Experimental Study of Reinforcing Methods for Existing Bridges on Soft Ground against Great Earthquakes (In-Cap Method)

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ABSTRACT

The foundations of many old bridges are without any doubt insufficiently resistant to level-2 earthquake motion. Therefore, we propose the anti-seismic reinforcement of existing foundations resting on soft ground (In-Cap Method). This construction method yields increased horizontal and vertical resistance by driving underground walls around the existing foundation and solidifying the ground inside.

We performed static loading experiments in clay layers at a scale of 1/30 under 1 G to examine the reinforcement effect qualitatively. We also executed static loading experiments in sandy ground with centrifugal modeling equipment at a scale of 1/50 under 50 G to examine the reinforcement effect quantitatively. This testing confirmed that the capacity of existing foundations can be increased, and measured the reduction in lateral and rotational motion and stress generated in existing piles.

Furthermore, a design model that tests a frame with the finite element method (FEM) was examined and a simulation of the above experimental results was performed. Although some disagreement was seen, the design model enabled us to simulate the load-deformation relationship with adequate accuracy. The validity of the design model was verified.

1. INTRODUCTION

It is clear that many foundations of existing old bridges are inadequate for protection against level-2 earthquake motion. When the effects of severe earthquake motion are taken into consideration in the revision of the design code, or when these structures are subjected to increased use, the insufficient aseismicity of existing bridges must be addressed.

As foundation reinforcement work generally involves very significant construction cost and time due to several factors such as the confined space under superstructures, and tends to become a large project, these works have been undertaken only infrequently in the past, compared with other types of reinforcement.

However, repetitions of events of the magnitude of the Kanto, the Tokai, the Tonankai, or the Nankai earthquake might be expected in the first half of this century(Nunomura, 2002). Disaster-prevention countermeasures for various kinds of civil structures are currently being reexamined, and development of an efficient anti-seismic reinforcing method for existing foundations is essential. Therefore, we decided to propose an anti-seismic reinforcement method for existing

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foundations on soft ground that can reduce the cost and time necessary for completion of the foundation and that can also be applied easily in a restricted space.

This method can be expected to increase the resistance to damage from both horizontal and vertical motion, by driving underground walls around the existing foundation and solidifying the ground inside. By this process, we aim to have the improved area within the surrounding underground walls perform as a foundation.

This paper describes the results of static loading experiments in clay layers at a scale of 1/30 under 1 G, and static loading experiments in sandy ground determined by centrifugal model equipment at a scale of 1/50 under 50 G. We also simulated these experiments using a design model that uses a frame with FEM elements. Although some disagreement was expected, the design model enabled to simulate the load-deformation relationship with adequate accuracy.

2. OUTLINE OF THE PROPOSED METHOD

This reinforcing method involves driving steel sheet piles to a given depth surrounding the existing foundation on soft ground, and consolidating the soil inside the sheet pile wall using a soil improvement method. Fig.1 outlines the method. Both the horizontal and vertical resistance are expected to improve with this treatment. The mechanism of resistance is shown in Table 1.

The features of the In-Cap method are as follows.

1) The construction area can be reduced because the outer sheet piles can be used as earth retaining walls.
2) The size of the structure is small, so the interference with traffic, etc., is minimal.
3) It is possible to carry this out within the limitations of a small work space with a small construction machine (sheet pile pressing machine, boring machine, etc.).

Here, this improvement method can be applied with the jet grout method using a threefold tube, with little influence on the existing structure.

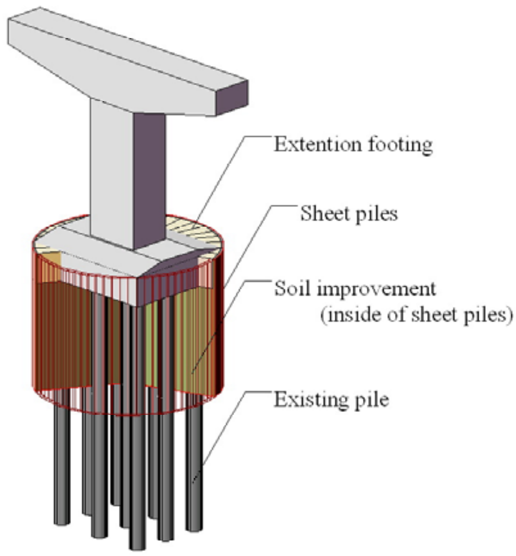


Fig.1 Outline of In-Cap Method

Table 1 Mechanism of Resistance

		Effect	Mechanizm of reinforcement
Horizontal resistance	Increase of resistance area	○	Originated in improved soil and shhet pile
	Strength increase of resistance element	×	
Vertical resistance	Increase of resistance area	○	Originated in friction of shhet pile
	Strength increase of resistance element	○	Originated in friction of between improved soil and pile
Rigid increase in base body		×	

3. STATIC LOADING TEST WITH A CLAY LAYER

Abstract of the Experiment

We executed model loading tests with a clay layer to confirm the effect of reinforcement on another soil type than sandy ground. Fig.2 shows the model container. A single pile model and group-pile model were set up in the clay layer, and static loading tests were performed. The group-pile model is shown in Fig.3. The soil used was a loam soil with water content adjusted to 55%. The average cone index was qc = 50 kN/m^2. The specifications of the model used are shown in Table 2. The experimental setup is shown in Table 3.

Two kinds of reinforcement structure were used. In Case 1 the surroundings of the footing were encased in sheet piles and in Case 2 the soil inside of the enclosure was solidified. The reinforcement depth was to 10 cm from ground level for both single pile and group piles cases.

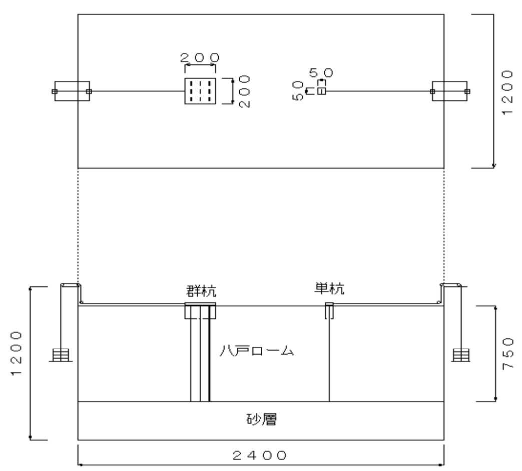


Fig. 2 Model Container

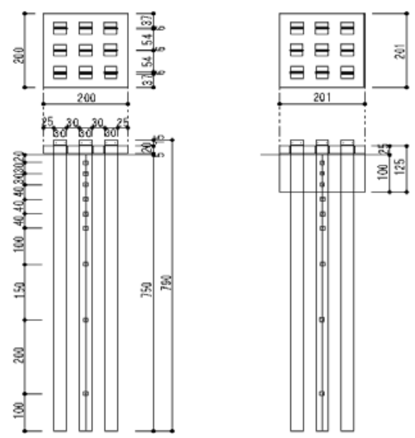


Fig.3 Group-Pile Model

Table 2 Experiment Case

Case 0	Model for existing structure
Case 1	Model for the reinforcement only by sheet piles
Case 2	Model for the reinforcement of In-Cap method

Table 3 Experimental Setup

Sheet pile	Material	Aluminium
	Size (width,depth,thickness)	200mm,100mm,0.5mm
	Moment of inertia I	0.0002 cm4
Improved area	Unconfined compressive strength qu	360 kN/m2
	Addition rate of cement	170kg/m3
Pile	Material	Aluminium
	Size (width,depth,thickness)	30mm,790mm,3.0mm
	Moment of inertia I	0.00675 cm4
Footing	Material	Steel
	Size (width,depth,thickness)	200mm,200mm,20mm

Results of the Experiment

Fig.4 shows the relationship of horizontal load and horizontal displacement in the group-pile models. The loading test was executed here with 3 mm or 1/10 of the width of the pile as the standard of loading test. Fig.4 shows that the bearing capacity are doubled or more in Case 2 compared with the existing base (Case 0), and the displacement is cut in half.

Case 1 showed intermediate behavior between Cases 0 and 2. Next, Fig.5 shows the distribution of the bending moment of the pile. The bending moment of the reinforcement compartment is very little in Case 2 while the bending moment distribution of Case 0 shows typical distribution for the group pile in the fixed condition.

Moreover, the tendency of the bending moment distribution in Case 1 shows a mode near the existing base. The effect of reinforcement with the In-Cap method was thus confirmed in the clay layer as well as in sandy ground.

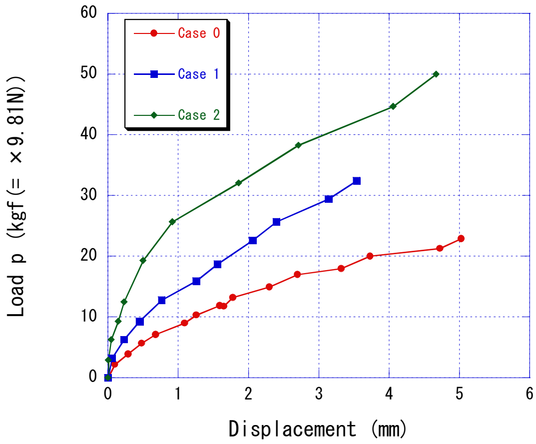


Fig.4 Relationship between P and δ

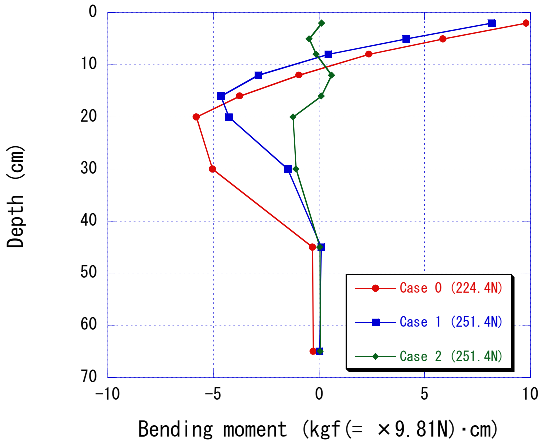


Fig.5 Bending Moment Distribution

4. STATIC LOADING TEST IN SANDY GROUND, CENTRIFUGAL MODEL

We performed the static loading experiment in sandy ground on a centrifugal model to confirm the effects of reinforcement quantitatively. The structural model was based a design example from "Reference data on reinforcement of existing Highway Bridge Foundations, Japan Highway Association (2000)." The pier model is shown in Fig.6.

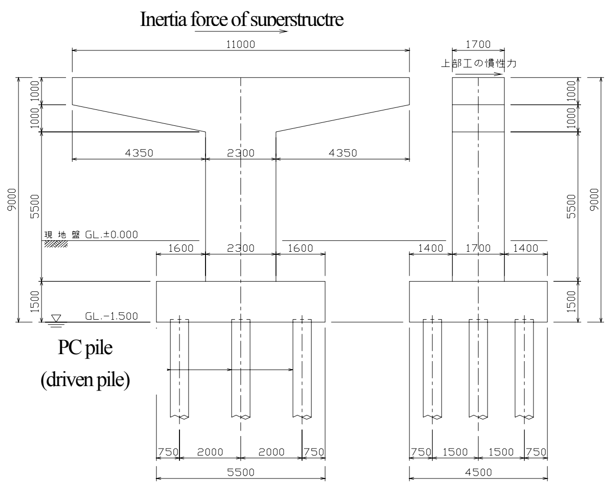


Fig.6 The Target Existing Structure

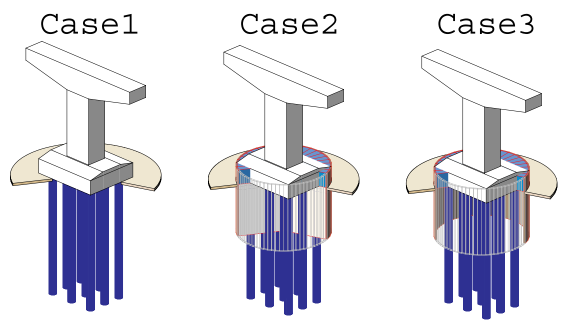


Fig.7 Experimental Setup

Abstract of the Experiment

The pier and footing are modeled at the reduced scale of 1/50. This experimental setup is shown in Fig.7. Case 1 is a model of the existing structure and case-2 is a model of the basic structure of the In-Cap method. Case 3 is a model of reinforcement by sheet piles alone.

The centrifugal acceleration is 50 G and the size of the steel container is 600 mm in length × 500 mm in width × 530 mm in height. The horizontal displacement was transferred from the electric screw jack to the model of the existing footing with the reinforcement footing set up in the container. The displacement speed was kept below 0.3 mm/min and maximum horizontal displacement was 4 mm (in terms of the real structure, 200 mm). The distance from the loading point to the bottom of the footing is 80 mm (in terms of the real structure, 4.0 m). The experiment container and the model arrangement are shown in Fig.8.

The model ground was the mixture of sand shown in Table 4, for reproducibility in the experiment. The pile head is fixed with the model footing. The bottom of pile is pinned with the model container. At the self-weight stress history stage, the vertical constraint of the bottom of pile was released so that the pile might follow to the settlement of the ground.

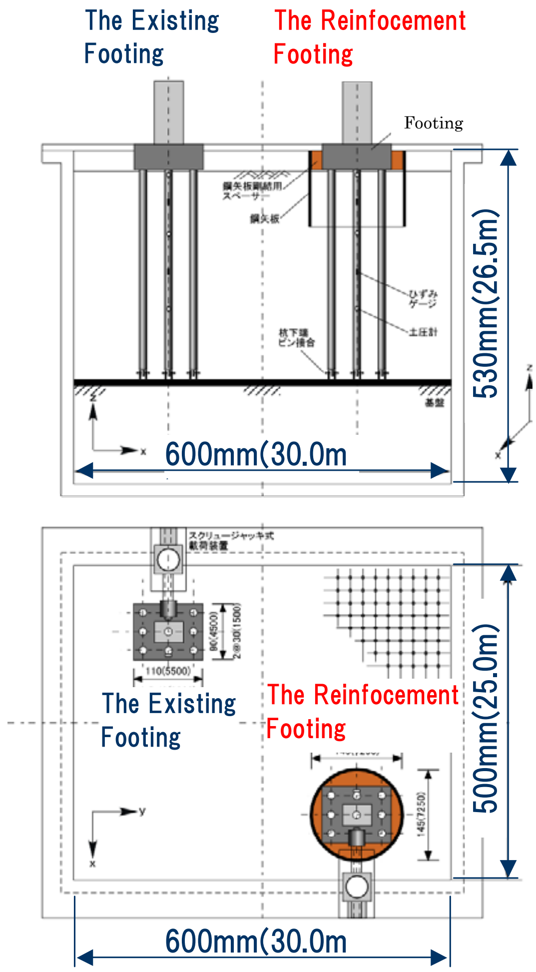


Fig.8 Experimental Container and Model Arrangement

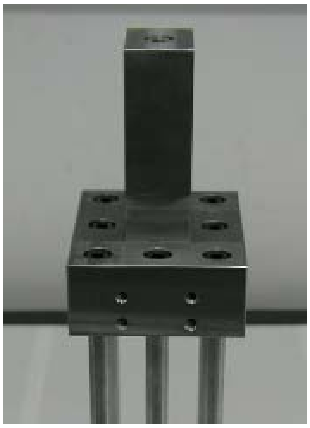
Table 4 Model Ground

Material	Toyoura sand 80% Caoline clay 20%
Compaction factor	wopt = 11.7% ρ dmax = 1.880 g/cm3
Relative density	Dr = 90 %
Strength	cd = 5.2 kN/m2 ϕ d = 33.4°

Table 5 Setup of the Model Structure

Sheet pile	Type Ⅳ	
	Material	Steel
	Cofficient of splice	α = 0.8
	Length	120mm
Improved area	Unconfined compressive strength qu	7,355 kN/m2
	Addition rate of cement	500kg/m3
	Thickness	90mm
	Diameter	144mm
Pile	Material	Aluminium
	Diameter	12mm
Footing	Material	Steel
Spacing body	Material	Aluminium

The model sheet piles were of the flat steel type and the model sheet piles were divided into eight parts in the direction of the circumference and each parts is connected with the spring steel of 0.5mm thickness to simulate the flexible joint. The head of the model sheet piles was fixed to the footing through the spacer. The setup of the model structure is shown in Table 5 and the detailed structure of the model footing is shown in Fig.9.



(a) Existing footing In-Cap method

Fig. 9 Detail of the Model Structure

The strength of the improvement of solidification in an underground wall ground was set to qu = 7355 kN/m^2 (= 75 kg/cm^2) in consideration of the average strength of the jet grout method in the field. The model ground material was added to cement milk of W/C = 0.8, and addition rate was 500 kg/m3. The mixed material was placed within an underground wall.

The measured variables were the horizontal load, the horizontal displacement at the loading point and footing, the axial and bending strain of piles, the soil pressure at the former and at the bottom of the reinforced compartment. An observation mesh and reference point were set up at ground level, and measurement of the ground movement under load was made by measuring the reference point coordinates before and after loading by the gravitational field (1 G).

Results of the Experiment

Fig.10 shows the relationship between the horizontal load and the horizontal displacement at the loading point. Fig.11 shows the bending moment distribution of the center pile at load P = 10,000 kN. Fig.10 shows that the base reinforced by the In-Cap method was able to sustain about 1.5 times greater force than the existing base, and reinforcement was confirmed to suppress the displacement by about half. Without solidification improvement, the results were intermediate between the existing base and the base reinforced by the In-Cap method.

Fig.11 shows that the bending moment of the pile with solidification improvement was almost 0 due to restraint by the solidification, while the bending moment of the existing base showed a typical distribution for the fixed pile. In Case 3, without the solidification improvement of the bending moment distribution, an intermediate value between that of the existing base and the base reinforced by the In-Cap method is indicated. The distribution shape shows a mode near the existing base without the effect of the restraint of solidification.

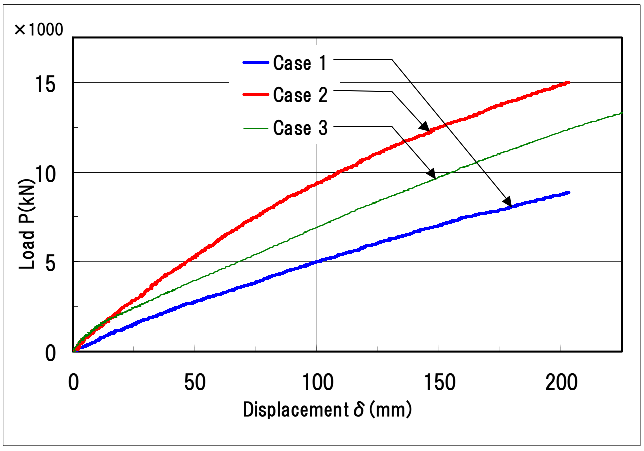


Fig.10 Relationship between P and δ

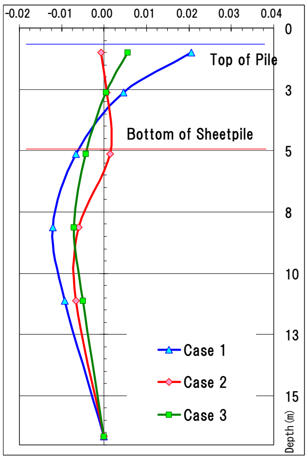


Fig.11 Bending Moment Distribution

5. APPLYING THE ANALYTICAL MODEL TO THE CENTRIFUGAL EXPERIMENT

Identification of the Ground Spring in the Centrifugal Experiment

The ground characteristics of the actual experimental model were needed to design an analytical model capable of reproducing the experimental result. In practice, we identified the ground characteristics that produced behavior similar to the experimental results by making trial calculations using the design technique in Design Codes for Japan Highway Bridges, Vol. Ⅳ as shown in Fig.12. As the bottom of the piles are pinned together, the vertical spring was omitted in the model.

A comparison of the experimental and analytical results obtained by this technique is shown in Figs.13 and 14. Fig.13 is the distribution of the bending moment of the center pile at load P = 5,000 kN, and Fig.14 shows the relationship between load and horizontal displacement (P-δ relation) at the loading point.

The distribution of the measured bending moment was approximated to the fifth polynomial functions, and the spring value k of the ground was calculated from the following expression using the relationship between ground reaction force p and displacement w. Expression (1d) is the boundary condition of expression (1c).

$$k = \frac{p}{w} \qquad \cdots\cdots\cdots\cdots(1a)$$

$$p = \frac{d^2M}{dz^2} \qquad \cdots\cdots\cdots\cdots(1b)$$

$$w = -\frac{1}{EI}\iint M dz^2 \qquad \cdots\cdots\cdots\cdots(1c)$$

$$\begin{aligned} top:&\quad z = -3.0\text{m}, \theta = \theta_0 \\ bottom:&\quad z = -19.0\text{m}, \theta = 0 \end{aligned} \qquad \cdots(1d)$$

Fig.15 compares the ground spring distribution at load P = 10,000 kN with the experimental result, demonstrating its validity. A decrease in the ground spring value in surface regions is seen in both cases due to ground plasticity. The ground spring value seems to be large in the deeper region, but it is thought that it is roughly within the range 1/β (β=0.189 m-1) of π/2β. This indicates that the identified ground characteristics are suitable for practical use.

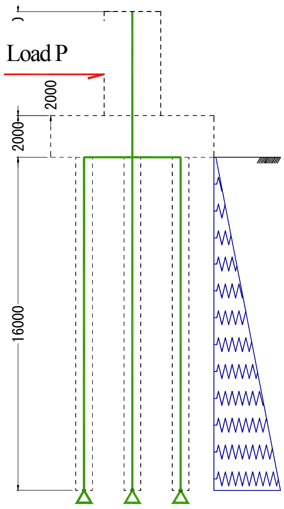


Fig.12 Design model

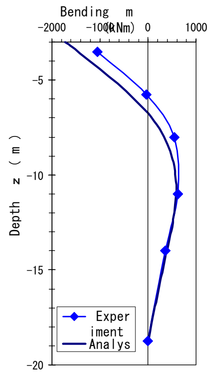


Fig.13 Comparison of bending moment

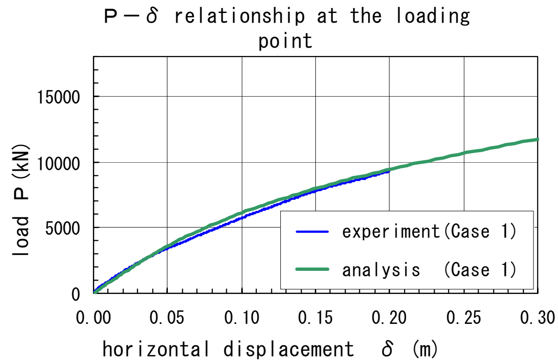


Fig.14 comparison of P - δ

Comparative Study by Analytical Model

It is thought that an existing footing reinforced by this method should produce an increase in ground resistance in the horizontal direction shown in Table 1.The reinforced footing becomes a compound footing structure.

Table 6 shows the ground resistance elements for this reinforced footing with the existing pile and reinforced part. These resistance elements are quoted from the pile foundation and the caisson foundation of Design Codes for Japan Highway Bridges, Vol. Ⅳ. We created a simple FEM model as an analytical model and reproduced the reinforced model of Case 2 and compared the analytical study with the experimental result.

Fig.16 shows the model used in the simple FEM analysis. The structure of each material was modeled with the beam material, and the ground resistance element shown in Table 6 was arranged in each part as a spring material. As the pile bottom is pinned in the experiment model, the axial spring constant value Kv of the pile was omitted. The reinforcement part is set up the plane element division as the improvement body as shown in figure.

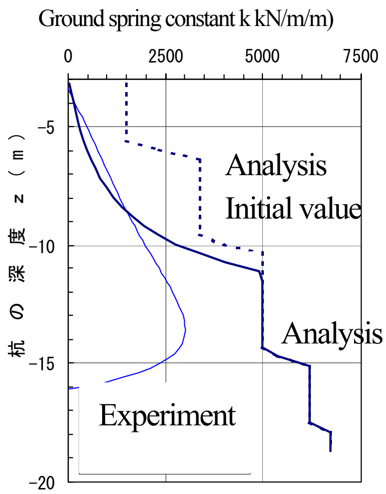


Fig.15 Ground Spring Distribution

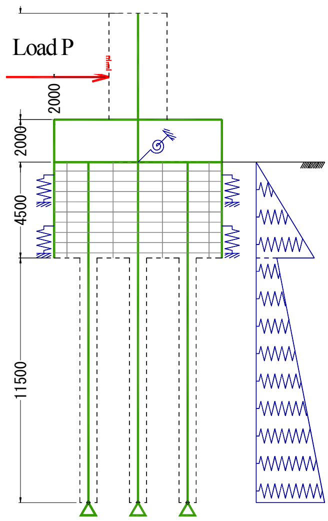


Fig.16 Design Model with FEM

Table 6 Ground Resistance Element

Resistance elements of existing structure (pile foundation)		kH : coefficient of horizontal subgrade reaction of pile
		kV : coefficient of axial spring of pile
Resistance elements of reinforcement (casion foundation)	Horizontal resistance	kH : coefficient of horizontal subgrade reaction of front sheet pile
		kSHD : coefficient of horizontal shear subgrade reaction of side sheet pile
	Vertical resistance	kSVB : coefficient of vertical shear subgrade reaction of front and back sheet pile
		kSVD : coefficient of vertical shear subgrade reaction of side sheet pile

The analytical result is shown in Figs.17 and 18. Fig.17 is the distribution of the bending moment of the center pile at load P = 5,000 kN, and Fig.18 is the relationship between load and horizontal displacement (P-δ relation) at the loading point.

It is understood that the analytical result only approximately reproduces the experimental result of the P-δ relationship. Nevertheless, it can be said that the simple FEM analysis model is appropriate because it is likely to lead to errors on the safe side when viewed as a design model.

Also, the simple FEM analysis model can roughly reproduce the bending moment distribution of piles both inside and outside of the improved area. However, the bending moment at the boundary of the reinforced part is very large.

It is thought that this tendency is similar to the section force at the top of pile in an ordinary pile foundation, and the section force is caused by the difference of the relative rigidity of a foundation improved by ground solidification.

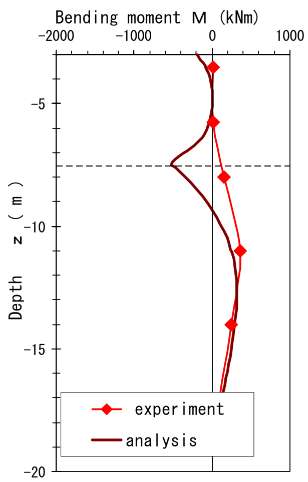


Fig.17 Comparison of bending moment

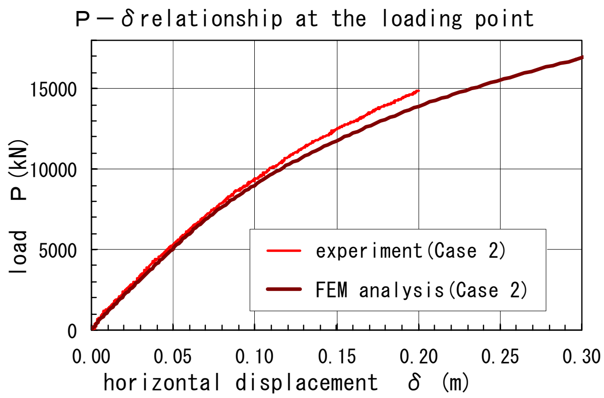


Fig.18 Comparison of P- δ relation

6. CONCLUSION

To quantitatively evaluate the effect of reinforcement by the In-Cap method, both experiments and analyses were carried out. The main conclusions are

1) It was confirmed that reinforcement with the In-Cap method and overall solidification could decrease the horizontal displacement by about half, and could increase the bearing capacity of the foundation by a factor of about 1.5 in the centrifugal model experiment.

2) It was confirmed that the maximum bending moment of the pile that is restrained in the improved area is decreased by this reinforcing method, and there was a decrease in the bending moment over the total length of the pile.
3) The effect of reinforcement with the In-Cap method was confirmed in the clay layer as well as in sandy ground.
4) The ability of a simple FEM analysis to reproduce the effect of this reinforcement method was confirmed.

However, we will continue performing studies to evaluate the behavior at the bottom of the improved area and the influence of the support conditions at the bottom of the pilings, among other things.

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