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Tamotsu Matsui
Osaka University, Japan

Ka Ching San
Osaka University, Japan

Terumasa Amano
Osaka Prefectural Government, Japan

Yoshinori Otani
Hirose and Co. Ltd., Japan

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Field Measurement on a Slope Cutting with Tensile Inclusions

Tamotsu Matsui
Professor, Osaka University, Japan

Ka Ching San
Graduate Student, Osaka University, Japan

Terumasa Amano
Assistant Chief, Osaka Prefectural Government, Japan

Yoshinori Otani
Engineer, Hirose and Co. Ltd., Japan

SYNOPSIS In a road widening project, tensile inclusions were used to stabilize some parts of cut slope works. The site condition and the construction of reinforced slope cutting are presented. A full scale field test on a reinforced cut slope was performed being incorporated with this road widening project. The field test consisted of a field loading test and a field excavation test. Details of the field test, field measurements and site observation are presented. Finite element analysis of the field test is performed. Based on the field measurements together with the analytical results, the reinforcement mechanism of a reinforced cut slope under a surcharge load and that under an effect of excavation are discussed.

INTRODUCTION

Natural slope stabilization by means of tensile inclusions, that is, root piles or soil nailing, has attracted special interests recently. Reticulated root piles which is an in-situ soil reinforcing technique were employed to stabilize some parts of cut slope works in a road widening project, in Osaka, Japan. The reinforcement mechanism and its estimation in practical projects, however, have not been elucidated yet. Therefore, a full scale field test was performed being incorporated with this road widening project. The field test consisted of a field loading test and a field excavation test. Long term site observation program continued to monitor the performance of the reinforced cut slope.

In this paper, first the general ground condition of the site of the road widening project and the construction of the reinforced slope cutting are described. Then the detail of the field test, field measurements and the site observation are presented. Finite element analysis of the field test is carried out. Finally, based on the field measurements together with the analytical results, the reinforcement mechanism of the reinforced slope cutting under a surcharge load and that under the effect of excavation are discussed.

ROAD WIDENING PROJECT

Site condition

The site is located on a mountainous region in the suburbs of Osaka, Japan. The site consists dominantly of gneiss-granite deposit. The existed road is at the mid-level of slope with the elevation of about 300m above sea level. The slope consists of an inclined soft rock stratum overburdened by a completely decomposed granite residual soil layer of several meters with a dip of 20°-35°. In the nearby area a slope failure happened previously during the cutting in the road widening works.

Construction of the reinforced cutting

In order to ensure the long term slope stability of the cut slope and the safety of the cutting during construction, slope stabilization by root piles was used in some part of cutting in the road widening project. The proposed plan and section of the reinforced slope cutting are shown in Figs.1 and 2, respectively.

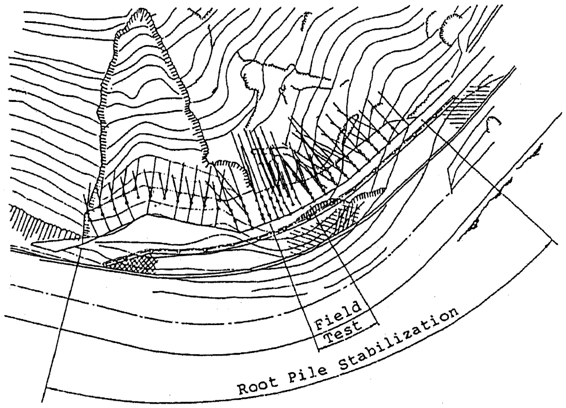


Fig. 1 Plan of the Reinforced Slope Cutting

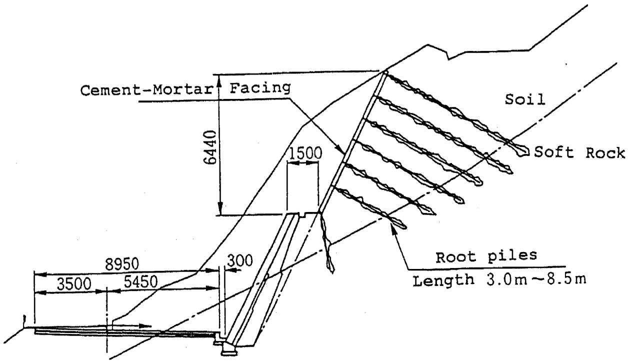


Fig. 2 Section of the Reinforced Slope Cutting

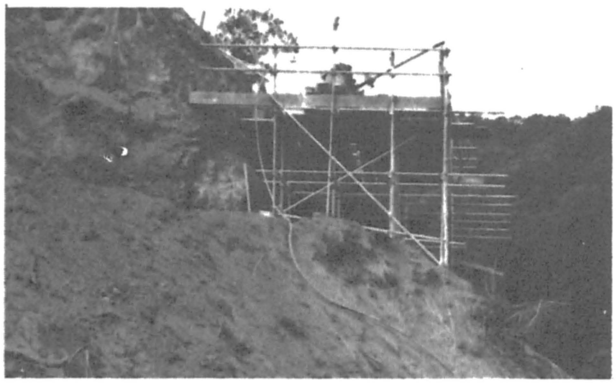


Photo 1 Construction of the Reinforced Slope Cutting in Progress

The extent of the reinforced slope cutting works is 46.75m long and the proposed reinforced cutting is in a gradient of 1:0.5. The excavation is carried out by steps with a pitch of 2.5m. After the completion of each step of excavation, drilling hole of diameter of 116mm is formed by a rotary drill (see Photo 1). The reinforcement of root pile is a small steel pipe with 36mm diameter and 6mm thickness. The root pile is formed by grouting the steel pipe with expansive mortar. In order to increase the bond between the mortar and reinforcement, a special ring is fixed in the steel pipe at 500mm interval. The head of the root pile is fixed with a bearing plate and a nut, as shown in Fig.3. The surface of the cutting is protected by 30mm thick mortar with a steel mesh (see Photo 2). The sequence of construction of root pile is illustrated in Fig.4.

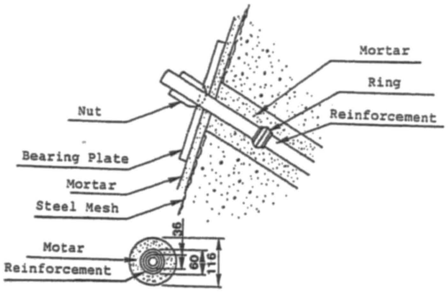


Fig. 3 Section of the Root Pile

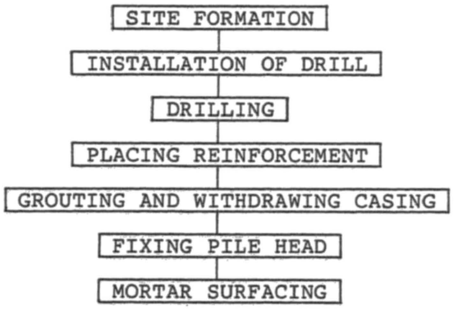


Fig. 4 Construction Sequence of Root Pile

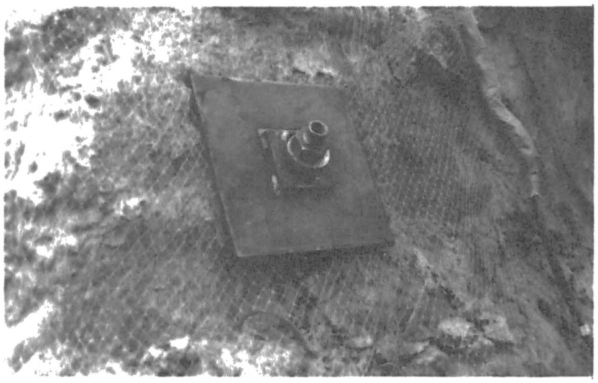


Photo 2 General View of the Root Pile Head

Design of reinforced slope cutting

Codes or Standards on the slope stabilization by tensile inclusions have not been established yet. In this project the reinforced cutting is designed by empirical method. The unreinforced cut slope is first analyzed by limit equilibrium slope stability method. Then the tensile force of reinforcement to obtain a required factor of safety of the cutting is estimated. From the required tensile force of the reinforcements, length, arrangement and inclination of the reinforcements are determined by considering the ultimate allowable stress of the section of the reinforcement and the ultimate allowable bond stress between the reinforcement and the soil.

The general design approach for the slope stability analysis on a slope cutting stabilized by tensile inclusions is illustrated in Fig.5. The analysis of the reinforced cutting, the equilibrium of forces and the strain compatibility between the reinforcement and the soil should be satisfied. In the limit equilibrium analysis the strain compatibility condition is not satisfied. It seems that the deformation analysis by finite element method could be a better solution for the reinforced cutting analysis. An appropriate design method of a reinforced slope cutting cannot be developed if the mechanism is not

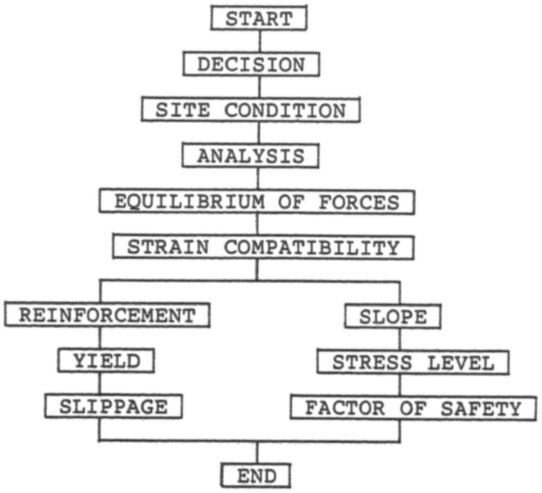
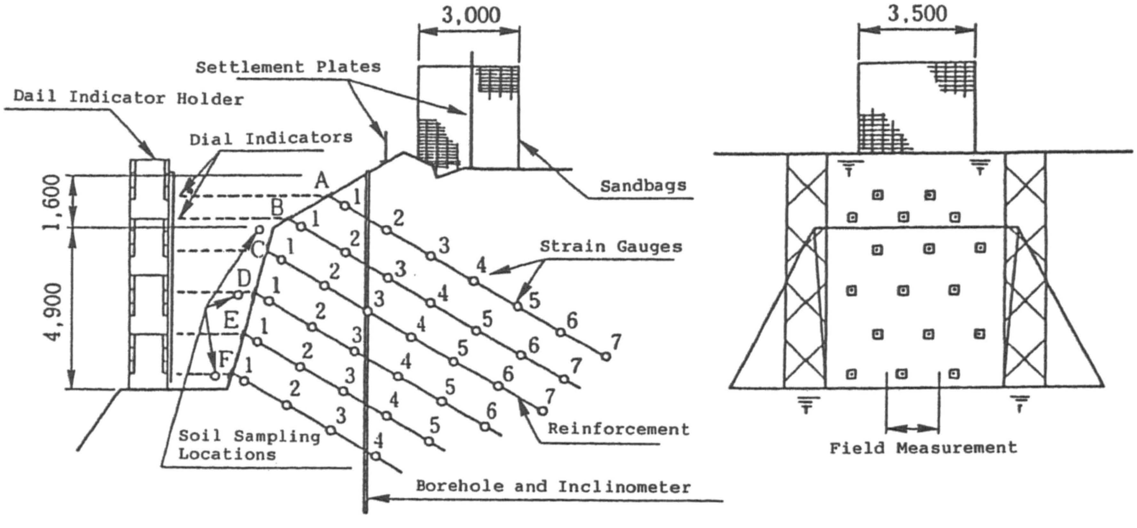


Fig. 5 Design Approach of Reinforced Slope Cutting



a) SECTION

b) ELEVATION

Fig. 6 Section and Elevation of the Reinforced Slope for the Field Test

clarified. Therefore a full scale field test is performed in the middle section of the reinforced cutting works to examine the mechanism of reinforced slope cutting.

FIELD TEST

Test site

In order to monitor the safety of the reinforced cutting, to ensure the effect of reinforcement and to examine the reinforcement mechanism, a field loading test and a field excavation test were performed (see Photo 3). Fig.6 shows the section and the elevation of the reinforced slope for the field test. The gradient of the slope cutting is 1:0.3. The soil profile at the borehole location is shown in Fig.7. The thickness of the decomposed granite layer is about 7m from the top of slope. The physical properties of the decomposed granite are given in Table 1.

The reinforced slope cutting was constructed by three steps as shown in Fig.8. In the first step, before first excavation the reinforcements A and B were constructed. In the second step, the upper portion of excavation was conducted, then the reinforcements C, D and E were installed. In the third step, the last reinforcement F was installed after the lower portion of excavation was completed.

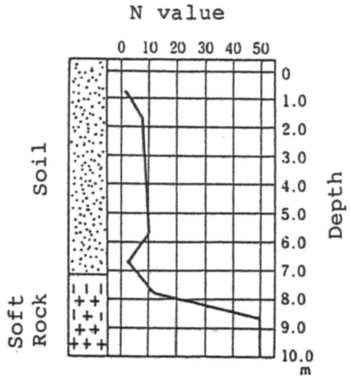


Fig. 7 Soil Profile at the Borehole Location

Photo 3 General View of the Field Test

Table 1 Test Results of Decomposed Granite

Test Items	Locations of Sample		
	C	D	F
Unit Weight (gf/cm^3)	1.97	1.96	1.90
Water Content (%)	8.3	5.7	14.0
Void Ratio	0.55	0.55	0.56
Ignition Loss (%)	3.7	3.5	6.1

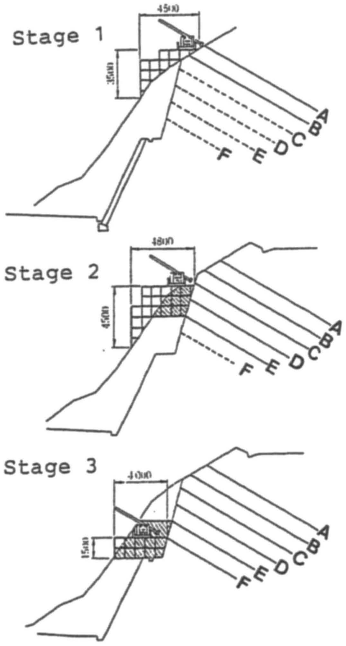


Fig. 8 Construction Sequence of Reinforced Slope Cutting

Instrumentation

The instrumentation consisted of numbers of strain gauges on the reinforcement, six dial indicators on the surface of the cutting, an inclinometer in the borehole and two settlement plates on the top of cut slope, as shown in Fig.6.

Limit equilibrium analysis

The limit equilibrium analysis was performed using the method of slices by assuming a circular slip surface. The material properties were estimated from the N values obtained from the borehole and the back analysis of the previous landslide. The parameters of the soil and the soft rock used in the slope stability analysis are summarized in Table 2.

Figs.9 and 10 show the results of slope analysis of the unreinforced slope under the surcharge load and the effect of excavation, respectively. The minimum of factors of safety obtained from the limit equilibrium analysis are summarized in Table 3.

Table 2 Parameters of Soil and Soft Rock

Parameters	Soil	Soft Rock
c (tf/m^2)	1.0	1.0
ϕ (degree)	19.0	45.0
Unit Weight (tf/m^3)	1.80	2.00

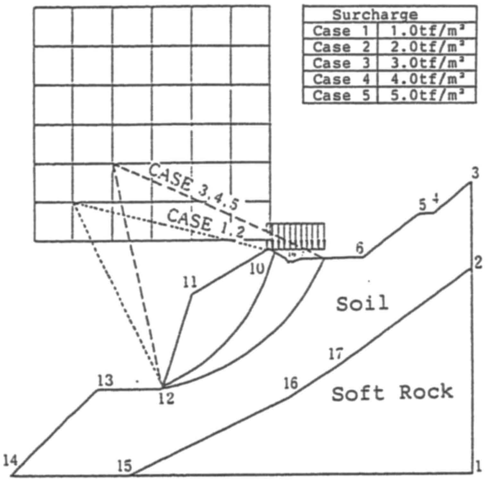


Fig. 9 Slope Stability Analysis of a Slope under a Surcharge Load

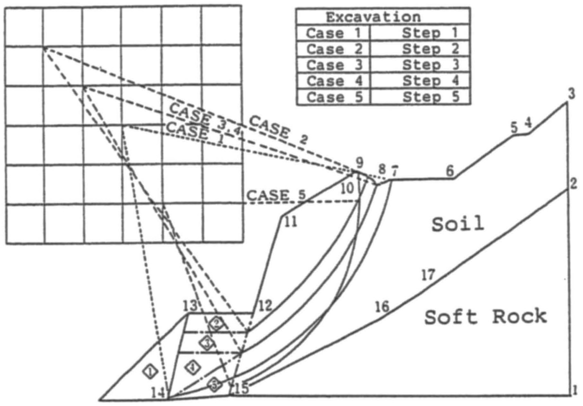


Fig. 10 Slope Stability Analysis of a Slope under an Effect of Excavation

Table 3 Factors of Safety of the Unreinforced Cut Slope

Cases	Factor of Safety	
	Load Test	Excavation Test
Case 1	0.835	0.763
Case 2	0.799	0.735
Case 3	0.745	0.666
Case 4	0.697	0.666
Case 5	0.655	0.615

Field loading test and field excavation test

In order to apply a uniformly distributed load, the loading test was carried out by piling up sandbags on the top of slope as shown in Fig.6. The sandbags were placed at a controlled loading speed of 0.59tf/m²/h. The loading curve is shown in Fig.11. For the purpose to check whether the instruments work properly, a preloading test was performed in the first day. The typical measured maximum tensile forces developed in the reinforcements, such as reinforcement A and C, are given in Fig.12.

The field excavation test was carried out after the sandbags were removed by excavating the lower part of slope up to about 5m depth. It was necessary to remove the dial indicator holder to carry out excavation, therefore the surface horizontal displacement could not be measured. The excavation was carried out by steps. Typical measured maximum tensile forces developed in the reinforcements, such as A and C, versus the elapsed time after excavation is shown in Fig.13.

From Figs.12 and 13 it can be seen that the tensile force developed in the reinforcement under an effect of surcharge reached a stable state immediately after the surcharge loading was applied and the tensile force slightly reduced after the surcharge loading was removed. However it took about two weeks for the tensile force developed in the reinforcement to reach a stable stage under an effect of excavation. This delayed response of the development of tensile force in the reinforcement may be due to the effect of the relic joint in the decomposed granite. When a surcharge loading is applied, the relic joint is compressed immediately and permanently. So the tensile force developed in the reinforcement immediately after the surcharge load is applied and such a tensile force reduces in a very small amount after the surcharge load is removed. On the other hand, stress relief produced by excavation may cause the relic joint to expand. Such swelling process is slow, because water absorption needs time for the water to penetrate. The field measurement shows that such a process takes about two weeks to reach a stable stage.

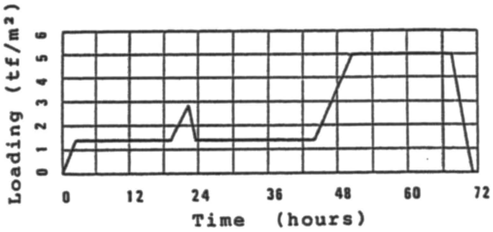


Fig. 11 Applied Surcharge Load versus Time

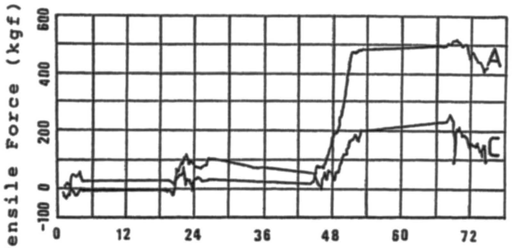


Fig. 12 Measured Tensile Force versus Time

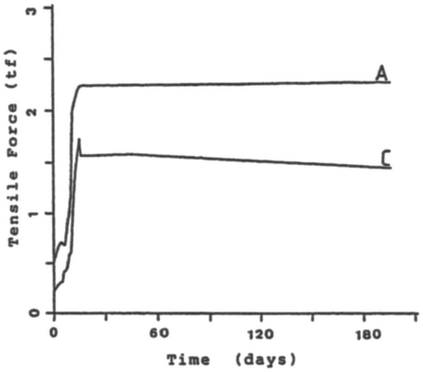


Fig. 13 Measured Tensile Force versus Days after Excavation

Field measurement

Fig.14 shows the measured horizontal displacement of slope surface for the loading test. Fig.15 shows the horizontal displacement at the borehole location for both loading test and excavation test. Field measurement shows that the upper portion of the slope moved forward while with negligible movement at the lower

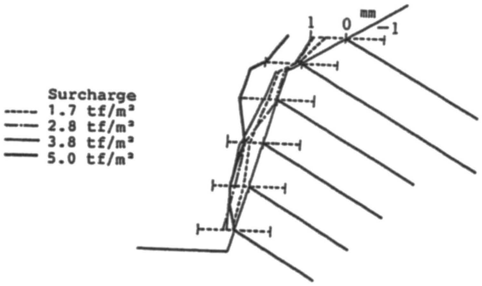
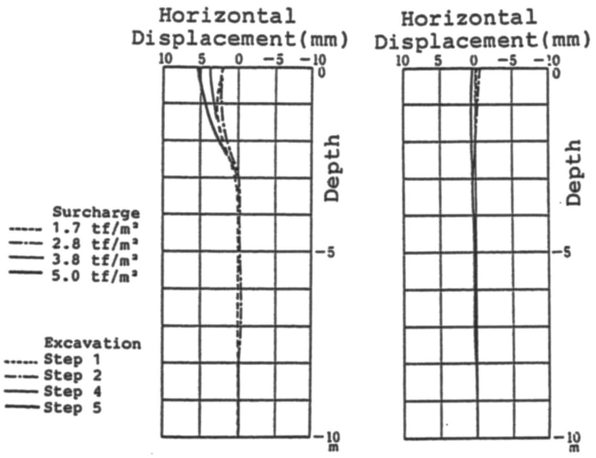


Fig. 14 Measured Horizontal Displacement at the Surface of the Slope



a) Surcharge

b) Excavation

Fig. 15 Measured Horizontal Displacement at the Borehole Location portion.

Figs.16 and 17 show the measured axial forces developed in the reinforcements for the loading test and the excavation test, respectively. Field measurement shows that the axial forces developed in the reinforcement are not all in tension in case of surcharge and that are mainly in tension in case of excavation.

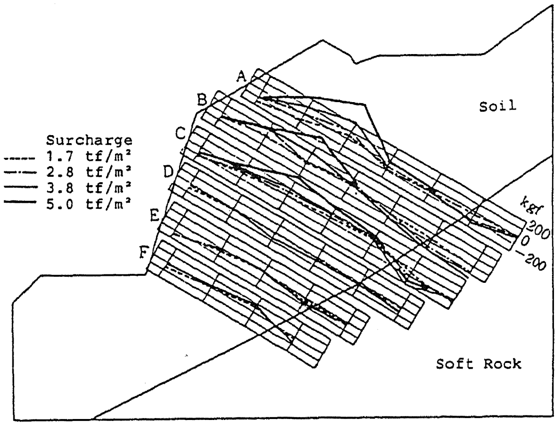


Fig. 16 Measured Axial Force Distribution of Reinforcement(1tf/m²-5tf/m²)

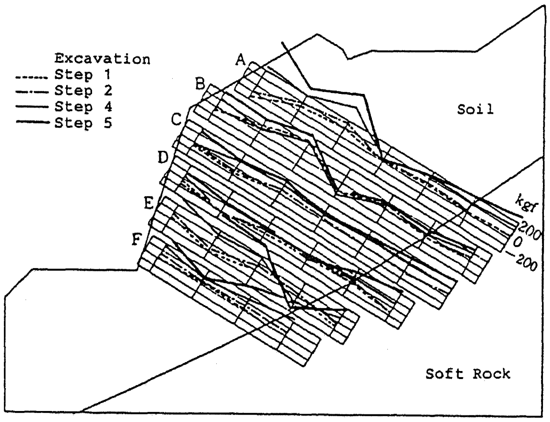


Fig. 17 Measured Axial Force Distribution of Reinforcement (At the End of Excavation Step)

COMPARISONS OF MEASURED AND ANALYTICAL RESULTS AND ITS CONSIDERATIONS

General remarks

Finite element analyses of the field test have been performed (Matsui and San, 1987). In the analyses, the soil is assumed to be nonlinear elastic with a hyperbolic tangent modulus (Duncan and Chang, 1970) and the soft rock linear elastic. The slippage between the reinforcement and the surround medium and between the soil and the rock is modeled by a elasto-plastic joint element (Matsui, Abe and San, 1986, Matsui and San, 1988). The reinforcement is considered as one dimensional bar element. The material properties used in the present analysis are summarized in Table 4.

Deformation of the slope and axial forces developed in the reinforcements

The deformation of the slope under 5tf/m² of surcharge loading obtained from finite element analysis is shown in Fig.18. By comparing Fig.18 with Figs.14 and 15(a), it can be seen that both analytical and measured results show that the top of slope surface moved forward, while with a small movement at the toe and that the horizontal displacement within the slope is large at the upper portion while with negligible movement at the lower portion.

Fig.19 shows the analytical axial force distribution of reinforcements for the case of

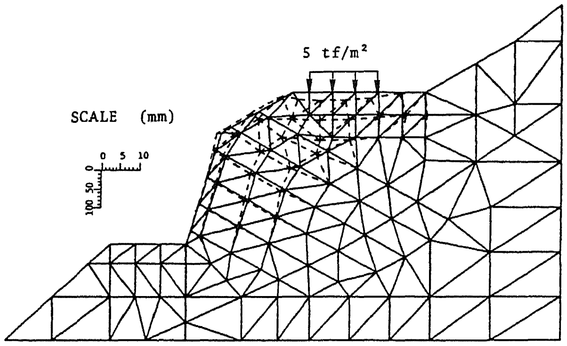


Fig. 18 Analytical Deformation of the Reinforced Cut Slope under 5tf/m²Loading

Table 4 Material Properties

	Decomposed granite	Soft rock	Reinforcement
Elastic modulus E (tf/m²)	2.2×10^{3}	1.4×10^{5}	2.1×10^{7}
Unit weight γ (tf/m³)	1.8	2.0	-
Poisson's ratio ν	0.3	0.3	0.3
Friction angle ϕ (degree)	19	45	-
Cohesion c (tf/m²)	1.0	1.0	-
Coefficient of earth pressure at rest K_0	0.67	0.67	-
Hyperbolic constant K	210	-	-
Hyperbolic constant K_{ur}	420	-	-
Hyperbolic constant n	1.02	-	-
Failure ratio R_f	0.69	-	-
Cross section area A (m²)	-	-	5.2×10^{-4}

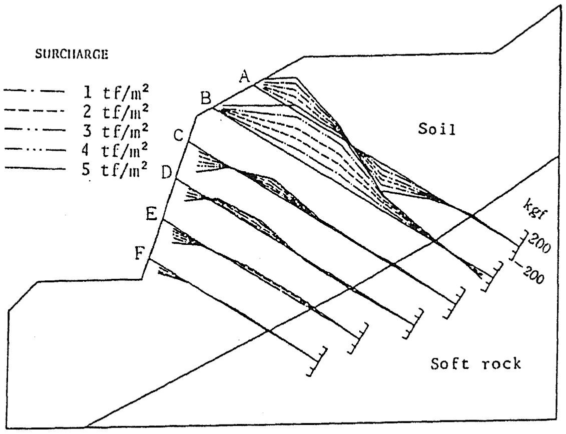


Fig. 19 Analytical Axial Force Distribution of Reinforcement (1tf/m²-5tf/m²)

field loading test. From Figs.16 and 19, it can be seen that both analytical and measured results show that the axial forces developed in the reinforcement are not all in tension, and that the tensile force developed in the upper reinforcements are significantly larger than the lower.

Shear strength of reinforced soil mass

Figs.20 and 21 show the distribution of total principal stress in the reinforced and unreinforced slopes under the loading of 5tf/m², respectively. It can be seen that the orientation of principal stress of the soil is slightly changed, while the minor principal stress is significantly increased in the reinforced soil mass. It is very clear that the increase in the minor stress contributes to increase the shear strength of the reinforced soil mass without any change of c,ϕ values.

CONCLUSIONS

A full scale field test on a reinforced cut slope incorporated with a road widening project has been presented. Finite element analyses of the field loading test have been also presented. The agreement between analytical results and field measurements is satisfactory. From the comparisons between measured and analytical results of the field loading test, the success of the slope stabilization by tensile inclusions, such as root piles, has been demonstrated. Both site observations and analytical results show that the upper part of the surface of the slope significantly moves away with small movement at the toe under the surharge. The analytical results indicate that the orientation of principal stress of soil is slightly changed, while the minor principal stress is significantly increased under the effects of reinforcement. The increase in the minor principal stress contributes to increase in the shear strength of soil without any change in c, ϕ values. Moreover, the reinforcement mechanism of a reinforced cut slope under an effect of excavation is different with that of surcharge. By comparing the reinforcement mechanism of a reinforced cut slope under a surcharge load and an effect of excavation, some distinguished aspects are summarized as follows:

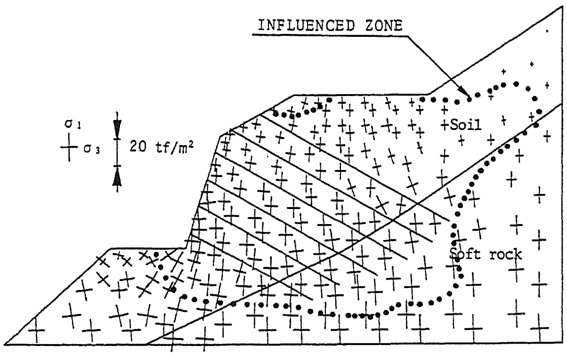


Fig. 20 Principal Stress Distribution of the Reinforced Cut Slope under 5tf/m² Loading

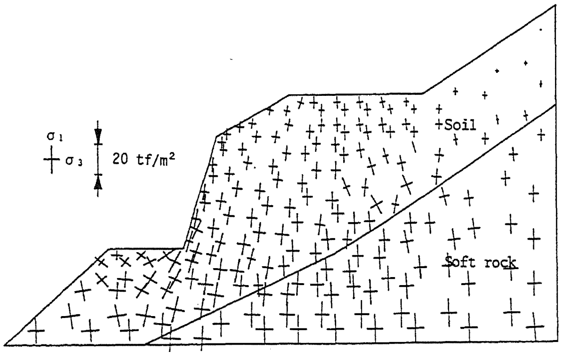


Fig. 21 Principal Stress Distribution of the Unreinforced Cut Slope under 5tf/m² Loading

(1) The axial forces developed in the reinforcement are not all in tension under surcharge loading. Such axial forces develop immediately as the surcharge is applied, and decreased in a small amount after the surcharge is removed.

(2) The axial forces developed in the reinforcement are mainly in tension under an effect of excavation with a maximum near the surface just after excavation is completed. Such axial forces increase with elapsed time and reach a stable condition after two weeks.

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