Uplift Behavior of Shallow Circular Anchor in Two-Layered Sand

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Summary

This study evaluated uplift behavior of a shallow circular anchor in two-layered sand, by comparing a model test with a finite element analysis. The finite element analysis was an elasto-plastic model in which progressive failure with shear band effect was introduced into the constitutive equation. The finite element analysis was able to predict the anchor problem in two-layered sand. In two-layered sand, a dense/medium bed gives greater peak uplift resistance than does a medium/dense bed. The direction of shear band propagation depended on the density of sand mass regardless of position.

Introduction

Research into the uplift resistance of an anchor provides a useful analogue for a soil structure interaction problem. The uplift resistance of shallow anchor has been evaluated in various studies using experiments and analysis[1,2]. These studies have focused on estimation of the vertical uplift resistance of an anchor buried horizontally in homogeneous ground. Rowe and Davis[3] studied the behavior of an anchor plate in sand using elasto-plastic finite element analysis. Sakai and Tanaka[4] studied the uplift resistance of a shallow anchor in dense sand using elasto-plastic finite element analysis. The result of this analysis was close to the experimental data, and the scale effect due to progressive failure was evaluated. However, a review of the previous studies shows that no work has been done to evaluate the uplift behavior in two-layered sand by using elasto-plastic finite element analysis. A purpose of the paper is to evaluate the uplift resistance and the scale effect of a shallow circular anchor in two-layered sand, by comparing the results of a conventional 1g-model test with those of elasto-plastic finite element analysis with shear band effect.

Testing Apparatus and Finite Element Analysis

A soil bin was a cylindrical container measuring 59 cm in diameter, whose dimensions was selected so that any boundary effects could be neglected. The anchors for the study were flat, circular steel plate of 0.5 cm thickness and diameters of 10 cm. The test was conducted at an embedment ratio (h/D, h: depth of sand mass, D: diameter of anchor) of two. Vertical pullout load was measured by use of a load cell and the anchor was moved up by D.C. motor. The tests were conducted in air-dry uniform

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silica sand (Toyoura sand). The physical properties of Toyoura sand were G_s=2.64, D_{50}=0.16 mm, e_{max}=0.98, e_{min}=0.61 and no fines contents less than 0.075 mm. The anchor was placed on the bottom of the soil bin, and the sand was rained through a raining device. Formation of a depth of sand mass with uniform density is important. Depending on the height of fall of sand and the intensity of deposition during the raining process, various uniform densities could be obtained. The sand mass had relative densities (*Dr*) of 53% (medium, density of 1.48 g/cm^3) and 95% (dense, density of 1.63 g/cm^3). In the two-layered sand mass, the lower and upper layers are of equal thickness (dense/medium and medium/dense beds). To study the shape of failure surface development, a semi-partial test was conducted.

In the finite element analysis, the shear band effect is introduced into a constitutive equation. The constitutive model uses an elasto-plastic model with non-associated flow rule and strain hardening-softening yield properties. A yield function of the Mohr-Coulomb model and a plastic potential function of the Drucker-Prager model were employed. The element was a pseudo-equilibrium model formed by one-point integration of a 4-noded Isoparametric element. A dynamic relaxation method with a return mapping algorithm was applied to the integration algorithm of the elasto-plastic constitutive relation including the shear band effect. The shear band effect was introduced in the form of a parameter S, which is the ratio of shear band area to finite element area and was introduced into the elesto-plastic constitutive model as a characteristic length. The shear band thickness (SB) is known to be about 20 times mean particle diameter. SB of Toyoura sand is estimated at 0.3 cm[5].

The yield function f and plastic potential function Ψ are give by the following expression;

$$f = 3\alpha(\kappa)\sigma_m + \frac{\sqrt{J_2}}{g(\theta)} - \gamma(\kappa) = 0 \tag{1}$$

$$\Psi = 3\alpha'(\kappa)\sigma_m + \sqrt{J_2} - \gamma'(\kappa) = 0 \tag{2}$$

The frictional hardening-softening function $\alpha(\kappa)$ are expressed as;

$$\alpha(\kappa) = \left\{ \frac{2\sqrt{\kappa\varepsilon_f}}{\kappa + \varepsilon_f} \right\}^m \alpha_p \quad \text{(hardening-regime; } \kappa \le \varepsilon_f\text{)} \tag{3}$$

$$\alpha(\kappa) = \alpha_r + (\alpha_p - \alpha_r)\exp\left\{ -\left(\frac{\kappa - \varepsilon_f}{\varepsilon_r} \right)^2 \right\} \quad \text{(softening-regime; } \kappa < \varepsilon_f\text{)} \tag{4}$$

where, m, ε_f and ε_r are the material constants.
α_p and α_r are estimated the following equations.

$$\alpha_p = \frac{2\sin\phi_p}{\sqrt{3}\,(3-\sin\phi_p)} \tag{5}$$

$$\alpha_r = \frac{2\sin\phi_r}{\sqrt{3}\,(3-\sin\phi_r)} \tag{6}$$

where, ϕ_p and ϕ_r are the peak and residual friction angle, respectively. ϕ_p is estimated from the empirical relations proposed by Bolton (1986).

$$I_r = D_r\left\{5-\ln\left(\frac{\sigma_m}{150}\right)\right\}-1 \quad (\sigma_m \geq 147\,\mathrm{kN/m^2}) \tag{7}$$

$$I_r = 5D_r - 1 \quad (\sigma_m < 147\,\mathrm{kN/m^2}) \tag{8}$$

$$\phi_p = 3I_r + \phi_r \tag{9}$$

where, D_r is relative density.
The mobilized friction angel (ϕ_{mob}) is given the following equation.

$$\phi_{mob} = \sin^{-1}\left\{\frac{3\sqrt{3}\alpha(\kappa)}{2+\sqrt{3}\alpha(\kappa)}\right\} \tag{10}$$

$\alpha^{'}(\kappa)$ in plastic potential function is expressive as,

$$\alpha^{'}(\kappa) = \frac{2\sin\psi}{\sqrt{3}\,(3-\sin\psi)} \tag{11}$$

The dilatancy angle (ψ) is estimated from modified Rowe's stress-dilatancy relationship.

$$\sin\psi = \frac{\sin\phi_{mob} - \sin\phi_r^{'}}{1-\sin\phi_{mob}\sin\phi_r^{'}} \tag{12}$$

$$\phi_r^{'} = \phi_r\left[1-\beta\exp\left\{-\left(\frac{\kappa}{\varepsilon_d}\right)^2\right\}\right] \tag{13}$$

where, β and ε_d are material constants.
The elastic moduli are estimated using the following equations;

$$G = G_0 \frac{(2.17 - e)^2}{1 + e} \sigma_m^{0.5} \tag{14}$$

$$K = \frac{1(1+\nu)}{3(1-2\nu)} G \tag{15}$$

where, ν is Poisson's ratio, e is void ratio and G_0 is material constant of initial shear modulus. The calculations are carried out by displacement control on axisymmetric condition.

In the analysis the soil constants were based on the data obtained from triaxial compression test conducted on Toyoura sand[6]. The stress-strain-volume change relationship in dense condition is shown in Fig.1. In the analysis the stress-dilatancy parameters were used $\varepsilon_d = 0.3$ and $\beta = 0.1$. The hardening-softening material parameters influence the stress-strain relationships. Fig.2 shows the finite element mesh used for analysis of anchor test. Calculated and experiment results is shown in Fig.3, which show the uplift resistance-displacement curves in dense sand. The material parameters influence the load-displacement curves. When the hardening-softening parameters were $\varepsilon_f = 0.1$, $\varepsilon_r = 0.1$ and $m = 0.1$, the calculated result coincided with the experimental result. The hardening-softening parameters of triaxial and anchor tests are not equal because the shear band development differ from each other. Table 1 summarizes the parameters used in

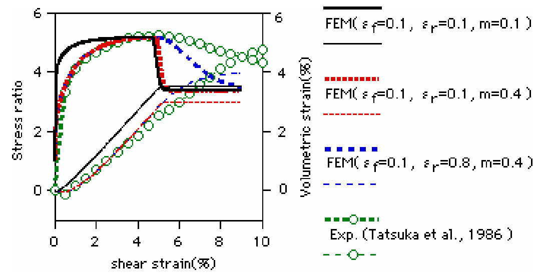


Fig.1 Stress-strain-volume change relationship in dense sand

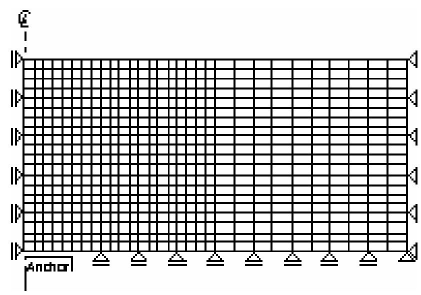


Fig.2 Finite element mesh

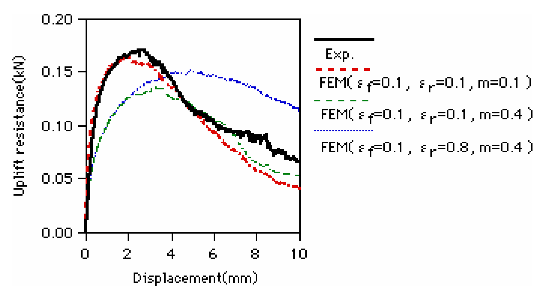


Fig.3 Uplift resistance-displacement curves in dense sand

the finite element analysis of anchor test in dense and medium sand. Fig. 4 shows the uplift resistance-displacement curves in medium sand. This figure shows that calculated result coincide with the experimental results.

Result of two-layered sand

Fig.5 shows the uplift resistance-displacement curves in two-layered sand obtained by experiment and analysis. The figure shows that the calculated results are close to the experimental results. This finite element analysis can accurately simulate the experiment in two-layered sand. The dense/medium bed gives a greater peak uplift resistance than the medium/dense bed. Fig.6 shows shear band propagation in two-layered sand. The direction of shear band propagation is dependent on the density of sand mass, regardless of position. Fig.7 shows the maximum shear strain distributions in two-layered sand. The direction of the localized narrow zone changes in the boundary between the layers. A steeper concentrated zone develops upward in a medium bed.

Table 1 Material parameters

	Dense	Medium
Density (ƒ Ï̈$_d$ □ g/cm^3)	1.63	1.48
Void ratio (e)	0.62	0.78
Relative density (D_r)	0.95	0.53
Cofficient of shear modulus (G_0)	500	500
Residual friction angle (ƒ Ó$_r$□ °F)	35	35
Poisson's ratio (ƒ Ë̈)	0.3	0.3
Shear band thickness (SB : cm)	0.3	0.3
ƒ Ã̃$_f$	0.1	0.1
ƒ Ã̃$_r$	0.1	0.5
m	0.1	0.2
ƒ Ã̃$_d$	0.3	0.3
ƒ À	0.1	0.1

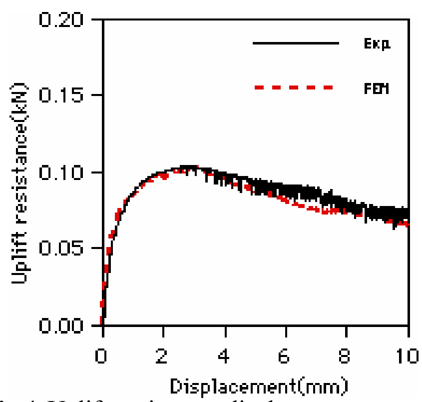
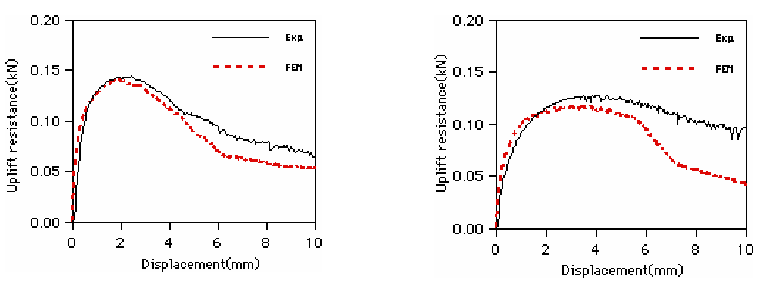


Fig.4 Uplift resistance-displacement curves in medium sand



(a)Dense/Medium bed (b)Medium/Dense bed

Fig.5 Uplift resistance-displacement curves in two-layered sand

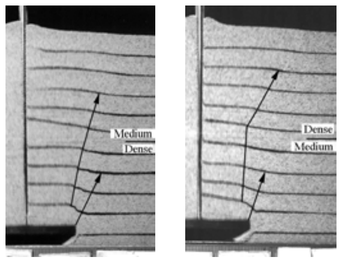


Fig.6 Shear band propagation in two-layered sand (disp.6mm)

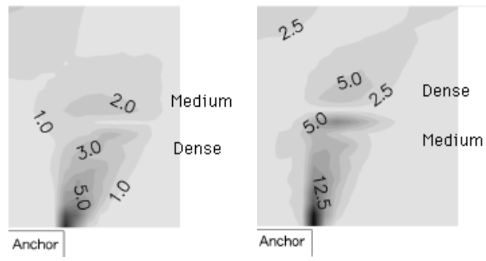


Fig.7 Maximum shear strain distribution in two-layered sand (disp.2mm and 5mm, unit:%)

Conclusion

This study evaluated the uplift resistance and the scale effect of a shallow circular anchor in a two-layered sand, by comparing the results of a conventional 1g-model test with the results of an elasto-plastic finite element analysis with shear band effect. The conclusions can be summarized as follows;

1) The results obtained by the finite element analysis show good agreement with experimental results. The finite element analysis can predict the anchor problem in two-layered sand.
2) The dense/medium bed gives a greater peak uplift resistance than the medium/dense bed. The direction of the shear band propagation was dependent on the density of sand mass regardless of position. With looser density, steeper shear band propagation developed upward.

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