Effective reinforcing method for increasing bearing capacity with geosynthetics

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ABSTRACT

To increase bearing capacity of foundation, geosynthetic is laid beneath the foundation. In the previous research, the authors investigated the reinforcement mechanism by changing the length and the laying depth of the reinforcement (Nakai et al, 2009). In the present study, for increasing bearing capacity, reinforcing effect in the case where each edge of the reinforcement is fixed with the soil is investigated. For this purpose, 2D model tests and the corresponding non-linear finite element analysis are carried out. In these tests and simulation, the depth of the reinforcement is changed under two kinds of length of reinforcement. Reinforcing effects for both concentric and eccentric loads are discussed. It is revealed that a significant increase of the bearing capacity is observed in the model tests when the reinforcement having mostly the same length as wide of the foundation or a slightly larger length is set up in the ground with an appropriate depth under both concentric and eccentric loads. The results of numerical simulation in which the stress-strain behavior of the soil and the frictional behavior between soil and reinforcement are properly taken into consideration shows a good agreement with the observed results.

Keywords: geosynthetics, bearing capacity, constitutive model of soils, finite element analysis, model test

1. INTRODUCTION

In Japan, a huge area of the ground consists of soft soils having insufficient bearing capacity at the surface layer which makes trouble to engineers in design and construction process. To increase the bearing capacity, ground improvement and replacement of good quality of soils are commonly used. However, these processes are expensive and also time consuming. Moreover, these processes sometimes restrict workability of the construction. In urban housing it is especially unpleasant to use cement in ground improvement which increases construction cost as well. Replacing the existing soft soils with good quality soils also has problems in cost and environment. Therefore, in this research it is focused on the use of geosynthetics to reinforce the ground for reducing ground deformation and increasing bearing capacity of the ground. The reinforcement in geosynthetics construction method consists of materials to withstand only against tensile forces acting upon the soils due to the upper surcharge. The authors (Nakai et al., 2009), explained some effective reinforcing method in the previous research. However, the edges of reinforcement were not fixed the surrounding soil. Some numerical and experimental researches on bearing capacity problem of reinforced soil have been done (e.g., Peng *et al.*, 2001). However,

in these researches, the influence of surface friction, condition of the edges of the reinforcements were not discussed.

2 LAYOUT OF THE MODELS AND NUMERICAL SIMULATIONS

2.1 Outline of 2D Model Tests

Fig. 1 shows a schematic diagram of a 2D model test apparatus for the investigation of bearing capacity of ground. The size of the model ground is 100cm in

Fig. 1. Schematic diagram of apparatus

Fig. 2. Model of foundation

Fig. 3. Model for reinforcement material

width and 50cm in height. Aluminum rods of 5cm in length, having diameters of 1.6mm and 3.0mm and mixed randomly with the ratio of 3:2 in weight, are used as the model ground (unit weight of the mass is 20.4kN/m³). Fig. 2 shows a model of the strip foundation. The foundation is 120mm in width and 35mm in height. Sandpaper is attached at the bottom of the foundation to attain surface friction between the foundation and the ground. Vertical load is applied on the top of foundation. A slider, which permits the movement of the foundation in the horizontal direction, and a load cell for measuring the load are set in the loading system. Vertical displacement and rotation of the foundation are measured setting two displacement transducers at the two edges of the foundation. Photographs are taken during the experiments, which are used later as input data for the determination of ground movements with a program based on the technique of Particle Image Velocimetry (PIV).

Fig. 3 shows the reinforcement material used in model test. Tracing paper is used as a geosynthetic which has almost no bending stiffness but has enough tensile stiffness. On the both surfaced of the tracing paper, aluminum rods of 1.6mm in diameter are glued with an interval of 10mm, to provide friction on the reinforcement. The length of shorter reinforcement (L) is 144mm, which is 1.2 times the width of the foundation ($B=120$ mm). The length of longer reinforcement is $L=180$ mm. The fixing condition at the edges of the geosynthetic is imposed by setting an aluminum plate in both edges of the reinforcement. The dimensions of each aluminum plate for modeling the fixed boundary condition of the reinforcement are - 2mm in thick and 15mm in height having the width of 50mm. It is projected from the tracing paper (geosynthetic) with an upper part of 5mm and a lower part of 10mm. The plate is moved with the movement of the ground during the application of load.

2.1 Outline of Numerical analysis

Numerical analyses have been conducted considering the same scale as the 2D model tests. Two-dimensional finite element analyses are carried

Fig. 4. Finite element mesh for numerical analyses

Table 1. Values of material parameters for aluminum rod mass

λ	0.008
κ	0.004
$N(e_N \text{ at } p = 98\text{kPa})$	0.3
$R_{CS} = (\sigma_1/\sigma_3)_{CS (comp.)}$	1.8
ν_e	0.2
β	1.2
$a/(\lambda - \kappa)$	1300

Fig. 5. Model for reinforcement material

out with FEMtij-2D program which is developed in our laboratory. Fig. 4 represents a typical mesh used in the numerical analyses. Isoparametric four-noded elements are used for soil elements, and elastic beam elements are used to simulate reinforcements. The frictional behavior between the reinforcement and aluminum rods, and the foundation and aluminum rods, is modeled employing the elastoplastic joint element (Nakai, 1985). The friction angle between the reinforcement and the model ground is determined by the sliding tests ($\delta=20^\circ$ for rough reinforcement). The friction angle between foundation and soil is $\delta=15^\circ$. In the numerical analyses,

the elastoplastic subloading t_{ij} model (Nakai and Hinokio, 2004; Nakai, 2012), is used as a constitutive model for the ground material. This model can describe typical deformation and strength characteristics of soils such as the influence of intermediate principal stress, the influence of stress path dependency of plastic flow and the influence of density and/or confining pressure. The same parameters of aluminum rods as those used in the numerical simulation of model tests on other geotechnical problems (*e.g.*, Nakai et al., 2007; Shahin *et al.*, 2011) are used for the ground materials. The values of the material parameters of aluminum rod mass are listed in Table 1. The parameters are fundamentally the same as those of the Cam clay model except the parameter α , which is responsible for the influence of density and confining pressure. The parameter β represents the shape of yield surface. The parameters can easily be obtained from traditional laboratory tests. Fig. 5 shows the results of biaxial test and calculated curves of aluminum rod mass. The stress-strain relation shows the positive and negative dilatancy of aluminum rod mass; and it is found from these figures that the strength and deformation behavior of aluminum rod mass is similar to those of medium dense sand.

3 PATTERNS OF EXPERIMENTS AND ANALYSES

Table 2 shows the patterns of experiments and analyses. Tracing paper is set underneath the foundation at different installation depths (D). Five sets of reinforcement depths are employed: $D/B=0.05$, 0.10, 0.20 and 0.40, where B is the width of the foundation. In the real field the load of super structure is not always

Table 2. Patterns of experiments

	Pattern (Length of reinforcement $L/B=1.2, 1.5$)				
	no reinforcement	Depth of reinforcement D/B			
		$D/B=0.05$	$D/B=0.10$	$D/B=0.20$	$D/B=0.40$
Concentric Loading	○	○	○	○	○
Eccentric Loading	○	○	○	○	○

being acted at the center of the foundation. Therefore, the effectiveness of the reinforcement has been investigated for the two different loading positions -*i.e.*, load is applied at the center (concentric loading) and at an eccentricity of $e=1/4B$ (eccentric loading).

4 RESULTS AND DISCUSSION

4.1 Concentric Loading

Figs. 6(a) and (b) show the observed and computed load-displacement relations of the foundation for different installation depths in concentric loading, where the reinforcement length is 144mm ($L/B=1.2$). Fig. 7 shows the results for the case of $L=180$ mm ($L/B=1.5$). The vertical axes represent vertical load q_v ,

which is divided by $\gamma B/2$; abscissas show the normalized vertical displacement that is normalized by the width of the foundation ($B=120$ mm). Fig. 7 shows the results for the case of $L=180$ mm ($L/B=1.5$). In these figures, solid lines show the load- displacement curves without reinforcement. It is seen from the figures that though the displacement of the computed results is larger than that of the experiment, bearing capacity increases for the installation depth of reinforcement at $D/B=0.05$, 0.10, and 0.20 compared with the results of no-reinforcement, In addition, almost the same reinforcing effect is seen when the installation depth of

Fig. 6. Vertical load vs. vertical displacement for concentric loading ($L/B=1.2$)

Fig. 7. Vertical load vs. vertical displacement for concentric loading ($L/B=1.5$)

Fig. 8. Computed bending moment and axial force for different installation depths of reinforcement (concentric loading; $L/B=1.2$)

reinforcement with $D/B=1.2$ lies in between $D/B=0.05$ to 0.20. On the other hand, the effect of reinforcement cannot be seen when the installation depth is deeper than a certain depth (D/B is greater or equal to 0.40). The tendency of the present results is similar to the results of the previous research in which the edges of the reinforcement were not fixed with the soil (Nakai et al, 2009), where it was shown that the reinforcement with the depth between $D/B=1/8$ to $D/B=1/2$ has been effective. However, It can be seen that the shorter reinforcement ($L/B=1.2$) is more effective than the longer reinforcement ($L/B=1.5$), though when the edges of reinforcement are not fixed, the long reinforcement ($L/B \geq 2.0$) is more effective as described in the previous paper (Nakai *et al.*, 2009).

Fig. 8 shows the computed distributions of bending moment and axial force of reinforcements. It is seen that the bending moment is almost zero in all cases as expected, however, having wide distribution of almost equal axial force is more important than having the larger value of axial force at the central part of reinforcement, to obtain efficient reinforcing effect.

Fig. 9 illustrates the observed and computed deviatoric strain distributions in the ground, when the load approaches the peak strength, it is at $v/B=0.06$ for the model test, and for the analysis it is at $v/B=0.10$ in the case of no-reinforcement and at 0.13 when the reinforcement is setup at $D/B=0.10$ and 0.40. The distribution of deviatoric strain of the model tests is obtained from the simulation of the PIV technique, taking two photographs before and after loading. The upper figure is the results of the no-reinforcement, and the middle and lower figures are the results of $D/B=0.10$ and $D/B=0.40$. It is seen that when the effect of reinforcement occurs ($D/B=0.10$), a zone of large deviatoric strain spreads vertically below the foundation and it is distributed widely, compared with no reinforcement. In the case of $D/B=0.40$, deviatoric strain develops within narrower zone and hence bearing capacity of the ground does not increase. The computed results describe well the differences of the deviatoric strain distribution observed in the model tests at different installation depths.

Fig. 9. Deviatoric strain distributions: concentric loading ($L/B=1.2$)

4.2 Eccentric Loading

Figs. 10(a) and (b) show the load- displacement relations of the foundation for different installation depths in eccentric loading where the reinforcement length is 144mm ($L/B=1.2$) in the same test patterns as the concentric loading. Here, the load is applied at $2e/B=0.5$, i.e., at 1/4th point from the edge of the foundation. The solid curves also show the results without reinforcement. The bearing capacity for the eccentric loading is smaller than that of the concentric loading (as illustrated in Fig. 6), as a whole. It is seen from Fig. 7 (a) that bearing capacity increases for the installation depth of $D/B=0.05$, 0.10, and 0.20 compared with the results of no-reinforcement, and the effect of reinforcement cannot be expected when the installation depth is deeper than a certain depth (D/B is larger than 0.40). These results are similar to those of concentric loading. Consequently, it can be said that the reinforcement set up at the proper depth as mentioned above is effective regardless the loading conditions.

Figs. 11(a) and (b) show that the observed and computed relations between the rotations of the strip foundation and the normalized vertical load in eccentric loading. Since uniform load is not usually applied to the foundation in practical problems, it is important to reduce the amount of rotations. It is seen that compared

Fig. 10. Vertical load vs. vertical displacement for eccentric loading ($L/B=1.2$)

Fig. 11. Rotation angle vs. load for eccentric loading ($L/B=1.2$)

with the result of no-reinforcement, a large rotation of the foundation starts at higher load when the reinforcement is installed at $D/B=0.05$, 0.10 . Also, when the reinforcement is installed at $D/B=0.40$, the result is almost the same as that without reinforcement. That is, the foundation can bear a higher load without rotating, if it is reinforced properly underneath the foundation. It is revealed that the rotation angle of the foundation decreases in the reinforced ground when the reinforcement is set up at $D/B=0.05$, 0.10 and 0.20 . The tendency of the reinforcing effect in the reduction of

Fig. 12. Computed bending moment and axial force for different installation depths of reinforcement (eccentric loading; $L/B=1.2$)

Fig. 13. Deviatoric strain distributions: eccentric loading

rotation angle of the foundation is similar to that of the relation of bearing capacity and displacement as described before.

Fig. 12 shows computed distributions of bending moment and axial force of reinforcements under eccentric loading. It is seen from this figure that when the reinforcement is effective ($D/B=0.05$ and 0.10), the axial force of the reinforcement increases monotonically from left side to right side. On the other hand, when reinforcing effect is not so large ($D/B=0.05$ and 0.10), the axial load shows the distribution which has a maximum value near the loading point

Figs. 13(a) and (b) illustrate the observed and computed deviatoric strain distributions of the ground when the load approaches the peak strength, it is at $v/B=0.03$ for the model test, and for the analysis it is at $v/B=0.06$ in the case of no-reinforcement and at 0.10 when the reinforcement is set up at $D/B=0.10$ and 0.40. The upper figure represents the results of the no-reinforcement. It is seen that even in the case of eccentric loading where the effect of reinforcement is expected ($D/B=0.10$), a zone of large deviatoric strain spreads deeply and widely below the foundation, compared to that of no-reinforcement. In the installation depth of reinforcement at $D/B=0.4$, deviatoric strain develops at narrower zone in the same way as the concentric loading. The computed results describe well the differences of the deviatoric strain distribution as observed in the model tests in the eccentric loading as well.

4 CONCLUSIONS

The bearing capacity of soil-reinforcement using geosynthetics has been investigated with model tests and the corresponding numerical analyses. The edges of the geosynthetics were kept fixed with the ground. It is revealed that the effectiveness of reinforcement mainly depends on the position of reinforcement and the maximum reinforcing effect can be achieved when it is set up in between $D/B=0.05$ to $D/B=0.20$ in the fixed condition, regardless of loading condition (concentric and eccentric load). If the reinforcement is set up at $D/B=0.40$ or deeper, the reinforcement effect is not expected. On the length of reinforcement, the reinforcement which length is equal to the wide of the foundation or a little larger is the most effective. By laying geosynthetics under the foundation in an appropriate depth, differential settlement can be also controlled in eccentric loading. The results obtained from the numerical analyses show qualitatively good agreement with the results of the model tests in all

patterns. It can be concluded that if the mechanical properties of ground material, reinforcing material and skin friction of reinforcement are appropriately considered, and the behavior of reinforced ground is treated as an interaction problem between the soil and structure (soil and reinforcement). It is possible to clarify the reinforcement mechanism with such model tests and numerical simulations.

ACKNOWLEDGEMENTS

This study was supported financially in part by the Grant-in-Aid for Scientific Research (B-25289144, Teruo Nakai) from the Ministry of Education, Science and Culture of Japan.

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