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Behavior of reinforced foundation under uplift and push-in loadings – model tests and analyses

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ABSTRACT: A pile foundation with reinforced bars has been proposed by Matsuo and Ueno and is put practical use for increasing uplift bearing capacity of transmission tower and others. For investigating the mechanism of such type of reinforced foundations under not only uplift loading but also push-in loading, two- dimensional model tests and the corresponding numerical analyses were performed. Model tests and numerical simulations are done with different stiffness of reinforcements and different insertion direction of reinforcements. It is shown through the experimental and numerical study on uplift bearing capacity that though the flexible reinforcements works as the tensile reinforcements, and the stiff reinforcements as the bending reinforcements, the reinforcements protruded diagonally downward is the most effective for both cases. On the other hand, the experimental and analytical results show that the foundation with flexible reinforcements is not so effective against push-in loading, though the stiff reinforcements protruded diagonally downward work most efficiently.

1 INTRODUCTION

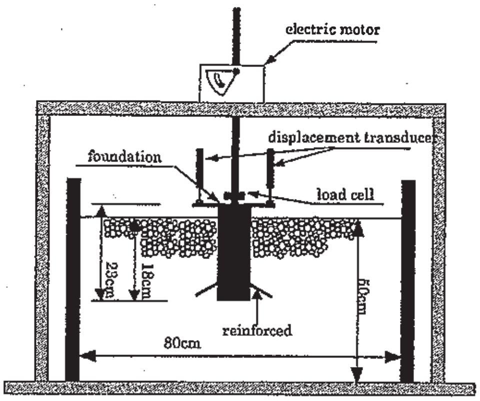
Foundations with reinforcements protruded diagonally downward were developed and put into practice in order to increase the uplift bearing capacity of electric transmission tower and others (Matsuo and Ueno, 1989; Tokyo Electric Power Company and Dai Nippon Construction, 1990). Numerical simulation was also carried out to investigate the mechanism of reinforcement, and its results were presented at the previous symposium in 1996 (Nakai and Ueno, 1996). The numerical results shows that the reinforcements protruded diagonally downward are the most effective regardless of the stiffness of the reinforcements. In the symposium, there were active comments and questions from the floor about the most effective direction of the stiff reinforcements - They were that the most effective direction of the stiff reinforcements should be diagonally upward, being different from the numerical results.

After then we carried out small scale model tests as well as numerical analysis and showed experimentally that the reinforcements protruded diagonally downward are the most effective against uplift load regardless of the stiffness in the same way as the numerical analyses (Nakai et al., 1999).

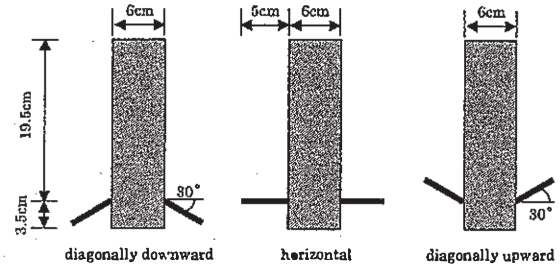
In the present study, we perform the model tests and the elastoplastic finite element analyses not only under uplift loading but also under push-in loading to investigate the influence of the stiffness of reinforcements and the insertion direction of reinforcements on the effect of reinforcements. In addition to the behavior under push-in loading, the following two points are newly considered in the present study: one is to employ an elastoplastic constitutive model for geomaterials which takes into account the influence of the density and/or the confining pressure as well as the soil dilatancy and others more elaborately, and the other is to measure the axial forces and the bending moments of the reinforcements with the strain gages in the model tests.

2 DESCRIPTION OF MEDEL TESTS

As shown in Figure 1, the foundation with the length of 23cm and the wide of 6cm is set up in the 2 dimensional ground. The penetration depth of the foundation is 18cm. The ground is made of a mass of aluminum rods in which two kinds of rods having diameter of 1.6 and 3.0mm are mixed in the weight 3:2. Such model ground exhibits the behavior like dense and/or medium dense sand with negative and positive dilatancy. The dots in Figure 2 show the observed stress-strain-dilatancy relations of biaxial tests on the aluminum rods mass under constant minor principal stress (σ_1=19.6kPa) and constant major principal stress (σ_2=19.6kPa). The reinforcements with the length of Scm are protruded to three different directions from the lower part of foundation at three levels (see Fig. 1(b)). Two kinds of thickness (3mm and 0.2mm) of aluminum plate are used as the reinforcements. Aluminum plates on which aluminum rods of 1.6mm in diameter are



(a) Apparatus



(b) Arrangement of reinforcements

Figure 1. Outline of model tests.

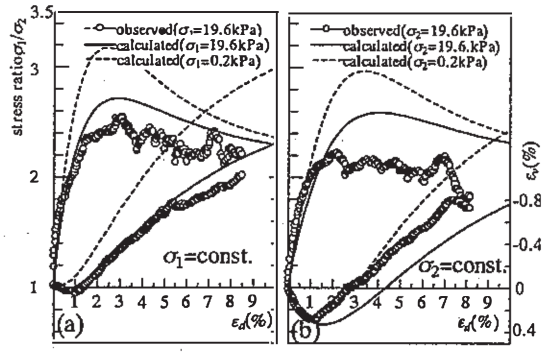


Figure 2. Stress ratio and volumetric strain vs. deviatric strain in bi-axial tests on aluminum rods mass.

glued at equal spacing of 1cm are employed. The friction angle between the reinforcement and the model ground is about 20°.

Upward or downward displacement is imposed continuously to the foundation. Displacement and uplift or push-in load of the foundation are measured by a displacement transducer and load cell. Axial force and bending moment of the reinforcement can be measured by the strain gages that are glued at the both sides of the reinforcement (The positions of the strain gages are 1cm, 2.5cm and 4cm from the side of the foundation). The measured data are recorded in a personal computer though a data logger. The movements of ground as a whole can be known by taking photo with a digital camera.

3 METHODS OF ANALYSIS

Plane strain finite element analyses under drained condition are carried out in the same scale as the model tests. Finite element meshes for the three cases are shown in Figure 3. Elastoplastic constitutive model for sand named subloading t;~ model (Nakai et al., 2001) is used. This model can describe properly the following typical characteristics of sand in the same way as the previous model named t;--sand model (Nakai, 1989), regardless of small numbers of parameters:

(i) Influence of intermediate principal stress on the deformation and strength of sand.
(ii) Influence of stress path on the direction of plastic flow.
(iii) Negative and positive dilatancy.

In addition to these points, the new model can take into consideration

(iv) Influence of density and/or confining pressure.

The values of soil parameters of the new model for the aluminum rods mass are listed in Table 1. The solid curves in Figure 2 are the calculated re-

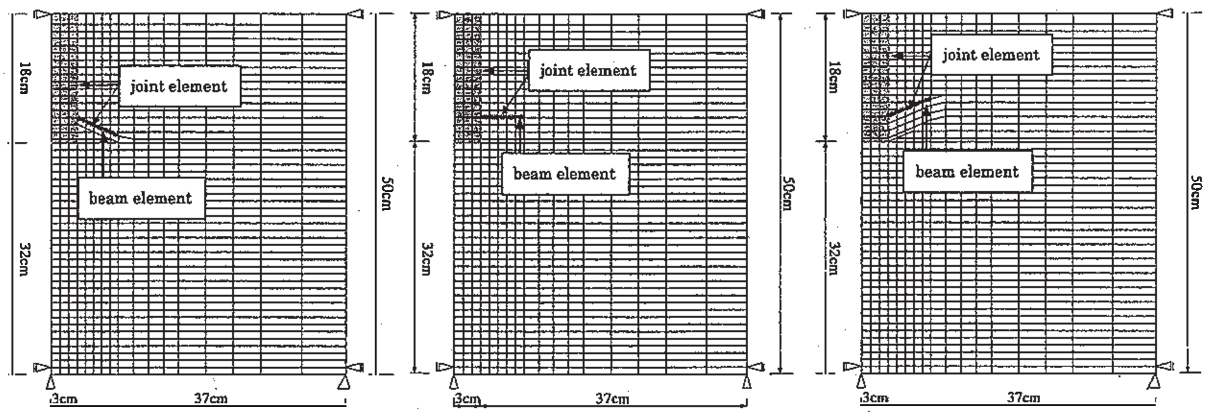


Figure 3. Finite element meshes for three cases.

Table 1. Values of soil parameters for aluminum rods mass.

λ	0.008
K	0.004
e_{NC} (p = 98kPa)	0.3
Rcs (comp.)	1.8
β	1.2
α	1300

sults corresponding to the observed ones, and the dotted curves are the calculated results in which the initial confining pressure is assumed to be two orders smaller in magnitude. This is because the initial confining pressure in model tests is much smaller than that in the bi-axial tests. We can see that the constitutive model describes strain softening behavior as well as the influence of the confining pressure. The initial state of the model ground is created by simulating the one-dimensional self-consolidation.

The foundation is assumed to be an elastic material with enough stiffness. The reinforcements are simulated by beam elements: Axial stiffness and bending stiffness are assumed as EA=8.44 x 10^{2}kN and EI=2.81 x 10^{2}kPa for flexible reinforcements, and EA=1.27 x 10^{4}kN and EI=9.50 x 10^{5}kPa for stiff reinforcements, respectively. In order to evaluate the friction between the foundation and the ground and between the reinforcements and the ground, an elastoplastic joint element is inserted between them (Nakai, 1985). The elastoplastic joint element can describe the slip behavior on the interface between structure and soil, which is described schematically in Figure 4. Here, (p_s and p_n) are the shear and normal stresses on the interface, and (w_s and w_n) the shear and normal relative displacements on the interface. The friction angle δ used in the analysis between the foundation and the ground is determined to be 14°, and those between the reinforcements and the ground 20° from the slip tests of the foundation and the reinforcement on the aluminum rods mass. Upward or downward displacement is increasingly applied on the top of the foundation in every case.

4 RESULTS AND DISCUSSIONS

Figures 5 (a)-(c) show the observed results of uplift test of the foundation with stiff reinforcements. Here, diagram (a) is the relationships between uplift load P and upward displacement d of the foundation, diagram (b) is the distributions of axial force in the reinforcement and diagram (c) the distribution of bending moment in the reinforcement. Figures 6 (a)-(c) are the corresponding computed results. Further, for the cases with flexible reinforcements, respectively. The self-weight of the model foundation is included in the observed uplift load in Figures 5 and 7. The dotted horizontal lines in the observed uplift load - displacement relation (diagram (a)) in these figures indicate the self-weight of the model foundation. Not only computed results but also experimental results show that the foundation with reinforcements protruded diagonally downward is the most effective against uplift load in every case. In diagram (b) and (c) in Figures 7 and 8 with flexible reinforcements, though the bending moment is almost zero in every case, tensile axial force of diagonally downward reinforcements near the foundation is the largest. We can then see experimentally and numerically that the flexible reinforcements protruded diagonally downward work most effectively as tensile reinforcements. From diagrams (b) and (c) in Figures 5 and 6 with stiff reinforcements, we can see that the reinforcements work as bending reinforcements as well as tensile reinforcements. Although the mechanism of reinforcing of stiff reinforcement is different from that of flexible reinforcement, reinforcements protruded diagonally downward are the most effective against uplift load, in the same way as the flexible reinforcements.

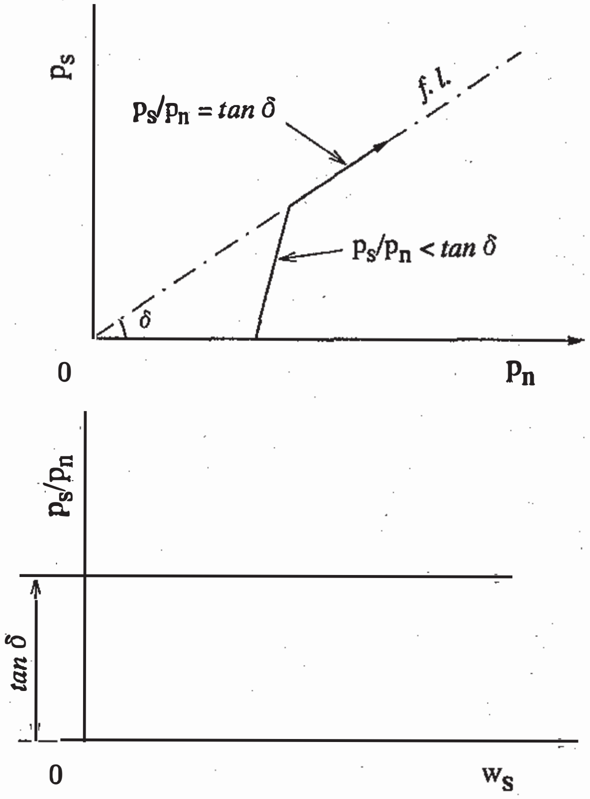
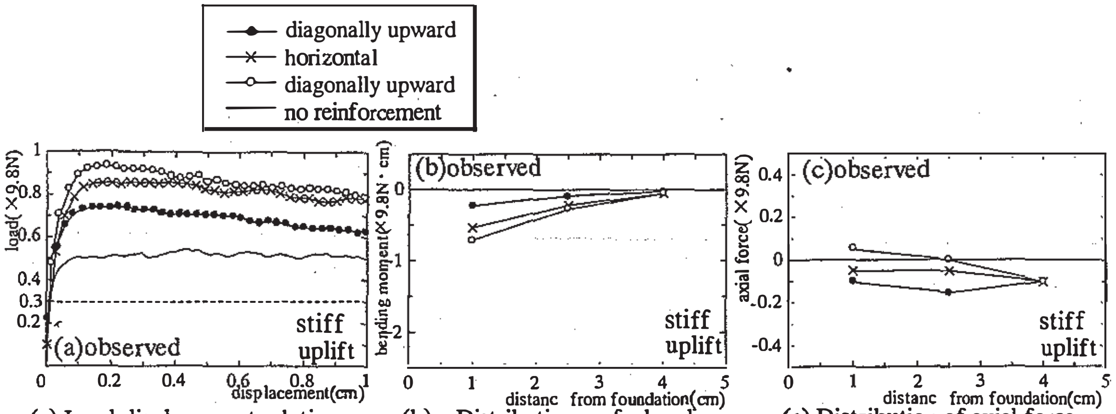


Figure 4. Schematic slip behavior at interface.

Figures 9 and 10 show the observed and computed results of push-in tests of the foundation with stiff reinforcements, respectively. Figures 11 and 12 are the results of push-in tests in case of flexible reinforcements. The resistance against push-in loading becomes larger when the reinforcements are protruded horizontally or diagonally downward in the

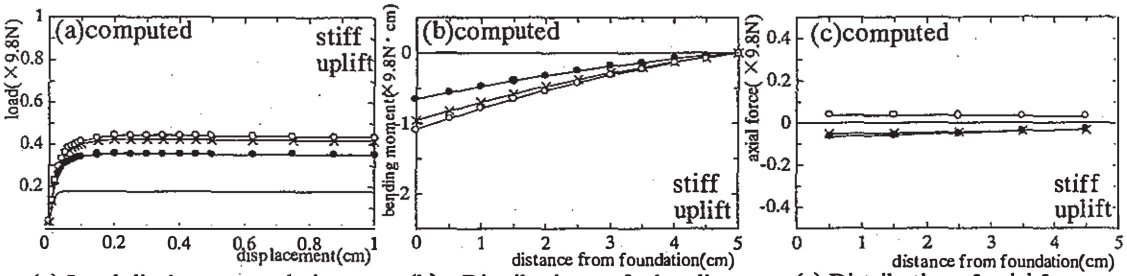


(a) Load-displacement relation

(b) Distribution of bending moment in reinforcement

(c) Distribution of axial force

Figure 5. Observed results of foundation with stiff reinforcements under uplift loading.

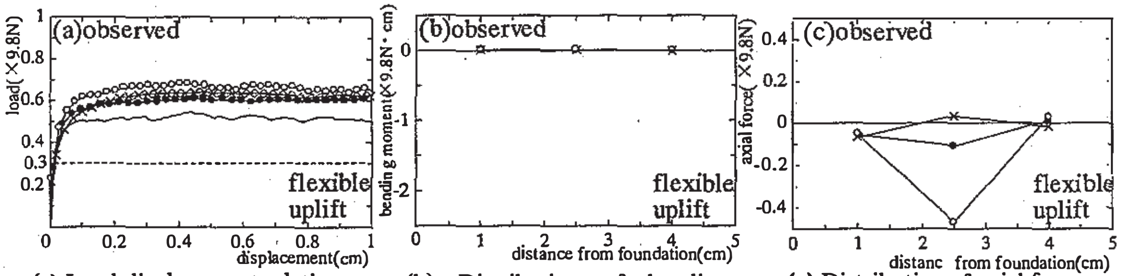


(a) Load-displacement relation

(b) Distribution of bending moment in reinforcement

(c) Distribution of axial force

Figure 6. Computed results of foundation with stiff reinforcements under uplift loading.

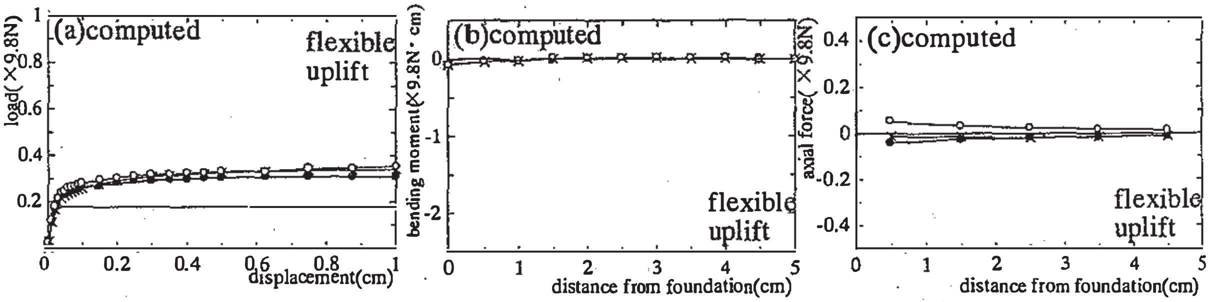


(a) Load-displacement relation

(b) Distribution of bending moment in reinforcement

(c) Distribution of axial force

Figure 7. Observed results of foundation with flexible reinforcements under uplift loading.

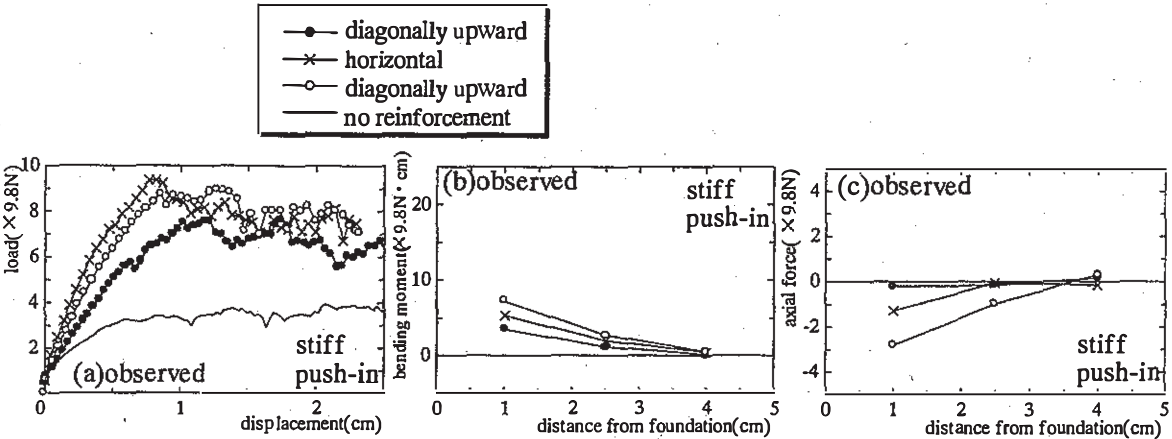


(a) Load-displacement relation

(b) Dist ibution of bending moment in reinforcement

(c) Distribution of axial force

Figure 8. Computed results of foundation with flexible reinforcements under uplift loading.

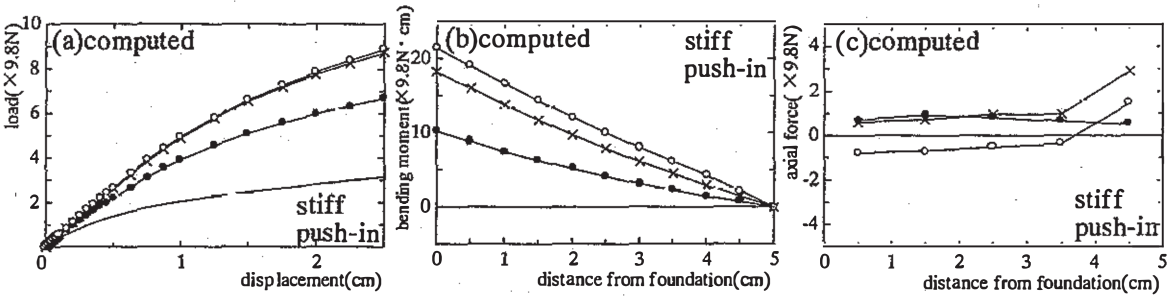


(a) Load-displacement relation

(b) Distribution of bending moment in reinforcement

(c) Distribution of axial force

Figure 9. Observed results of foundation with stiff reinforcements under push-in loading.

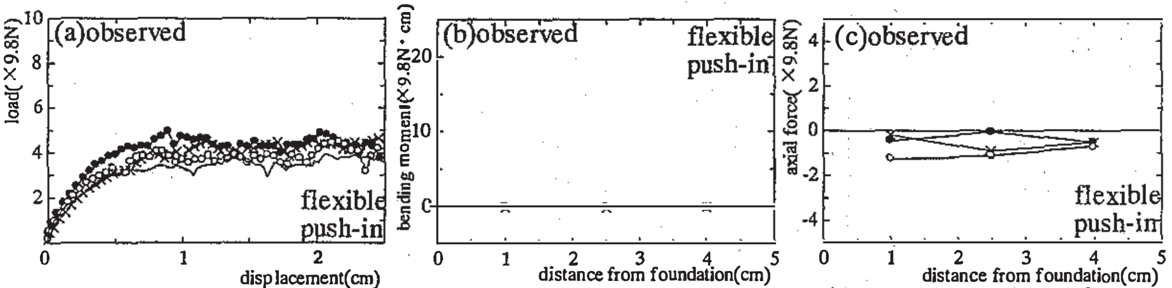


(a) Load-displacement relation

(b) Distribution of bending moment in reinforcement

(c) Distribution of axial force

Figure 10. Computed results of foundation with stiff reinforcements under push-in loading.

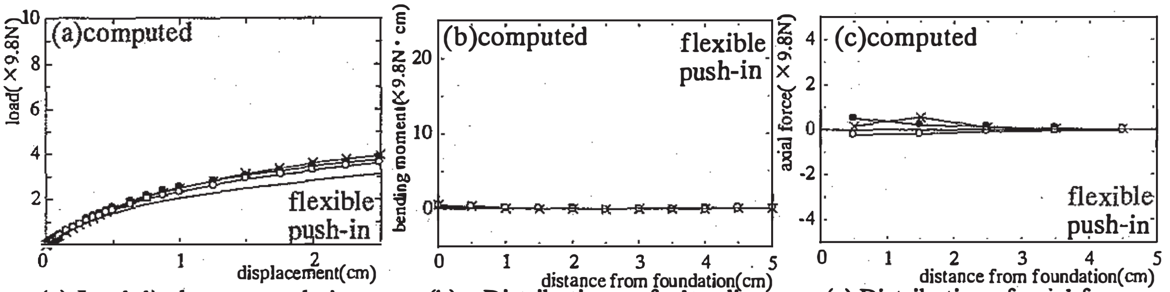


(a) Load-displacement relation

(b) Distribution of bending moment in reinforcement

(c) Distribution of axial force

Figure 11. Observed results of foundation with flexible reinforcements under push-in loading.

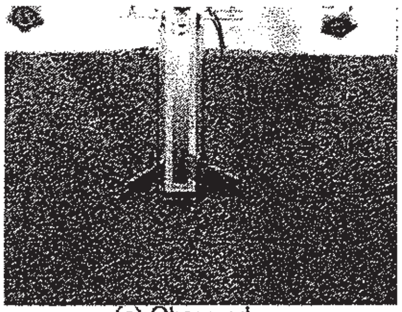


(a) Load-displacement relation

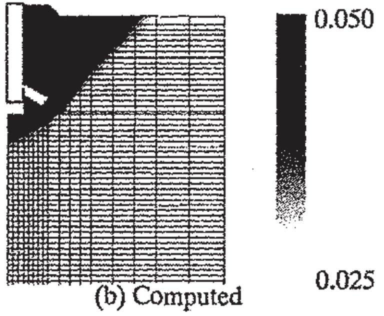
(b) Distribution of bending moment in reinforcement

(c) Distribution of axial force

Figure 12. Computed results of foundation with flexible reinforcements under push-in loading.

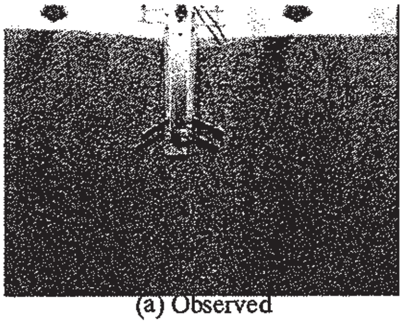


(a) Observed



(b) Computed

Figure 13. Movements of ground under up-lift loading.



(a) Observed

(b) Computed

Figure 14. Movements of ground under push-in loading.

analyses and the model tests. On the other hand, we can see from the experimental and computed results that the flexible reinforcements are not so effective against push-in loading regardless of their insertion direction, even though the tensile force acts on the reinforcements. i.e., The tensile force of reinforcements to increase bearing capacity of foundation works more effectively against uplift loading than against push-in loading. The bending moment is efficient push-in loading as well as uplift loading.

Figure 13 shows the observed and computed movements of the ground, when the foundation with the stiff reinforcements protruded diagonally downward is pulled up from 0.0cm to 1.0cm. Figure 14 shows the observed and computed movements when the same foundation is pushed down from 0.0cm to 2.5cm. The observed movements are shown as photos that are taken by means of multiple exposures. The computed movements show the distributions of the magnitude of total displacements. We can see that there are good qualitative agreements between the observed and the computed movements.

5 CONCLUSIONS

Experimental and numerical study on uplift and push-in bearing capacity of reinforced foundation has been done. The numerical results in which mechanical behavior of the soil and the reinforcement and frictional behavior between the soil and the reinforcement are taken into account properly describe well the experimental results.

The flexible reinforcements work as tensile reinforcements, and the stiff reinforcements as tensile and bending reinforcements. The reinforcements protruded diagonally downward are the most effective against uplift loading regardless of the stiffness of reinforcements. On the other hand, the stiff reinforcements protruded horizontally or diagonally downward are effective against push-in loading, but the flexible reinforcements are not so effective.

6 ACKNOWLEDGEMENTS

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REFERENCES

Matsuo, M. and Ueno, M. 1989. Development of ground reinforcing type foundation. *Proc. 12th ICSMFE 2:* 1205-1208.

Nakai, T., 1985. Finite Element Computations for active and passive earth pressure of retaining wall. *Soils and Foundations* 25(3): 98-112.

Nakai, T. 1989. An isotropic hardening elastoplastic model for sand considering the stress path dependency in three-dimensional stresses. *Soils and Foundations* 29(1): 119-137.

Nakai, T., Hinokio, M., Hoshikawa, T., Yoshida, H. and Chowdhury, E. Q. 2001. Shear behavior of sand under monotonic and cyclic loadings and its elastoplastic modeling. *Proc. 10th IACMAG.* 1: 367-372.

Nakai, T., Isobe, Y., Suzuta, and Teranishi, T. 1999. Numerical simulation and model tests of reinforced foundation under uplift loading. *Proc. NUMOG III* 1:451-456.

Nakai, T. and Ueno, M. 1996. Numerical study on uplift bearing capacity of caisson type pile. *Proc. Int. Sym. on Earth Reinforcement.* 1: 629-634.

Tokyo Electric Power Company and Dai Nippon Construction 1990. *Report on bearing capacity of caisson type foundation with reinforcing bars* (4) (in Japanese).