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The effect of inclination of reinforcement on the horizontal bearing capacity of the ground reinforcing type foundation

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ABSTRACT: The ground reinforcing type foundation, which is a caisson type pile foundation with steel reinforced bars around the pile, was developed with the aim of increasing compression and uplift bearing capacity of the foundation. Compared to current popular foundation, the ground reinforcing type foundation can dramatically reduce the construction cost because of the smaller in size of the new foundation. Form the past practical experiences, it was found that this method can improve not only uplift bearing capacity but also horizontal capacity. It is inferred that inclination of reinforcements is effective to the horizontal bearing capacity. Therefore, this research is focusing on the effect of inclination of reinforcements on the horizontal capacity of the caisson type pile foundation by using of steel reinforced bars. For that purpose, the horizontal loading tests in the centrifugal acceleration were then conducted. Testing results showed that the horizontal capacity of foundation that placing the reinforcement in the diagonal direction is higher than that of the foundation placing the horizontal reinforcement because normal force can act on the reinforcements effectively.

1 GENERAL

An auxiliary geo-reinforcing type foundation (GRF) around a caisson type foundation increases compression and uplift bearing capacity of the main foundation. The mechanism of reinforcement and the evaluation method of compression as well as uplift bearing capacity were clarified by Matsuo et al. (1989) and Nakai et al. (1996) respectively. This paper is focused on the optimal inclination of reinforcement against horizontal loading during earthquake load or wind load. When a caisson foundation with GRF receives horizontal loads, it acts like a rigid foundation and displacement by rotation becomes dominant as indicated in Figure 1. In consideration of such behaviour, it is thought effective to arrange reinforcements in a slant direction for following reasons.

- Resistance moment increases as arm length between the rotation centre and each reinforcements of GRF foundation becomes large.

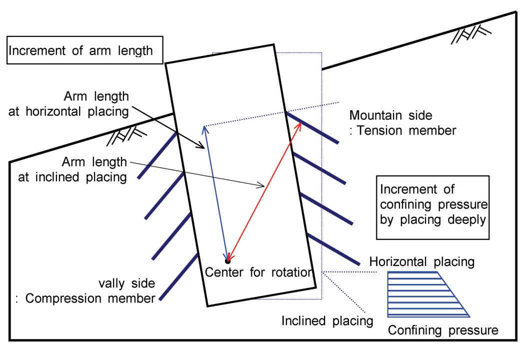

Figure 1. Schematic view of horizontally loaded caisson foundation with inclined reinforcement.

- Since reinforcements can be placed at various depths with large confining pressure, frictional force between reinforcement and ground increases.

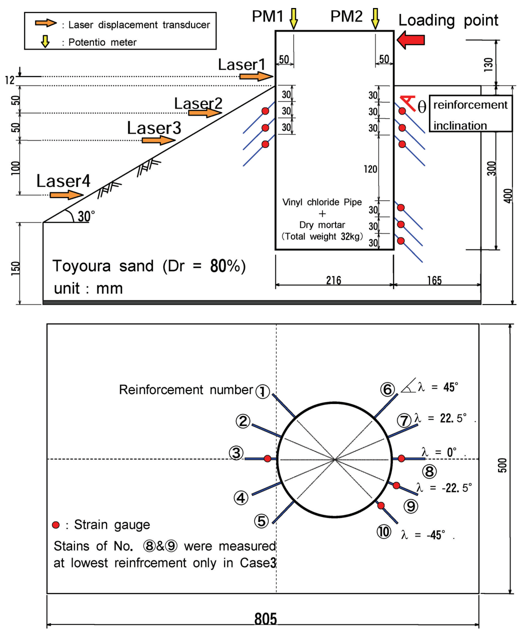

Figure 2. Centrifuge model of caisson foundation with GRF.

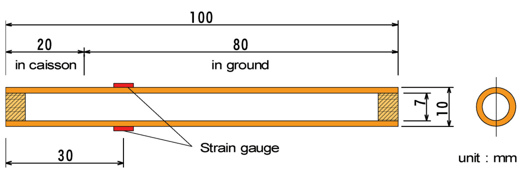

Figure 3. Model reinforcement.

In order to evaluate these influences, this research is focused on horizontal loading tests and centrifuge model tests were performed.

2 THE OUTLINE OF THE TEST

Figure 2 shows a configuration of a model caisson foundation with reinforcement. The foundation was installed on the foundation with 30 inclinations supposing the case where it applies to an alpine area. Model was created with dry Toyoura sand with relative density of 80% ($D_{50} = 0.19$ mm, $U_c = 1.56$, $\phi = 41$ deg.) in a rigid container of 805 mm (length) × 500 mm (width) × 400 mm (height). A vinyl chloride pipe with outside diameter of 216 mm and thickness of 8 mm was used for model caisson. The pipe was filled up with cement mortar with compression strength of 24 MPa. The total weight of model caisson was 32 kg. The hollow bakelite stick was used for the model reinforcement as shown in Figure 3. Tensile rigidity (EA) of the model was coincided to a prototype model. In order to measure sectional force acting on reinforcement, strain gauges were pasted on upper and lower surface of reinforcement. Toyoura sand was pasted on the surface of model reinforcement in order to achieve sufficient friction between soil and reinforcement. Friction characteristics obtained from pullout test were indicated in Figure 4. The Reinforcements were arranged in all the cases as shown in Figure 2 and Table 1. The model was loaded horizontally by using electric jack with displacement velocity of 1.0 mm/min and jack displacement up to 20 mm at loading height in centrifugal acceleration of 50 G. Loading point was at 13 0mm from ground surface in model scale.

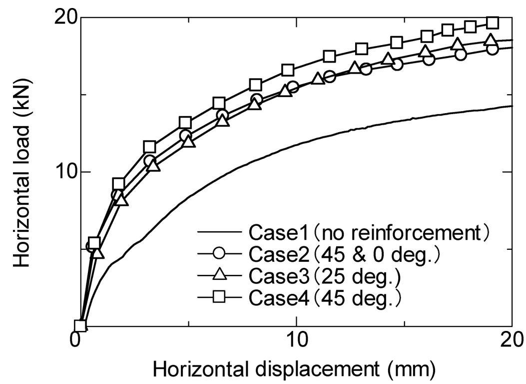

Figure 4. Horizontal load vs Horizontal displacement.

Table 1. Test case and inclination of reinforcement.

	Vally side	Mt. side upper	Mt. side bottom
Case 1	No reinforcement		
Case 2	45°	0°	45°
Case 3	25°	25°	25°
Case 4	45°	45°	45°

3 TEST RESULTS

Figure 4 shows relationships between horizontal load and horizontal displacement of caisson. Case-4 with placing angle of 45 degree shows larger horizontal bearing capacity in compare to Case-3 with reinforcement inclination of 25 degree. In Case-2 which showed lowest horizontal bearing capacity among the reinforced cases, an increment of horizontal bearing capacity could be seen by about 25% as compared with Case-1 with no reinforcement.

Figure 5 shows schematic views of the movement of the caisson foundation, which were calculated from three displacement measurements: Laser1, PM1 and

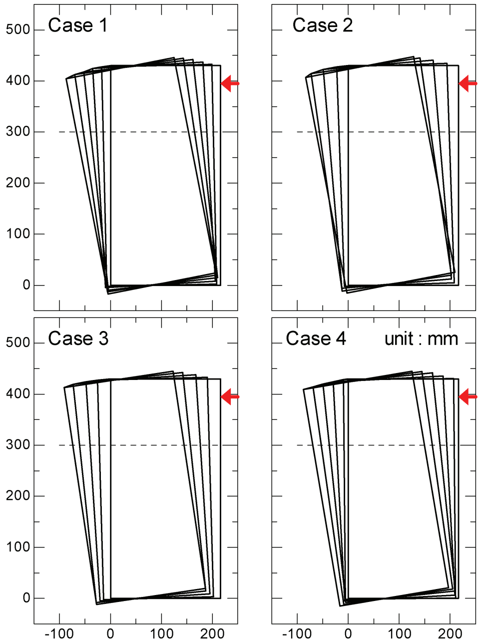

Figure 5. Behavior of model caisson.

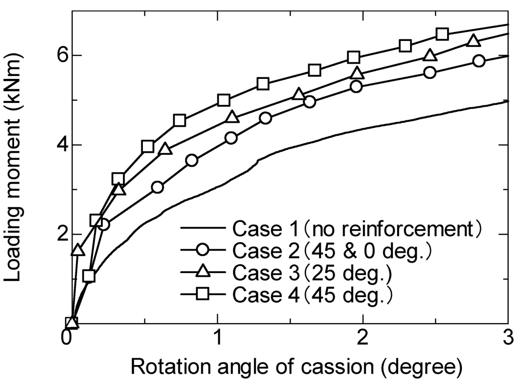

Figure 6. Loading moment vs Rotation angle of caisson.

PM2, before rotation angle of the caisson goes to 10 degree. From these figures, it can be confirmed that most horizontal displacements were depended on rotation and sliding was very small. Therefore, relationships between rotational moment at loading point and rotation angle of the caisson were calculated and are shown in Figure 6. Here, center of rotation was assumed to be center of bottom of the caisson. If the moment was the same as in Figure 6, rotation of the caisson could be greatly restricted by the reinforcements. The effect of these reinforcements was the largest in Case-4 with placing angles of 45 degrees and increment of moment capacity was about 15%

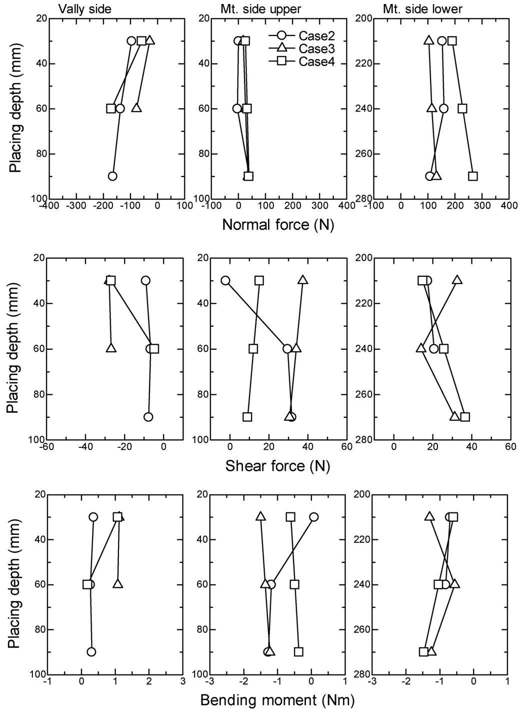

Figure 7. Sectional force acting on reinforcement (Rotation angle = 10 deg.).

in compare with that of Case-2 with smallest bending capacity. Case-3 with 25 degrees placing angles shows a little larger value than Case-2. From these results, highest reinforcement effect can be obtained by arranging them at 45 degree angle.

Figure 7 shows distributions of normal force, shear force and bending moment acting on reinforcement when rotation angle of the caisson was 1.0 degree. Here, sectional forces during a centrifugal acceleration rise were neglected as they were much smaller than those in horizontal loading phase. Since the strain gauges were pasted on a position of 10 mm from junction of reinforcement and caisson, sectional forces were converted into values at the junction. In next chapter, reinforced mechanism and effect of inclination of reinforcement are mentioned by using sectional force results.

4 THE GENERAL EXPECTED MECHANISM

4.1 *Reinforced mechanism*

A caisson type foundation with no reinforcement resists horizontal load by bearing capacity of ground and friction between caisson and ground. In a case of Geo-reinforcing type foundation, resistance against

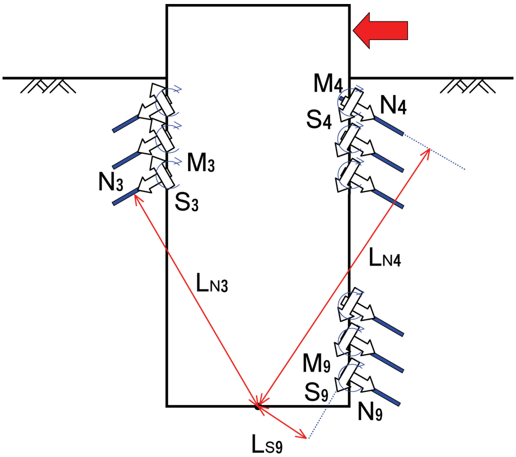

Figure 8. Structure effect.

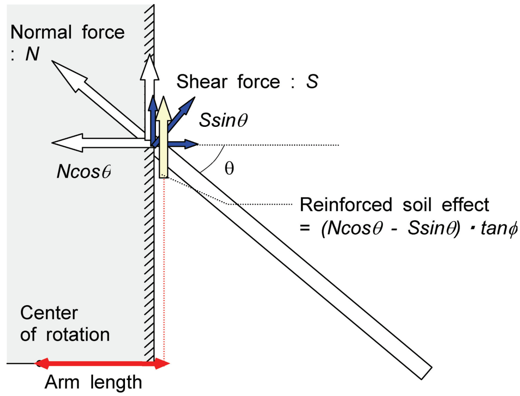

Figure 9. Reinforced soil effect.

horizontal loading can be increased by "structural effect" and the "reinforced soil effect" of reinforcement. Therefore, the increment of resistance moment is expressed by following.

$$\Delta M_R = \Delta M_{RS} + \Delta M_{RR} \tag{1}$$

ΔM_{RS}: Increment by structural effect.
ΔM_{RR}: Increment by reinforced soil effect

In the structural effect, reinforcement shares a part of load acting on the caisson foundation as shown in Figure 8. As a result, sectional force occurs in reinforcement. Accordingly, increment of moment resistance by structural effect can be calculated by Equation (2).

$$\Delta M_{RS} = \Delta M_{SN} + \Delta M_{SS} + \Delta M_{SM} \tag{2}$$

$\Delta M_{SN} = \sum N_i \cdot L_{Ni}$: Increment by normal force
$\Delta M_{SS} = \sum S_i \cdot L_{Si}$: Increment by shear force
$\Delta M_{SM} = \sum M_i$: Increment by bending moment
N_i: Normal force acting of reinforcement i
S_i: Shear force acting of reinforcement i
M_i: Bending moment force acting of reinforcement i
L_{Ni}: Arm length to reinforcement I (Normal force)
L_{Si}: Arm length to reinforcement I (Shear force)

In the reinforced soil effect, confining pressure of the ground is increased by sectional force of reinforcement and frictional force between reinforcement and ground increase as shown in Figure 9. The moment resistance increment by the reinforced soil effect can be calculated by Equation (3).

$$\Delta M_{RR} = \Sigma\left(N_i \cos\theta - S_i \sin\theta\right) \cdot \tan\phi \cdot L_{Ri} \tag{3}$$

L_{Ri}: Arm length to reinforcement (reinforced soil effect)

Validity of reinforcement mechanism as assumed above is verified by using Equations (1) with sectional force obtained from the centrifuge tests.

Loading moment acting on model caisson can be expressed by Equation (4).

$$M_D = F_D \times L_D \tag{4}$$

M_D: Loading moment
F_D: Horizontal Load
L_D: Arm length from rotation center to loading point

Loading moment in Case-1 "$MD_{\_Case1}$" was in agreement with that of caisson with no reinforcement. Therefore, the sum of resistance moment increment obtained from Equation (1) and $MD_{\_Case1}$ are resistance moment M_R of Geo-Reinforcing Type foundation. That is, it can be expressed as following equation.

$$M_R = M_{D\_Case1} + \Delta M_{RS} + \Delta M_{RR} \tag{5}$$

In order to validate the assumed mechanism, resistance moments were calculated by using Equation (5) and sectional force obtained from tests. Then, calculated results are compared to loading moment measured in the centrifuge test as shown in the figure.

4.2 *Validation of assumed mechanism*

Figure 10 shows resistance moment calculated by Equation (1) and loading moment measured in the tests. In calculation, all sectional force of the reinforcement radially arranged at the same height was assumed to be equal. As shown in this figure, since calculated values show good agreement with measured loading moment, it can be said that the reinforce mechanism currently assumed is appropriate.

The amount of resistance moment increment contributed by normal force, shear force and bending

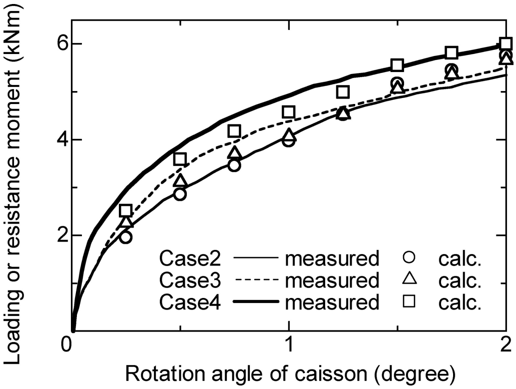

Figure 10. Comparison between measured results and calculation results.

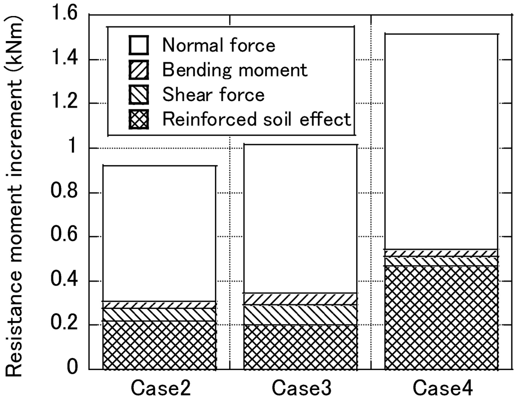

Figure 11. Items of amount contributed in resistance moment increment.

moment were shown in Figure 11. The contribution of structural effect by shear force and bending moment were very small and were about 5 ~ 10% of total resistance moment increment. Reinforcement could not resist horizontal loading sufficiently as well as shear and bending because bending rigidity of reinforcement was lower than stiffness of ground. On the other hand, contribution of normal force was very large in all cases and it accounts for about 90% of total resistance moment increment. Moreover, structural effect by normal force is larger than reinforced soil effect.

4.3 *Effect of reinforcement inclination*

From these results, it turned out that arrangement of reinforcement to which normal force can act on reinforcement effectively is optimal method. Moreover, 45-degree placing was the most effective in the test series. In this chapter, effect of the inclination of reinforcement is evaluated.

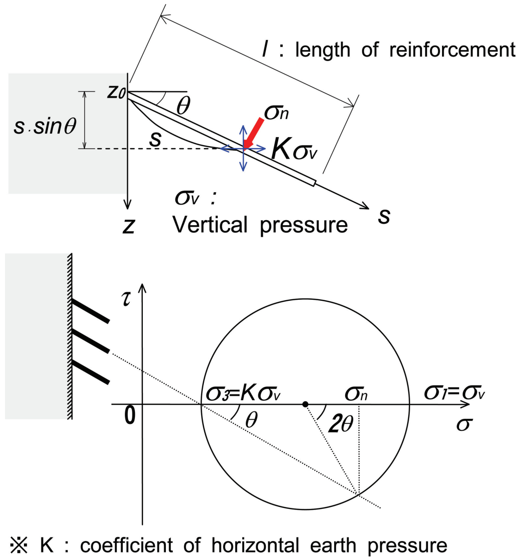

Figure 12. Confining pressure of reinforcement.

It can be thought that normal force acting on reinforcement is caused by pullout resistance between reinforcement and ground. Pullout resistance can be calculated by using following equation obtained from pullout test:

$$T_p = A \cdot c_p + P_c \cdot \tan\delta_p \tag{6}$$

T_p: Pullout resistance
A: Surface area of reinforcement
c_p: apparent cohesion of pullout
δ_p: friction angle between soil and reinforcement
P_c: confining force acting on reinforcement

Since stress state around the reinforcement is considered as shown in Figure 12, confining force P_c can be calculated by following equation

$$\begin{aligned} P_c &= \int_0^l \pi r (1+K)\sigma_n ds \\ &= \pi r \rho (1+K)\left(\frac{1+K}{2}+\frac{1-K}{2}\cos 2\theta\right)\left(z_0 l+\frac{1}{2}l^2\sin\theta\right) \end{aligned} \tag{7}$$

ρ: density of soil
K: horizontal earth pressure coefficient

Tateyama et. al. (1993) suggested that a correction coefficient in consideration of the direction of minor principal strain of the ground should be multiplied for reinforced effect. The correction coefficient is given by following equation.

$$f(\theta) = \frac{2\cos^2\left\{\theta-\left(45^\circ-\nu/2\right)\right\}-\left(1-\sin\nu\right)}{1+\sin\nu} \tag{8}$$

ν: dilatancy angle of soil

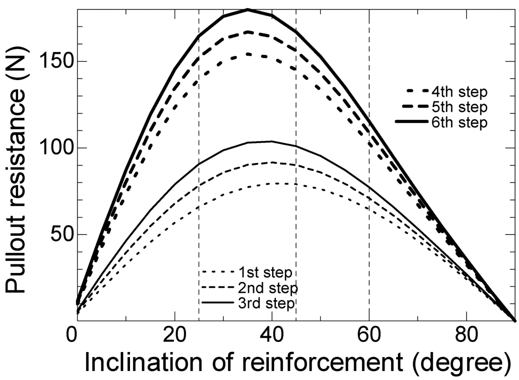

Figure 13. Pullout resistance vs reinforcement inclination.

As mentioned before, since normal force acting on reinforcement is caused by pullout resistance, it can be evaluated by calculating pullout resistance obtained from following equation.

$$T_{PC} = \left(2\pi r \cdot l \cdot c_p + P_c \cdot \tan\delta_p\right) \cdot f(\theta) \tag{9}$$

Figure 13 shows relationships between calculated pullout resistance and inclination of reinforcement. Here, coefficient of Rankin's passive earth pressure, which is expressed as $K_A = \tan^2(45 - \phi/2)$, was used in Equation (7). Smaller dilatancy angle of 5 degrees was selected because displacement between soil and reinforcement was much smaller until rotation angle of caisson is about 3 degrees. As shown in Figure 13, the largest pullout resistance can be obtained near 40 degrees. Therefore, in the centrifuge tests also, large normal force was acquired at reinforcement inclination of 45 degrees, and it is thought that rotation of caisson could be controlled efficiently.

5 CONCLUSIONS

By introducing Geo-Reinforcing Type foundation for a caisson foundation, horizontal bearing capacity could be increased. Reinforced mechanism of it is divided in to "structural effect" and "reinforced soil effect". Such reinforced mechanism was validated by result of centrifuge horizontal loading tests.

Additionally, since structural effect by normal force acting on reinforcement showed about 90 percent of total resistance moment increment, inclination of reinforcement on which normal force acts effectively is an optimal. Such optimal inclination can be evaluated in consideration of pullout resistance between reinforcement and ground, confining pressure of reinforcement, and a correction coefficient relevant to the direction of minor principal strain of ground.

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