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Field measurement and numerical analysis of soil nailing on volcanic cohesive soil

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ABSTRACT: The field measurement of the slope reinforced with steel bars and facing panels was carried out to investigate the effect of reinforcement at Kirishima of Kagoshima Prefecture. The slope was mainly composed of volcanic cohesive soil called Kuroboku in Japanese and andesite. The axial force on the steel bars attached to the facing panels were measured from March to November, 1995. In this paper, the slope stability analysis by circular slip method and elasto-plastic finite element analysis are carried out. Several problems are discussed by comparing the analytical results with those of field observations.

1 INTRODUCTION

Kagoshima Prefecture is located in the southern part of Kyushu Island, Japan, and has several active volcanoes which have been producing volcanic materials. The material of surface ground produced by these volcanic products has been changed into soil by weathering, which is commonly classified as regional soils in the geotechnical engineering. The slope failures often occur on the natural slopes composed of such regional soils when heavy rains fall in the rainy season. In Kirishima area of Kagoshima Prefecture, the volcanic ash derived from Mt. Kirishima is partially spread and called Kuroboku in Japanese. In order to protect slope failures, various methods have been developed and applied in the volcanic area of Kyushu Island. The earth reinforcement technique to strengthen or stabilize cuttings in situ using steel bars and facing panels has been known as soil nailing.

The effect of reinforcement by soil nailing had been investigated on the slope composed of Kuroboku and andesite in the field from March to November, 1995. In this paper, slope stability analysis is carried out by the circular slip method. The minimum safety factors and critical circles of natural and cut slopes are compared with those of slope reinforced with steel bars and facing panels. In addition, the behavior of reinforced slope by steel bars and facing panels in the field site is simulated by elasto-plastic finite element analysis. Finally, the analysis results are compared with those of field observations.

2 FIELD OBSERVATIONS

The details of the field observations can be found in Kitamura et al. (1996). Figure 1 shows the slope profile where the field measurement was carried out. The size of facing panel is 180 cm in width, 120 cm in height and 12 cm in thickness. The steel bar is 25 mm in diameter and 3.0 m in length. The slope is covered with five layers of facing panels. Figure 2 shows

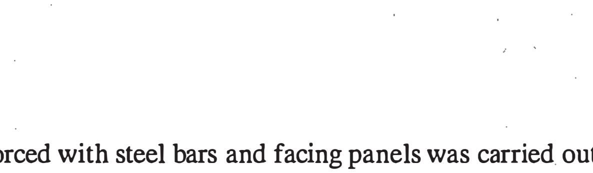


Figure 1. Elevation view of slope profile at field site.

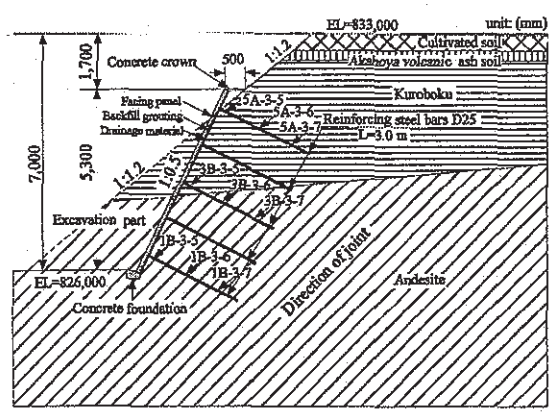
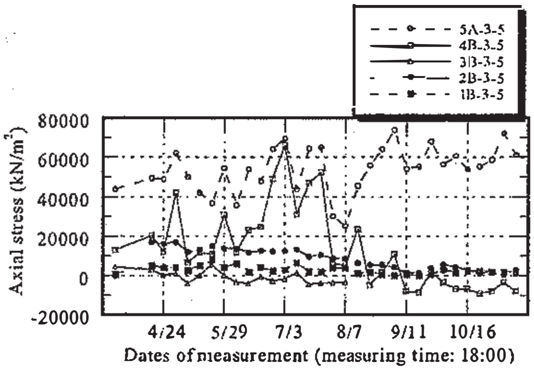
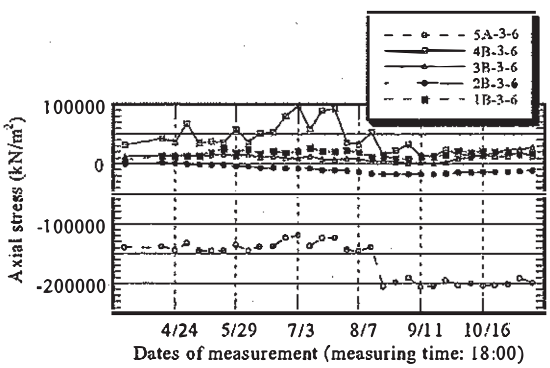


Figure 2. Cross section of slope with reinforcing steel bars and facing panels.

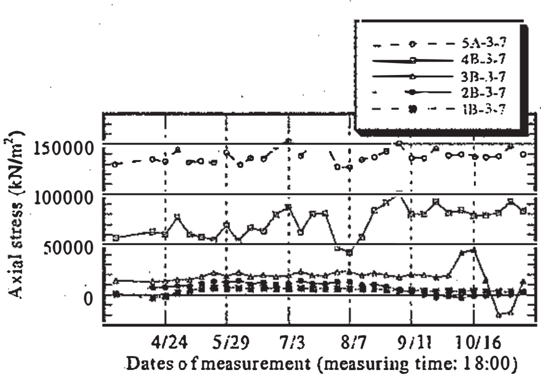
the cross section of slope, where both the natural slope (dotted line) and reinforced slope with steel bars and facing panels (solid line) are indicated. The sign such as '5A-3-6' in Fig. 2 represents that 5A is the 5th layer with two steel bars (B: one steel bar), 3 is the location of facing panel in Fig. 1 and 6 is the position of strain gauge on the steel bar. The data of axial force obtained from strain gauges on the steel bars are automatically acquired at intervals of an hour.



(a) Position of strain gauge: 5 (i.e., 0.3 m from facing panel in Fig. 2)



(b) Position of strain gauge: 6 (i.e., 1.3 m from facing panel in Fig. 2)



(c) Position of strain gauge: 7 (i.e., 2.3 m from facing panel in Fig. 2)

Figure 3. Measured change in axial stress (Section 3).

Figure 3 shows the change in axial stress on each reinforcing steel bar, measured at 18:00hrs of each Monday for about 8 months. It is found that the axial stress of steel bars of 1st, 2nd and 3rd layers inserted into andesite are comparatively stable as the time elapses. On the other hand, those of 4th and 5th layers inserted into Kuroboku are considerably changeable by day. The breakage of data of 3B-3-5 in Fig. 3(a) is seen after August 7. Comparing the axial stress at '5A-3-5' with '5A-3-6' and/or '5A-3-7', the axial stress at the measuring point nearest to the facing panel (5A-3-5) is very changeable in the 5th layer. The measured values of 4th layer are similar to those of 5th layer. The axial stress of steel bars inserted into Kuroboku are qualitatively larger at the deeper measuring points.

3 METHOD OF ANALYSIS

3.1 *Circular slip method*

Safety factor of slope is usually calculated using the circular slip method, which is currently being used in design. The safety factor of slope reinforced with steel bars and facing panels is obtained in the following equation by taking the effects to keep the soil mass back ($T_i \cos\beta$) and to tighten the soil mass ($T_i \sin\beta\tan\phi$) into account (JHPC, 1995):

$$F_S = \frac{M_R + \sum R(T_i \cos\beta + T_i \sin\beta \tan\phi)}{M_D} \qquad (1)$$

where F_S = safety factor of circular slip; M_R = resisting moment due to shear strength of soil; M_D = sliding moment; T_i = design tensile strength of reinforcing steel bar; R = radius of slip circle; β = intersected angle of reinforcing steel bars to slip surface; and ϕ = internal friction angle of soil.

In the case of unreinforced slope, the safety factor of slope is obtained without taking account of the summation term of the numerator in Eq.(1).

3.2 *Finite element method*

In order to take account of the dilatancy behavior of soils, 2-D elasto-plastic finite element method using Drucker-Prager failure criterion with non-associated flow rule is applied for the field site which is assumed in plane strain condition (Yamamoto et al., 1999). The soils at field site was well compacted, so that the positive constant value of dilatacy is used as a dilatancy angle in the analysis. Reinforcing steel bar and facing panel are modeled by beam element which resists bending and torsion. It is assumed that panel and steel bar are tightly connected. The soil properties and material properties are shown in Tables 1 and 2, respectively. For the interaction between andesite and Kuroboku whose stiffnesses are

Table 1. Soil properties.

Soil	Young's modulus E (kN/m^2)	Poisson's ratio ν	Cohesion c (kN/m^2)	Internal friction angle ϕ (deg.)	Unit weight (kN/m^3)
Andesite	3.5*10^6	0.26	490.0	45	26.5
Kuroboku	3.6*10^4	0.30	29.4	20	18.0
Akahoya soil	3.6*10^4	0.30	29.4	20	18.0
Cultivated soil	8.0*10^4	0.30	0.0	35	20.0

Table 2. Material properties.

Material	Young's modulus E (kN/m^2)	Poisson's ratio ν	Sectional area A (m^2)	Moment of inertia I (m^4)	Unit weight (kN/m^3)
Steel bar	2.1*10^8	0.30	5.07*10^{-4}	2.04*10^{-8}	
Facing panel	2.8*10^7	0.20	0.14	1.73*10^{-4}	23.0
Foundation	2.8*10^7	0.20			23.0
Crown	2.8*10^7	0.20			23.0

Table 3. Interface properties

Joint element	Poisson's ratio ν	Cohesion c (kN/m^2)	Internal friction angle ϕ (deg.)	Shearing stiffness K_s (kN/m^2)	Normal stiffness K_n (kN/m^2)
Andesite-Kuroboku	0.20	19.6	45	1.0*10^5	
Andesite-grout	0.20	19.6	45	1.0*10^5	1.0*10^7
Kuroboku-grout	0.20	19.6	20	1.0*10^5	1.0*10^7

considerably different, joint element is used in order to express the discontinuous behavior. The joint element used here is evaluated by shearing and normal stiffness without considering the dilatancy effect. The analysis is conducted with step-by-step loading condition. The two cases of analysis are listed below:

CASE 1: The interaction between soil and grout is ignored. The soil and grout are perfectly bonded.

CASE 2: The interaction between soil and grout is considered by joint element, which is used for the interaction between andesite and Kuroboku. The interface properties are determined as in Table 3.

4 RESULTS AND DISCUSSION

Figure 4 shows the minimum safety factors and critical circles by the circular slip method for the natural, cut and reinforced slopes. It is shown that the critical circle corresponding to each slope is caused on andesite. The values of the minimum safety factor and the radius of critical circle are smallest for the cut slope. These values become larger for the natural and reinforced slopes as shown in this figure. Also, it is found that the critical circle of reinforced slope is deeper due to the reinforcing effect, comparing with the cut and natural slopes.

Figure 5 shows the analysis results of deformation for CASE 2. The deformation behavior shows that settlement occurs only in the upper part of the slope. The analysis result for CASE 1 also indicates almost the same deformation behavior. Thus, the behavior of deformation from the analysis results is in nearly good agreement with the results of field observations.

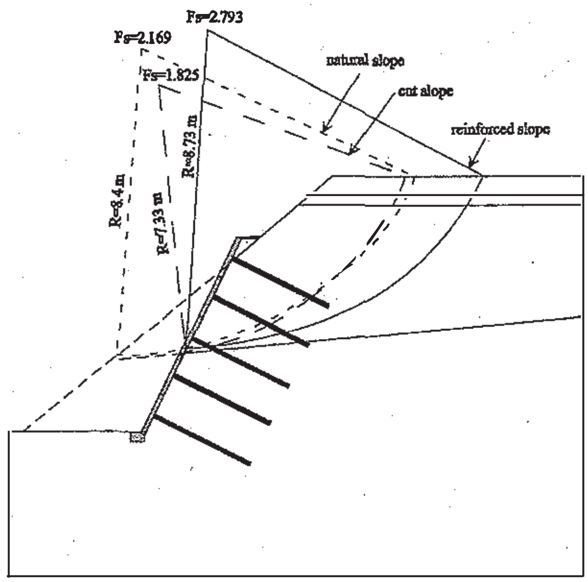


Figure 4. Minimum safety factors and critical circles for natural, cut and reinforced slopes.

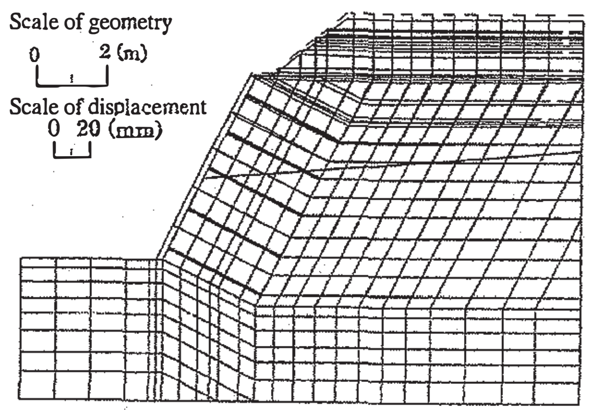


Figure 5. Deformation property from analysis result (CASE 2).

Figure 6 shows the comparison between measured values and analysis results of distributions of axial stress of reinforcing steel bars. As the measured values, the data on November 13, 1995 corresponding to the sections 2 and 3 in Fig. 1 are used, because these data are comparatively stable during the observation period. This figure indicates that the measured axial stress of section 2 are appreciably different from those of section 3. Comparing Fig. 6(a) with Fig. 6(b), it is apparent that the axial stress in measured values are considerably larger than those of analysis results on each layer. The measured values of axial stress vary with the distance from the facing panel. In addition, the measured axial stress of steel bars inserted into Kuroboku (in the upper

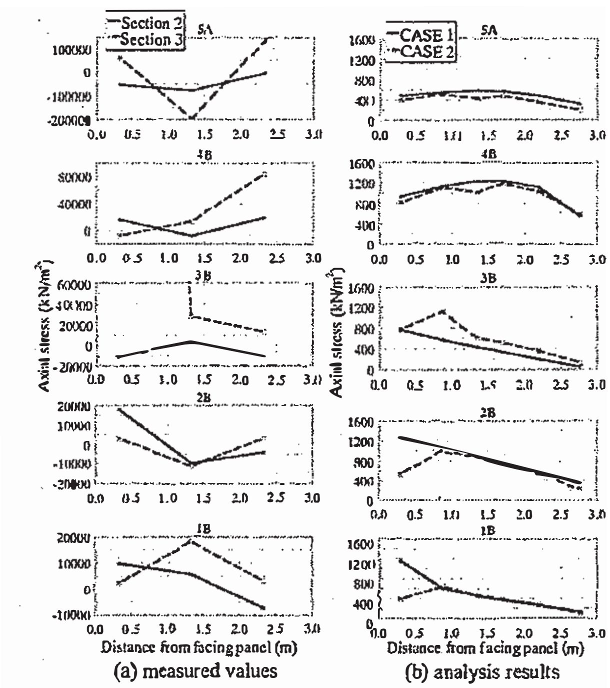


Figure 6. Comparison between measured values and analysis results of distributions of axial stress of reinforcing steel bars.

part of the slope) are larger than those inserted into andesite (in the lower part of the slope). Regarding the analysis results in Fig. 6(b), a little different tendency is indicated at the shallow depth of the reinforcing steel bars (1st, 2nd and 3rd layers) comparing CASE 1 with CASE 2.

The difference between the axial stress of measured values and those of analysis results comes from ignoring the sectional efficiency of grouting in the interface model and fixing around the tip of steel bar tightly in the field. Although the soil nailing is actually 3-D behavior, it is also noted that 3-D analysis is not performed in this paper. Moreover, the axial stress of measured values itself are strongly affected by the change of temperature and the rain even in a single day. In particular, the axial stress of steel bars (4th and 5th layers) inserted into Kuroboku are appreciably changeable within a day.

5 CONCLUSIONS

The slope stability analysis by the circular slip method was carried out for the natural, cut and reinforced slopes. The minimum safety factor and critical circle to each slope was discussed. In addition, the elasto-plastic finite element analysis was conducted for the purpose of simulating the behavior of reinforced slope with steel bars and facing panels. The pattern of deformation from the analysis results qualitatively agrees with the results of field observations. However, several problems are still to be addressed such as the quantitative evaluation of the axial stress of reinforcing steel bars in the measured and calculated values.

Furthermore in order to conduct the analysis of soil nailing strictly, it is more important to investigate the adhesive and frictional properties between soil and grout by many experiments, and to perform 3-D analysis considering the process of construction.

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