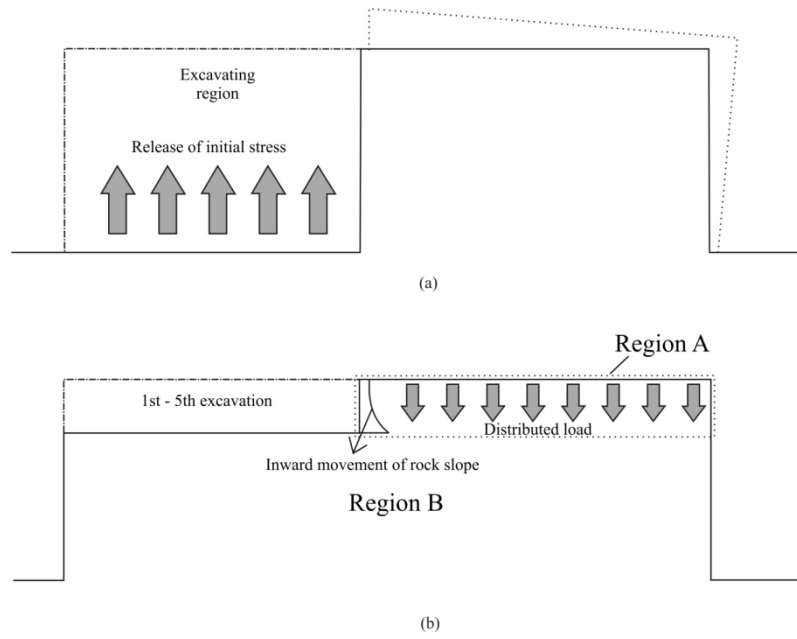


Fig. 2.13 Schematic diagram showing (a) shear deformation of the mountain, and (b) DLE due to partial excavation for a 90° slope. The vertical displacement is also shown.

Figures 2.14, 2.15, 2.16 and 2.17 show the horizontal displacement of the surface of the rock slope and horizontal strain distribution ( $\epsilon_{xx}$ ) with slope angle 45° when the depth of the excavation was  $h/4$ ,  $h/2$ ,  $3h/4$ , and  $h$ . Horizontal surface displacement for four Poisson's ratios was also shown for comparison results (Fig. 2.18). Figs. 2.14(a)-2.18(a) and Figs. 2.14(b)-2.18(b) show results for an excavated depth of  $h/4$  and  $h$  from the initial mountaintop (i.e., the 5th and 20th excavation steps), respectively.

From Fig. 2.14 to 2.17, it can be seen that tensile strain was found around the top of the rock slope and compressive strain was concentrated at the toe of the cut rock slope. Magnitude of tensile strain decreased with the increasing Poisson's ratio.

It can be seen that the cut rock slope formed by the first to fifth steps of the excavation was displaced forward because of the excavation regardless of  $\nu$ , although some backward movement can be seen at the toe of the slope (see Fig. 2.18a). The displacement was similar for an excavation depth of  $h/2$  (see Fig. 2.18b). When the excavation depth increased to  $3h/4$  and  $h$  by further excavation, the displacement direction of the rock slope changed to backward (see Figs. 2.18c and 2.18d) at  $0.1 \leq \nu \leq 0.3$ , whereas forward displacement was still observed at  $\nu = 0.4$ . It also can be seen

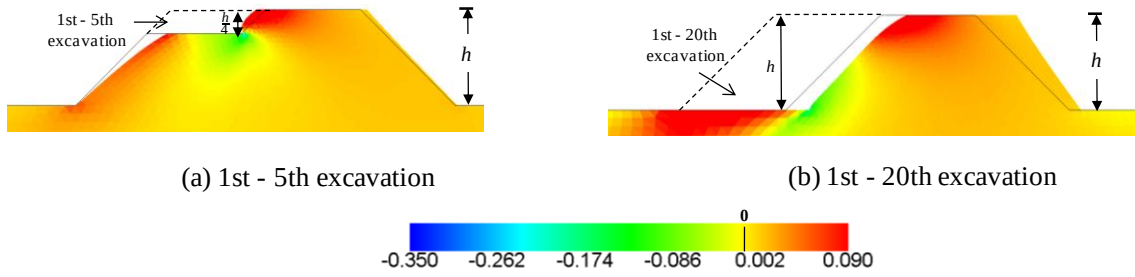


Fig. 2.14 Distributions of the horizontal surface displacement and horizontal strain ( $\epsilon_{xx}$ ) of the mountain due to partial excavation with a slope angle of  $45^\circ$  at  $\nu = 0.1$ . The horizontal displacement is shown magnified by a factor of 500. The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps) and (b)  $h$  (1st to 20th excavation steps). A negative value means compressive strain.

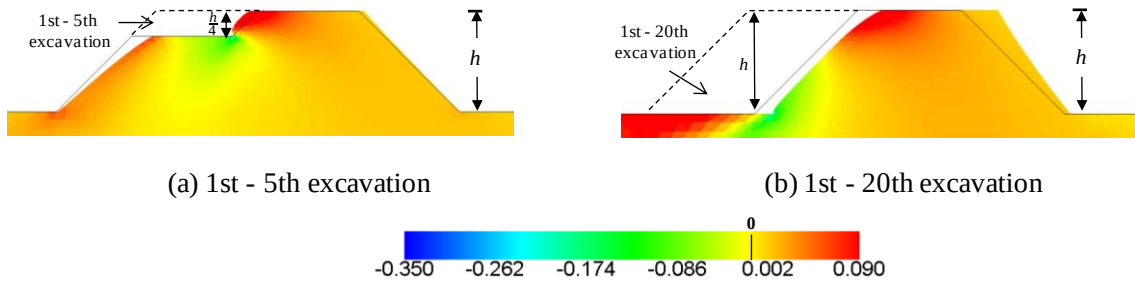


Fig. 2.15 Distributions of the horizontal surface displacement and horizontal strain ( $\epsilon_{xx}$ ) of the mountain due to partial excavation with a slope angle of  $45^\circ$  at  $\nu = 0.2$ . The horizontal displacement is shown magnified by a factor of 500. The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps) and (b)  $h$  (1st to 20th excavation steps). A negative value means compressive strain.

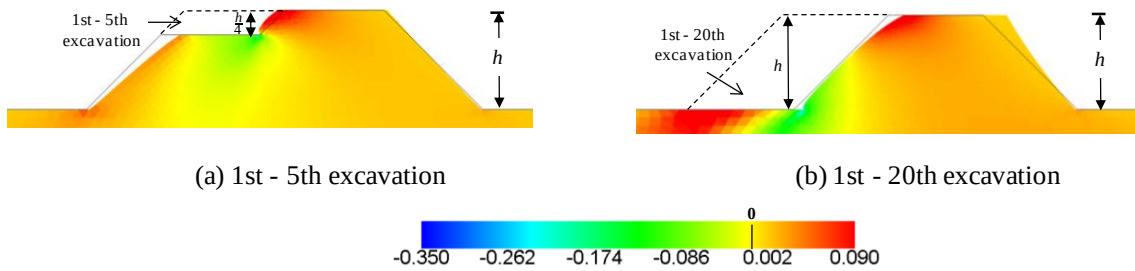


Fig. 2.16 Distributions of the horizontal surface displacement and horizontal strain ( $\epsilon_{xx}$ ) of the mountain due to partial excavation with a slope angle of  $45^\circ$  at  $\nu = 0.3$ . The horizontal displacement is shown magnified by a factor of 500. The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps) and (b)  $h$  (1st to 20th excavation steps). A negative value means compressive strain.

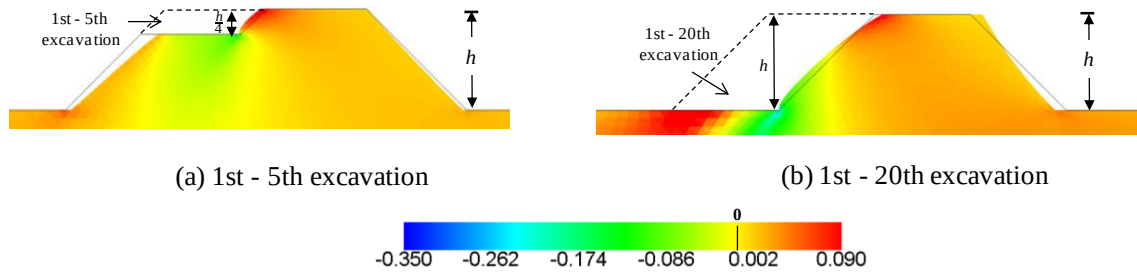


Fig. 2.17 Distributions of the horizontal surface displacement and horizontal strain ( $\epsilon_{xx}$ ) of the mountain due to partial excavation with a slope angle of  $45^\circ$  at  $\nu = 0.4$ . The horizontal displacement is shown magnified by a factor of 500. The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps) and (b)  $h$  (1st to 20th excavation steps). A negative value means compressive strain.

that the cut rock slope with slope angle  $45^\circ$  was extended for all excavation progresses and Poisson's ratios.

The direction of the horizontal surface displacement in the early stages of the excavation with the  $45^\circ$  slope (see Fig. 2.18a) was in the opposite direction to that for the  $90^\circ$  model (see Fig. 2.12a). This can be explained by considering the horizontal stress. As discussed in sub chapter 2.2.2, the concentration of the compressive stress around the center of the top of the mountain due to bending effect was dominant with the  $45^\circ$  model, and the magnitude of this stress was smaller with a larger Poisson's ratio. The horizontal extension can be explained by the release of large horizontal stress, which is less significant in the  $90^\circ$  model. The bending effect may be the dominant mechanism in the early stages of excavation, which are conducted near the mountaintop, although the aforementioned clockwise shear distortion and either PE or DLE also contribute to the deformation of the slope. The DLE resulted in backward surface displacement near the toe of the slope in the later stages of excavation. The PE resulted in forward surface displacement.

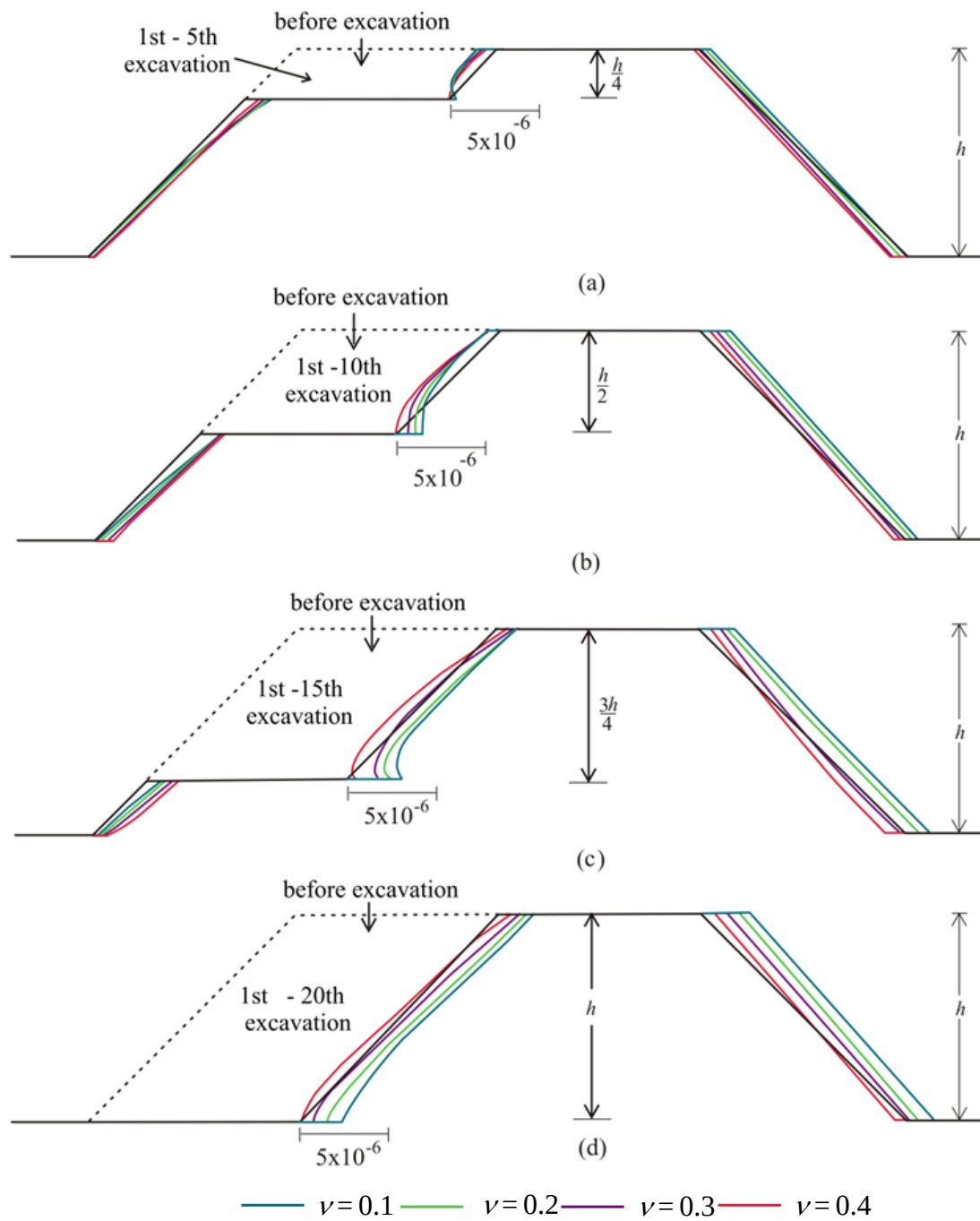


Fig. 2.18 Surface displacement of the mountain due to partial excavation with a 45° slope. The excavated region is shown by the dashed lines. The horizontal displacement normalized by  $h$  is shown magnified by a factor of 500. The height of the cut rock slope was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps), and (d)  $h$  (1st to 20th excavation steps).

### 2.4.3. Internal displacement and deformation

The horizontal displacement along the lines H1 and H2 shown in Fig. 2.19 was analyzed to investigate the internal displacement of the cut rock slope. The heights of the lines H1 and H2 were  $h/2$  and  $h$ , respectively, and the lengths of the two lines were  $h$  and  $2h$ , respectively. The displacement relative to the points A and B was calculated along the lines H1 and H2. This is normalized to the slope height,  $h$ . A positive relative displacement corresponds to displacement of the target point away from the reference point, as shown by the bold arrows in Fig. 2.19. In other words, a positive sign corresponds to extension between the target point and the reference point.

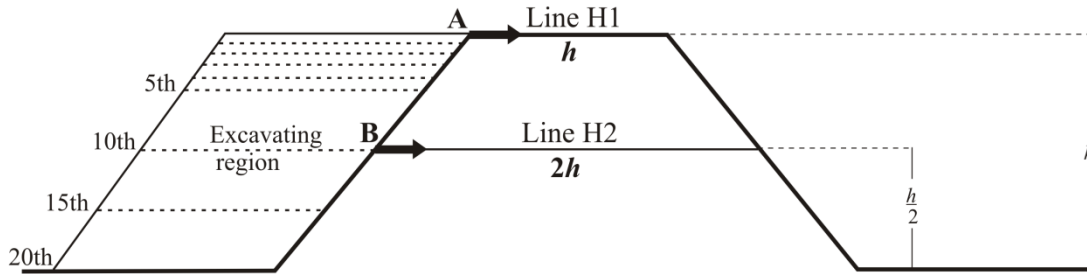


Fig. 2.19 Direction and location of each target line used in the displacement analysis.

The distribution of the normalized horizontal relative displacement along the lines H1 and H2 is shown in Figs. 2.20 and 2.21, respectively. Figures 2.20 (a-d) and 2.21 (a-d) correspond to a Poisson's ratio of 0.1–0.4. The relative displacement increased toward the inside of the cut rock slope, although a slight decrease was also found during the latter stages of excavation in the deep part. The gradient of the displacement with respect to the reference point was positive and larger closer to the surface of the slope. It follows that the slope exhibited extension due to excavation, and the extension became larger closer to the surface of the slope. The relative displacement decreased with increasing Poisson's ratio; however, a significant difference could not be found between the characteristics of the relative displacement along the lines H1 and H2 with different Poisson's ratios.

Figure 2.22 shows the normalized relative horizontal displacement along the lines H1 and H2 at depths of  $h/4$ ,  $h/2$  and  $h$  from the surface, as a function of the excavation depth of 0 to  $h$  and  $h/2$  to  $h$ , respectively. Figure 2.22(a-d) correspond to Poisson's ratios

of 0.1–0.4. The relative displacement along the line H2 was calculated from the 11th excavation step, whereby the excavation depth goes just below  $h/2$ . An apparent extension was observed in the displacement along the line H1 during the earlier stages of excavation. The rate of increase in the extension decreased with respect to the rock surface as the excavation progressed. Slight contraction was observed as excavation progressed from  $h/4$  to  $h/2$ . This behavior was observed for all three depths at all four Poisson's ratios, and the magnitude of the extension depended on the Poisson's ratio.

The trends in the normalized relative displacement along the line H2 were similar to those along the line H1 (see Fig. 2.22). Apparent extension was observed in the earlier excavation stages followed by slight contraction at all three depths when the excavation depth approached  $3h/4$ .

The rock slope in a pit-type mine exhibits contraction with a small Poisson's ratio, and extension with a large Poisson's ratio (Kodama et al., 2009). It may therefore conclude that the deformation mode of a rock slope in a mountain-type mine differs significantly from that in a pit-type mine because the predominant deformation mode in the mountain-type mine is extension regardless of the Poisson's ratio.

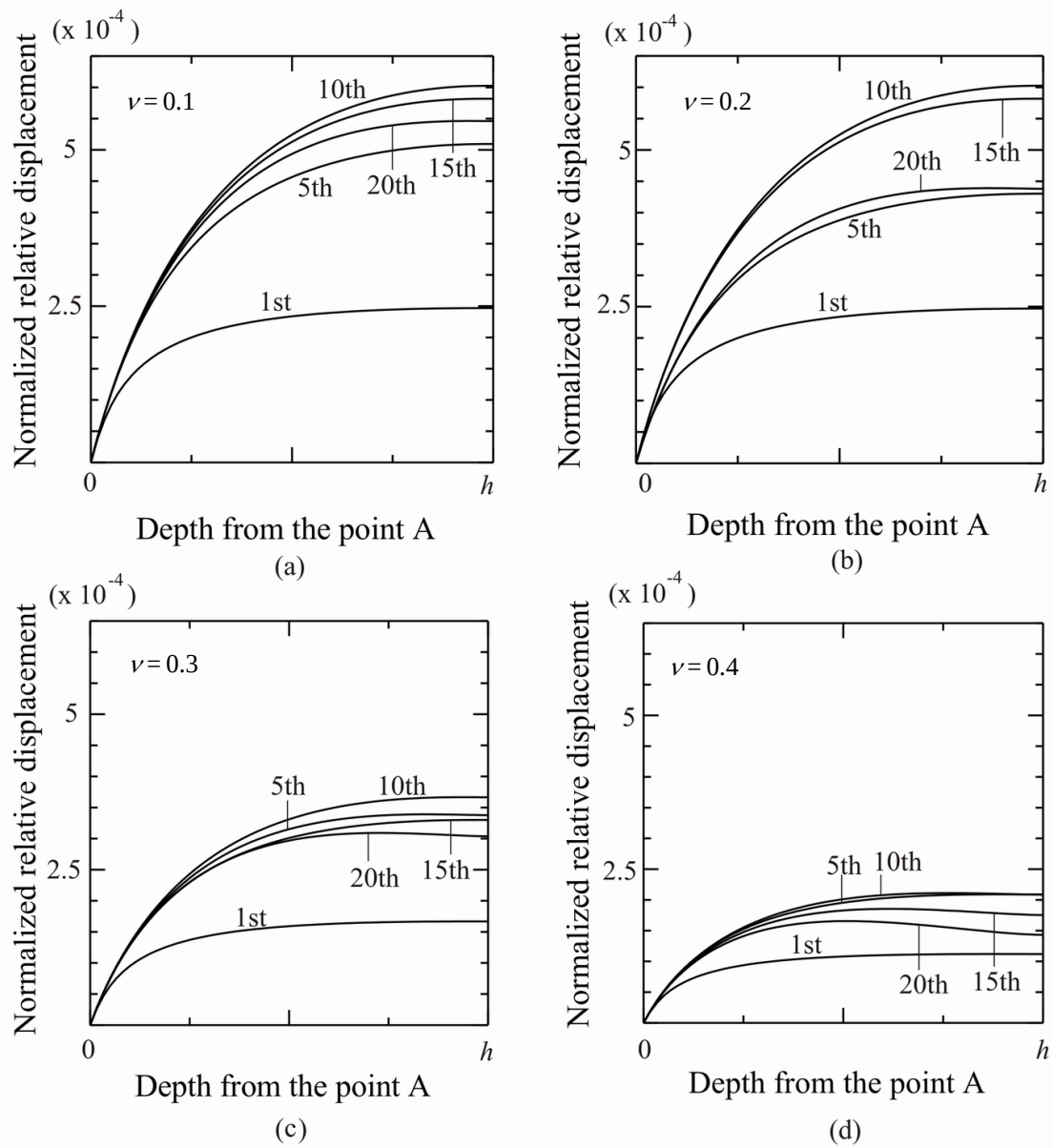


Fig. 2.20 Normalized horizontal relative displacement along line H1 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

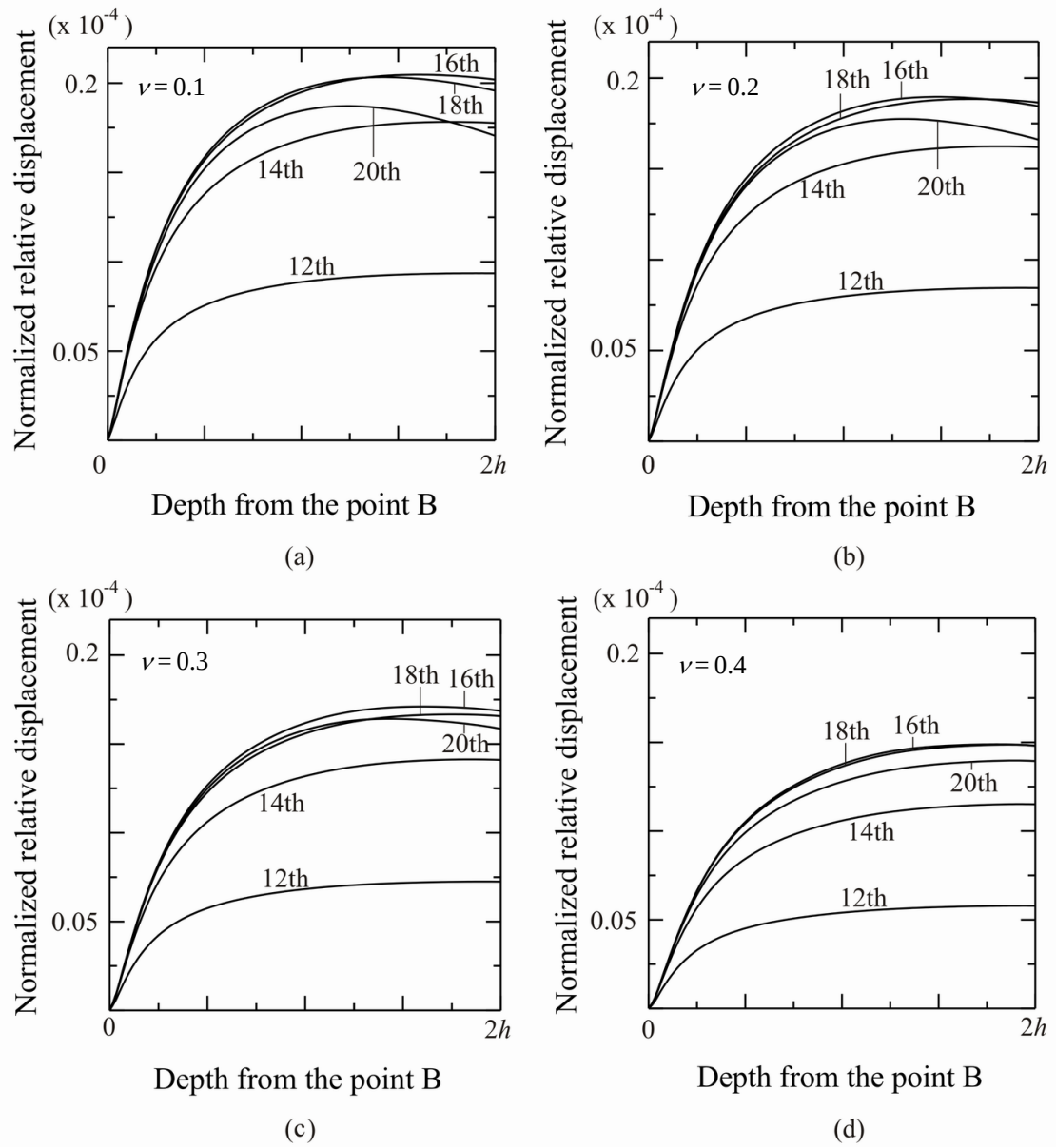


Fig. 2.21 Normalized horizontal relative displacement along the line H2 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

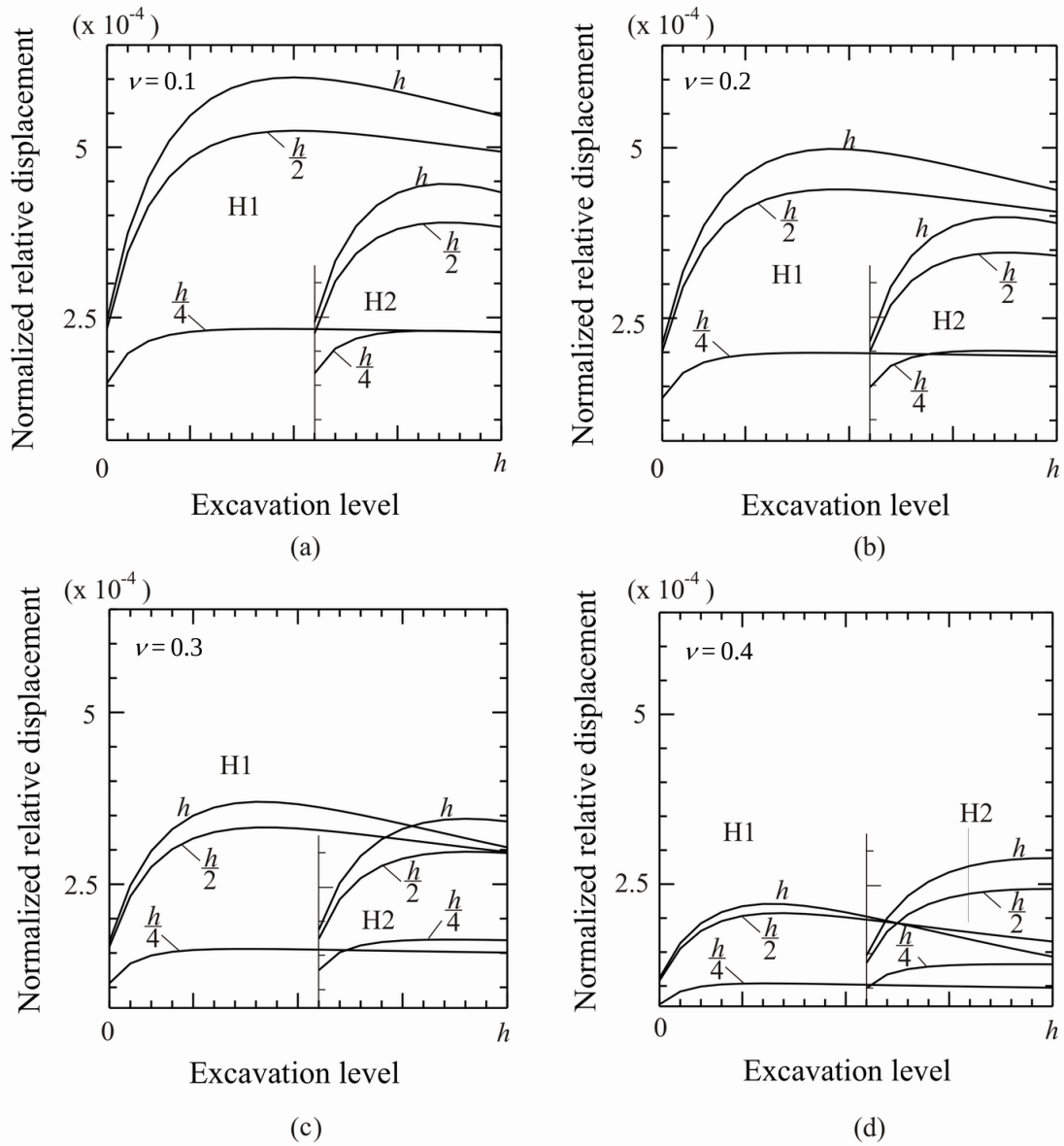


Fig. 2.22 Change in the normalized horizontal relative displacement along lines H1 and H2 at depths of  $h/4$ ,  $h/2$ , and  $h$  as a function of the excavation progress at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

## 2.5 Concluding Remarks

The elastic deformation of a cut rock slope formed in a homogeneous mountain-type mine was investigated using 2D FEM analyses. The behavior of the slope was studied with various Poisson's ratios in the range of 0.1–0.4, and for slope angles of  $45^\circ$  and  $90^\circ$ , with a progressive excavation.

Through a basic analysis of horizontal deformations 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: the well-known Poisson's effect (PE), which enhances the horizontal extension of the mountain and dominates at larger Poisson's ratios, and the distributed load effect (DLE), which induces horizontal contraction 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 occurred. This "bending effect" dominates at smaller Poisson's ratios.

The horizontal surface displacement of a cut rock slope formed by excavation was analyzed using a model with the face of the excavation inclined at  $45^\circ$ . It was found that forward surface displacement of the cut rock slope occurred during the early stages of excavation by the release of horizontal compressive stress due to bending around the center of the mountaintop. Either horizontal forward surface displacement due to the PE or backward surface displacement due to DLE occurred during the latter stages of the excavation, depending on the Poisson's ratio; the bending effects became less significant as the excavation progressed. Asymmetric stress release due to excavation affects the horizontal deformation of mountain and induces a moment that enhanced the backward surface 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.

From 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 depth from the surface. It was also found that the horizontal extension increased rapidly during the early stages of excavation but that further increases in the extension were not observed in the latter stages of excavation.

## **CHAPTER 3**

# **DEFORMATION MODES OF ROCK SLOPES FORMED IN MOUNTAIN-TYPE MINES CONSISTING OF LIMESTONE AND BEDROCK**

### **3.1 Introduction**

Rock mass of the mountain-type mine was assumed to be homogeneous for simplicity in chapter 2. However, geological formation of open-pit mines in Japan is usually complex. Limestone deposit is often found on bedrock such as sandstone, slate and schalstein (Study committee on slope stability and environmental preservation in Chichibu area, 1996; Nakamura et al., 2003). Folding of the geological formations due to tectonic stress is also observed (Nakamura et al., 2003). In Shiriya limestone mine, for example, limestone deposit distributing between inclined slate formations has been extracted (Nakamura et al, 2003). It is expected that mechanical property of bedrock is different from that of limestone. In particular, investigation of impact of difference in Young's modulus or Poisson's ratio between both the rocks is important because it might strongly affect elastic deformation of a cut rock slope. However, the study about the deformation behavior of rock slopes formed in alternating geological formation of limestone and bedrock is hardly found. In Japan, a part of limestone deposit is often left over the bedrock as a natural buttress to prevent the bedrock from weathering because bedrock of slate is expected to be less resistant to weathering than limestone (Kodama et al., 2003). However, mechanical effect of a buttress on deformation of a cut rock slope has not been cleared.

In this chapter, the influence of difference of Young's modulus between limestone and bedrock on the mining-induced elastic deformation of a cut rock slope formed in a mountain-type mine consisting of both rocks was investigated. The mechanical effect of a buttress was also studied by varying its thickness.

### 3.2 Impact of difference of Young's modulus between limestone and bedrock

#### 3.3.1 Analytical Method

Excavation along the left mountainside from the top to bottom was modeled, as shown in Fig. 3.1. The basic configuration of the models including the shape, size and boundary conditions was the same as those shown in Fig. 2.1 in chapter 2. The width of the excavation zone was equal to the final slope height of  $h$  and dashed lines show examples of some excavation levels. It should be noted that dashed-dotted lines show the geological boundary between limestone and bedrock. The excavation was successively completed through 20 steps with an excavated depth per step of  $h/20$ . The displacement due to the excavation was calculated by applying the nodal forces equivalent to the excavation using Eq. (2.2) in chapter 2. The mechanical properties for limestone and bedrock used in the analysis are shown in Table 3.1. Young's modulus of bedrock in the cases of in M-GB-1 and in M-GB-2 was set at half and twice, respectively, of that of limestone which was fixed at 5 GPa. For simplicity, unit weight and Poisson's ratio of bedrock were assumed to be equal to those of limestone.

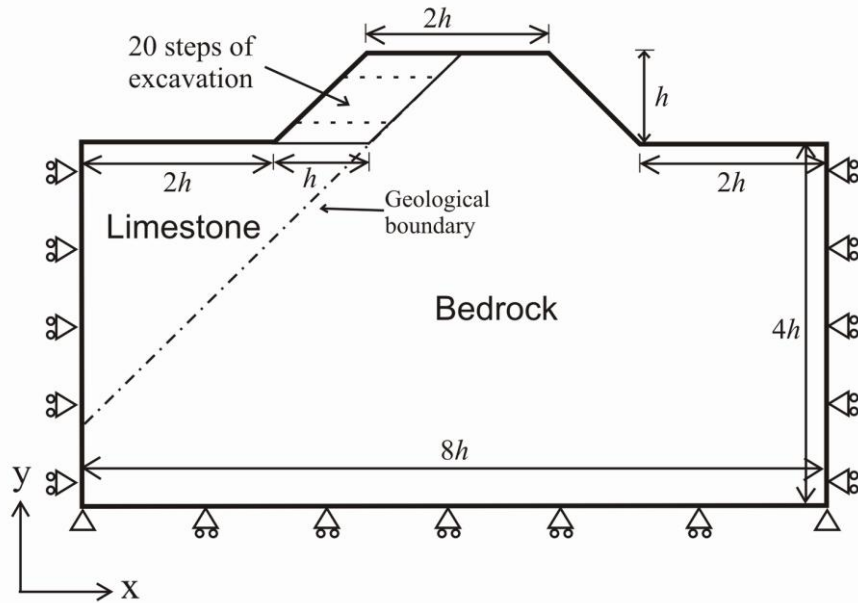


Fig. 3.1 configuration of the analytical model with a slope angle of  $45^\circ$ . The dashed lines indicate the progress of the excavation. Dashed-dotted lines indicate the geological boundary between limestone and bedrock.

Table 3.1 Mechanical properties of limestone and bedrock

| Case   | Young's modulus (GPa)       |                          | Poisson's ratio $\nu$ | Unit weight $\gamma$<br>(kN/m <sup>3</sup> ) |
|--------|-----------------------------|--------------------------|-----------------------|----------------------------------------------|
|        | Limestone $E_{\text{lime}}$ | Bedrock $E_{\text{bed}}$ |                       |                                              |
| M-GB-1 | 5.0                         | 2.5                      | 0.1                   | 27.0                                         |
|        |                             |                          | 0.2                   |                                              |
|        |                             |                          | 0.3                   |                                              |
|        |                             |                          | 0.4                   |                                              |
| M-GB-2 |                             | 10.0                     | 0.1                   |                                              |
|        |                             |                          | 0.2                   |                                              |
|        |                             |                          | 0.3                   |                                              |
|        |                             |                          | 0.4                   |                                              |

### 3.3.2 In the case that Young's modulus of limestone is greater than that of bedrock

Figures 3.2 and 3.3 show total of the horizontal surface displacement and horizontal strain ( $\varepsilon_{xx}$ ) of the mountain-type mine for the case of M-GB-1 ( $E_{\text{Lime}} > E_{\text{bed}}$ ) at  $\nu = 0.1$  and 0.4, respectively. Only results for  $\nu = 0.1$  and 0.4 are shown because the deformation behaviors of the rock slope at  $\nu = 0.2$  and 0.3 were almost identical to that at  $\nu = 0.1$ . The horizontal surface displacement at an excavated depth of  $h/4$ ,  $h/2$ ,  $3h/4$  and  $h$  from the initial mountaintop, i.e. the 5th, 10th, 15th and 20th excavation steps, is shown and magnified by a factor of 500. A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain. The dashed-dotted lines show geological boundary between limestone and bedrock. All these descriptions also apply to Figures 3.8 and 3.9 showing total of the horizontal surface displacement and  $\varepsilon_{xx}$  for the case of M-GB-2 ( $E_{\text{Lime}} < E_{\text{bed}}$ ) in sub chapter 3.3.3.

From Figs. 3.2 and 3.3, it can be seen that the horizontal strain distributions are similar to those in homogeneous model (Figs. 2.14 and 2.17). The tensile and compressive strains were found at the top and toe of the cut rock slope, respectively. Regarding the surface displacement at  $\nu = 0.1$ , up to 5th and 10th excavation steps (Fig. 3.2a-b), the cut rock slope exhibited horizontally forward from the toe to the top. Afterward, up to 15th and 20th excavation steps (Fig. 3.2c-d), horizontal forward displacement was also found even though a slight backward displacement was seen at the toe of cut rock slope. The forward surface displacement was observed from the toe

to the top of the cut rock slope for all excavation stages at  $\nu = 0.4$  (Fig. 3.3). The tendency of surface displacement was similar to the case of  $\nu = 0.1$ . Namely, the cut rock slope at  $\nu = 0.4$  tended to extend throughout excavation stages although the magnitude was approximately half of that at  $\nu = 0.1$  at the final excavation stage. These results show that the deformation behaviors of the case that Young's modulus of limestone is larger than that of bedrock are almost similar to those of homogeneous model with some exceptions. The difference was found in the case of smaller Poisson's ratio. In homogeneous model, the cut rock slope exhibited backward displacement (Fig. 2.18).

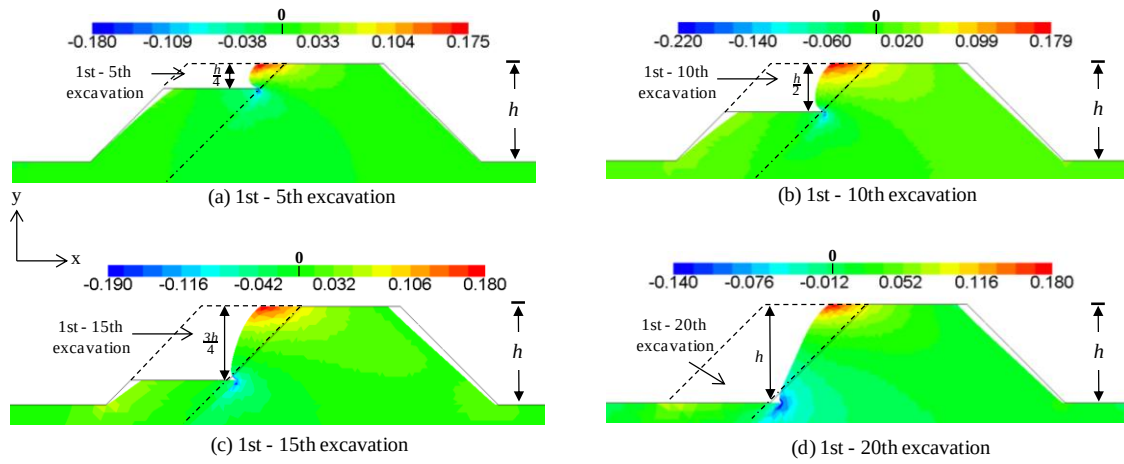


Figure 3.2 Horizontal surface displacement and strain ( $\varepsilon_{xx}$ ) distribution in the case of M-GB-1 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 2.5$  GPa) in each 5 step of excavation at  $\nu = 0.1$ . The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain.

The distribution of the normalized horizontal relative displacement along the lines H1 and H2 shown in Fig. 3.4 was analyzed to clarify the interior deformation mode. Calculation method of the displacement was same as the interior displacement analysis in sub chapter 2.4.3. Figures 3.5 and 3.6 correspond to the normalized relative horizontal displacement distribution along the lines H1 and H2, respectively. Fig. 3.7 shows the relative horizontal displacement on the lines H1 and H2 at depths of  $h/4$ ,  $h/2$

and  $h$  from the surface, as a function of the excavation depth from 0 to  $h$  and  $h/2$  to  $h$ , respectively. The normalized relative displacement along the line H2 was calculated from the 11th excavation step, whereby the excavation depth proceeds just below  $h/2$ . These descriptions are also used in Fig.3.12 in sub chapter 3.3.3.

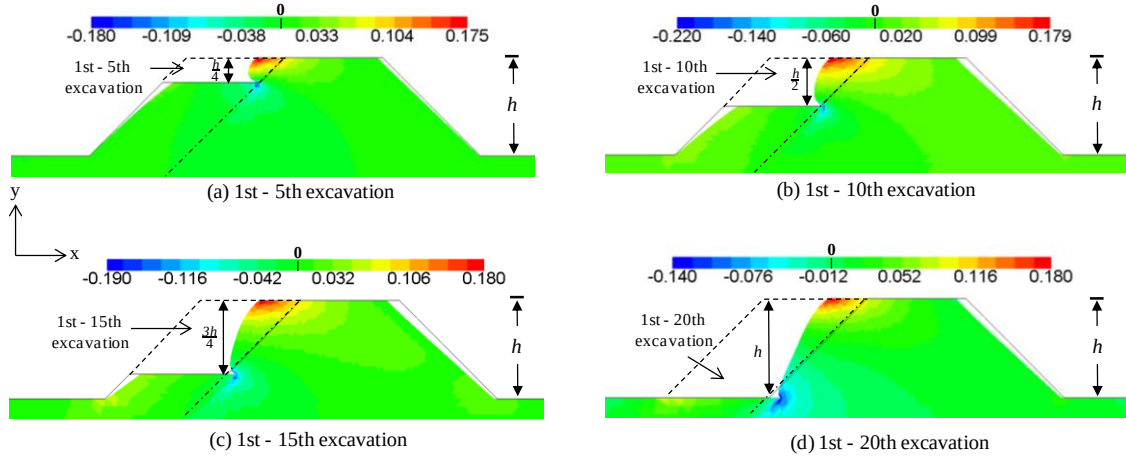


Figure 3.3 Horizontal surface deformation and strain ( $\varepsilon_{xx}$ ) distribution in the case of M-GB-1 ( $E_{\text{Lime}} = 5.0\text{GPa}$ ,  $E_{\text{Bed}} = 2.5\text{GPa}$ ) in each 5 steps of excavation for  $\nu = 0.4$ . The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain.

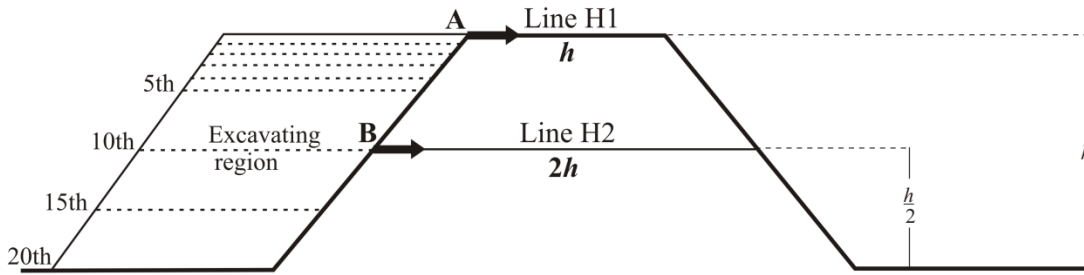


Fig. 3.4 Direction and location of each target line used in the displacement analysis.

The characteristics of the normalized relative horizontal displacement along the lines H1 and H2 in the case of M-GB-1 (Figs. 3.5 and 3.6) were almost similar to those along the lines H1 and H2 of the homogeneous model (Figs. 2.20 and 2.21). This means

that the rock slope in the case that Young's modulus of bedrock is smaller than limestone basically extends due to excavation. This also means that the extension becomes larger toward the surface of the cut rock slope. The change in the normalized relative horizontal displacement on the lines H1 and H2 in the case of M-GB-1 (Fig. 3.7) due to excavation showed little difference from those of homogeneous model (Fig. 2.22). The rock slope extends for all excavation steps and no apparent contraction is found. In the case that Young's modulus of bedrock is smaller than limestone, it was found that the rock slope extends due to excavation and the magnitude of extension decreases with excavation depth.

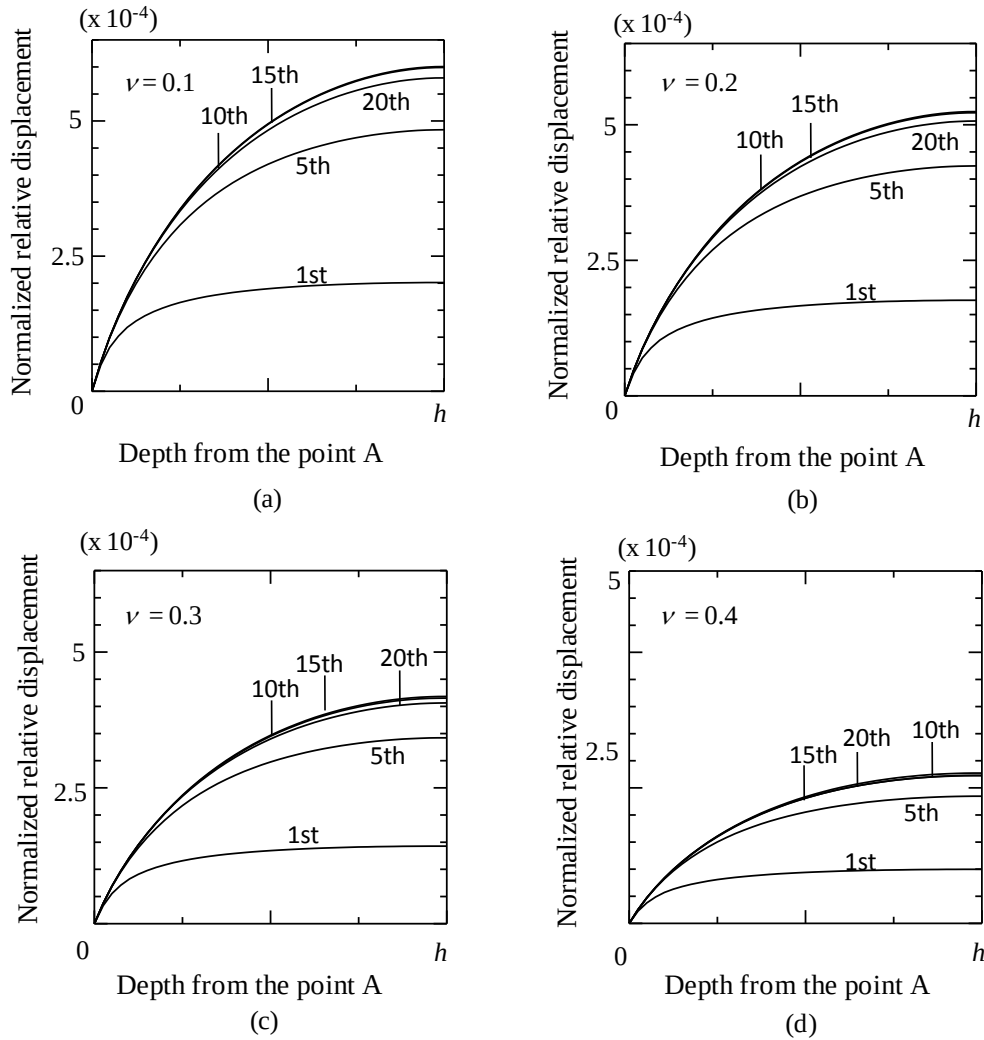


Fig. 3.5 Normalized horizontal relative displacement along line H1 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

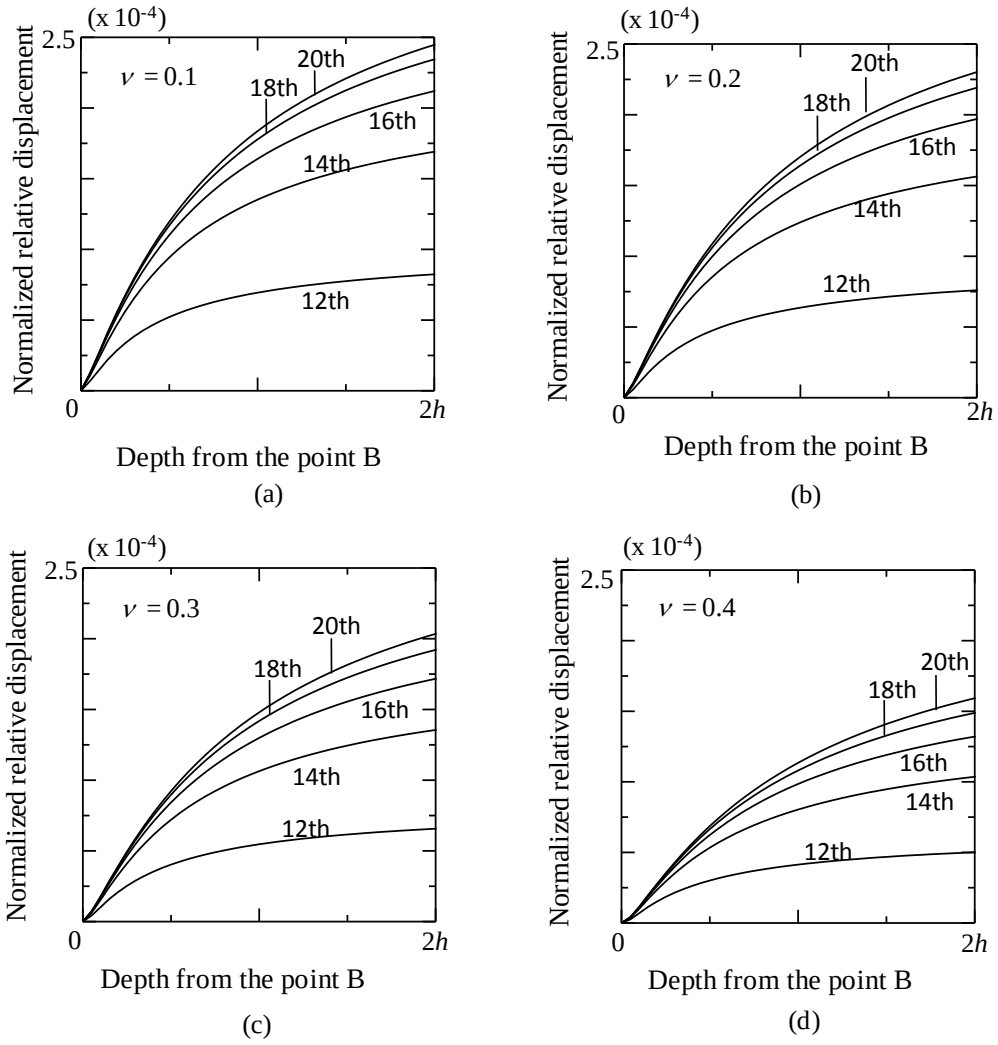


Fig. 3.6 Normalized horizontal relative displacement along line H2 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

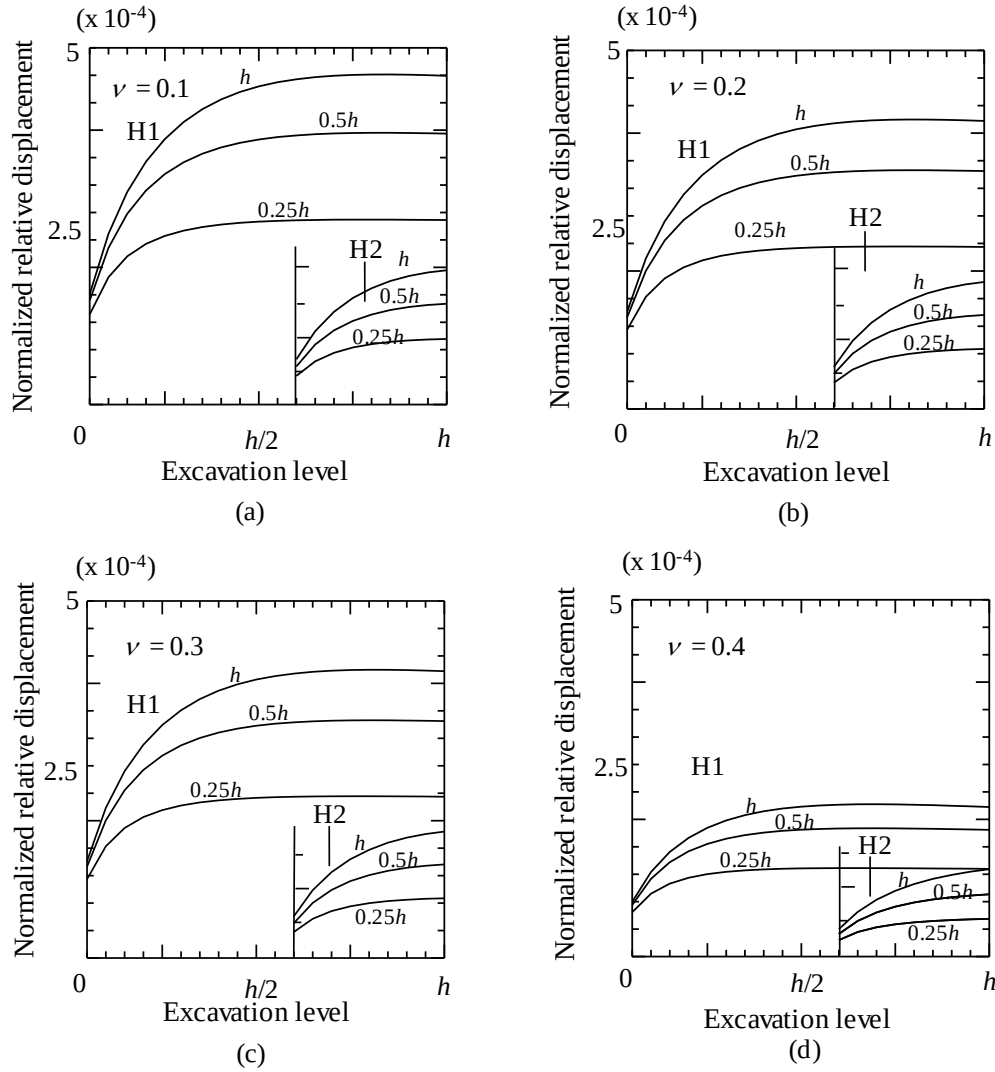


Fig. 3.7 Change in the normalized horizontal relative displacement along lines H1 and H2 at depths of  $h/4$ ,  $h/2$ , and  $h$  as a function of the excavation progress for  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

### 3.3.3 In the case that Young's modulus of bedrock is greater than that of limestone

Figures 3.8 and 3.9 show the total of the horizontal surface displacement and horizontal strain ( $\varepsilon_{xx}$ ) of the mountain-type mine for the case of M-GB-2 model ( $E_{\text{Lime}} < E_{\text{bed}}$ ) at  $\nu = 0.1$  and  $\nu = 0.4$ , respectively. From these figures, it can be seen that the horizontal strain distributions in the case that Young's modulus of bedrock is greater than limestone are significantly different from those of homogeneous model (Figs. 2.14 and 2.17). Little tensile strain was found in the rock slope at the top near the rock slope

surface and tended to decrease with excavation. The compressive strain near the rock slope surface tended to increase with excavation.

The cut rock slope exhibited the backward displacement from the toe to the top at  $\nu = 0.1$  regardless of excavation steps (Fig. 3.8). In the case at  $\nu = 0.4$  (Fig. 3.9), the tendency of horizontal backward surface displacement of cut rock slope is almost similar to that at  $\nu = 0.1$ .

These results show that the cut rock slope formed in a mountain-type mine basically exhibits the backward displacement and contracted deformation when Young's modulus of bedrock is greater than that of limestone although extension was seen at the early stage of excavation at smaller Poisson's ratios. It was found that the deformation modes of a rock slope in the case that Young's modulus of bedrock is greater than limestone are significantly different from those of homogeneous model.

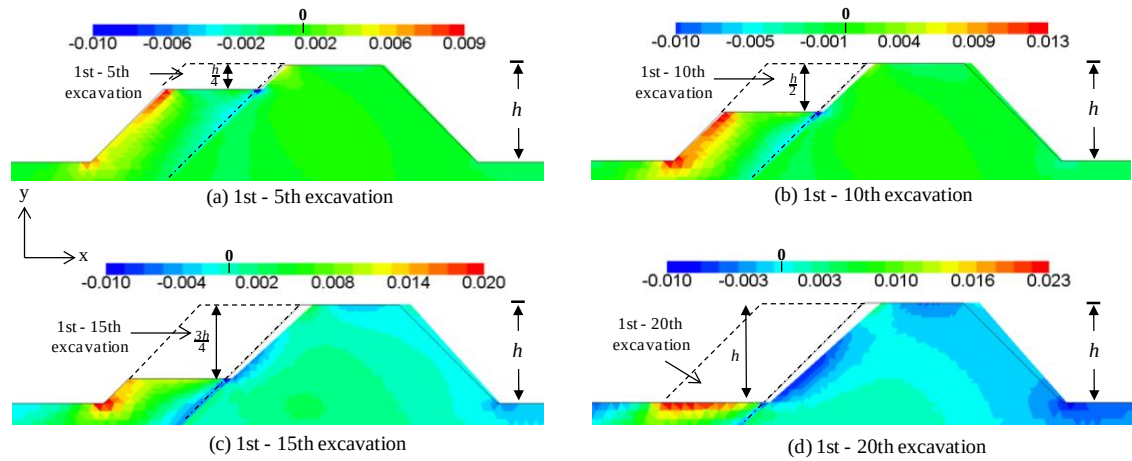


Figure 3.8 Horizontal surface deformation and horizontal strain ( $\epsilon_{xx}$ ) distribution in the case of M-GB-2 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 10.0$  GPa) in each 5 step of excavation at  $\nu = 0.1$ . The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\epsilon_{xx}$  corresponds to compressive strain.

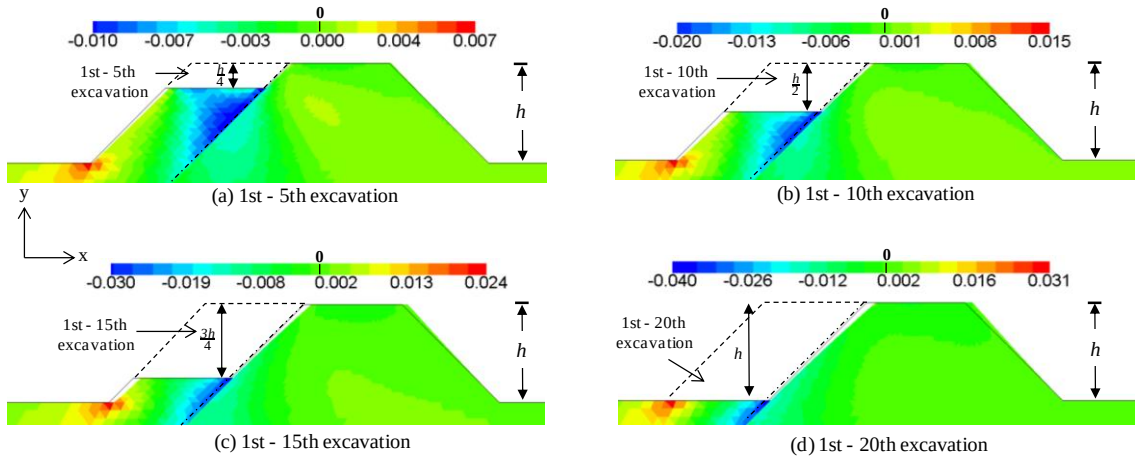


Figure 3.9 Horizontal surface deformation and horizontal strain ( $\varepsilon_{xx}$ ) distribution in the case of M-GB-2 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 10.0$  GPa) in each 5 step of excavation for  $\nu = 0.4$ . The depth of the excavation from the initial mountaintop was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain.

Figures 3.10 and 3.11 correspond to the normalized horizontal relative displacement of M-GB-2 along the lines H1 and H2 shown in Fig. 3.4, respectively. Fig. 3.12 shows the normalized relative horizontal displacement on the lines H1 and H2 at depths of  $h/4$ ,  $h/2$  and  $h$  from the surface in the case of M-GB-2. The calculation of the interior displacement was same as interior displacement analysis in sub chapters 2.4.3 and 3.3.2.

From these figures, it was found that characteristics of the normalized relative horizontal displacement along the lines H1 and H2 in the case of M-GB-2 were apparently different from those of the homogeneous model (Figs. 2.20, 2.21 and 2.22). The relative displacement increased to negative with increasing both the distance from the slope surface and excavation stage, although it showed a slight increase to positive near the surface in the earlier stage in the H1 (Figs. 3.10, 3.11 and 3.12). It follows that the cut rock slope basically showed the contraction although extension was seen near the slope surface in the earlier of excavations. From the results of the line H1, it is seen that the increment of contraction tended to decrease with excavation progresses.

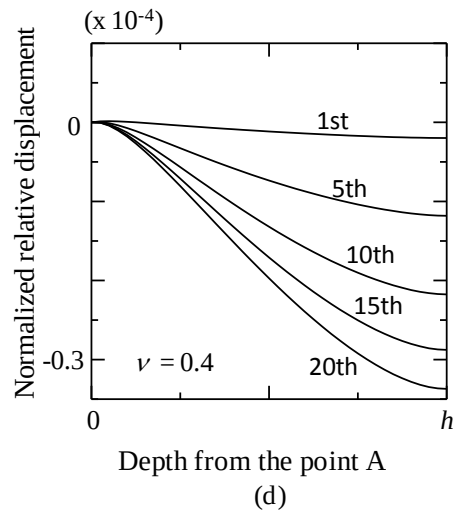
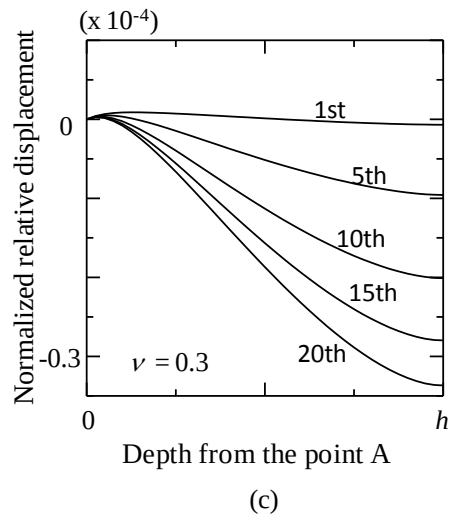
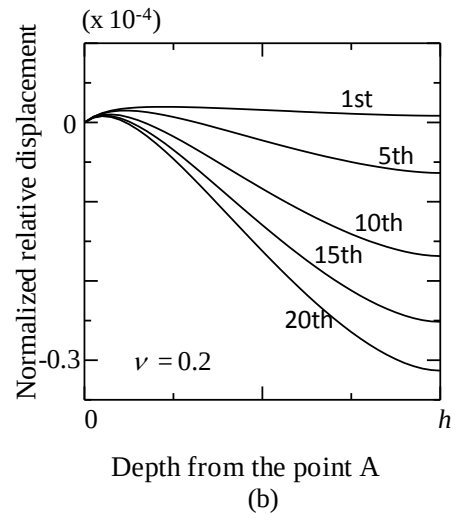
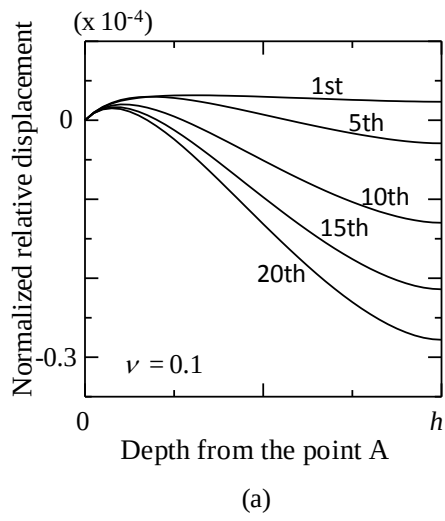


Fig. 3.10 Normalized horizontal relative displacement along line H1 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

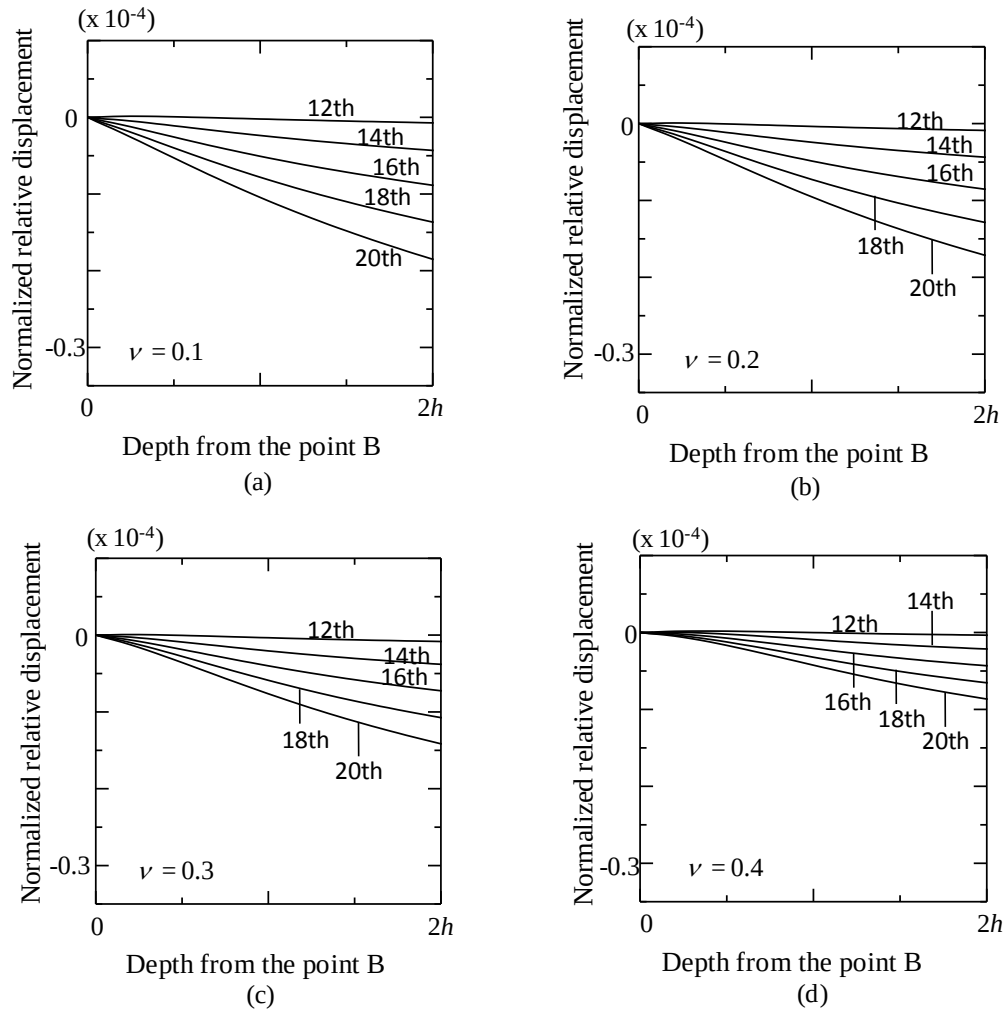


Fig. 3.11 Normalized horizontal relative displacement along line H2 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

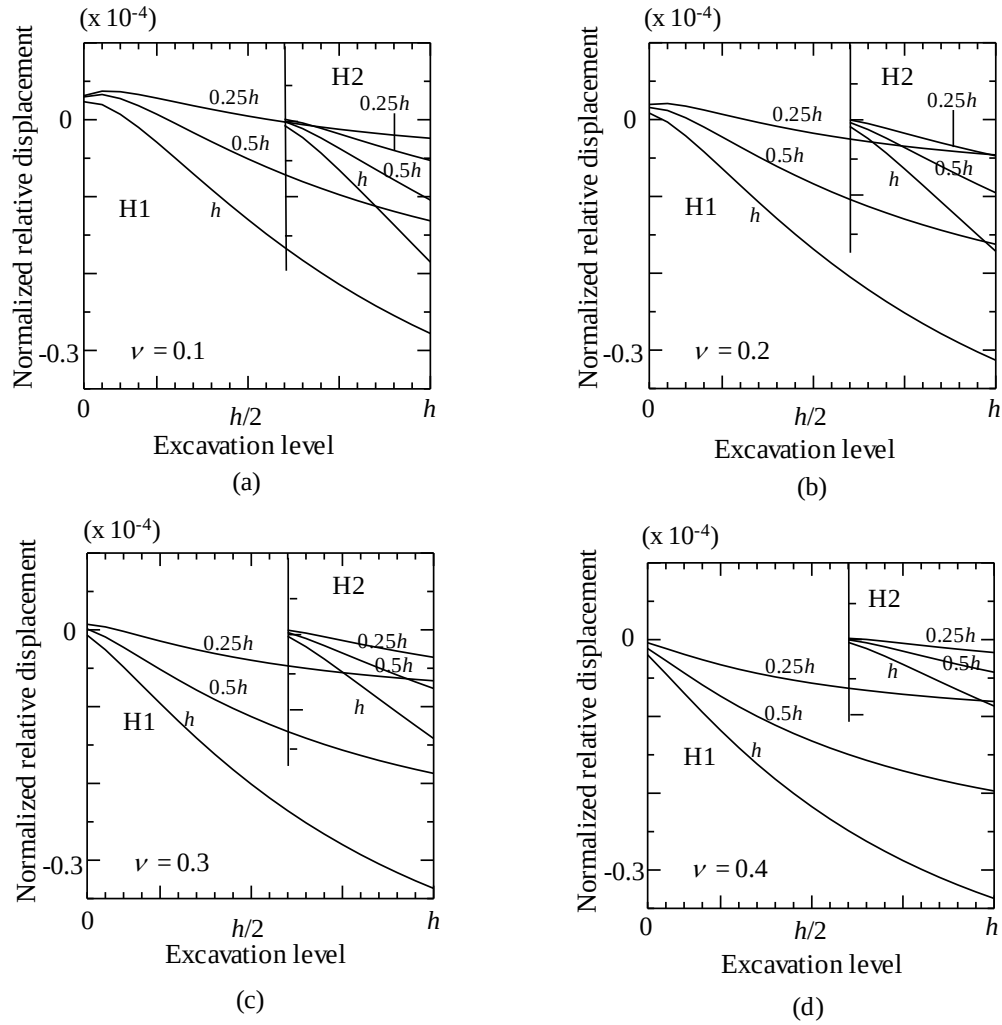


Fig. 3.12 Change in the normalized horizontal relative displacement along lines H1 and H2 at depths of  $h/4$ ,  $h/2$ , and  $h$  as a function of the excavation progress for  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

### 3.3 Effect of buttress of intact limestone

#### 3.3.1 Analytical Method

Figure 3.13 shows diagram that illustrates the analytical model with buttress of intact limestone. Mechanical properties of limestone and bedrock are same as M-GB-1 in Table 3.1, i.e., Young's modulus of limestone was greater than that of bedrock. The width of the buttress ( $w$ ) was set as 0,  $h/10$ ,  $h/4$  and  $h/2$ , where  $h$  was the depth of final excavation.

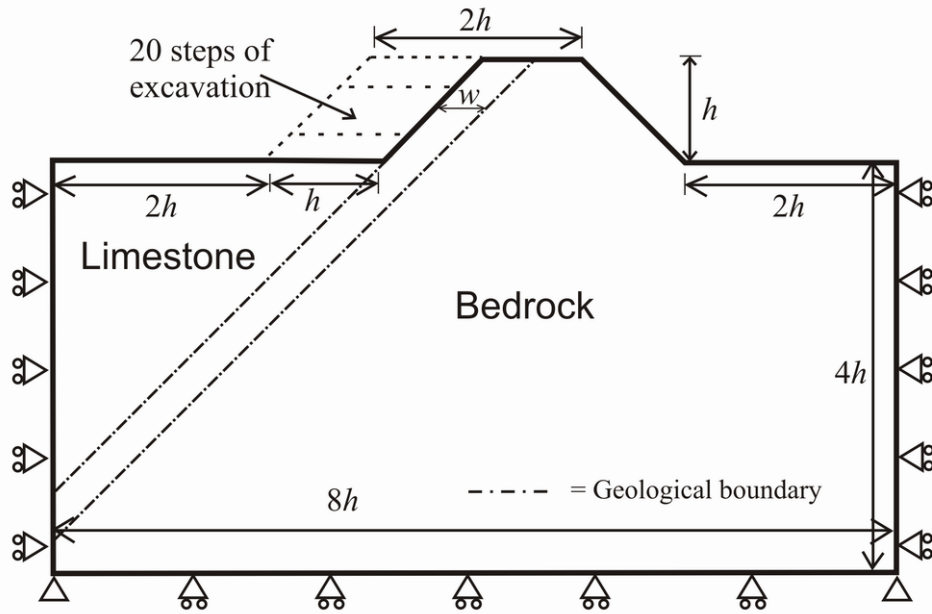


Fig. 3.13 Initial configuration of the analytical model having buttress of intact limestone with a slope angle of  $45^\circ$ . The dashed lines indicate the progress of the excavation. Dashed-dotted lines indicate the geological boundary between limestone and bedrock.  $w$  is buttress width.

### 3.3.2 Analytical results and discussion

Figures 3.14 shows total of the horizontal surface displacement and horizontal strain ( $\epsilon_{xx}$ ) around the cut rock slope at  $\nu = 0.2$  after 20th (final) step of excavation. The horizontal displacement is magnified by a factor of 500. A negative value of  $\epsilon_{xx}$  corresponds to compressive strain. The dashed-dotted lines show the geological boundary between limestone and bedrock. It can be seen that no qualitative difference can be seen in horizontal strain distribution between Figs. 3.14(a), (b), (c) and (d). Significant tensile strain was found around the top of the slope and compressive strain was concentrated at the toe of slope in all four figures. The cut rock slope tended to exhibit horizontal forward surface displacement regardless of thickness of the buttress. However, the magnitude of the surface horizontal displacement and extension of cut rock slope depends on buttress width. They apparently decreased with increase in buttress width. These results show that there is no significant difference in the deformation mode between the cut rock slopes with or without buttress, but thicker

buttress can highly reduce the magnitude of forward surface displacement and extension due to excavation.

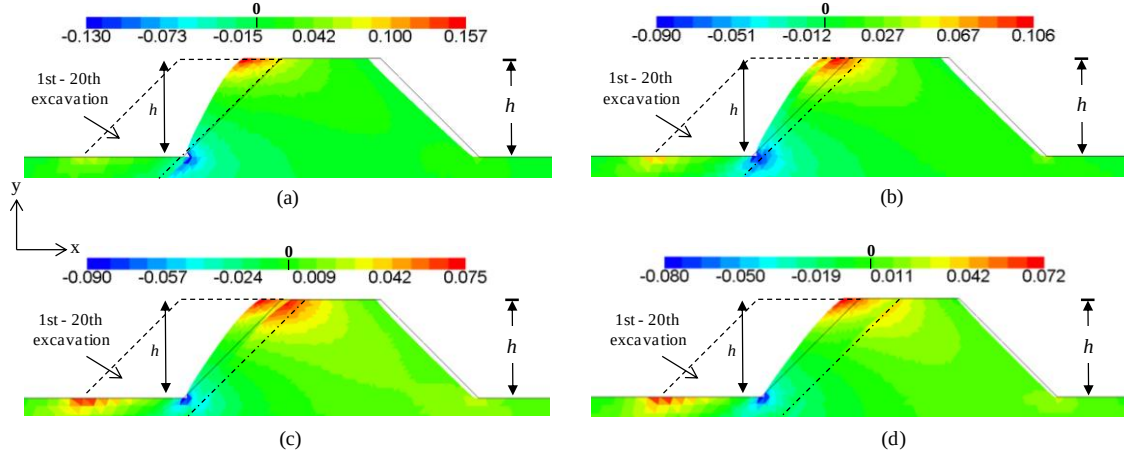


Figure 3.14 Horizontal surface deformation and horizontal strain ( $\varepsilon_{xx}$ ) distribution in the case of M-GB-1 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 2.5$  GPa) in the final excavation (20th excavation) at  $\nu = 0.2$ . The width of buttress ( $w$ ) is (a) 0, (b)  $h/10$ , (c)  $h/4$  and (d)  $h/2$ . A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain.

### 3.4 Concluding remarks

In this chapter, 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 rocks. The impact of intact limestone buttress on the deformation of the cut rock slope was also investigated. It was found that the behavior of the cut 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 forward displacement and extension regardless of Poisson's ratio. The magnitude of the forward surface displacement and extension increases with decreasing in Poisson's ratio. The extension tends to decrease with 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 backward displacement and contraction. The contraction tended to

decrease with increase in distance from the slope surface and progress of excavation. The cut rock slopes with or without buttress exhibit extension, but the magnitude of forward surface displacement and extension decreases with the increasing in thickness of buttress.

## CHAPTER 4

### DEFORMATION OF ROCK SLOPES FORMED IN PIT-TYPE MINES CONSISTING OF LIMESTONE AND BEDROCK

#### 4.1 Introduction

Elastic deformation of rock slopes in pit-type mines have been investigated by some researchers (Kaneko et al., 1996; Kaneko et al., 1997; Obara et al., 2000; Kodama et al., 2003; Kodama et al., 2009). However, the deformation behavior of homogeneous rock slope was estimated in their studies. Nakamura et al. (2003) measured deformation behavior of rock slopes due to excavation in a pit-type limestone mine using multi-stage extensometers. They found that the deformation behavior in a rock slope formed in slate was significantly different from that formed in limestone. This suggests that elastic deformation of a rock slope formed in a pit-type mine can be affected by geological structure or property. However, the effect of these has not been clarified yet.

In this chapter, the influence of differences in Young's modulus between limestone and bedrock on mining-induced rock slope deformation formed in a pit-type mine was investigated. In addition, effect of a buttress on deformation of the rock slope was also investigated.

#### 4.2 Impact of difference of Young's modulus between limestone and bedrock

##### 4.2.1 Analytical Method

A pit-type mine consisting of limestone and bedrock was modeled, as shown in Fig. 4.1. The rock mass was assumed to be an isotropic and elastic body. The nodal displacements perpendicular to the right, left and the bottom surfaces 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. All analyses were carried out under a plane-strain condition using six-node triangular elements. The total number of elements was 32808, and there were 66051 nodes in the initial configuration before excavation. The angle of a cut rock slope and its final height were set at  $45^\circ$  and  $h$ , respectively. The excavation was successively completed throughout 20 steps with an excavated depth per step of  $h/20$ . The displacement due to the excavation was calculated

by applying the nodal forces equivalent to excavation using Eq. (2.2) in the same manner as in chapter 2. The mechanical properties for limestone and bedrock used in this analysis are shown in Table 4.1. Unit weight and Poisson's ratio of bedrock were assumed to be equal to those of limestone for simplicity.

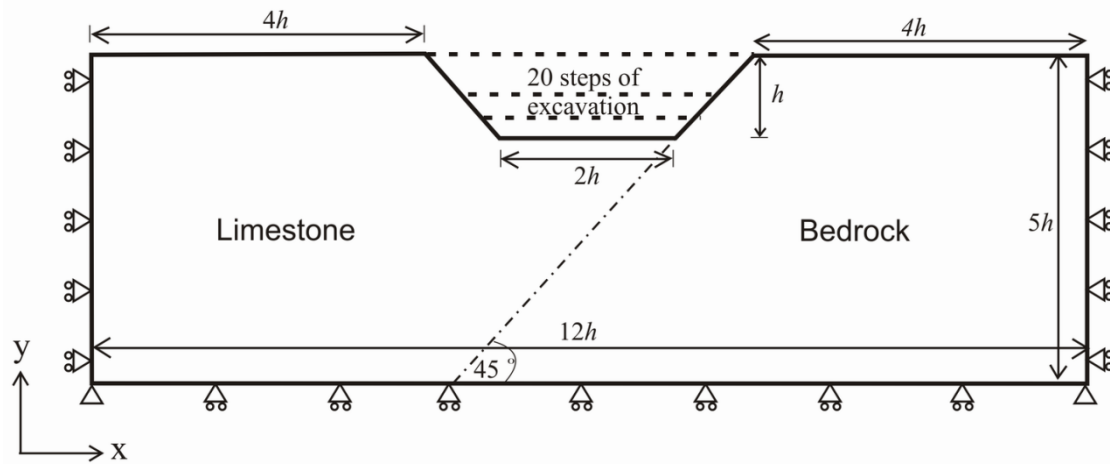


Fig. 4.1. Configuration of the analytical model. Dashed lines indicate progress of the excavation. Dashed-dot lines indicate geological boundary.

Table 4.1. Mechanical properties value of limestone and bedrock

| Case   | Young's modulus (GPa)       |                          | Poisson's ratio $\nu$ | Unit weight $\gamma$<br>(kN/m <sup>3</sup> ) |
|--------|-----------------------------|--------------------------|-----------------------|----------------------------------------------|
|        | Limestone $E_{\text{lime}}$ | Bedrock $E_{\text{bed}}$ |                       |                                              |
| P-GB-1 | 5.0                         | 5.0                      | 0.1                   | 27.0                                         |
|        |                             |                          | 0.2                   |                                              |
|        |                             |                          | 0.3                   |                                              |
|        |                             |                          | 0.4                   |                                              |
| P-GB-2 |                             | 2.5                      | 0.1                   |                                              |
|        |                             |                          | 0.2                   |                                              |
|        |                             |                          | 0.3                   |                                              |
|        |                             |                          | 0.4                   |                                              |
| P-GB-3 |                             | 10.0                     | 0.1                   |                                              |
|        |                             |                          | 0.2                   |                                              |
|        |                             |                          | 0.3                   |                                              |
|        |                             |                          | 0.4                   |                                              |

#### 4.2.2 In the case that Young's modulus of limestone is equal to that bedrock

Figures 4.2 and 4.3 show total of the horizontal surface displacement and horizontal strain ( $\varepsilon_{xx}$ ) of the pit-type mine for the case of P-GB-1 model ( $E_{\text{Lime}} = E_{\text{bed}}$ ) at  $\nu = 0.1$  and 0.4, respectively. Only results at  $\nu = 0.1$  and 0.4 are shown because the deformation behavior of the cut rock slope for  $\nu = 0.2$  and 0.3 was almost identical to that for  $\nu = 0.1$ . The horizontal displacement at an excavated depth of  $h/4$ ,  $h/2$ ,  $3h/4$  and  $h$  from the initial mountaintop (i.e., the 5th, 10th, 15th and 20th excavation steps) is magnified by a factor of 500. A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain. All these descriptions also apply to all the figures showing total of the horizontal surface displacement and  $\varepsilon_{xx}$  in this chapter. The analytical model is shown geometrical symmetry because Young's modulus was equal between limestone and bedrock. Therefore, only the left hand side of the cut rock slope is discussed.

Figure 4.2 shows that the cut rock slope exhibited backward displacement for all excavation steps and contraction was predominant in the cut rock slope at  $\nu = 0.1$ . In the case of  $\nu = 0.4$ , up to 5th and 10th steps of excavation (see Fig. 4.3 (a), (b)), the cut rock slope exhibited backward displacement. Thereafter, up to 15th and 20th (final) steps of excavation (Fig. 4.3(c), (d)), the shoulder part of the cut rock slope continued to displace backward, but forward surface displacement was found around the toe of slope. There are differences in the horizontal strain distribution in the cut rock slope between  $\nu = 0.1$  and 0.4. Contraction is seen around both the shoulder and toe parts at  $\nu = 0.4$  as well as at  $\nu = 0.1$ , but extension can be found near the surface of the middle part of the slope at  $\nu = 0.4$ .

It is noticed that the pit floor shows significant extension in the case of  $\nu = 0.1$ . It is also noticed that much extension can be seen around the lower left toe in Fig. 4.3 at  $\nu = 0.4$ . The floor extension and an extension around lower left toe can be caused by release of gravity and horizontal stress, respectively. It can be interpreted that the backward surface displacement and contraction at  $\nu = 0.1$  is resulted from gravity release due to excavation. It can be also interpreted that the forward surface displacement and extension at  $\nu = 0.4$  is caused by release of horizontal stress due to excavation.

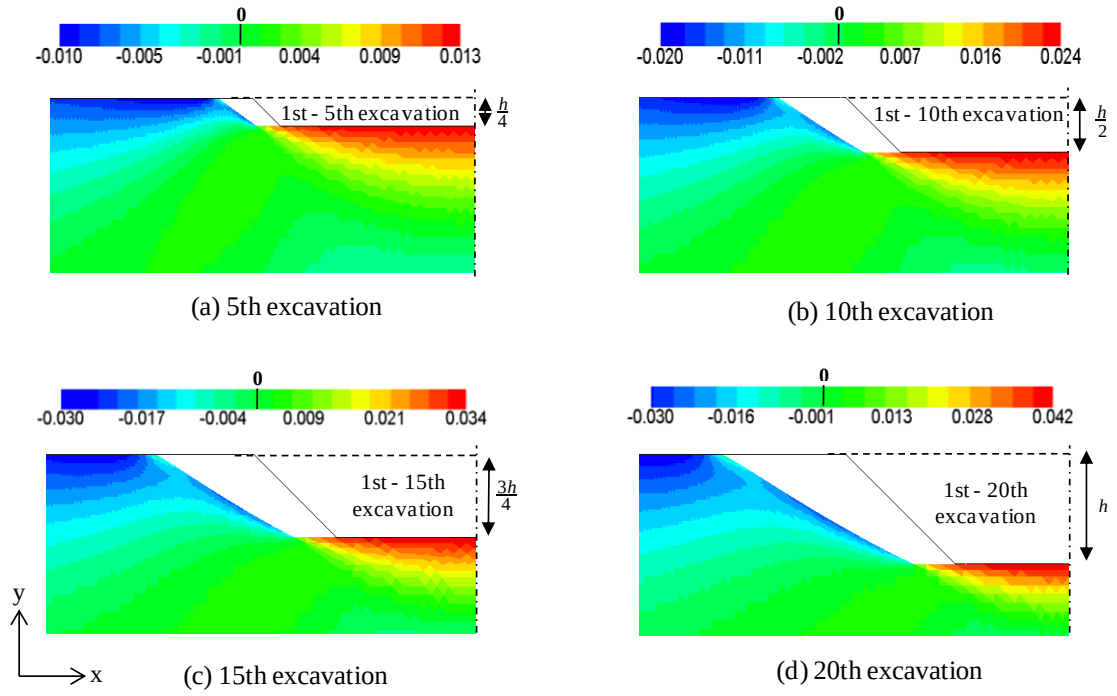


Figure 4.2 Horizontal surface deformation and strain ( $\epsilon_{xx}$ ) distribution in the case of P-GB-1 ( $E_{\text{Lime}} = E_{\text{Bed}} = 5.0$  GPa) in each 5 step of excavation for  $\nu = 0.1$ . The depth of the excavation from the initial model was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\epsilon_{xx}$  corresponds to compressive strain.

The horizontal displacement along the horizontal lines H1 and H2 shown in Fig. 4.4 was analyzed for clarifying the deformation characteristics with the progress of excavation. The height of the lines H1 and H2 were  $h/2$  and  $h$ , respectively. The lengths of the lines H1 and H2 were  $h$  and  $2h$ , respectively. Relative displacement to the reference points A or B was calculated and was normalized by the slope height  $h$ . A positive relative displacement corresponds to displacement of the target point away from the reference point, as shown by the bold arrows in Fig. 4.4. This means a positive sign in normalized relative displacement corresponds to extension between the target and reference points. The distributions of the normalized horizontal relative displacement along the lines H1 and H2 are shown in Figs. 4.5 and 4.6, respectively. The normalized relative displacement along the line H2 was calculated from the 11th excavation step, whereby the excavation depth proceeded just below  $h/2$ .

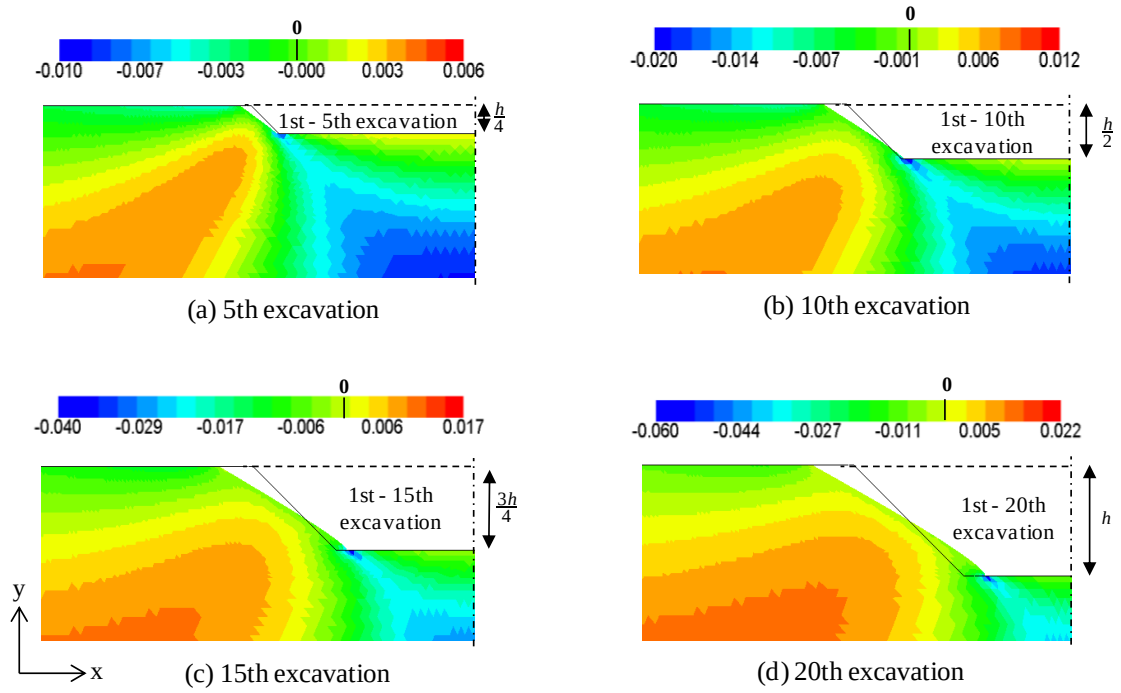


Figure 4.3 Horizontal surface deformation and strain ( $\epsilon_{xx}$ ) distribution in the case of P-GB-1 ( $E_{\text{Lime}} = E_{\text{Bed}} = 5.0$  GPa) in each 5 step of excavation for  $\nu = 0.4$ . The depth of the excavation from the initial model was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\epsilon_{xx}$  corresponds to compressive strain.

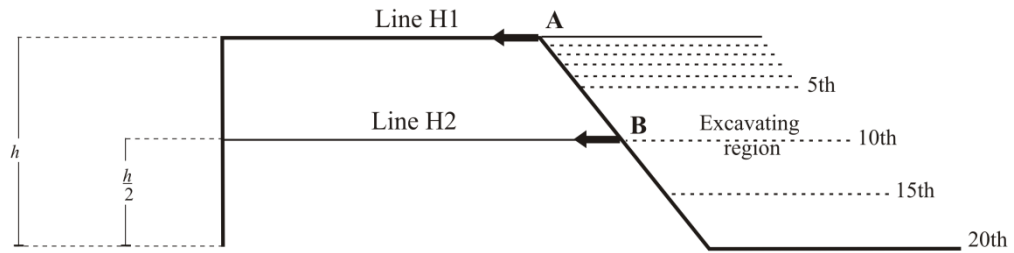


Fig. 4.4 Direction and location of each target line used in the displacement analysis.

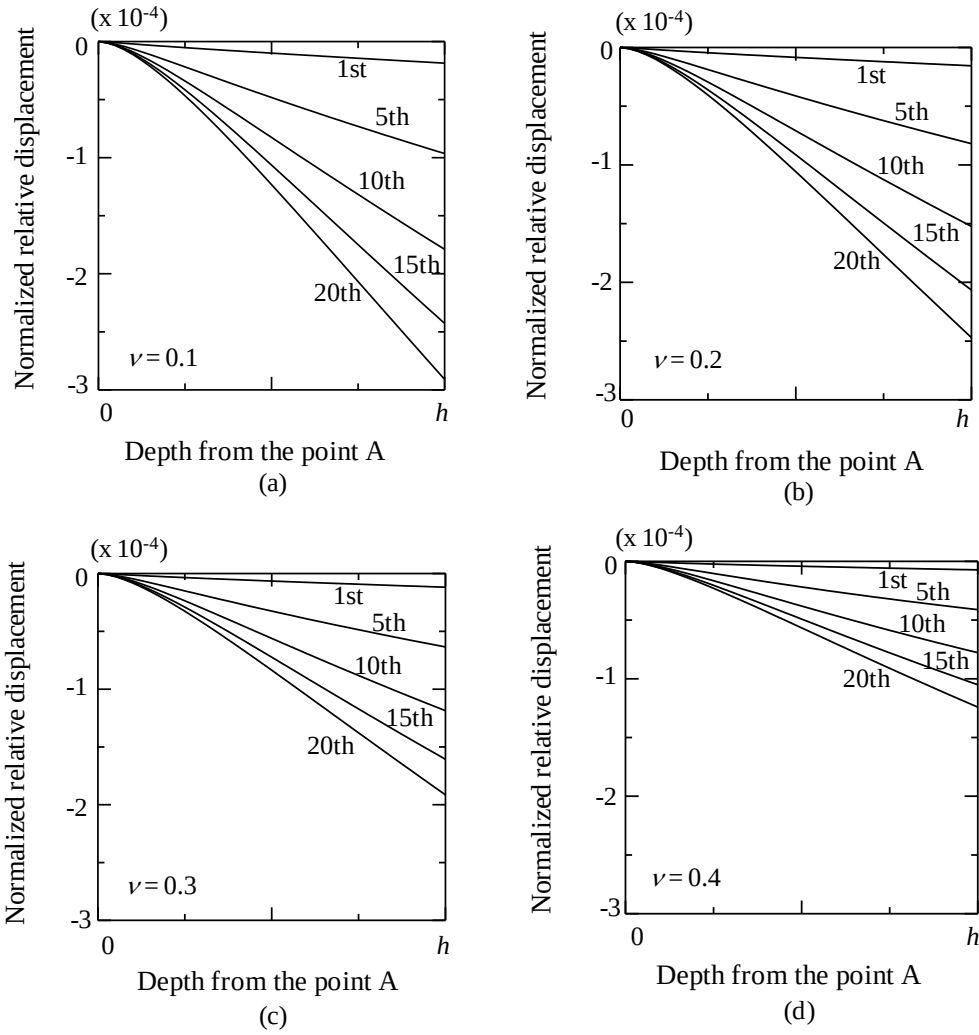


Fig. 4.5 Normalized horizontal relative displacement along line H1 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

In the case of line H1, the gradient of the displacement with the respect to depth from the reference point was negative. It follows that the slope exhibited contraction due to excavation. The normalized relative displacement decreased with the increasing Poisson's ratio. Significant difference could not be found between the characteristics of normalized relative displacement along the lines H1 and H2 with  $\nu = 0.1$ – $0.3$ . However, clear difference is found in the case of  $\nu = 0.4$ . The normalized relative displacement along the line H2 increased toward positive and turned from increase to negative during the latter stages of excavation in the deeper part in the rock slope. Thus, the gradient of

the displacement with respect to depth from the reference point was positive at shallower part and then turned to be negative at a certain depth. It follows that deformation mode of the slope changed from extension to contraction as distance from the surface increases.

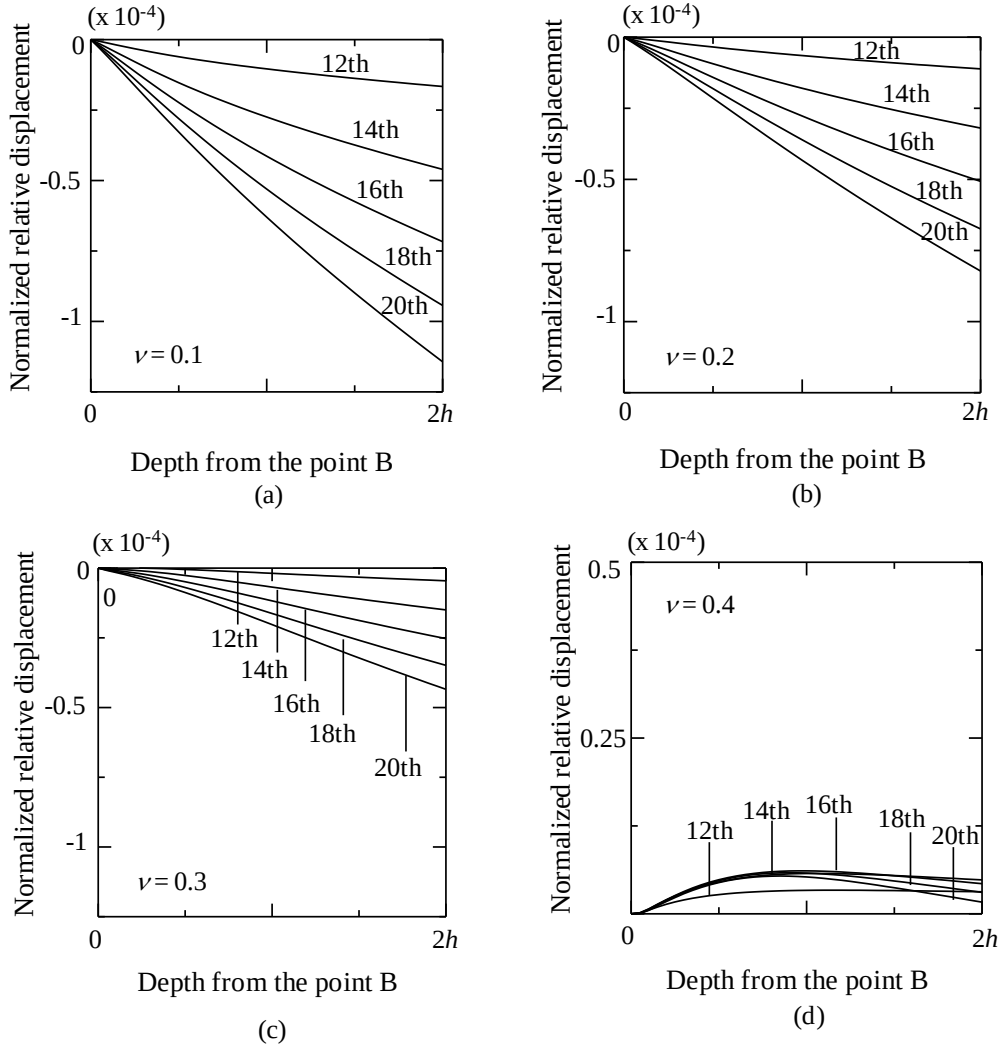


Fig. 4.6 Normalized horizontal relative displacement along line H2 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

Figure 4.7 shows the normalized relative horizontal displacement on the lines H1 and H2 at the depths of  $h/4$ ,  $h/2$  and  $h$  from the surface, as a function of the excavation depth of 0 to  $h$  and  $h/2$  to  $h$ , respectively. Clear contraction was observed in the displacement on the line H1 for all three depths at all four Poisson's ratios. The rate of

increase in the contraction with respect to the rock surface gradually decreased as the excavation progressed. The magnitude of the contraction depended on the Poisson's ratio and it decreased with increasing in Poisson's ratio. The trends in the normalized relative displacement on the line H2 were similar to those along the line H1 with  $\nu = 0.1$ – $0.3$  (see Fig. 4.7 (a), (b) and (c)). Clear contraction was observed at all three depths and the magnitude of the contraction depended on the Poisson's ratio. In the case  $\nu = 0.4$ , no clear deformation due to excavation could be seen.

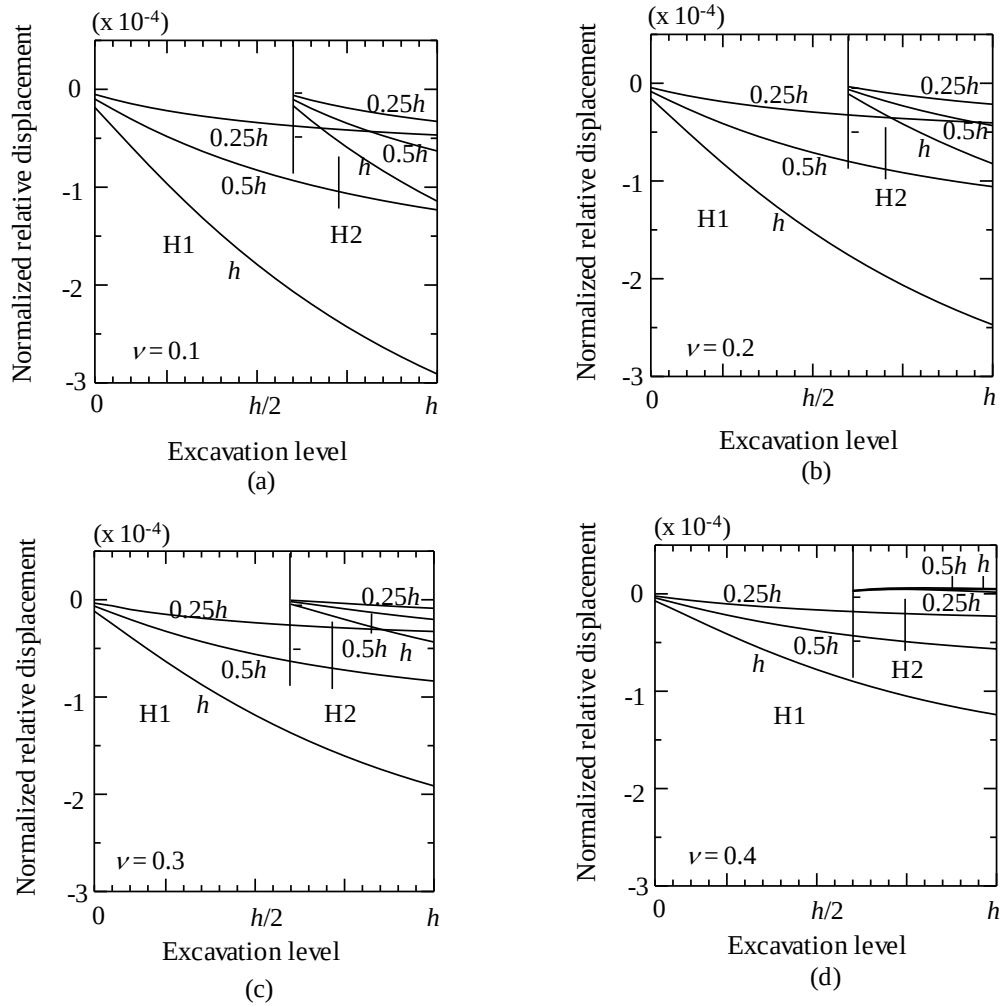


Fig. 4.7 Change in the normalized horizontal relative displacement along lines H1 and H2 at depths of  $h/4$ ,  $h/2$ , and  $h$  as a function of the excavation progress for  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

#### 4.2.3 In the case that Young's modulus of limestone is greater than that of bedrock

Figures 4.8 and 4.9 show total the horizontal surface displacement and horizontal strain ( $\varepsilon_{xx}$ ) of the pit-type mine for the case of P-GB-2 model ( $E_{\text{Lime}} > E_{\text{bed}}$ ) at  $\nu = 0.1$  and 0.4, respectively. Regardless of the value of  $\nu$ , backward surface displacement was observed from the toe to the top of the left cut rock slope consisting of limestone with the progress of excavation (Figs. 4.8 and 4.9). Contraction was predominant in the left cut rock slope throughout all the excavation steps although extension could be seen around the toe of slope at  $\nu = 0.1$  (Fig. 4.8). Contraction was also predominant in the left cut rock slope up to 5th and 10th step of excavation at  $\nu = 0.4$  (Figs. 4.9(a) and 4.9 (b), respectively) even though extension could be observed around the toe of slope. However, the extension appeared in the left cut rock slope accompanied by following excavations (see Fig. 4.9(c), (d)). These results show that the deformation behaviors of left cut rock slope consisting of limestone are almost similar with the case where Young's modulus of limestone was equal to that of bedrock with a few exceptions. A cut rock slope exhibits backward displacement and contraction for smaller  $\nu$  and tends to exhibit forward surface displacement and extension at larger  $\nu$ .

On the other hand, in the earlier steps of excavation (up to 5th step of excavation, Fig. 4.8a), the right cut rock slope consisting of bedrock tended to exhibit forward displacement at  $\nu = 0.1$ . This behavior was also seen up to 10th step of excavation (Fig. 4.8b). However, by further excavations (see Fig. 4.8c–d), the cut rock slope exhibited backward displacement. At  $\nu = 0.4$ , the cut rock slope exhibited forward displacement regardless of excavation step. Horizontal strain distribution in the right cut rock slope was also different from that in the left one. Significant extension was found around the shoulder part of cut rock slope while contraction was seen around the toe of cut rock slope for all Poisson's ratios. These results show that there is remarkable difference in deformation characteristic between the cut rock slope consisting of limestone and that consisting of bedrock when Young's modulus of bedrock is smaller than that of limestone.

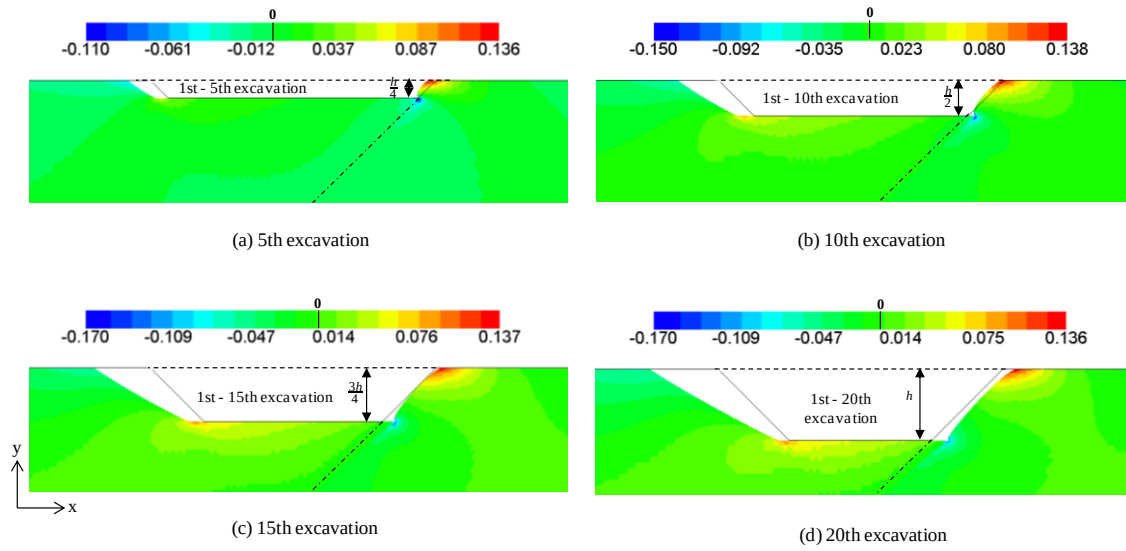


Figure 4.8 Horizontal surface deformation and strain ( $\varepsilon_{xx}$ ) distribution in the case of P-GB-2 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 2.5$  GPa) in each 5 step of excavation for  $\nu = 0.1$ . The depth of the excavation from the initial model was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain.

The horizontal displacement along the lines H1, H2, H3 and H4 shown in Fig. 4.10 was analyzed. The height of the lines H1 and H3 were  $h$  and H2 and H4 were  $h/2$ , while the length of the lines H1 and H3 were  $h$  and H2 and H4 were  $2h$ . The displacement relative to the reference points A, B, C and D was calculated along the lines H1, H2, H3 and H4, respectively. These were normalized by the slope height,  $h$ . A positive relative displacement corresponds to displacement of the target point away from the reference point, as shown by the bold arrows in Fig. 4.10. This means that positive sign corresponds to extension between the target and reference points. The relative displacement along the lines H2 and H4 was calculated from the 11th excavation step, whereby the excavation depth proceeds just below  $h/2$ . These descriptions also apply to the remaining part of this chapter.

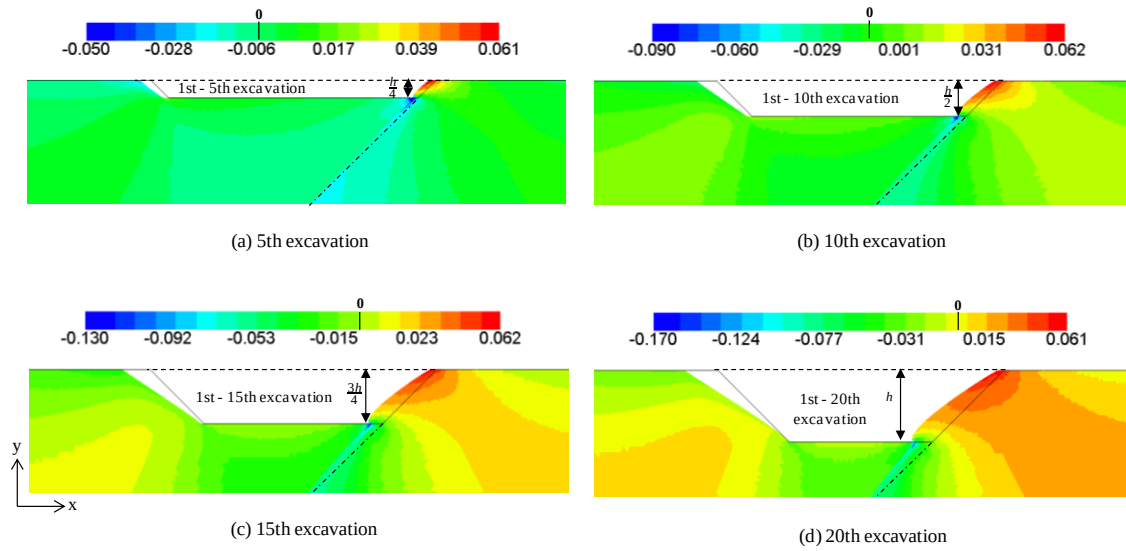


Figure 4.9 Horizontal surface deformation and strain ( $\varepsilon_{xx}$ ) distribution in the case of P-GB-2 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 2.5$  GPa) in each 5 step of excavation for  $\nu = 0.4$ . The depth of the excavation from the initial model was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain.

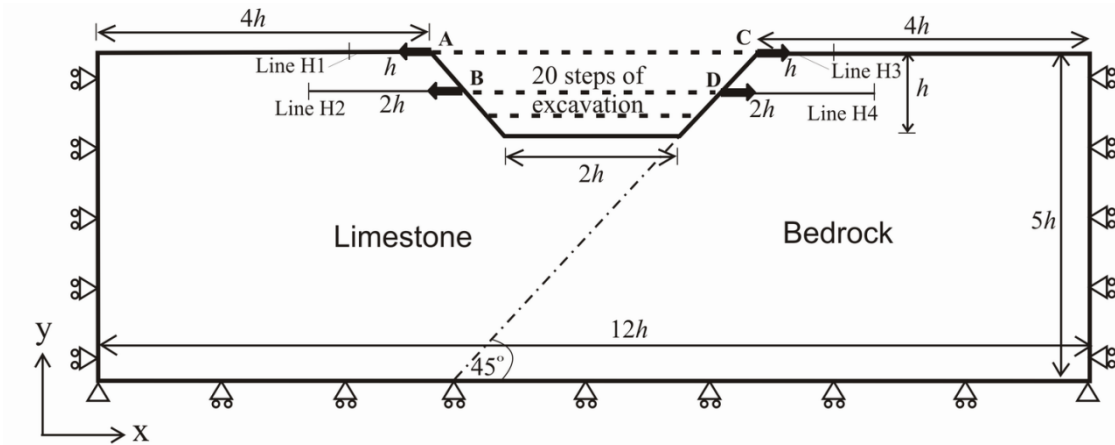


Fig. 4.10 Direction and location of each target line used in the displacement analysis.

The distribution of the relative horizontal displacement along the lines H1 and H2 is shown in Figs. 4.11 and 4.12, respectively. Figure 4.13 shows the relative horizontal displacement along the lines H1 and H2 at depths of  $h/4$ ,  $h/2$  and  $h$  from the surface, as a function of the excavation depth of 0 to  $h$  and  $h/2$  to  $h$ , respectively.

The characteristics of the relative horizontal displacement along the lines H1 and H2 in the case of P-GB-2 (Figs. 4.11, 4.12 and 4.13) were similar to those along the H1 and H2 in the case of P-GB-1 (Figs. 4.5, 4.6 and 4.7). This means that the cut rock slope consisting of limestone exhibited contraction due to excavation. This also means that the contraction became larger near the surface of the slope, and the rate of increase in the contraction deformation with respect to the rock surface decreased with the progress of excavation.

On the other hand, the characteristics of the normalized relative horizontal displacement along the lines H3 and H4 in the case of P-GB-2 (Figs. 4.14, 4.15 and 4.16) were obviously different from those along the H1 and H2 in the case of P-GB-1 (Figs. 4.5, 4.6 and 4.7). The relative displacement increased toward the inside of the cut rock slope (Figs. 4.14 and 4.15). The gradient of the displacement with respect to the depth from the reference point was positive and became larger near the surface of the slope (Figs. 4.14 and 4.15). The relative displacement increased with the progress of excavation, but its increment tended to decrease. Neither slight increase nor decrease was observed along the line H1 as excavation progressed from  $h/4$  to  $h/2$ . This means that the cut rock slope consisting of bedrock exhibited extension due to excavation. This also means that the extension became larger near the surface of the slope, and the rate of increase in the extension with respect to the slope surface decreased with the progress of excavation.

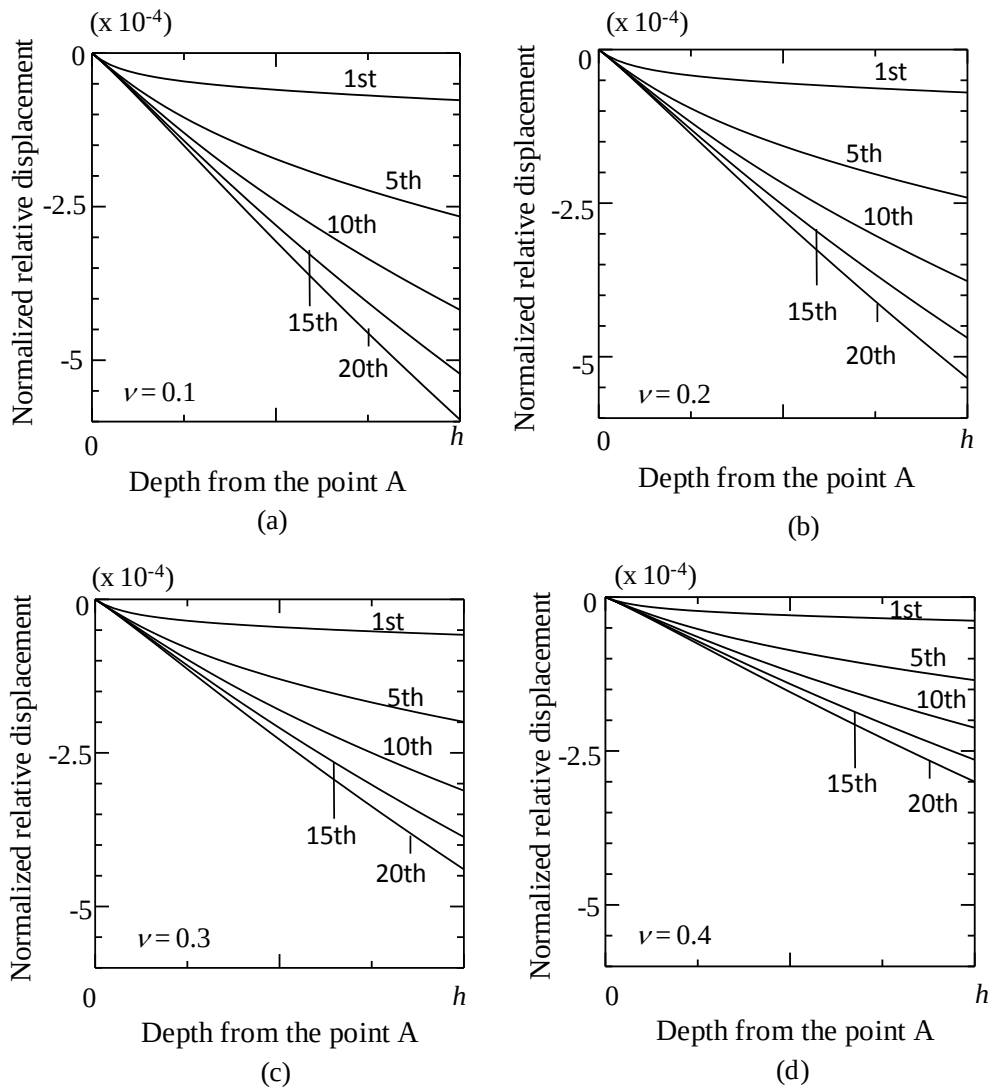


Fig. 4.11 Normalized horizontal relative displacement along line H1 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

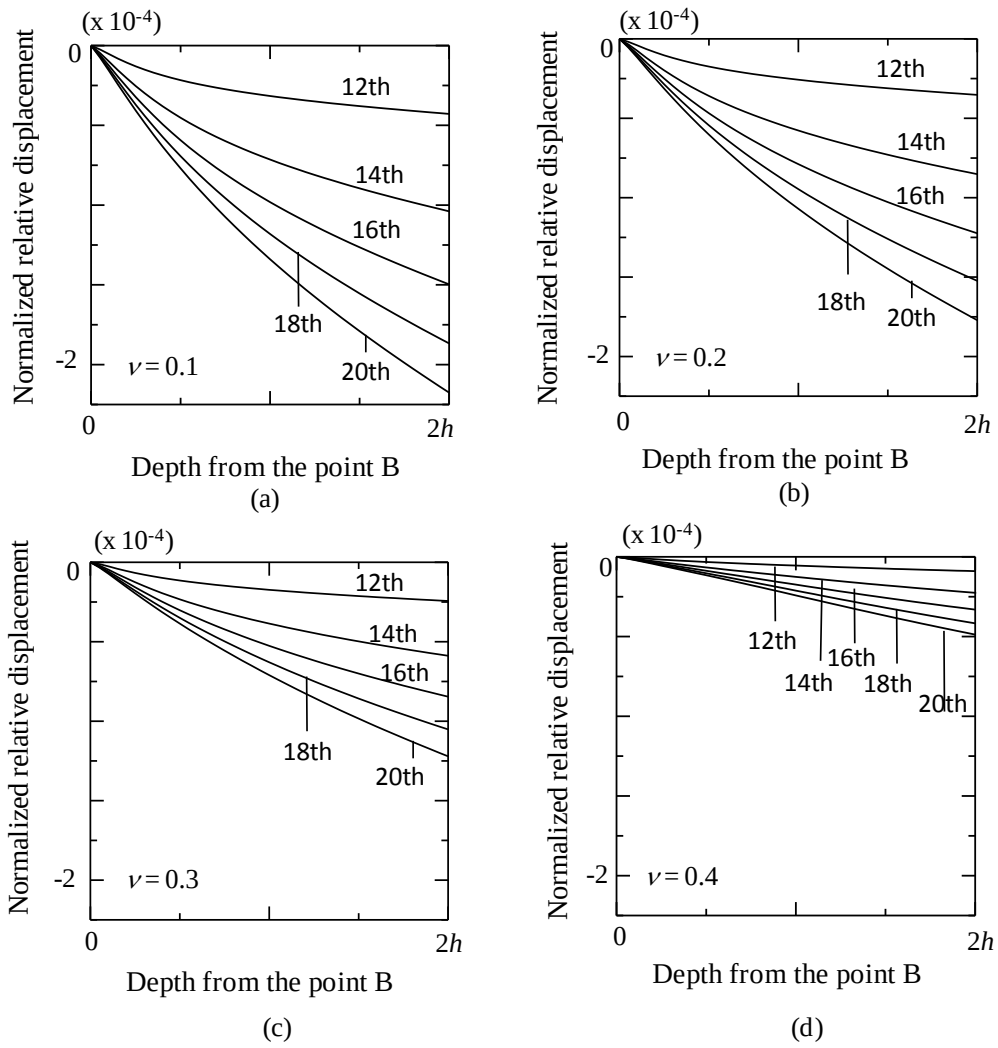


Fig. 4.12 Normalized horizontal relative displacement along line H2 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

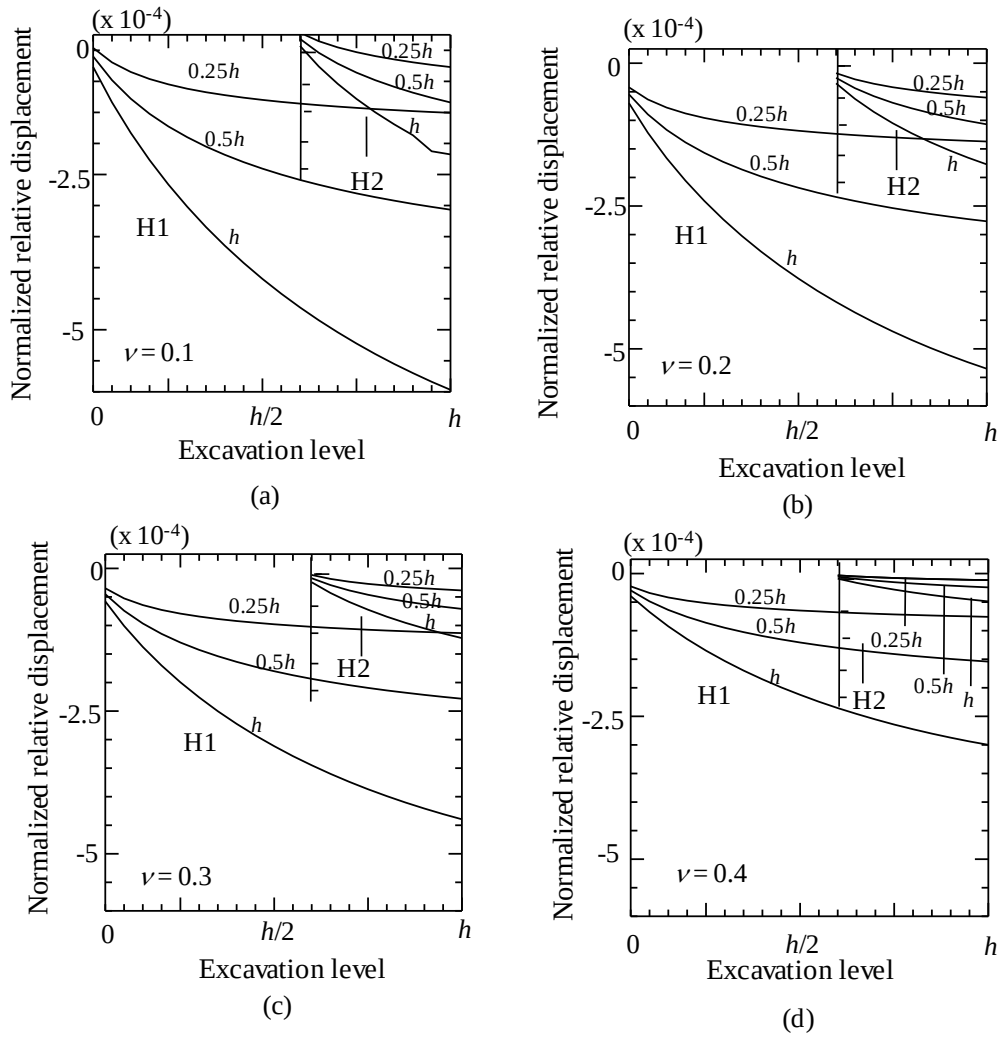


Fig. 4.13 Change in the normalized horizontal relative displacement along lines H1 and H2 at depths of  $h/4$ ,  $h/2$ , and  $h$  as a function of the excavation progress for  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

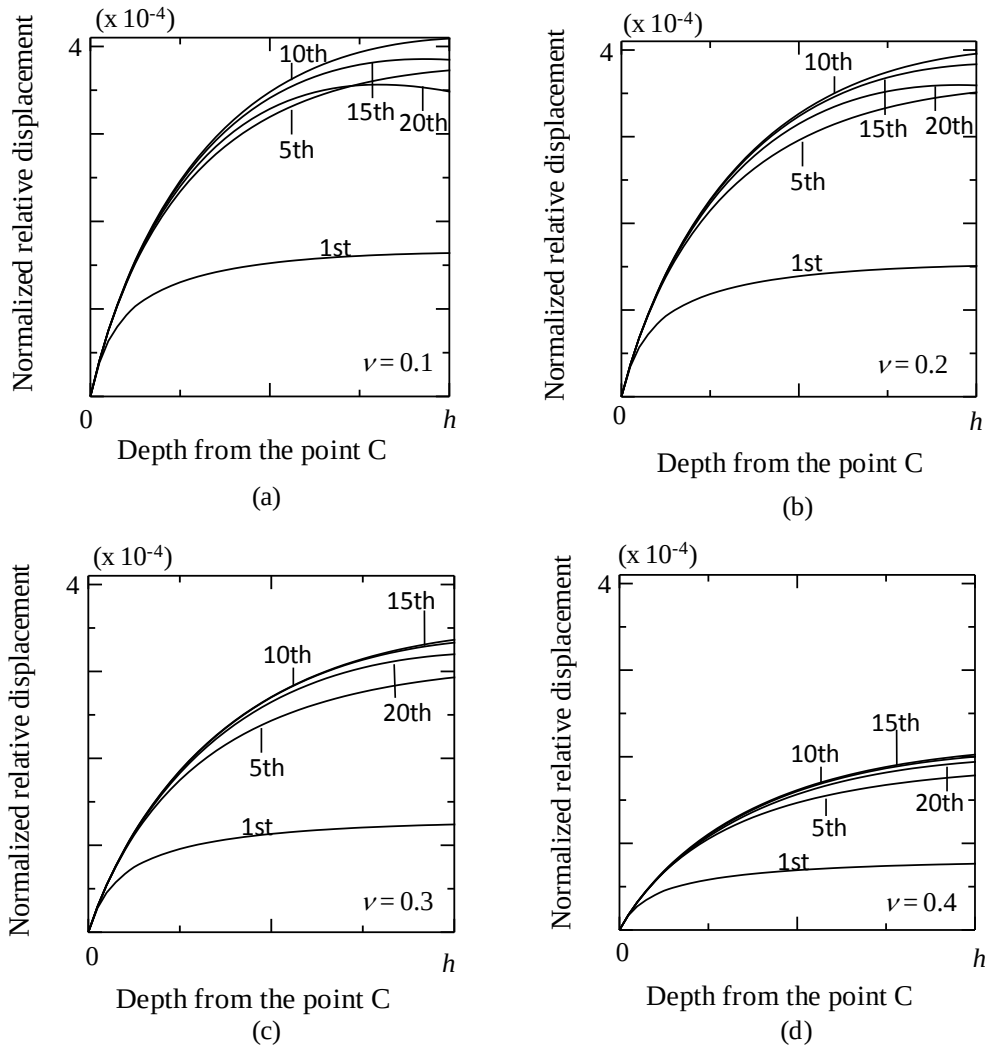


Fig. 4.14 Normalized horizontal relative displacement along line H3 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

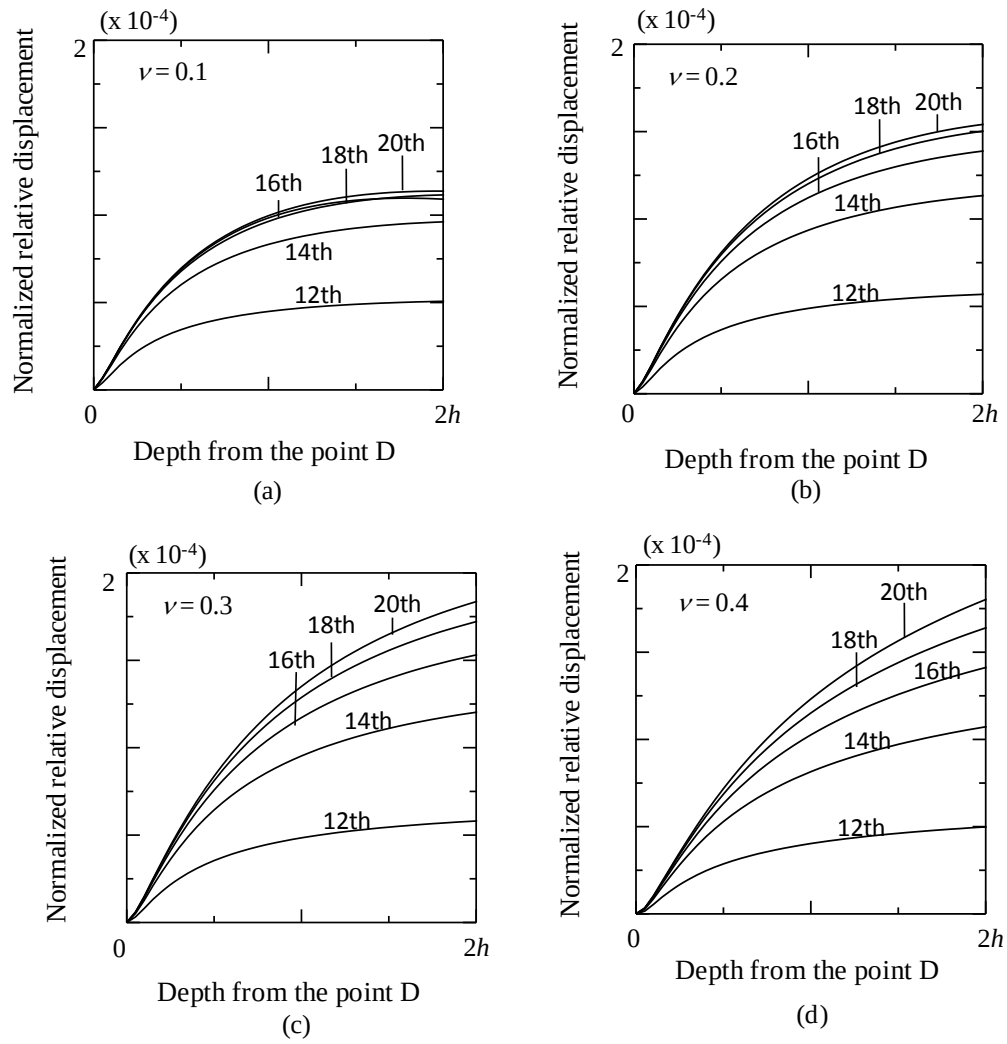


Fig. 4.15 Normalized horizontal relative displacement along line H4 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

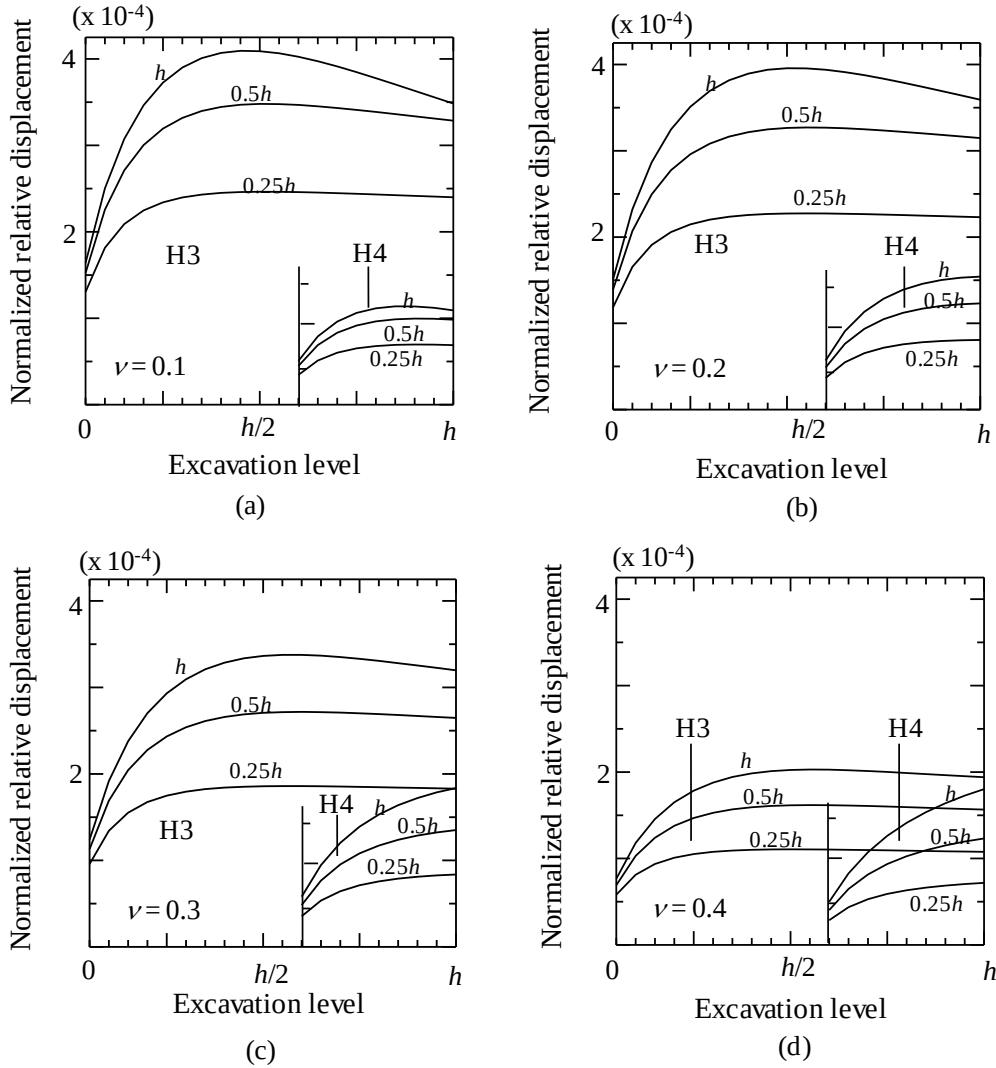


Fig. 4.16 Change in the normalized horizontal relative displacement along lines H3 and H4 at depths of  $h/4$ ,  $h/2$ , and  $h$  as a function of the excavation progress for  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

#### 4.2.4 In the case that Young's modulus of bedrock is greater than that of limestone

Figures 4.17 and 4.18 show the total horizontal surface displacement and horizontal strain ( $\epsilon_{xx}$ ) of the pit-type mine for the case of P-GB-3 model ( $E_{\text{Lime}} < E_{\text{bed}}$ ) at  $\nu = 0.1$  and 0.4, respectively. By the progress of excavation, backward displacement was seen from the toe to the top of the left cut rock slope consisting of limestone at  $\nu = 0.1$  (Fig. 4.17). The contraction was predominant in the left cut rock slope throughout all excavation steps although the extension could be seen around the shoulder of cut rock

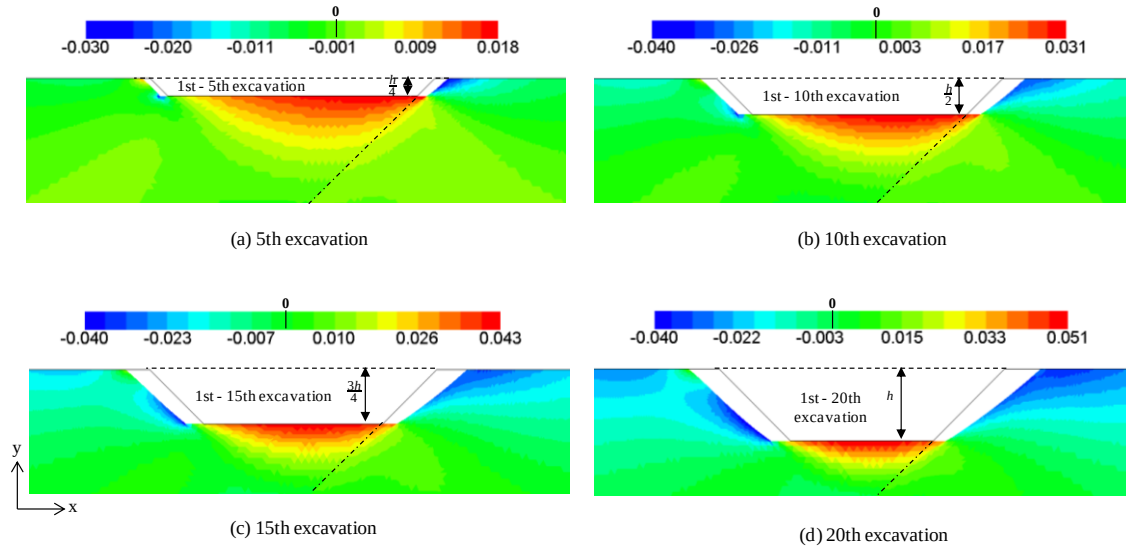


Figure 4.17 Horizontal surface deformation and strain ( $\varepsilon_{xx}$ ) distribution in the case of P-GB-3 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 10.0$  GPa) in each 5 step of excavation at  $\nu = 0.1$ . The depth of the excavation from the initial model was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain.

slope at  $\nu = 0.1$ . The left cut rock slope exhibited backward displacement around the shoulder of cut rock slope and forward surface displacement around the toe of cut rock slope by excavation progresses at  $\nu = 0.4$  (Fig. 4.18). An extension was predominant in the left cut rock slope throughout all the steps of excavation even though the contraction could be found around the toe at  $\nu = 0.4$ . These results show that the deformation behaviors of left cut rock slope consisting of limestone are almost similar to the case where Young's modulus of bedrock is equal to and smaller than limestone. A cut rock slope exhibits backward displacement and contraction at smaller  $\nu$  and forward surface displacement and extension at larger  $\nu$ .

On the other hand, the right cut rock slope consisting of bedrock apparently exhibited backward displacement with the progress of excavation regardless of  $\nu$  (Figs. 4.17 and 4.18). The contraction was found in the right cut rock slope throughout all the excavation step regardless of  $\nu$ , in which the magnitude of contraction decreased with increasing Poisson's ratio. These results show the significant difference in deformation

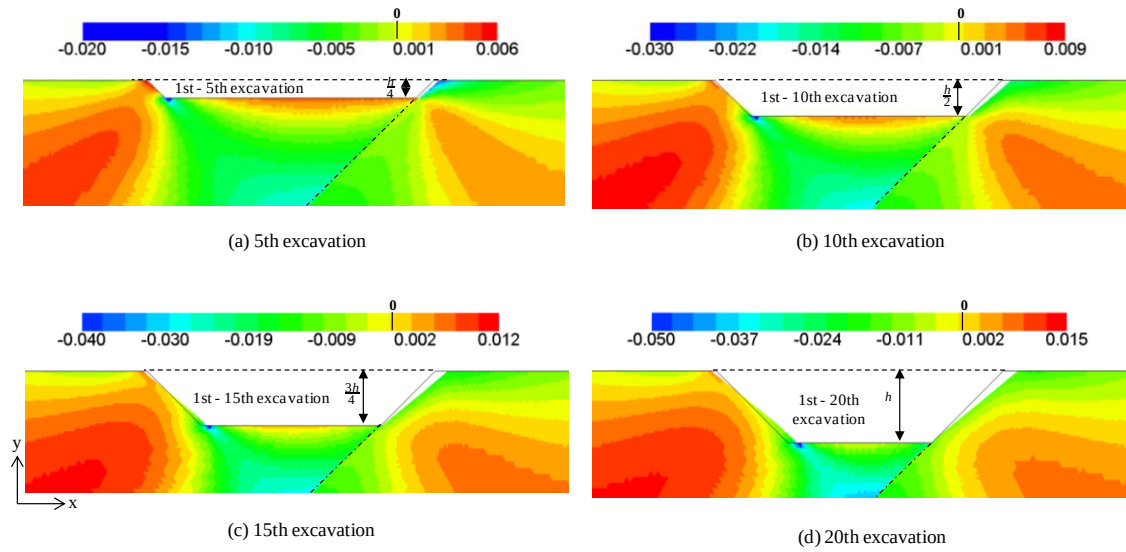


Figure 4.18 Horizontal surface deformation and strain ( $\varepsilon_{xx}$ ) distribution in the case of P-GB-3 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 10.0$  GPa) in each 5 step of excavation at  $\nu = 0.4$ . The depth of the excavation from the initial model was (a)  $h/4$  (1st to 5th excavation steps), (b)  $h/2$  (1st to 10th excavation steps), (c)  $3h/4$  (1st to 15th excavation steps) and (d)  $h$  (1st to 20th excavation steps). A negative value of  $\varepsilon_{xx}$  corresponds to compressive strain.

characteristic between the cut rock slopes consisting of limestone and bedrock when Young's modulus of bedrock is larger than that of limestone.

The horizontal displacement along the lines H1, H2, H3 and H4 shown in Fig. 4.10 was analyzed to clarify the interior deformation of right and left cut rock slopes. The direction and location of each target line are the same with the model in Fig. 4.10. The distributions of the relative horizontal displacement along the lines H1 and H2 are shown in Figs. 4.19 and 4.20, respectively. Figure 4.21 shows the normalized relative horizontal displacement on the lines H1 and H2 at depths of  $h/4$ ,  $h/2$  and  $h$  from the surface, as a function of the excavation depth of 0 to  $h$  and  $h/2$  to  $h$ , respectively.

The characteristics of the normalized relative horizontal displacement along the lines H1 and H2 in the case of P-GB-3 (Figs. 4.19, 4.20 and 4.21) were basically similar to those along the H1 and H2 in the case of P-GB-1 (Figs. 4.5, 4.6 and 4.7). The cut rock slope consisting of limestone exhibited contraction due to excavation although an extension was seen near the surface and on the line H2 at  $\nu = 0.4$ . The rate

of increase in the contraction with respect to slope surface tended to decrease with the progress of excavation and increase with Poisson's ratio.

The characteristics of the normalized relative horizontal displacement along the lines H3 and H4 in the case of P-GB-3 (Figs. 4.22, 4.23 and 4.24) were also similar to those along the H1 and H2 in the case of P-GB-1 (Figs. 4.5, 4.6 and 4.7). The cut rock slope consisting of bedrock exhibited contraction due to excavation and the contraction became larger near the surface of the slope. The rate of increase in the contraction with respect to slope surface decreased with the progress of excavation.

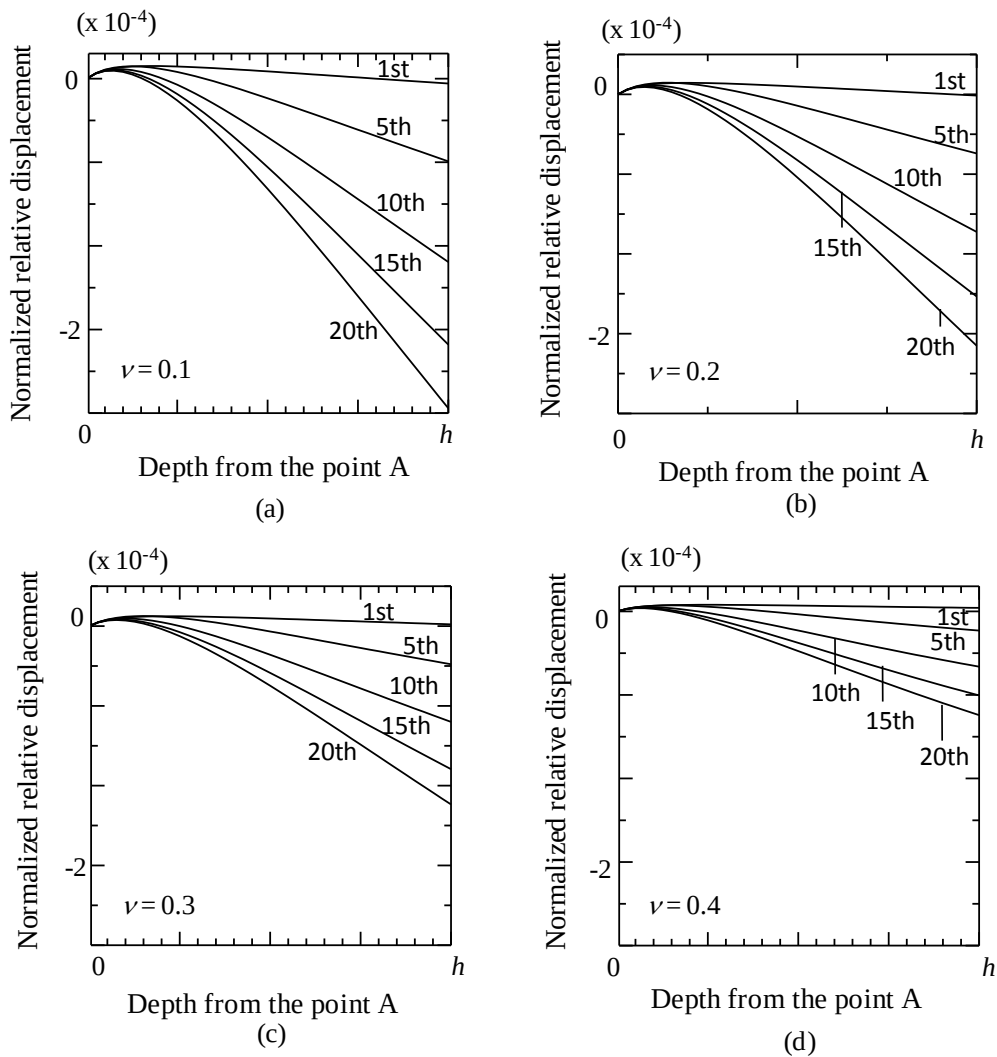


Fig. 4.19 Normalized horizontal relative displacement along line H1 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

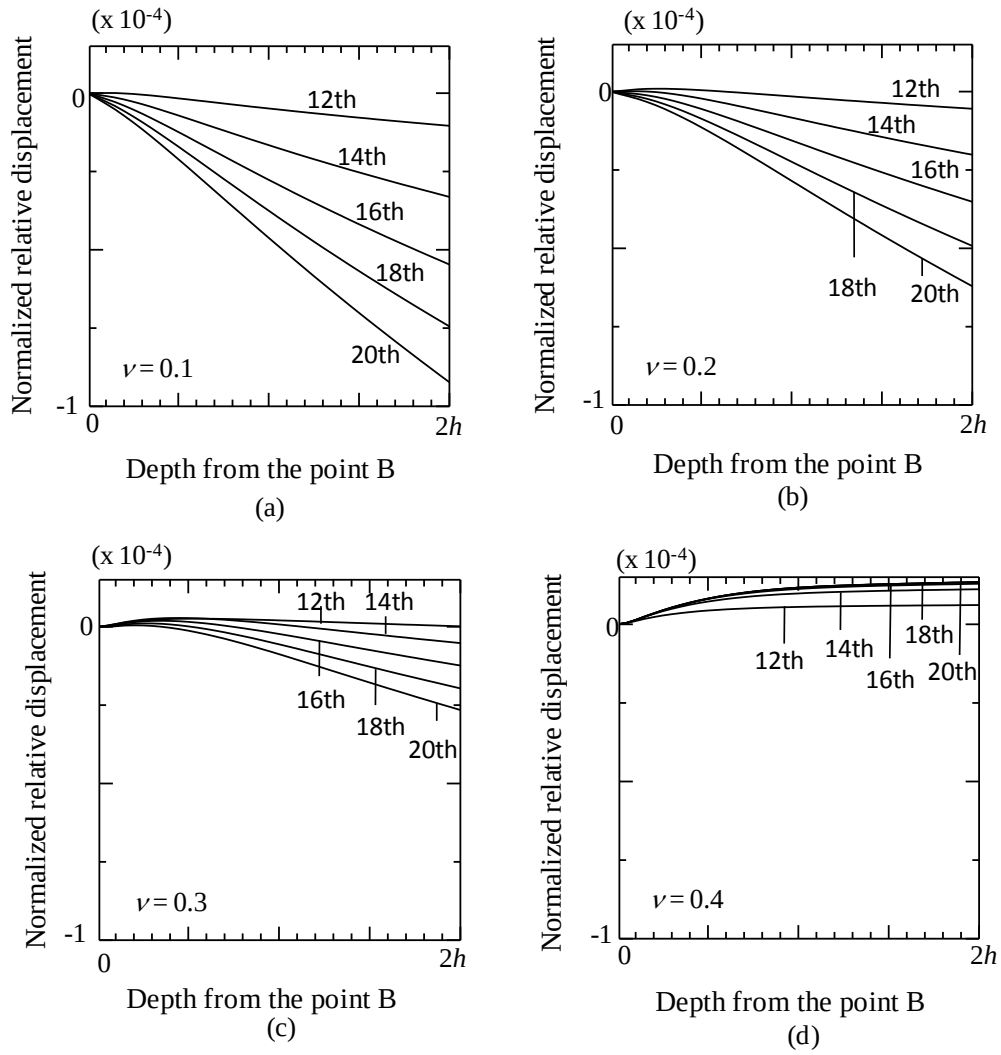


Fig. 4.20 Normalized horizontal relative displacement along line H2 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

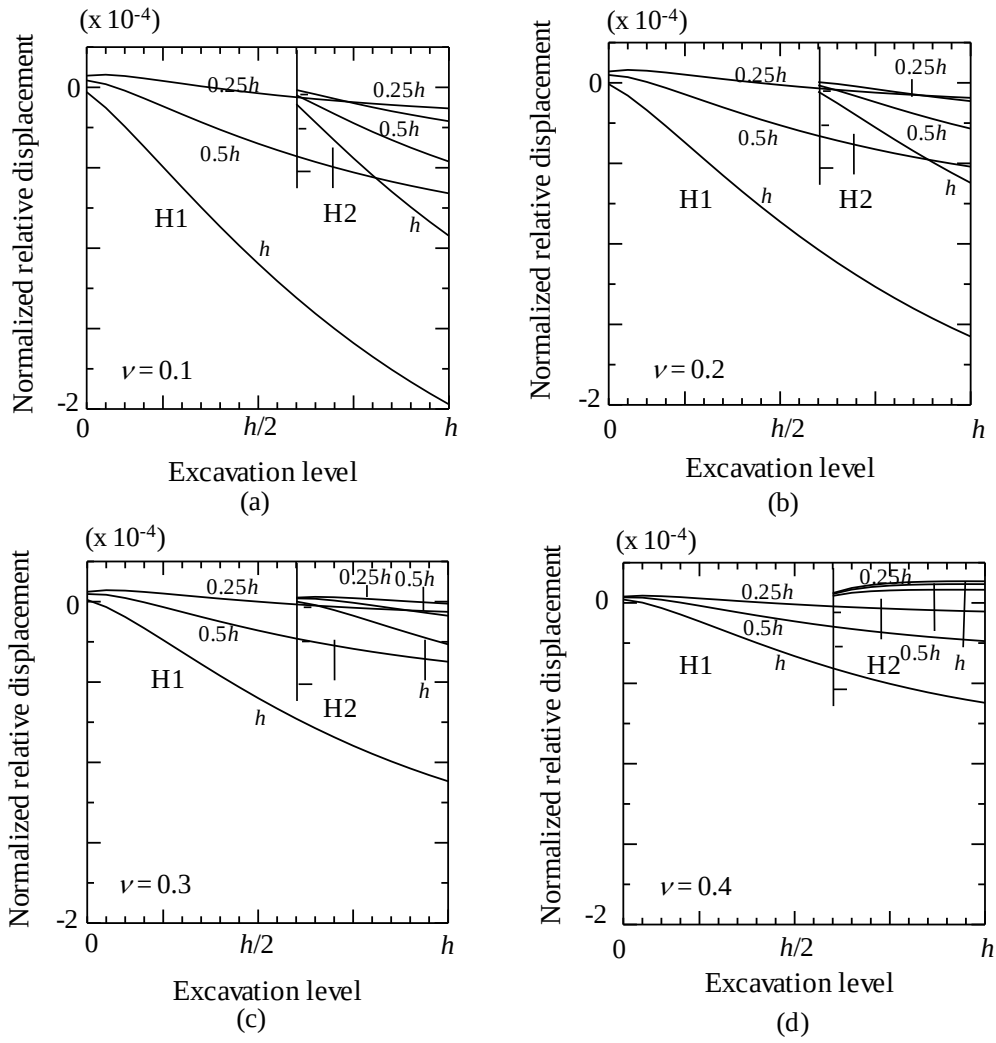


Fig. 4.21 Change in the normalized horizontal relative displacement along lines H1 and H2 at depths of  $h/4$ ,  $h/2$ , and  $h$  as a function of the excavation progress for  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

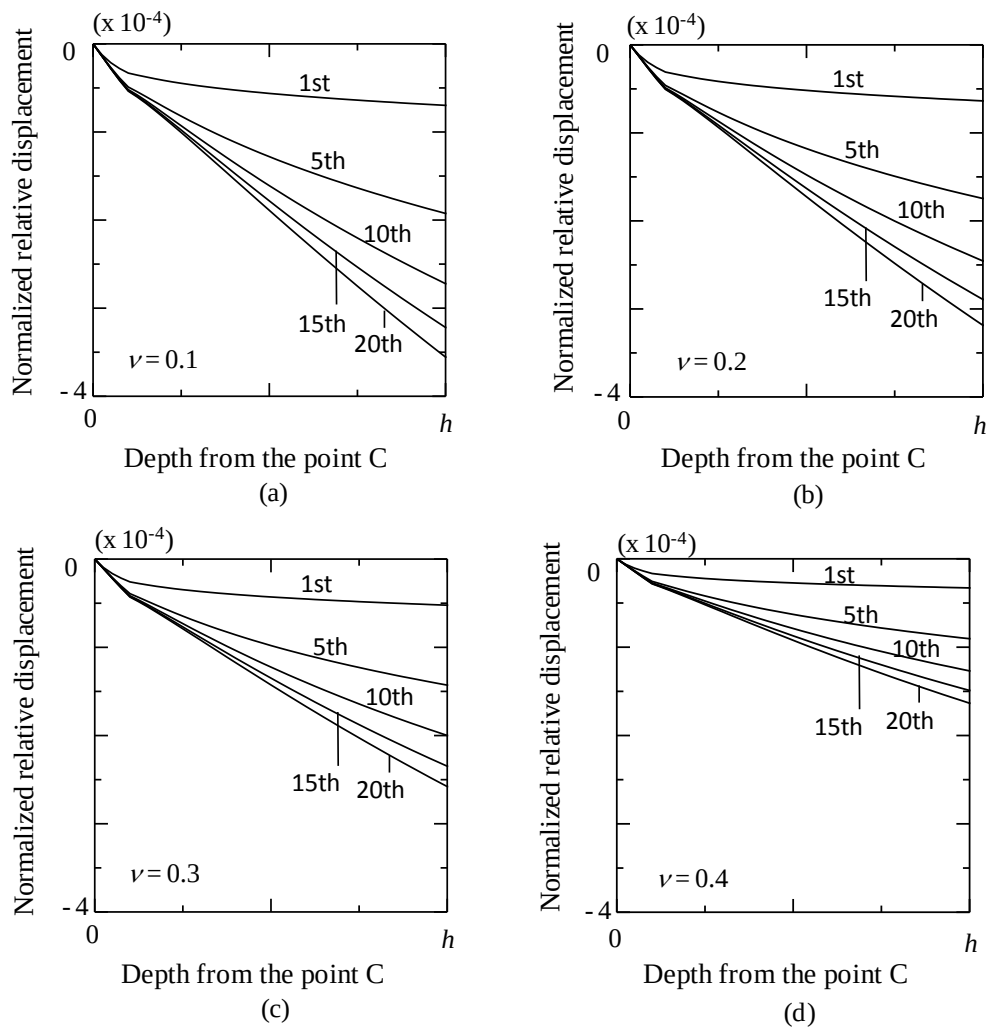


Fig. 4.22 Normalized horizontal relative displacement along line H3 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

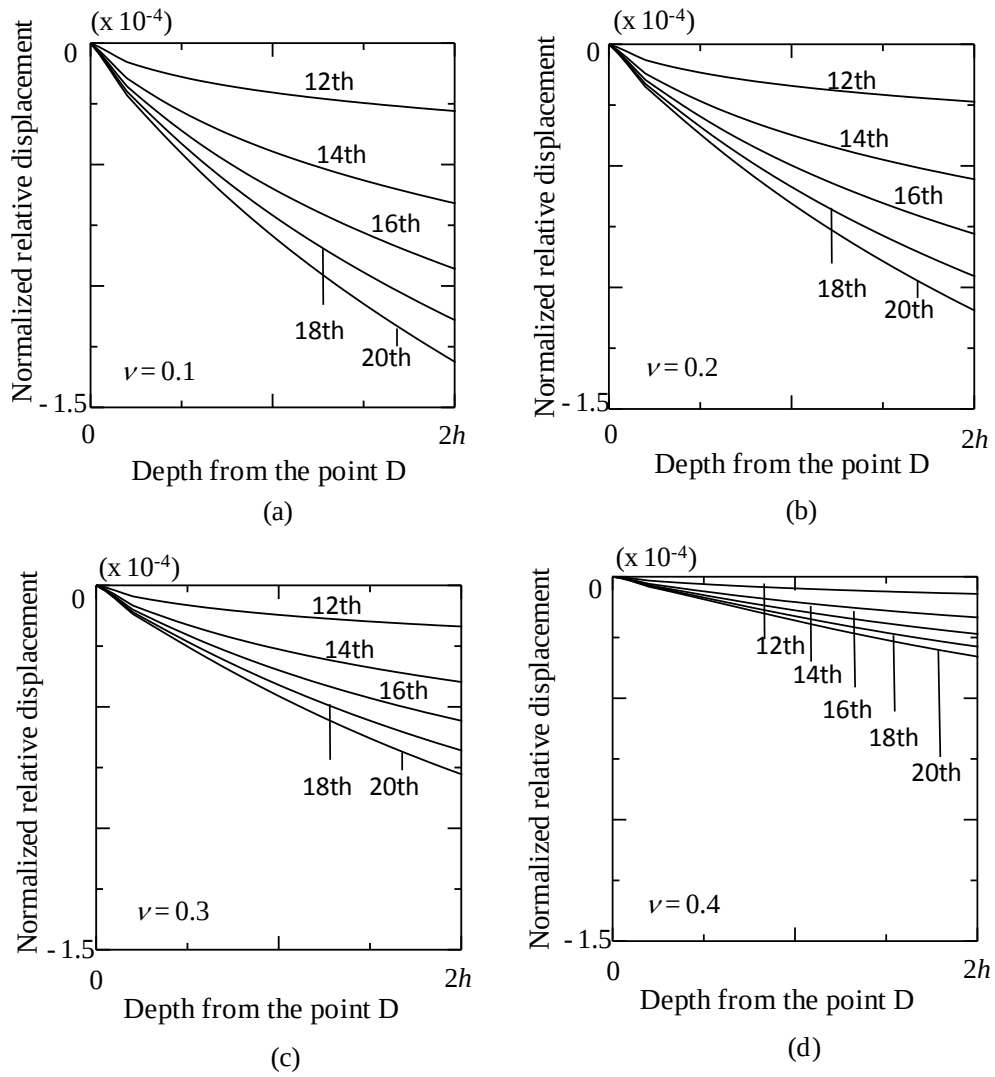


Fig. 4.23 Normalized horizontal relative displacement along line H4 due to excavation at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

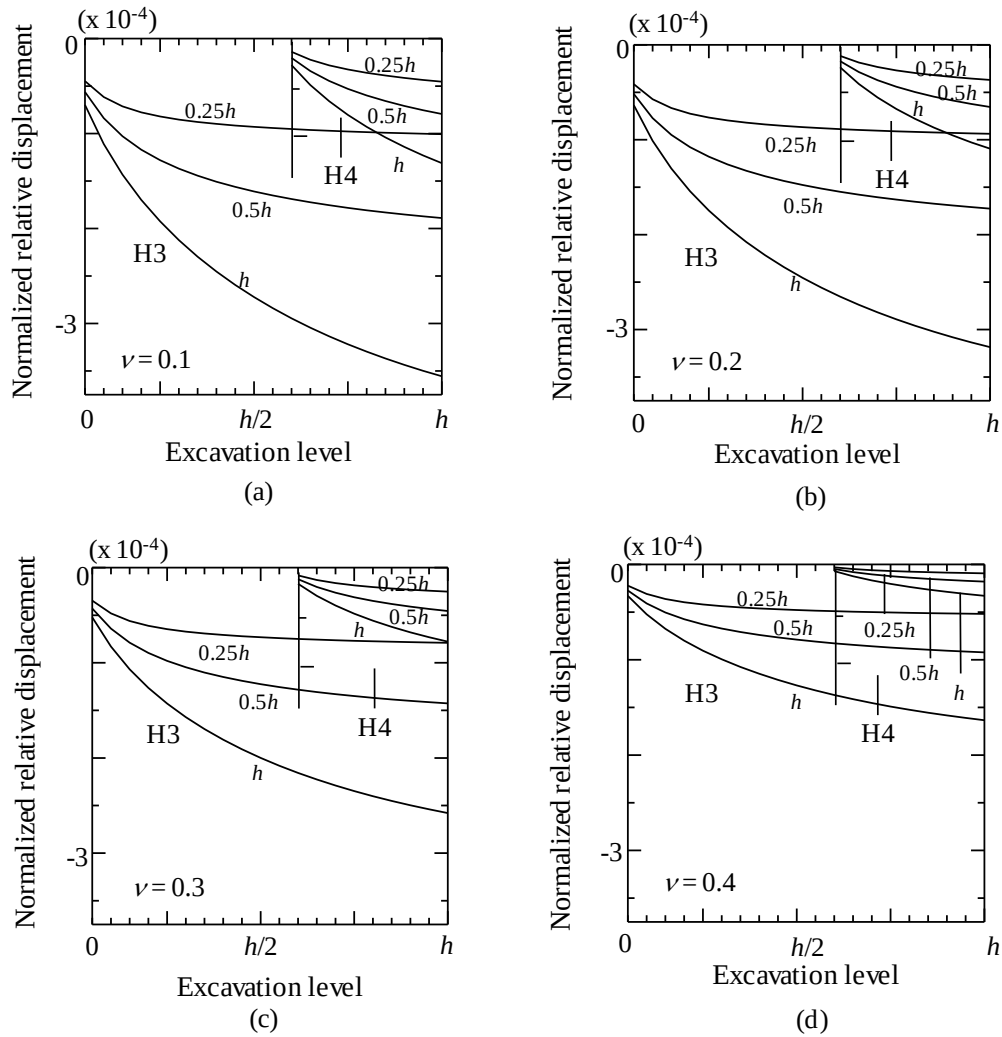


Fig. 4.24 Change in the normalized horizontal relative displacement along lines H3 and H4 at depths of  $h/4$ ,  $h/2$ , and  $h$  as a function of the excavation progress for at  $\nu =$  (a) 0.1, (b) 0.2, (c) 0.3 and (d) 0.4.

### 4.3 Effect of buttress of intact limestone

#### 4.3.1 Analytical Method

Figure 4.25 shows a diagram that illustrates the analytical model with buttress of intact limestone for pit-type mine. Mechanical properties of limestone and bedrock are same as P-GB-1 in Table 4.1. Young's modulus of limestone was greater than that of bedrock. The thickness of the buttress ( $w$ ) was set as 0,  $h/10$ ,  $h/4$  and  $h/2$ , where  $h$  was the depth of final excavation.

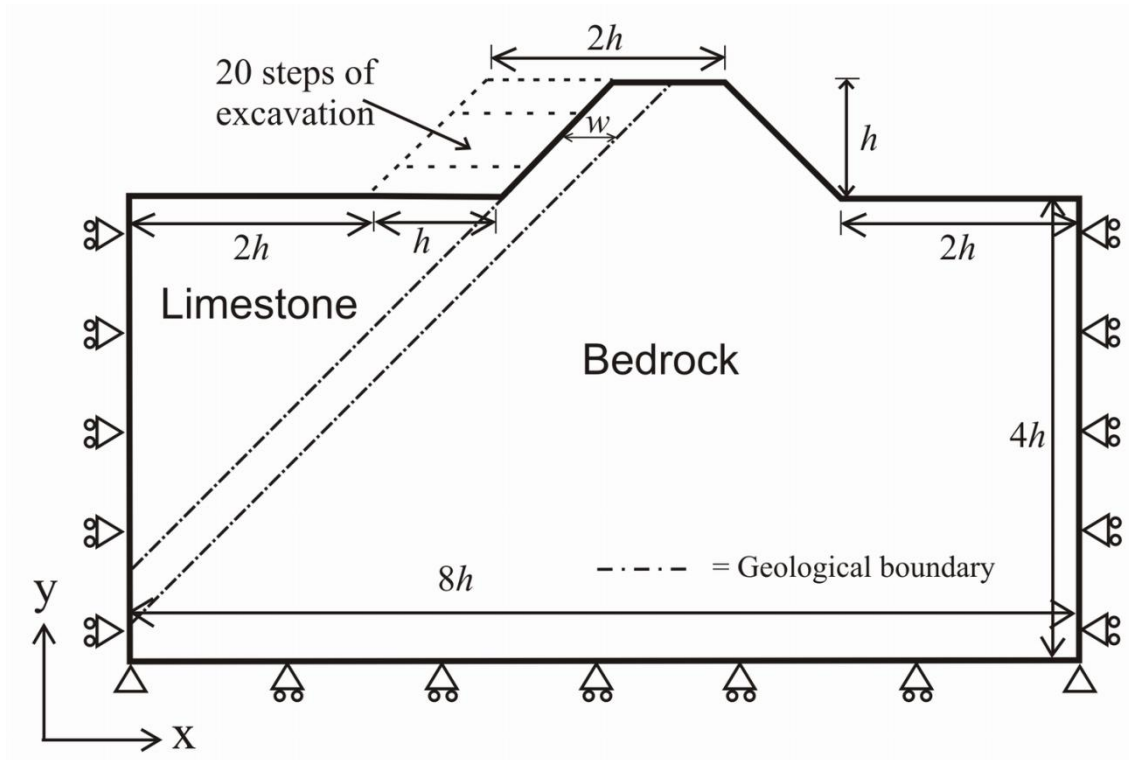


Fig. 4.25 Configuration of the analytical model having buttress of intact limestone with a slope angle of  $45^\circ$ . The dashed lines indicate the progress of the excavation. Dashed–dotted lines indicate the geological boundary between limestone and bedrock.  $w$  is buttress width.

#### 4.3.2 Analytical results and discussion

Deformation of the right cut rock slope was mainly focused on since a buttress was put on the right cut rock slope. The right cut rock slope without buttress tended to exhibit slight forward displacement (Fig. 4.26(a)). The cut rock slope with  $w = h/10$  exhibited little displacement (Fig. 4.26(b)). Then, the backward surface displacement was found when  $w$  was greater than  $h/4$ , and it increased with the increasing of  $w$  (Fig. 4.26(c), (d)). Qualitative characteristics of horizontal strain distribution in the right cut rock slope with the buttress were similar to those without buttress. An extension was found around the shoulder in all cases. The extension was generated in the buttress as well as bedrock and the magnitude of the extension decreased with the increasing  $w$ .

These results are similar to the effect of the buttress in mountain-type mine described in chapter 3. It can be concluded that the deformation characteristic of the cut

rock slope in the pit-type mine was hardly affected by the presence of the buttress; however, thicker buttress can highly reduce the magnitude of both the backward surface displacement and the extension of the cut rock slope.

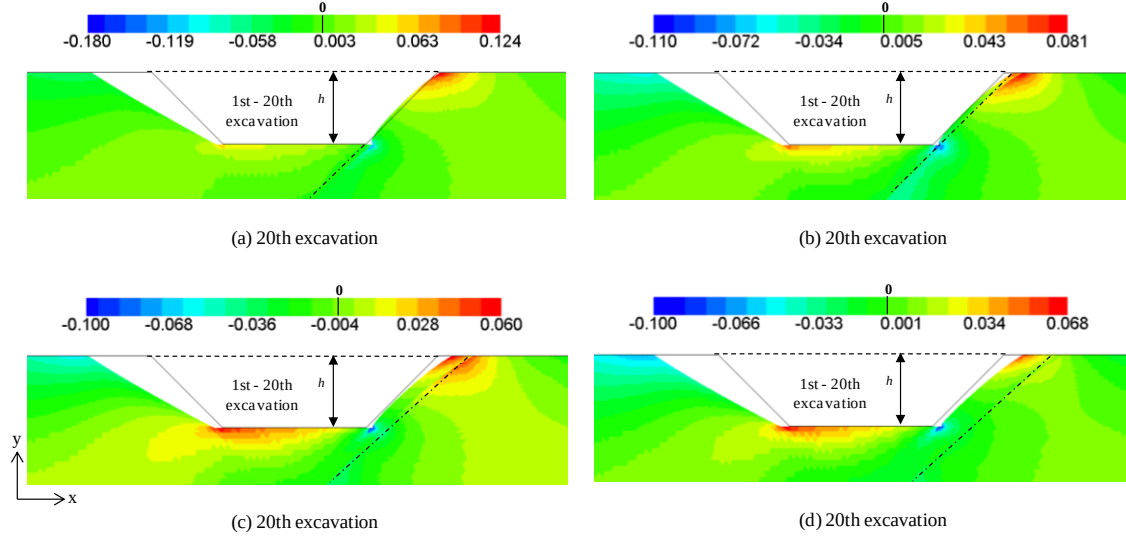


Figure 4.26 Horizontal surface deformation and horizontal strain ( $\epsilon_{xx}$ ) distribution in the case of P-GB-2 ( $E_{\text{Lime}} = 5.0$  GPa,  $E_{\text{Bed}} = 2.5$  GPa) in the final excavation (20th excavation) for  $\nu = 0.2$ . The width of buttress is (a) 0, (b)  $h/10$ , (c)  $h/4$  and (d)  $h/2$ . A negative value of  $\epsilon_{xx}$  corresponds to compressive strain.

#### 4.4 Concluding Remarks

In this chapter, the impact of difference of Young's modulus between limestone and bedrock on mining-induced deformation of a cut rock slope in a pit-type mine consisting of limestone and bedrock was investigated. The effect of an intact limestone buttress on a cut rock slope deformation due to excavation in a pit-type mine was also investigated.

It was found that deformation modes of cut rock slope formed in limestone was independent of the ratio of Young's modulus of limestone and bedrock. It always showed backward surface displacement and contraction for smaller Poisson's ratios, but showed forward surface displacement and extension around the toe of slope at larger Poisson's ratios. In contrast, the deformation behavior of the cut rock slope formed in bedrock depended on the ratio of Young's modulus of both the rocks. In the case that Young's modulus of bedrock was smaller than that of limestone, the cut rock slope

formed in bedrock tended to exhibit backward surface displacement and contraction for small Poisson's ratios, whereas it tended to exhibit forward surface displacement and extension for large Poisson's ratios. In the case that Young's modulus of the bedrock was greater than that of limestone, the cut rock slope formed in bedrock tended to exhibit backward surface displacement and contraction for all Poisson's ratios. These results demonstrated that the mining-induced elastic deformation behaviors of a cut rock slope formed in a pit-type mine are significantly different from those in a mountain-type mine.

The contraction and extension due to excavation tended to become larger near the slope surface with some exceptions and extension rate or contraction rate of cut rock slope decreased with the progress of excavation.

The effect of buttress in a pit-type mine was similar to that in a mountain-type mine. The presence of the buttress only affected the magnitude of the cut rock slope deformation, in which the magnitude of the deformation decreased with increasing in the thickness of the buttress.

## CHAPTER 5

### SUGGESTIONS AND APPLICATION TO ROCK SLOPE MONITORING

#### 5.1. Introduction

From previous chapters, it was found that elastic deformation modes of cut rock slopes in open-pit mines is quite complex because they often depend on not only geological structure and mechanical properties of rock mass but also progress of excavation and mine geometry. For the purpose of comparison of above factors affecting the deformation mode or quick assessment of rock slope stability, listing of deformation mode is expected to be useful. The list is also useful to consider suggestion to stability assessment based on the rock slope monitoring. In this chapter, deformation modes of rock slopes formed in both mountain-type and pit-type mines estimated in previous chapters were summarized in lists. Then, effective rock slope monitoring methods are proposed based on the estimated elastic deformation modes. Finally, rock slope deformation measured by extensometers in a particular open-pit mine was attempted to be interpreted by elastic analysis applied in this dissertation.

#### 5.2. Summary of deformation modes of rock slopes due to excavation

The deformation modes of cut rock slopes described in chapters 2, 3 and 4 were summarized in Tables 5.1, 5.2 and 5.3. In the tables,  $h$  and  $h_{\text{final}}$  are the excavation depth and final cut rock slope height, respectively. The interior deformation modes at horizontal depth of  $h_{\text{final}}/2$  from the rock surface are shown. Only analytical results at  $\nu = 0.1$  and  $0.4$  are shown because the analytical results at  $\nu = 0.2$  and  $0.3$  have no significant difference with those at  $\nu = 0.1$ . Red and blue arrows indicate horizontal extension and contraction, respectively. Black arrows indicate the directions of horizontal surface displacement.

Table 5.1 shows the list of homogeneous mountain-type and pit-type mines described in chapters 2 and 4. In the case of the mountain-type mine, it was found that the deformation mode changed with the progress of excavation and depended on

Table 5.1 Fundamental deformation modes of homogenous rock slopes.

| $\nu$ | Mountain-type mine | Pit-type mine |
|-------|--------------------|---------------|
| 0.1   |                    |               |
| 0.4   |                    |               |

Table 5.2 Deformation modes of rock slopes in mountain-type mine consisting of limestone and bedrock having different Young's moduli.

| $\nu$ | $E_{\text{Lime}} > E_{\text{Bed}}$ | $E_{\text{Lime}} < E_{\text{Bed}}$ |
|-------|------------------------------------|------------------------------------|
| 0.1   |                                    |                                    |
| 0.4   |                                    |                                    |

Table 5.3 Deformation modes of rock slopes in pit-type mine consisting of limestone and bedrock having different Young's moduli.

| $\nu$ | $E_{\text{Lime}} > E_{\text{Bed}}$ |         | $E_{\text{Lime}} < E_{\text{Bed}}$ |         |
|-------|------------------------------------|---------|------------------------------------|---------|
|       | Limestone                          | Bedrock | Limestone                          | Bedrock |
| 0.1   |                                    |         |                                    |         |
| 0.4   |                                    |         |                                    |         |

Poisson's ratio. At smaller Poisson's ratios, forward surface displacement with extended deformation and backward surface displacement with contracted deformation were seen around the top and toe of the cut rock slope, respectively. Afterward, direction of the surface displacement around the top changed to backward although interior deformation still showed extension. At larger Poisson's ratios, the cut rock slope showed forward surface displacement and extended deformation through the cut rock slope regardless of the excavation stage. The deformation modes of the cut rock slope in the pit-type mine are significantly different from those of mountain-type mine. The backward surface displacement and contracted deformation were seen through the cut rock slope at smaller Poisson's ratios, but the forward surface displacement with the extended deformation was found around the toe at larger Poisson's ratios. These deformation modes in the pit-type mine are independent of the excavation stage.

Table 5.2 shows the list of mountain-type mines consisting of limestone and bedrock described in chapter 3. In the case that Young's modulus of bedrock is smaller than that of limestone, the deformation modes of the cut rock slope are almost similar to those of homogeneous mine. The mode of interior deformation is identical to that of the homogeneous mine although direction of the surface displacement is not same the homogeneous mine in some cases at smaller Poisson's ratios. In contrast, in the case that Young's modulus of bedrock is greater than that of limestone, the deformation modes at larger Poisson's ratios are significantly different from those of homogeneous mine. The backward surface displacement with the contraction is seen through the cut rock slope. The deformation mode at smaller Poisson's ratio is almost similar to that of homogeneous mine although the change in the deformation mode with the progress of excavation is not seen.

Table 5.3 shows the list of pit-type mines consisting of limestone and bedrock described in chapter 4. The deformation modes of the cut rock slope formed in limestone are similar to those of homogeneous mine regardless of Young's modulus of bedrock. On the other hand, the deformation modes of the cut rock slope formed in bedrock strongly depended on the ratio of Young's modulus of bedrock to limestone. In the case that Young's modulus of bedrock is smaller than that of limestone, the deformation modes of the cut rock slope are different from those of homogeneous mine. The extension was found around the shoulder part of cut rock slope at smaller Poisson's

ratios, and the surface displacement was changed from forward to backward with the progress of excavation. Furthermore, the forward surface displacement with the extension was found through the cut rock slope near the surface at larger Poisson's ratios. In the case that Young's modulus of bedrock is larger than that of limestone, the deformation mode at smaller Poisson's ratios is similar to that of homogeneous mine. In contrast, the mode of interior deformation at larger Poisson's ratios is different from that of homogeneous mine. The backward surface displacement with the contraction was observed around the toe of the cut rock slope.

### **5.3. Suggestion to rock slope monitoring**

Based on the lists of deformation modes of rock slopes summarized in Tables 5.1, 5.2 and 5.3 and characteristics of internal deformation modes described in previous chapters, several suggestions for monitoring rock slopes using GPS, APS and/or extensometers are proposed.

It is expected that inelastic deformation, such as sliding along a discontinuity or plastic deformation will usually cause the forward surface displacement and interior extension of a rock slope (Deng and Lee, 2001; Sheng et al, 2002; Rose and Hughr, 2006). However, as summarized in 5.2, the interior deformation modes of cut rock slopes in pit-type mines is mostly contraction. These suggest that, if the extension is measured in a pit-type mine, it is certainly a sign of inelastic deformation. However, it should be also noted that the cut rock slope consisting of limestone and bedrock having different Young's moduli shows extension if Young's modulus of bedrock is smaller than that of limestone (Table 5.3).

Elastic extension due to excavation is often seen in cut rock slopes in mountain-type mines (Tables 5.1 and 5.2). In particular, the upper part always shows extension except the case where Young's modulus of bed rock is greater than that of limestone and Poisson's ratio is larger. This means that the horizontal extension of a cut rock slope in mountain-type mine is not always a warning sign of instabilities. The surface of the cut rock slope may displace forward during the early stages of excavation and then backward during the later stages of excavation in the homogeneous mine (Table 5.1). The surface of the cut rock slope may continue to displace backward if Young's modulus of bedrock is greater than that of limestone (Table 5.2). This means that the cut

rock slope with an extended deformation is in a stable state as long as the cut rock slope surface is displaced backward. This suggests that the measurement of the horizontal surface displacement using APS and/or GPS in open-pit mines is important for stability assessment of cut rock slopes.

From the internal displacement analysis, it was found that the magnitude of horizontal extension or contraction due to excavation was greatest at the surface of the cut rock slope and decreased with increasing horizontal depth from the surface for both mountain-type and pit-type mines (For example, Figs. 2.20 and 4.19). It was also found that the horizontal extension or contraction increased rapidly during the early stages of excavation but that further increases in the extension or contraction were not observed in the latter stages of excavation (For example, Figs. 2.21 and 4.20). This has important consequences in the monitoring of cut rock slopes using extensometers especially in the extended deformation; i.e., neither larger extension deformation deeper in cut rock slope than at a shallow part, nor a rate of increase in the extension that does not slow as the excavation progresses, appears to result from the elastic deformation of the cut rock slope. Such behavior is, therefore, expected to be indication of inelastic deformation; i.e., an unstable state of rock slopes. These results also suggest that the elastic deformation can be monitored using a relatively short extensometer. Although longer extensometers are useful for obtaining detailed information relating to the deformation of cut rock slopes, this may not be efficient from an economic point of view; however, little difference in the trends of the relative displacement due to excavation was found as the excavation progressed through the results at the three different depths (For example, Figs. 2.22 and 4.13). It follows that the extensometer with a length of quarter of slope height is sufficient for the use in monitoring elastic deformation.

The aforementioned results also indicate that the measurement using additional extensometers at lower levels of the rock slope is an effective method because the sensitivity of the extensometer decreases as the excavation progresses. Inelastic deformation may be detected by comparing the obtained measurement results using extensometers installed at different slope heights with the simulation results for elastic deformation. Based on the above discussion, it may be concluded that the combination of monitoring the internal displacement using extensometers and surface displacement

using APS and/or GPS is a powerful tool for stability assessment of rock slopes in open-pit mines.

#### **5.4. Interpretation of rock slope deformation observed in Shiriya limestone quarry**

##### **5.4.1. Overview of the quarry and displacement measurement**

Shiriya limestone mine is located about 4 km southwest of Shiriya in the northeast Honshu, the main island of Japan. Based on the geological condition, the rock mass primarily consists of limestone and slate (Resources and materials society, 2009). The limestone has been extracted by a bench cut method and the height of each bench is 12 m. The displacement measurement of the rock slopes was carried out on the north and south rock slopes by multi-stage extensometers shown as SD-1 and SD-4 in Figs. 5.1 and 5.2 from January 1997. The limestone on 94 m level had been extracted from January 1997 to June 1999. The geological structure of each vertical section of two rock slopes including multi-stage extensometers SD-1 and SD-4 are shown in Fig. 5.2(a) and (b), respectively. The height of rock slope in the beginning of measurement was 126 m (January 1997) and the average dip of geological boundary was approximately 50°. Boring cores from the boreholes of SD-1 and SD-4 are shown in Fig. 5.3. In the figure, the geological boundary between limestone and slate is found to be at depth of approximately 30 m. The alternation of limestone and slate strata (hereafter, alternation zone) is also found at depth of between approximately 20 m and 30 m. In contrast, only limestone can be seen in the boring core from SD-4.

The results of displacement measurement along the SD-1 and SD-4 are shown in Fig. 5.4. In the figure, the horizontal axis is the distance from the surface of each borehole. The vertical axis is relative displacement to the bottom of each borehole. A positive sign corresponds to the extension between measured point and bottom point. Clear extension is seen at depth of between 30 m and 70 m in Fig. 5.4(a). This means that the slate in the north rock slope showed extension in horizontal direction due to excavation. In contrast, the deformation behavior at the depth of between 0 m and 30 m is not simple. The alternation zone may affect the deformation in this depth range. It can be seen from Fig. 5.4(b) that the south cut slope tended to show contraction although its magnitude was quite small. It is noticed that the sudden extension was found at depth of

between 0 m and 10 m. It is expected that the extension is caused by development of damaged zone due to blasting.

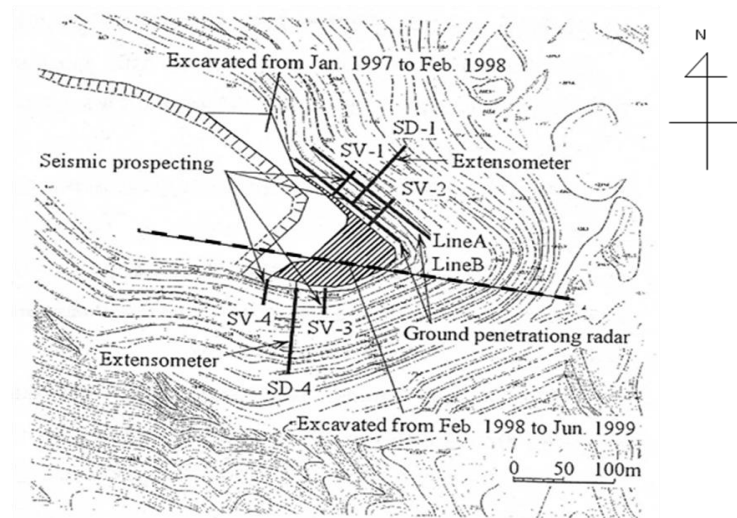


Fig. 5.1 Plan view of the mining area at Shiriya limestone quarry. This map shows the progress of mining and measurement locations of multi-stage extensometers installed in the rock slopes (Nakamura et al., 2003).

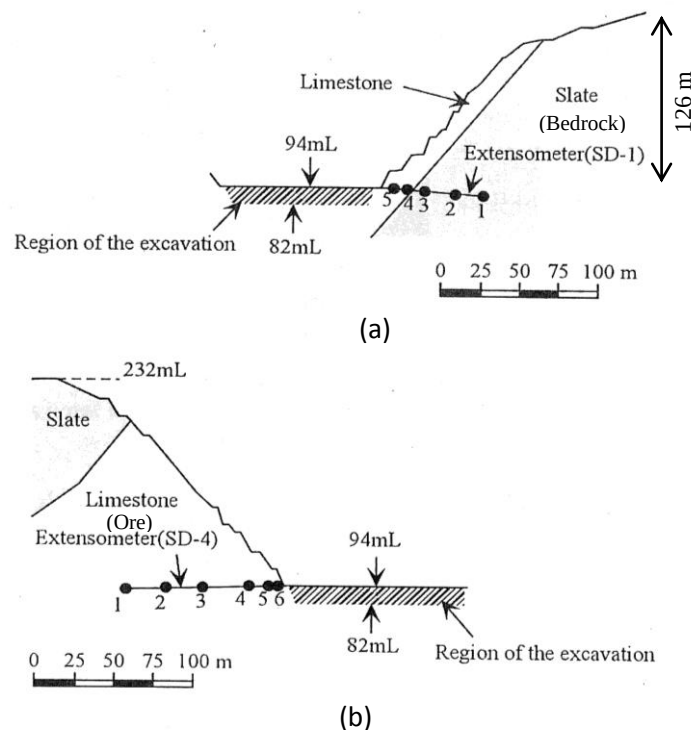


Fig. 5.2 Cross sectional view of rock slope for (a) the northern and (b) southern rock slopes including a multi-stage extensometers SD-1 and SD-4 (Nakamura et al., 2003).

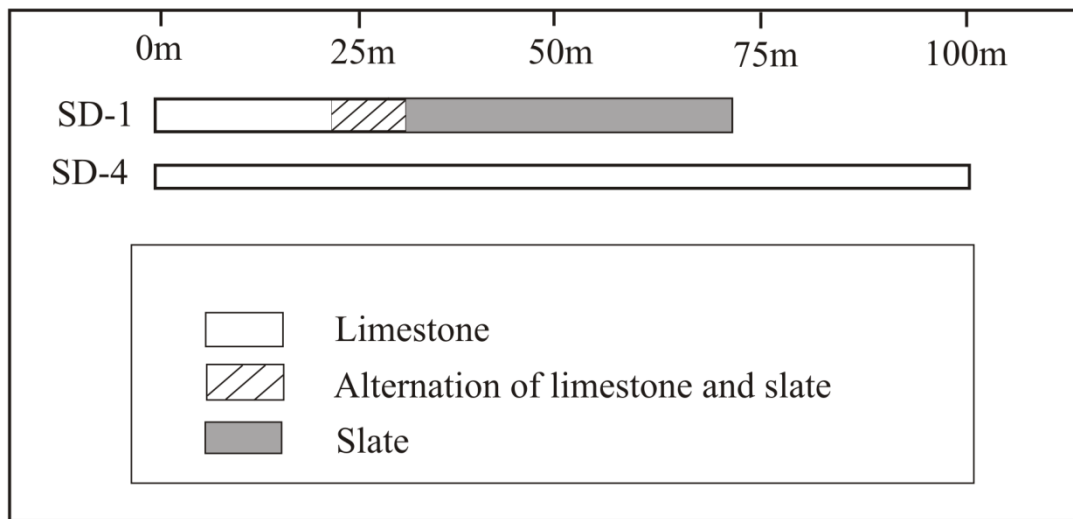


Fig. 5.3 The boring cores from SD-1 and SD-4 (Nakamura et al., 2003).

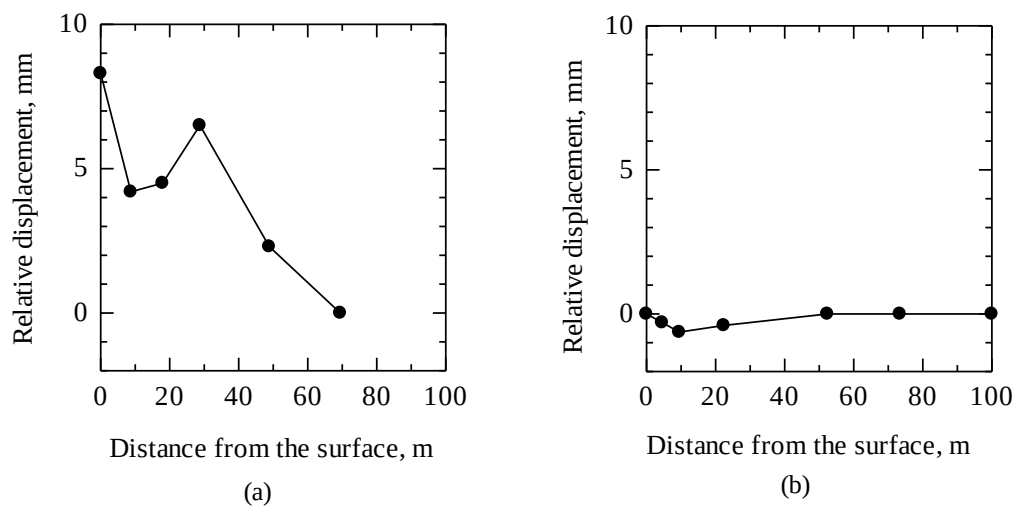


Fig. 5.4 Relative displacement distribution with respect to the bottom of borehole that has been measured by (a) SD-1 (bedrock with limestone buttress) and (b) SD-4 (limestone). (Nakamura et al., 2003).

#### 5.4.2. Qualitative comparison of analytical and measured deformation

In order to interpret the measurement results in Shiriya limestone mine by elastic analysis, a 2-D FEM model of a pit-type mine consisting of limestone and bedrock was prepared (Fig. 5.5). Referring to geometry of Shiriya limestone mine, the height of rock slopes and dip of geological boundary was set at 130 m and 45°, respectively. In the

right rock slope, a buttress of limestone with a thickness of 20 m was left over bedrock. Then, elastic deformation due to excavation of 10 m depth was estimated. Young's modulus of limestone ( $E_{\text{lime}}$ ) was fixed at 5 GPa, and that of bedrock ( $E_{\text{bed}}$ ) was varied with 2.5 GPa, 5 GPa and 10 GPa. Namely, the following three cases were analyzed; (a)  $E_{\text{lime}} > E_{\text{bed}}$ , (b)  $E_{\text{lime}} = E_{\text{bed}}$  and (c)  $E_{\text{lime}} < E_{\text{bed}}$ . For simplicity, Poisson's ratio of bedrock was assumed to be equal to that of limestone and it was varied between 0.1– 0.4. Figs. 5.6 and 5.7 show horizontal relative displacements along the lines  $H_L$  and  $H_R$  shown in Fig. 5.5, respectively. The line  $H_L$  with the length of 100 m was within limestone, while the line  $H_R$  with the length of 70 m was within bedrock with limestone buttress. In these figures, the horizontal and vertical axes are the distance from the surface of the rock slope and relative horizontal displacement normalized by inverse of Young's modulus of limestone, respectively. The reference points for the calculation of normalized relative horizontal displacement along the lines  $H_L$  and  $H_R$  are at depth of 100 m and 70 m, respectively. Positive sign in the normalized relative horizontal displacements means extension.

From Fig. 5.6, it can be seen that the analysis results at  $\nu = 0.3$  and 0.4 in the case of  $E_{\text{lime}} < E_{\text{bed}}$  are in qualitatively good agreement with the measurement results along SD-4 (Fig. 5.4(b)). The qualitatively good agreement with the measurement results is also found in the case of  $E_{\text{lime}} = E_{\text{bed}}$  at  $\nu = 0.2$  and 0.3. In these results, the contraction was seen through the line and extension was found near the surface. As mentioned in 5.4.1, sudden extension near the surface in SD-4 is certainly caused by the development of damaged zone due to blasting. It is expected that the contraction is the predominant deformation mode along SD-4. Therefore, it can be said that the analysis results in the cases of  $E_{\text{lime}} > E_{\text{bed}}$  and  $E_{\text{lime}} = E_{\text{bed}}$  at  $\nu = 0.1$  are also qualitatively coincident with the measurement results along SD-4.

From Fig. 5.7, it can be seen that analysis results in the case of  $E_{\text{lime}} > E_{\text{bed}}$  are in qualitatively good agreement with measurement results along SD-1 even though the measurement results showed complex behavior in alteration zone (Fig. 5.4(a)). Qualitatively good agreement with measurement results is also found in the case of  $E_{\text{lime}} = E_{\text{bed}}$  at  $\nu = 0.4$ . The extension was observed at least at depth of between 30 m and 70 m of the line  $H_R$  (see Figs. 5.7(a), (b)).

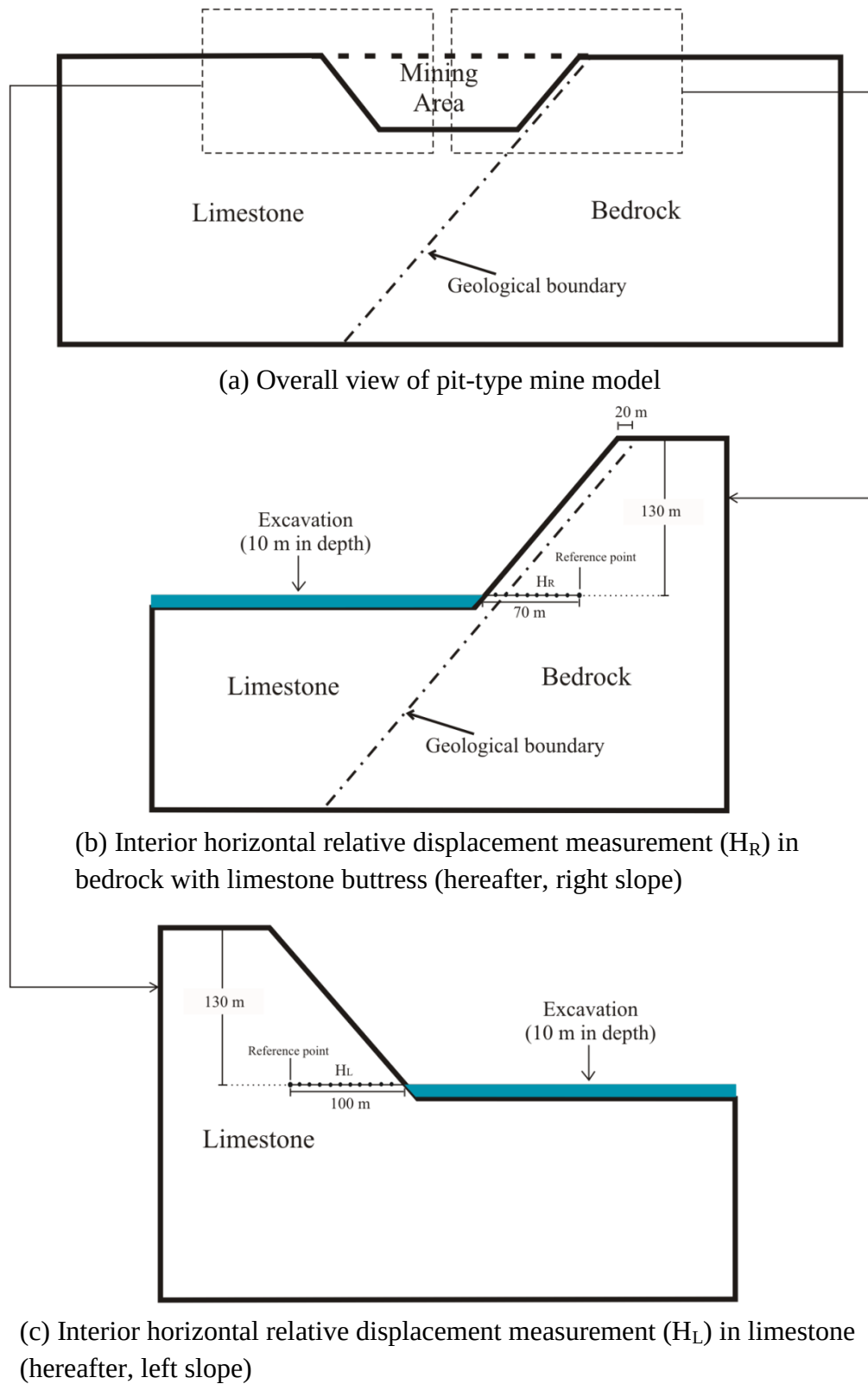


Fig. 5.5 Internal horizontal measurement of pit-type mine model.

From the above discussion, it is concluded that deformation behavior of rock slopes in Shiriya limestone mine can be qualitatively interpreted as being elastic deformation if Young's modulus of bedrock is smaller than that of limestone. However, deformation behavior within the alteration zone in SD-1 and that near the surface in SD-4 disagreed with the analysis results. These may be caused by inelastic deformation.

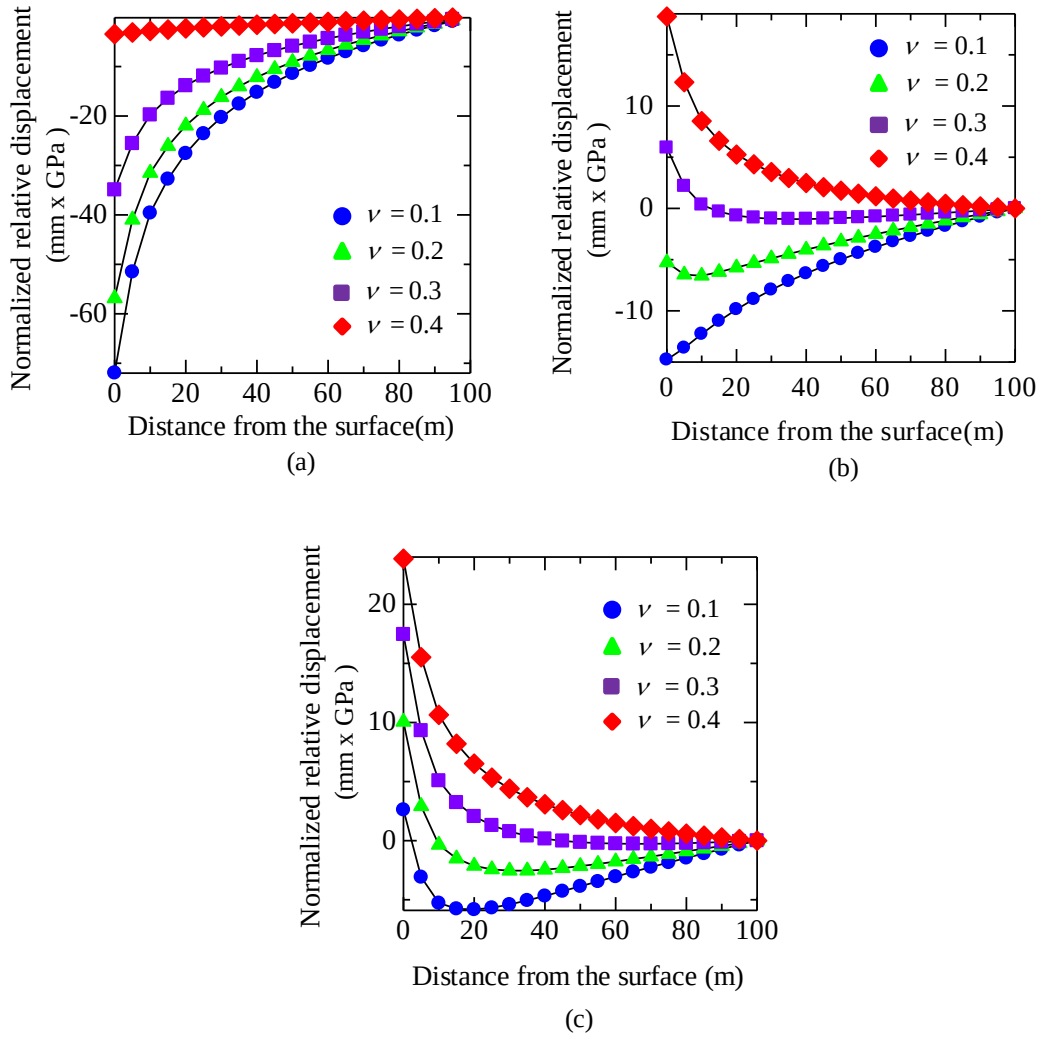


Figure 5.6 Normalized horizontal relative displacement along the line  $H_L$  in the case of (a)  $E_{\text{lime}} > E_{\text{bed}}$ , (b)  $E_{\text{lime}} = E_{\text{bed}}$  and (c)  $E_{\text{lime}} < E_{\text{bed}}$ .

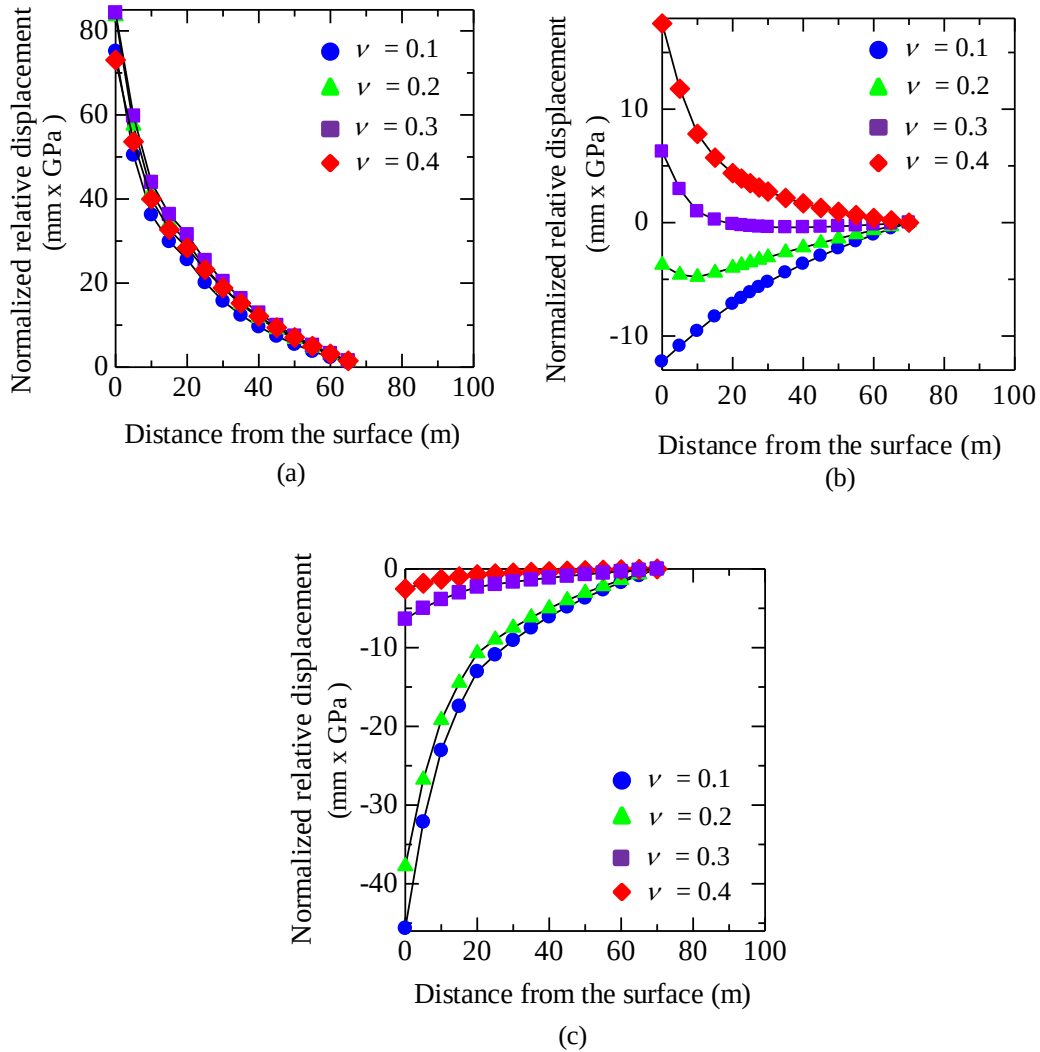


Figure 5.7 Normalized horizontal relative displacement along the line  $H_R$  in the case of (a)  $E_{\text{lime}} > E_{\text{bed}}$ , (b)  $E_{\text{lime}} = E_{\text{bed}}$  and (c)  $E_{\text{lime}} < E_{\text{bed}}$ .

### 5.5. Concluding Remarks

The Deformation modes of rock slopes in mountain-type and pit-type mines described in chapters 2, 3, 4 were summarized in the lists for quick interpretation and understanding of stable deformation. From the lists, it was noticed that interior deformation of rock slopes in pit-type mines is mostly contraction whereas extension is frequently seen in rock slopes in mountain-type mines. These results suggest that extension is certainly a warning sign of instable deformation of the rock slope in a pit-type mine. In contrast, the rock slope with an extended deformation in a mountain-type

mine can be in a stable state as long as the rock slope surface is displaced backward. In this case, measurement of the horizontal surface displacement is also important in stability assessment.

From the internal displacement analysis of rock slope, it is suggested that the following deformation behaviors are also indication of an unstable state, i.e. extension deeper inside the rock slope than near the slope surface. A rate of increase in the extension does not decrease as the excavation progresses.

Rock slope deformation measured by extensometers in Shiriya limestone mine were attempted to be interpreted by elastic analysis. It was concluded that deformation behavior of rock slopes can be qualitatively interpreted as being elastic deformation if Young's modulus of bedrock is smaller than that of limestone.

## CHAPTER 6

### CONCLUSIONS

In this dissertation, open-pit mines consisting of limestone and bedrock as well as homogeneous mines were modeled, and the characteristics of elastic deformation of cut rock slopes formed by excavation in mountain-type and pit-type mines were investigated by using 2-D FEM. First, the characteristics of deformation of a cut rock slope formed in a homogeneous mountain-type mine were analyzed, and its deformation mechanism was discussed in terms of the variation of Poisson's ratio, the slope angle and excavation progress. Afterward, the influence of difference in Young's modulus of limestone and bedrock forming rock slopes in open-pit mines, i.e. mountain-type and pit-type mines, was analyzed. The mechanical effect of a buttress of intact limestone left over bedrock on the rock slope deformation was also investigated by varying its thickness. Based on the characteristics of estimated elastic deformation, the effective methods of rock slope monitoring for stability assessment were suggested. Finally, results of field measurement in an open-pit mine was attempted to be interpreted by elastic analysis. The contents and findings of this dissertation are summarized as follows:

In chapter 1, background and objectives of research were described and previous studies related to the assessment of rock slope stability were reviewed.

In chapter 2, 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  $45^\circ$  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.

In chapter 3, 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.

In chapter 4, 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.

In chapter 5, 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.

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