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Applicability of an elasto-plastic model for reinforced soil structures

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ABSTRACT: The reinforcement technique using flexible materials such as geosynthetics has been widely employed in the current engineering practice. However, the reinforcement mechanism has not revealed sufficiently, i.e. the mechanical interaction between the reinforcements and soils, the confining effect induced by reinforcements and so forth, and then it has not yet led into a proposal of rational design procedure. This paper reports in-situ loading tests carried out on the compacted soil structure reinforced by flexible beltlike materials. Elasto-plastic finite element simulations were also performed considering dilatancy characteristics of compacted soils during shearing. Throughout comparison with the field records monitored in the site and the results obtained from the conventional elastic computation, discussed are the applicability of the elasto-plastic analysis and the role of dilatancy characteristics of compacted soils in the reinforcement mechanism.

1 INTRODUCTION

The reinforcement technique for the soil structures has been widely employed. However, the analysis technique has not established yet, and it is expected to establish the rational design method. Stability of the reinforced soil structures is thought to be improved through complex mechanical interaction between soils and reinforcement materials. Dilatancy characteristics would play an important role in the interaction. Therefore, in order to simulate the behavior of the reinforced soil structure, an elastoplastic model proposed by Sekiguchi-Ohta (Sekiguchi and Ohta, 1977) was employed, in which dilatancy characteristics is taken into consideration.

The model was originally proposed for saturated soil materials. But, in this study, an attempt was made to apply the model to compacted soils by introducing an idea of equivalent over-consolidation ratio (Hirata, M et al. 1999). And the behavior of a reinforced soil structure backfilled with compacted soil was simulated. The idea introduced is based on the similarity of dilatancy characteristics during shearing between compacted soils and heavily overconsolidated clays.

Throughout comparison with the monitored records when a giant trailer passed on the reinforced soil structure, applicability of the model was discussed in this paper. Moreover, conventional elastic simulations were also carried out to examine the reinforcement effect. The effect is expected to be brought by confining the dilatancy characteristics of soils by reinforcement materials.

2 ANALYSIS TECHNIQUE

2.1 *Elasto-plastic model*

Numerical analysis was carried out by the "DAC-SAR", in which an elasto-plastic model proposed by Sekiguchi-Ohta is incorporated. Basically the model was constructed to analyze saturated normally consolidated clayey materials and based on the following principles.

1) Volumetric strain of normally consolidated clay is given by linearly summing up volumetric changes due to consolidation and dilatancy.
2) Volumetric strain of normal-consolidated clay is determined by initial and present effective stress states, and independent of stress path.

The yield function f is expressed as follows,

$$f = \frac{\lambda - \kappa}{1 + e_0} \ln \frac{p'}{p_0} + D\eta^* \tag{1}$$

where D is dilatancy coefficient proposed by Shibata (1963). η^* is normalized stress ratio expressed as,

$$\eta^* = \sqrt{\frac{3}{2}\left(\frac{s_{ij}}{p'} - \frac{s_{ij0}}{p'_0}\right)\left(\frac{s_{ij}}{p'} - \frac{s_{ij0}}{p'_0}\right)} \tag{2}$$

where s_{ij} is deviatoric stress tensor ($s_{ij} = \sigma_{ij} - p'\delta_{ij}$). By introducing normalized stress ratio η^*, it is possible to consider anisotropic shear properties induced

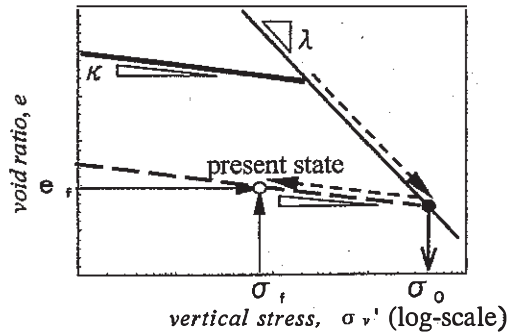

Figure 1. Process to evaluate equivalent OCR.

by rotation of principal stresses. Then, the stress and strain relationship is expressed by employing the associated flow rule.

2.2 *Application for the compacted soil*

While Sekiguchi and Ohta's model has been developed for naturally consolidated-saturated clays, materials that are dealt with here are artificially compacted and unsaturated soils. However, since the unsaturated compacted soils, in general, show positive dilatancy (dilatation) and strain softening behavior like over-consolidated clay under shearing, we may consider the over-consolidated clay equivalent to the compacted soil and apply Sekiguchi and Ohta's model to it if the mechanical property of the compacted soil can be characterized from viewpoint of over-consolidated saturated clays (see, Ohta and Hata, 1977, Ohta et al., 1978). Characteristics of strain softening, strength and stiffness depend on the value of OCR. Then, it is assumed that the degree of compaction can be evaluated by the equivalent overconsolidation rate OCR. Figure 1 shows the process to determine the equivalent OCR. When void ratio and vertical stress of in-situ soil is evaluated e_f and σ_f, respectively. The soil is assumed to be in the present stress state after over-consolidated to predecessor stress σ_0 Then equivalent OCR is evaluated as σ_0/σ_f.

3 TEST SITE

The site, where a series of in-situ monitoring were carried out, was the reinforced retaining wall structure as shown in Figure 2. It was reinforced by Terre Armee method, flexible beltlike materials (steel strip) and concrete plates (skin plate) were used as facing of the wall structure. It is a fairly flexible structure if comparing with the conventional gravitytype retaining wall structure. The merits of Terre Armee method would be summarized as, 1) not require larger work volume, 2) not need highly skilled technique, 3) not need longer executive period and 4) more applicable to a narrower site. The retaining retaining structure was 8.75 m high, and 11 steel strips were installed in each cross section. It was backfilled with compacted soils that were compound made up of clay, sand and gravel. After completion of construction, the mechanical performance of reinforced soil structure was investigated by passing a giant trailer on the structure (Nishikata U. et al. 1999 & 1998).

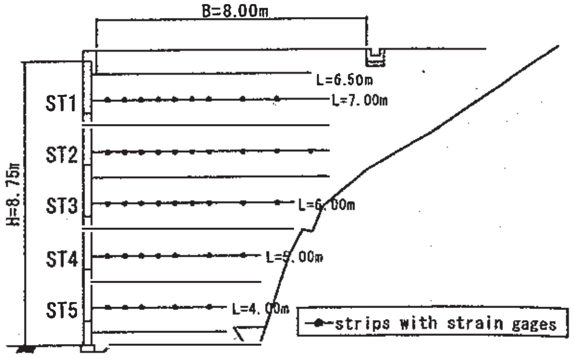

Figure 2. Cross section of the retaining structure.

In order to monitor the tension stress (strain) acting to strips when the giant trailer was passed through on the structure, strain gauges were installed on the strips at a certain interval as indicated in Figure 2. Vertical load of 67kN/m^2 was applied to the structure and the maximum force acting to the strips reached 25 kN when a giant trailer was passed on the structure.

4 INPUT PARAMETERS

The soils were sampled from the site and a series of constant volume shear box tests (CV-SBT test) were carried. First, very loose disturbed soil specimens, which were prepared at the in-situ water content (8%) were consolidated in the shear box by the vertical pressure of 78.4, 156.8, 313 and 616 kPa and then sheared under the constant volume after completion of the consolidation. Thus obtained results of consolidation process were potted on void ratio *e* and vertical stress log σ' diagram and then the virgin compression line was drawn as shown in Figure 1. The compression index λ was determined from the gradient of virgin compression line. And the effective stress paths during shear were obtained from the shear process of the test and plotted in Figure 3.

Next, the undisturbed soil sample of which natural water contents was around 8% was subjected to the consolidation (σ'_{v0} = 156.8 and 616 kPa) and shear tests in the same manner. The effective stress path obtained from shear process of the test was also plotted in Figure 4.

Input parameters needed in the analysis (Table 1) were determined as follows.

The increase ratio of undrained shear strength S_u/σ'_{v0} was determined from shear test results (Figure 3). On the other hand, S_u/σ'_{v0} has been theoretically derived from the elasto-plastic constitutive

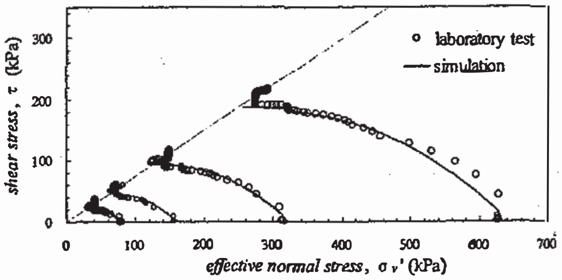

Figure 3. Effective stress paths (loose & disturbed samples).

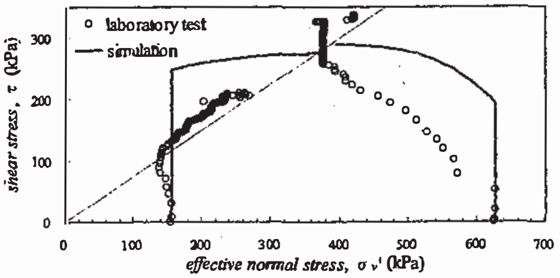

Figure 4. Effective stress paths (undisturbed samples).

model by Sekiguchi and Ohta as (see, Ohta, Nishihara and Morita 1985),

$$\frac{S_u}{\sigma'_{v0}} = \frac{1+2K_0}{3\sqrt{3}} M \exp(-\Lambda) \qquad (3)$$

where S_u and σ'_{v0} are undrained shear strength and vertical preconsolidation stress, respectively. Moreover, when the following empirical relations are introduced,

$$M = 1.75\Lambda \quad \text{(Karube)} \qquad (4)$$

$$K_0 = 0.44 + 0.42 \cdot \frac{PI}{100} \quad \text{(Massarsch)} \qquad (5)$$

$$\sin\phi' = 0.81 - 0.233 \cdot \log PI \quad \text{(Kenny)} \qquad (6)$$

three unknown parameters M, Λ and K_0 can be specified. Thus determined input parameters are summarized in Table 2 together with other input parameters, $v' = K_0/1 + K_0$.

In order to confirm validity of input parameters, then the effective stress paths under constant volume shear were calculated by the elasto-plastic constitutive model and compared with experimental values. Calculated (theoretical) stress paths are drawn and indicated by solid lines in Figures 3 and 4.

Table 1. Input parameters.

λ	= 0.434Cc Cc; compression index
κ	= 0.434Cs Cs; swelling index
D	= $\lambda\Lambda/M(1+e_0)$; dilatancy coefficient
M	= $6\sin\phi'/(3-\sin\phi')$; critical state parameter
Λ	= $1-\kappa/\lambda$; irreversibility ratio
K_0	coefficient of static earth pressure at rest at the completion of virgin consolidation
e_0	initial void ratio
V'	effective Poisson's ratio
OCR	over-consolidation ratio

Table 2. Input parameters.

λ	0.159
κ	0.014
D	0.058
M	1.978
Λ	0.912
v'	0.309
K_0	0.448
e_0	0.253
OCR	47(mean value)

5 FINITE ELEMENT SIMULATION

Elasto-plastic finite element simulation was carried out. Finite element model is shown in Figure 5. In the simulation, strips, skin plates and rock mass were assumed to be elastic materials. Uniformly distributed load of 67kN/m^2 by the giant trailer was applied as the surcharge load on the surface as shown in Figure 5.

Figure 6 shows distributions of tension force working to the strips S1-S5, when the giant trailer just passed on the monitoring cross section (when load of 67kN/m^2 was just applied). In the figure, the distributions of tension force obtained not only from the elasto-plastic simulation but also from the linearly elastic simulation are compared with monitored values. It seems that the elasto-plastic simulation relatively explains monitored values, except for strip S2 where monitored stresses were quite small comparing with those of other strips. The tension force calculated from conventional linearly elastic simulation is fairly larger than those obtained from the field monitoring.

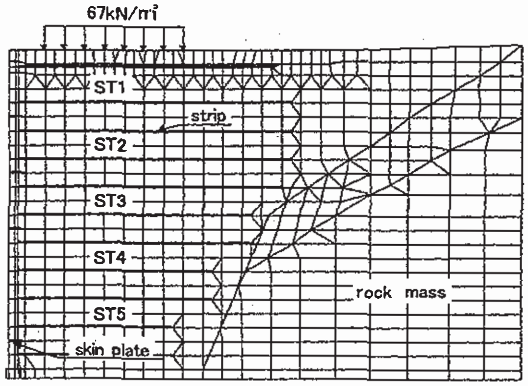

Figure 5. Element breakdown.

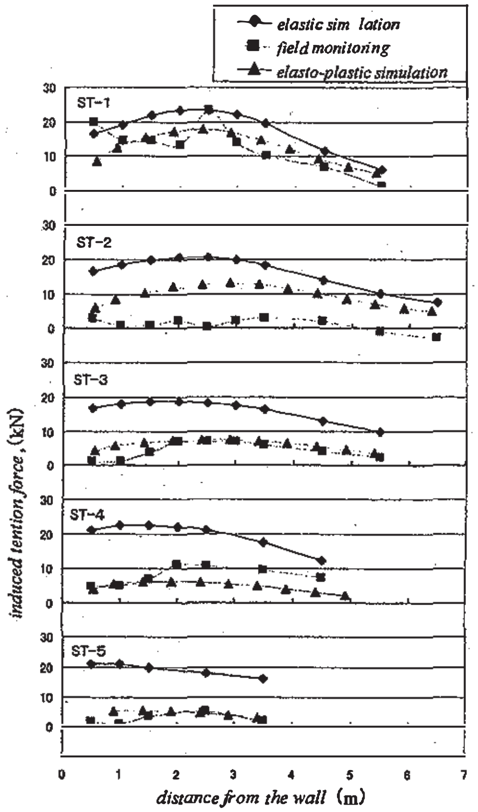

Figure 6. Induced tension in the strips.

6 DISCUSSION

Tension force working to the strips is examined. The elasto-plastic simulation in which dilatancy characteristics is taken into account predicts fairly smaller value of tension force than conventional linearly elastic simulation and results in being consistent with monitored values. This suggests that it is important to consider dilatancy characteristics of compacted soils and the reinforcement effect is brought by preventing the dilation of soils due to shearing. For establishment of rational design procedure of reinforcement of soil structures, dilatancy characteristics of compacted soils is not negligible.

7 CONCLUSION

An attempt was made to apply an elasto-plastic model considering dilatancy characteristics of compacted soils to explain the reinforcement effect of an actual retaining wall structure backfilled with compacted soils. Throughout comparison with the field records, applicability of the model was examined. The following conclusions would be pointed out.

1) The way that an elasto-plastic constitutive model for saturated clays is applied to unsaturated compacted soils is shown.

2) Shear behaviors of compacted soils can be modeled into heavily over-consolidated clays by introducing "equivalent OCR".

3) Dilatancy characteristics play an important role in reinforcement mechanism of the soil structures.

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