Two-dimensional model experiments on the pile group effect on existing piles by using additional piles with different properties

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ABSTRACT

Advancements in press-in have machines facilitated the penetration of piles. In line with this trend, the additional pile method is expected to be useful for the seismic reinforcement of existing pile foundations. In the additional pile method, differences in pile stiffness and length are assumed. However, its effect on reinforcement has not yet been studied. Therefore, in this paper, model horizontal loading experiments were conducted in which the pile stiffness was varied. The experiment results showed that the reduction effect and bearing capacity of the entire foundation increased with the stiffness of the additional piles. Furthermore, the image analysis results showed that the magnitudes of the compressive and passive areas of the existing piles in the ground changed with the influence of pile stiffening during the horizontal loading tests conducted on the piles. From these results, it is necessary to consider the difference in the stiffness of the additional piles, which affects the strain area and the conventional pile diameter ratio, when designing the additional pile method.

Key words: *Pile group effect, Image analysis, Additional pile method, Aluminum rod*

1. Research Background

Advances in press-in machines have facilitated the penetration of piles. Accordingly, the additional pile method will provide earthquake-resistant reinforcement for existing pile foundations.

In this method, new piles are driven around an existing pile foundation. The reinforcement effect of this method is twofold: an increase in the overall bearing capacity of the foundation and a reduction in the load on existing piles.

This reduction is caused by the group-pile effect. The typical evaluation of the group pile effect is determined by the ratio of the separation distance to the pile diameter, assuming that the same piles are used for the existing and additional piles.

However, different piles may be used in the additional pile method because additional piles are later added to the existing pile foundation. In this situation, reasonable and economical reinforcement requires a proper understanding of the interactions between the existing and additional piles.

In this paper, two-dimensional model experiments were conducted to simulate the ground behavior of two piles with different stiffnesses on the centerline. The two piles considered are existing and additional piles. Moreover, the bending stiffness of the model with additional piles and the separation distance between the two piles were varied. The load–displacement relationship during loading was examined to determine the effect of reducing the load on existing piles. Image analysis investigated the relationship between the reduction effect and ground behavior.

2. Experiment summary

2.1 Model ground and model pile

Figure 1 shows an overview of the experimental apparatus, whereas **Figure 2** shows the aluminum rod model. Three types of aluminum rods, each 150 mm long and with thicknesses of 1.5 mm, 2.0 mm, and 3.0 mm, were mixed at equal weight ratios as the model ground material. This material was used to create ground that is 700 mm wide and 280 mm high. The unit volume weight was 21.8 kN/m^3, and the porosity was 17.6%.

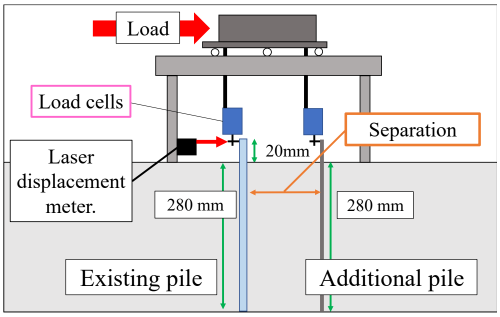

Fig. 1 Experimental apparatus

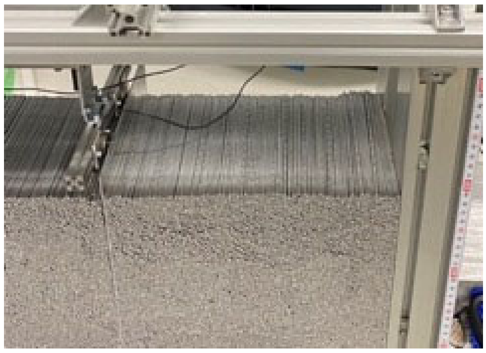

Fig. 2 Aluminum rods

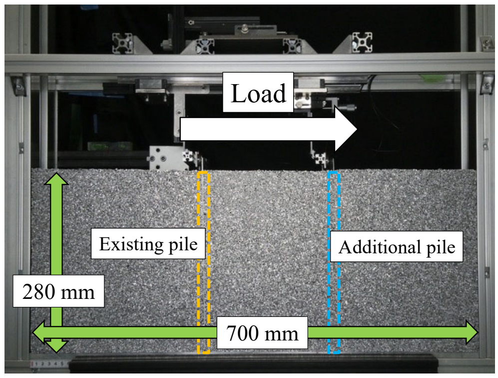

Fig. 3 Model ground

When the model ground was prepared, the model piles were installed by stacking aluminum rods of up to 150 mm, which was approximately half the rooting length of 280 mm. At this point, the model pile penetrated vertically to the bottom. The remaining aluminum rods were stacked to create the ground. **Figure 3** shows the model ground at completion.

All model piles were simulated using aluminum plates (Young's modulus E = 73 GPa) that were 200 mm wide and 300 mm long. The plate thicknesses were 2.0 mm, 1.5 mm, and 1.0 mm. These penetrated the model ground to simulate the piles in two dimensions.

2.2 Measurement Method

As shown in **Figure 1**, a load cell was placed at the top of each model pile, and a direct point load was applied to the receiving section. The load cell was installed such that the displacements of the two piles were comparable, and the load was applied to both piles simultaneously.

The horizontal displacement during the loading was measured using a laser displacement meter at the loading point height of the existing pile. The rotation of the pile head was not constrained. For image analysis, the ground was photographed from the front every 4 s during loading. As a static loading experiment, a sufficiently slow load was applied (0.01mm/s).

2.3 Experimental case

For the experiments, 1.5 mm thick piles were used for the existing piles, and the thickness of the additional piles varied between 1.5 mm, 2.0 mm, and 0.8 mm, as shown in **Table 1**. In each combination, the separation distance varied from 30 mm to 210 mm at 30 mm intervals. A total of 24 cases were considered, including single piles experiments.

Table 1. Experimental case

	Additional pile thickness		
	A	B	C
	1.5 mm	2.0 mm	0.8 mm
separation distance	30 mm		
	60 mm		
	90 mm		
	120 mm		
	150 mm		
	180 mm		
	210 mm		

2.4 Similarity rule

On the similarity side of the pile, βL was set to a value close to that of the real structure. **Table 2** lists the β and βL values for each model pile. β indicates the stiffness ratio of the pile to the soil, as defined in **Eq. 1**. β was back calculated from the load of 1 mm pile head displacement in the single experiment on the model piles using **Eq. 2**. (Chang, 1937)

Table 2. Pile characteristic values

	t=2.0 mm	t=1.5 mm	t=0.8 mm
β (1/mm)	0.0095	0.01178	0.01792
βL	2.66	3.30	5.02

$$\beta = \sqrt[4]{\frac{k_h B}{4EI}} \tag{1}$$

$$y_t = \frac{(1+\beta \cdot h)^3 + \frac{1}{2}}{3EI \cdot \beta^3} H \tag{2}$$

Here, y_t is the horizontal displacement at the loading point, H is the pile head load, I is the sectional secondary moment, h is the height at the loading point, k_h is the horizontal coefficient of the subgrade reaction, and B is the foundation width (150 mm).

βL is multiplied by the pile rooting depth L = 280 mm. All model piles satisfy the condition that $\beta L > 2.5$, which allows them to be treated as semi-infinite-length piles in the pile design.

Here, the similarity rule for pile separation is summarized. In standard design practice, evaluating the interaction of group pile foundations with identical piles often involves normalizing the pile center spacing by the pile diameter. In addition, Japanese design standards for railroads and roads specify a minimum pile center spacing of 2.5 times the pile diameter (1.5 times the pile diameter for spacing between pile surfaces). In this experiment, the pile diameter in the model was not clear because the pile was modeled using a 2-dimensional plate. Therefore, in this experiment, as a similarity rule for pile diameter D, we first consider that the dimensionless quantity obtained by multiplying β in **Eq. 1.** by the pile diameter D is equivalent between the real and model.

An analysis of case studies of horizontal loading tests on actual piles in Japan confirmed that the value of βD ranged from 1/3 to 1/5 (Nakatani et al., 2009). Using β calculated from this method, the largest D among the model piles was 26.3 mm.

From the reference, a displacement of 10% of the pile diameter is considered sufficient for horizontal loading of the pile (Nakatani et al., 2009). In this experiment, the maximum displacement was set at 3 mm, which meets 10% of 26.3 mm, to ensure that all piles were fully loaded.

Figure 4 shows the coefficient of the horizontal subgrade reaction, k_h, for the single experiments on the model piles at horizontal displacements of 1.0 mm, 2.0 mm, and 3.0 mm. Generally, the coefficient of the

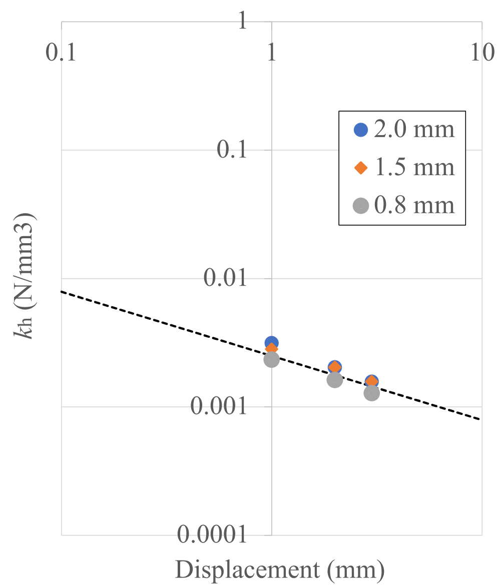

Fig. 4 Coefficient of horizonal subgrade reaction

horizontal subgrade reaction of a pile is proportional to the -0.5 power of the foundation displacement (indicated by the black dotted line) (Nishioka et al.,2011).

The figure shows that each model pile satisfied this value and simulated the general relationship between the pile and the ground.

3. Experimental results

3.1 Load displacement relationship

Figures 5, 6, and 7 show the load–displacement relationships of the existing piles in each experiment. For reference, the load-displacement relationship for single experiments on the model piles is also shown.

3.2 Pile head load

Figures 8, 9, and 10 show the loads generated in the experimental cases for each type of additional pile when a 3 mm load was applied. The blue and orange bars represent the loads on the existing and additional piles, respectively.

First, we focused on the experiment with the 1.5 mm additional pile. In all cases, the load generated on the existing pile was smaller than that of the single pile. Moreover, a reduction effect occurred owing to the group pile effect. The magnitude of this reduction effect tended to be stronger when the separation distance was shorter. The foundation load with the two bars combined was greater than 25.32 kN in all cases. The additional piles improved the foundation load, regardless of the separation distance.

Second, we focused on the experiment with the 2.0 mm additional pile. In most cases, the load on the existing pile was smaller than that on the single pile, as in the experiment with the 1.5 mm additional pile. The separation distance tended to be the same as in the experiment with an additional pile of 1.5 mm. Compared to the 1.5 mm additional pile experiment at the same separation distance, the loads on the existing pile in the 2.0 mm additional pile experiment were smaller than those in the 1.5 mm additional pile experiment at all separation distances. Although the load on the existing pile was reduced, the overall load on the foundation was higher than that in the experiment with the 1.5 mm additional pile because of the more significant load on the additional pile.

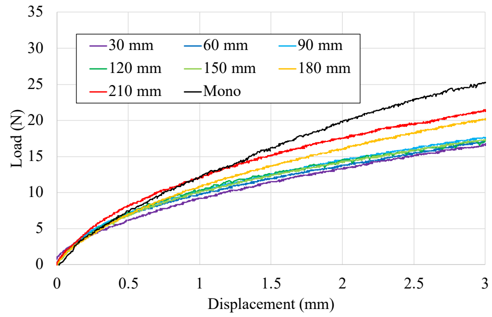

Fig. 5 Load displacement relationships (additional pile 1.5 mm)

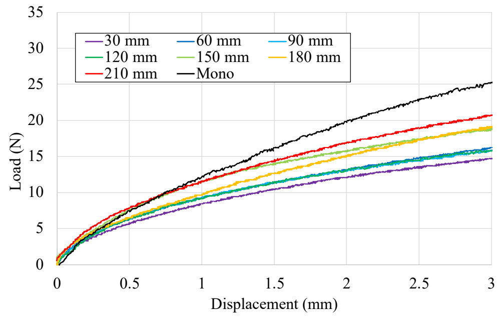

Fig. 6 Load displacement relationships (additional pile 2.0 mm)

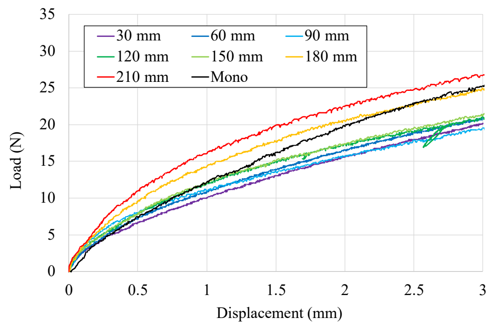

Fig. 7 Load displacement relationships (additional pile 0.8 mm)

Third, we focused on the experiment with 0.8 mm additional piles. Here, the load on the existing pile was close to that of the single pile at separation distances of 180 mm and 210 mm. In other cases, the larger the separation distance, the smaller the load. In all cases, the load on the existing pile with the 0.8 mm additional pile was greater than that with the 1.5 mm additional pile when compared to the experiment with the 1.5 mm additional pile at the same separation distance. In addition, the load

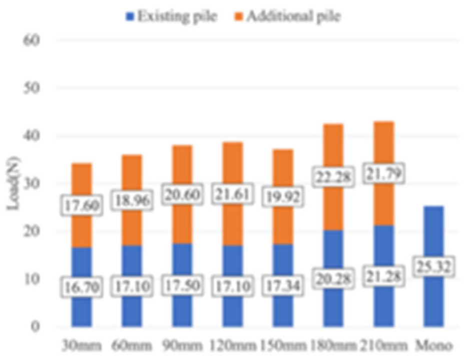

Fig. 8 Pile head load (additional pile 1.5 mm)

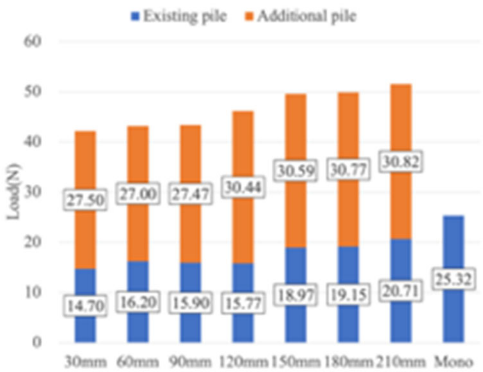

Fig.9 Pile head load (additional pile1.5 mm)

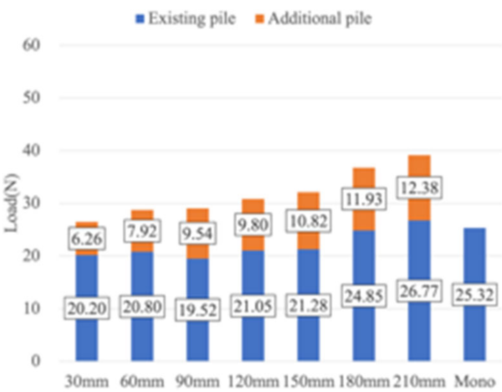

Fig. 10 Pile head load (additional pile 0.8 mm)

on the existing pile exhibited a higher value; however, the load on the additional pile was smaller, and the overall load on the foundation was smaller than in the experiment with the 1.5 mm increase pile.

Therefore, the additional pile method is conventionally considered to use the same piles, and the reduction effect is evaluated only by the separation distance ratio and pile diameter ratio. However, different combinations of piles have different reduction effects. The larger the additional pile, the higher the reduction effect and the smaller the load generated on the existing pile. In addition, the load on the existing piles decreased; however, the load on the additional piles increased; thus, the bearing capacity of the entire foundation also increased. The reduction ratios are listed in **Table 3**. This shows the ratio of the reduction effect to the load when the reduction effect is independent of each experimental case.

Table 3. Reduction ratio

(%)	Additional pile thickness		
	A	B	C
	1.5 mm	2.0 mm	0.8 mm
30 mm	34.1	41.9	20.2
60 mm	32.5	36.0	17.9
90 mm	30.9	37.2	22.9
120 mm	32.5	37.7	16.9
150 mm	31.5	25.1	16.0
180 mm	19.9	24.4	1.8
210 mm	16.0	18.2	-5.7

3.3 Image analysis result

This difference in reduction is understood to be owing to the influence of behavior on the ground.

Figure 11 shows the horizontal strain up to a displacement of 3 mm obtained from the image analysis of the single-loading experiment. The results showed that when displacement occurred, compressive and expansive strain areas occurred on both sides of the pile. The red region indicates expansion, whereas the blue region indicates compression. The extent of the area was larger in the cases with larger plate thicknesses. Image analysis was performed using DippStrain software (Ditect).

Figures 12, 13, and **14** show the image analysis results for each additional pile thickness.

From these figures, in the experiment with two piles, the strains between the two piles are smaller due to the influence of each other. And the change in strain occurs to a greater extent for those with smaller separation distances.

It can also be seen that at the same separation distance, the change in strain is stronger the larger the plate thickness of the additional pile.

This is because the expansion strain of the additional piles causes the ground between the piles to expand and compress the existing piles to a shallow depth. The

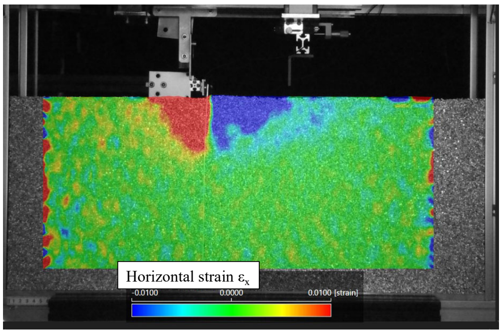

Fig. 11 Image analysis result (single)

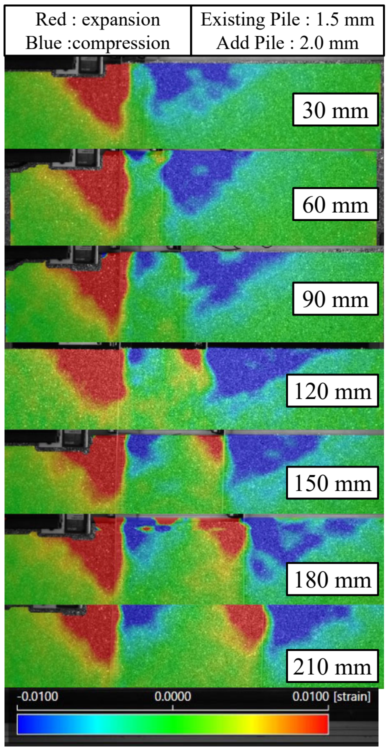

Fig. 13 Image analysis result (additional pile 2.0 mm)

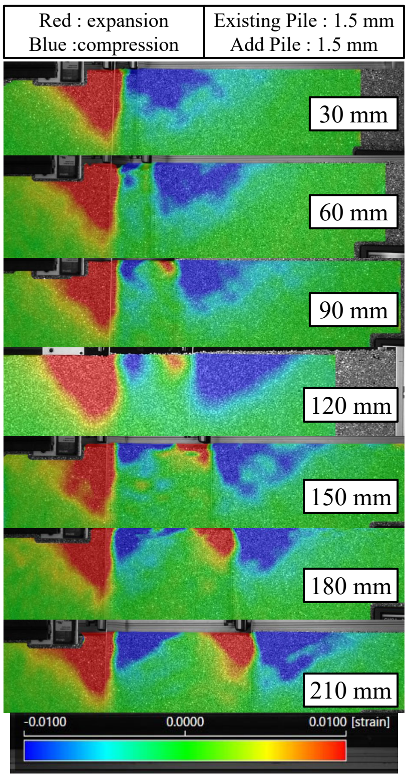

Fig. 12 Image analysis result (additional pile1.5 mm)

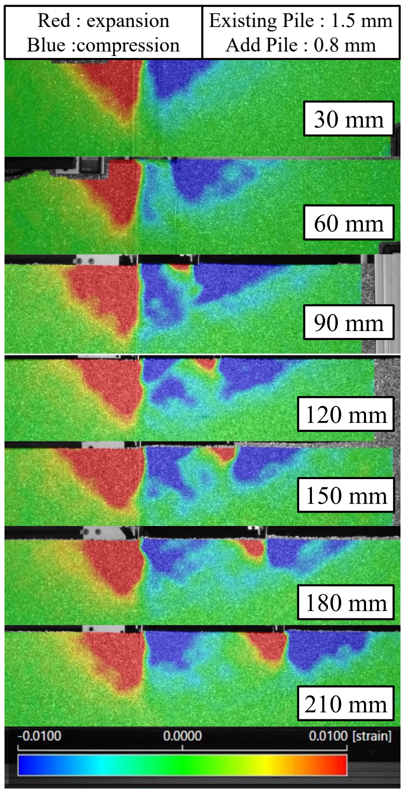

Fig. 14 Image analysis result (additional pile 0.8 mm)

greater the thickness of the additional pile, the greater the expansion strain, which is thought to cause this change.

This trend is the same as the resistance to reduction effect.

3.4 Relationship between reduction effect and ground strain

To evaluate the relationship with the reduction effect, a strain area was assumed, as shown in **Figire 15**. The magnitude was determined using the depth of no displacement and the angle based on Rankine's earth pressure theory.

The depth of no displacement is the shallowest depth at the pile where no subgrade displacement occurs. It is determined using Chang's equation (**Eq. 3**).

$$l = \frac{1}{\beta}\tan^{-1}\frac{1+\beta h}{\beta h} \tag{3}$$

This assumption was made because the strain in the ground caused by the pile loading was caused by the ground being pushed by the pile.

Figure 16 shows the assumed overlap of the two generated strain areas. The size of the overlapping area between the compression area of the existing pile and the expansion area of the additional pile, as shown in the red box, is considered to affect the reduction effect. Therefore, overlapping areas were calculated. The overlap ratio is the ratio of this area to the compressive-strain area of an existing pile.

Figure 17 shows the relationship between the reduction and overlap ratios. This figure shows that the reduction effect also increases proportionally as the overlap ratio increases.

The reduction effect on existing piles depends on the change in the strain area. This trend has a single relationship even if the additional piles are different.

Because different pile stiffnesses produce different strain areas, the combination of piles significantly affects the reduction effect.

4. Conclusions

The magnitude of each pile load at the same displacement in this experiment indicates the magnitude of the ground resistance and the degree to which these changes from the resistance of each pile correspond to the pile group effect.

The results of this experiment indicated that the reduction effect of the existing piles changed with the thickness of the additional piles.

The larger the plate thickness of the additional pile, the larger the reduction effect. The relationship between the two rates suggests that the magnitude of the reduction depends on the overlap of the sliding soil mass. For the pile group effect with different types of piles, it is necessary to consider the composite of piles, which affects the size of the strain area.

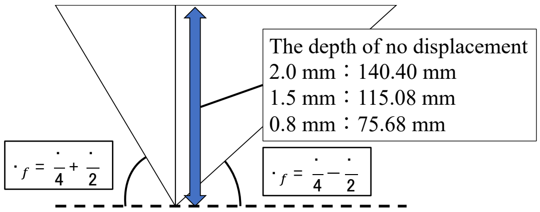

Fig. 15 Calculation of the strain area

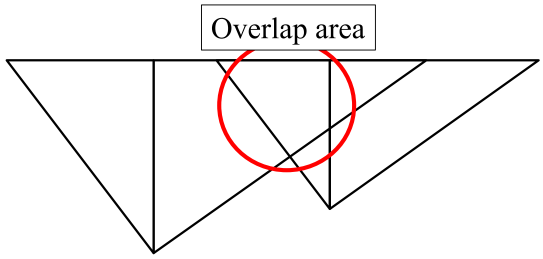

Fig. 16 Overlap area

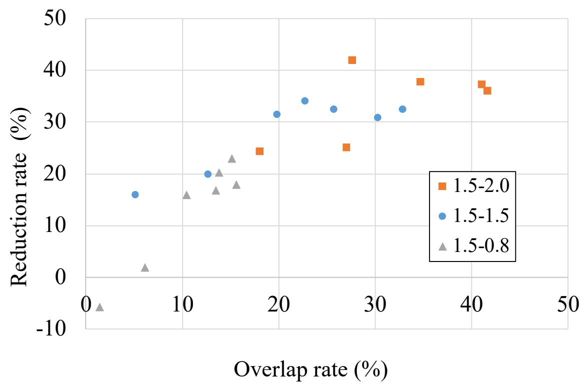

Fig. 17 Relationship between the reduction ratio and overlap ratio

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