Numerical analysis of load share mechanism of additional piles subjected to seismic load

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ABSTRACT

The additional pile method is a technique used to reinforce existing foundations by piles and footings. The main problem with this method is that it takes a lot of time and effort to combine the existing foundation and the additional foundation. Another problem is that the design of this method cannot be sufficiently rationalized because the load share mechanism is unclear due to the generation of the pile group effect. The objectives of this study are to develop a new high-workability combining method and to investigate the load share mechanism of the reinforced foundation. In this paper, 1G seismic loading tests are conducted on group piles, namely, 4 existing piles and 6 additional piles. Then, a simulation analysis of the loading tests is performed. Finally, a parametric analysis that simulates the superstructure and the steel outer shell is conducted.

Keywords: additional pile method, FEM analysis, pile group effect, 1G seismic experiment

1 INTRODUCTION

Lessons from The Great East Japan Earthquake have increasingly pointed out the importance of incorporating seismic reinforcement in the design of structures. The additional pile method is the most popular technique for the seismic reinforcement of foundations. It is employed to reinforce existing foundations through the use of piles and footings.

The main problem with this method is that it takes a lot of time and effort to combine the existing foundation and the additional foundation (Photo 1). To combine the two footings, it is necessary to chip the side of the existing footing concrete and expose the main rebar, and then to drill the top side of the footing and install a steel bar as a connector. Due to the above problem, a new high-workability method to connect the existing footing and the additional footing needs to be developed. At the end of this study, a new structure, shown in Fig. 1, will be suggested.

Another problem is that the design of the method cannot be sufficiently rationalized because the load share mechanism is unclear due to the generation of the pile group effect. The pile group effect has been investigated by many researchers using model tests, in-situ loading tests and numerical analyses, etc. (Poulos, 1964; Tamaki et al., 1971; Shibata et al., 1989). However, the mechanism has still not been completely clarified. The pile group effect for the elastic range has been evaluated quantitatively by e.g., Tamaki's experimental equation (Tamaki et al., 1973) and

Photo 1. Construction of additional pile method

Fig. 1. New high-workability additional pile method

Fig. 2. Test cases

Fig. 3. Experimental and simulation analysis conditions

Randolph's solution (Randolph, 1981), calculated from the influence coefficient between the piles (Poulos, 1964). From the equation, the major factors of the pile group effect are: (1) the spacing between the piles, (2) the degree of fixation at the pile head, (3) the arrangement of the piles and (4) the relative stiffness between the piles and the ground. However, these factors are unclear for the additional pile method, leading to difficulties in the calculation of the load share of the existing and the additional foundations.

The objectives of this study are to develop a new high-workability combining method and to investigate the load share mechanism of the reinforced foundation in order to suggest a rational design method for the additional pile method.

2 CONDITIONS OF 1G SEISMIC LOADING TESTS AND SIMULATION ANALYSIS

Seismic loading tests on group piles, using a 1G shaking table, and a FEM simulation analysis were firstly conducted to investigate the influence of combining the footings and the load share mechanism.

Next, a parametric analysis of group piles, covered with a steel outer shell that included a superstructure, was conducted to investigate the influence of the steel outer shell footing. The test cases are shown in Fig. 2.

2.1 Conditions of 1G seismic loading tests

An outline of the 1G seismic loading tests is given in Fig. 3(a). 4 piles of the existing foundation are reinforced by 6 piles of the additional foundation; they are arranged in a Toyoura sand ground ($D_r = 85\%$).

The model piles are made of PVC ($E = 3.3\text{GPa}$) and the pile tips are fixed on the bottom of the chamber using a steel pedestal. The footings are made of mortar ($w/c = 65\%$) and adhered to the pile heads through steel pile caps. The existing and the additional footings are adhered to each other in Case-1a (combined) and not adhered to each other in Case-1b (not combined).

As shown in Fig. 3(a), strain gauges are attached to the piles to measure the shear force, the axial force and the bending moment. A laser displacement gauge is arranged in front of the additional footings to measure the lateral displacement of the footings. The input acceleration to the 1G shaking table is shown in Fig. 4.

In addition to these tests, static lateral loading tests are also conducted for comparison with the seismic loading tests. Static load was applied to the footings in one direction by using a pulley and a steel weight.

2.2 Conditions of simulation analysis in the tests

The simulation analysis of the 1G seismic loading tests was conducted using a 3-dimensional elasto-plastic finite element method (FEM). The FEM code is DBLEAVES (Ye et al., 2007). The FEM mesh is shown in Fig. 2(b). The piles were modeled by elastic hybrid models (Zhang et al., 2004); the ground was modeled by the subloading t_{ij} model (Nakai et al., 2004). The parameters were set as seen below.

The elastic parameters of the void ratio = 0.64, Poisson's ratio $\nu = 0.32$ and soil particle density $\rho_s = 2.65 \text{ g/cm}^3$ were determined by the test conditions.

The elastic parameters of the principal stress ratio = 3.2, the density parameter = 60 and the dilatancy parameter = 2.0 were determined by referring to a past study using Toyoura sand. The damping ratio was assumed to be 0.05. Swelling index κ was calculated by equation (1). Compression index λ was assumed to be 5 κ . Young's modulus E in this equation was set at 1/2.7 of Young's modulus in the penetration tests (shown in Fig. 5) so that the results of the static loading tests could be simulated by FEM with sufficient accuracy.

$$\kappa = \frac{3(1-2\nu)(1+e)p}{E} \quad (1)$$

In Case-1b (not combined), the elastic perfectly plastic model of the joint element was arranged at the boundary between the existing footings and the additional footings. The parameters of the joint element were chosen such that the results of the seismic loading tests on the series two group piles (shown in Fig. 6) could be simulated by FEM with enough accuracy. These loading tests were conducted for two cases, namely, when pile footings were combined and when they were not combined.

2.3 Conditions of parametric FEM analysis

The FEM mesh is shown in Fig. 7. The conditions of this parametric analysis are the same as those of the simulation analysis, except as shown below.

A pier and a superstructure model were added to the upper surface of the existing footings through the additional footings. The height at the top of the superstructure is 160 mm (10 m in prototype).

According to common structures, the self-weight of the superstructure was determined to be equal to that of the pier, and the total self-weight of both of them was set to be equal to that of the existing foundation.

The node of the pier was not sheared with the additional footings. This means that the pier and the additional footings do not transfer force to each other.

In Case-2c, the side surfaces of the additional footings were surrounded by a steel outer shell. The shell is composed of a solid elastic element. The parameters are

Fig. 4. Acceleration of shaking table

Fig. 5. Results of portable cone penetration test

Fig. 6. Seismic loading tests of series two group piles

Fig. 7. FEM mesh in parametric analysis

Fig. 8. Procedure of shear force at pile head per pile (test and FEM simulation)

Fig. 9. Load share distributions

the same as steel, $E = 2.0 \text{ GPa}$, $\rho = 7.9 \text{ g/cm}^3$ and $\nu = 0.3$. The thickness of the shell was set to be thick ($= 9 \text{ mm}$) to make the influence of the steel outer shell clear.

3 RESULTS

3.1 Results of tests and simulation analysis

The procedure of the shear force at the pile head is shown in Fig. 8. This shear force was calculated as an average of each foundation. At all times, the load share of the existing piles (dotted lines) was lower than that of the additional piles (real lines), especially in the tests. In Case-1a in the FEM simulation, around 20% larger shear force was generated. This is supposed to be because of the influence of the relative displacement between the ground and the foundation, although finding the exact cause will require more research. However, there is not a large distinction in vibration mode or quantity between Case-1a and Case-1b. Therefore, both foundations are integrated without combining them.

Load share distributions are shown in Fig. 9. The

load share is the shear force of each pile that is normalized by the front pile. From the results of the FEM simulation and the tests, the load share of the front pile is found to be the largest and that of the existing piles in the center is the smallest. Additionally, the load share of the existing piles in the dynamic case is lower than that in the static case. This indicates that the group piles subjected to seismic load influence the pile group effect more than when they are subjected to static load. These results show the same tendency as the past static loading tests and FEM simulation shown in Fig. 9(b) (Shibata et al., 2007, Teramoto et al., 2014). Therefore, the load share mechanism of seismic loaded group piles is close to that of static loaded group piles, and the amount of pile group effect generated is larger.

3.2 Results of parametric FEM analysis

The procedure of the shear force at the pile head for each pile is shown in Fig. 10. The amplitude of the shear force and the load share of the existing piles are shown in Table 1. The amplitude of the shear force is calculated as shown in Fig. 10. From a comparison of

Fig. 10. Procedure of shear force at pile head per pile (parametric FEM analysis)

Table 1. Load share of existing pile

	Amplitude of shear force (N)		Load share (b)/(a)
	(a) Additional pile	(b) Existing pile	
Case-2a	24.6	5.0	0.20
Case-2b	32.7	12.5	0.38
Case-2c	28.3	7.6	0.27

Fig. 11. Bending moment distributions

Fig. 12. Axial force distributions

Case-2a (combined) and Case-2b (not combined), larger shear force is generated in Case-2b; that is the same tendency seen between Case-1a and Case-1b in the simulation analysis. Additionally, an approximately middle quantity of shear force is generated in Case-2c.

This is also because the rotating stiffness of the foundation in Case-2b is the lowest and the relative displacement between the foundation and the ground become the largest. The total shear force in the pile head is equal to the total applied lateral load in the case

of the static loaded group piles. On the other hand, in the case of the seismic loaded group piles, the larger relative displacement of the foundation, the larger the shear force is.

The load share of the existing piles is the largest in Case-2c and the smallest in Case-2a. In other words, the greatest pile group effect is generated in Case-2a. This is because the degree of fixation at the pile head (rotating stiffness of the foundation in a broad sense) is higher in Case-2a due to the combined footings. The

higher the fixation is, the larger the pile group effect is generated (Tamaki et al., 1971).

The bending moment distribution for each pile is shown in Fig. 11. The maximum bending moment of the existing piles is somewhat larger in Case-2a than in the other cases; however, the difference is not large. In all the cases, the bending moment distribution of the front pile has the same shape as common static loaded group piles; however, the other piles are different. From past static loading tests (Teramoto et al., 2014), the maximum bending moment of piles that influence the group pile effect is smaller than the other piles. Therefore, from these results, seismic loaded group piles are also seen to generate a larger pile group effect than static loaded group piles.

The axial force distribution of each pile is shown in Fig. 12. The initial stress of the self-weight is excluded from this axial force and only the variation due to vibrations is calculated. Outside piles generate large axial force, while inside piles generate small axial force. This is the same tendency as that seen for laterally loaded common group piles. The amount of axial force in Case-2a is larger than that in the other cases. After considering the fact that the bending moment in Case-2a is larger than that in the other cases, the group piles in Case-2a are seen to resist external force by bending stiffness compared to the other cases.

4 CONCLUSIONS

1G seismic loading tests on group piles and a simulation analysis for the tests, as well as a parametric analysis, have been conducted. The conclusions drawn from the results of the tests and the simulation analysis are given as follows.

- 1) The load share of existing piles was found to be lower than that of the additional piles. The FEM results showed that this difference was smaller, although the tendency was the same.
- 2) The shear force in the not combined case in FEM was larger than that in the combined case at around 20%. However, there was no large difference between the combined case and the not combined case in terms of the vibration mode or the load share. That means the existing foundation and the additional foundation were integrated without combining the footings.
- 3) The load share of the front pile is the largest and that of the existing piles (positioned in the center) is the smallest. This tendency is the same as that of the static tests for the additional piles and in the static tests in the past study. Moreover, the seismic loaded group piles generated a larger pile group effect than the static loaded group piles.

The conclusions from the parametric FEM analysis are given as follows.

- 4) The shear force in the combined case was found to

be smaller than that in the not combined case; this is the same tendency as that seen in the simulation analysis. And the shear force in the not combined case was reduced by surrounding the piles with the steel outer shell. This is supposed to be the relative displacement between the piles and the ground due to the difference in the rotating stiffness of the foundation.

- 5) From the load share of the existing piles, the largest pile group effect was generated in the combined case. This is also supposed to be due to the rotating stiffness of the foundation.
- 6) The bending moment of the back piles was much lower than that of the front pile which is a different tendency from that of the static loaded group piles. It also means that a larger pile group effect was generated in the seismic loaded group piles.
- 7) In all the cases, the axial force distribution shows the same tendency as the static loaded common group piles. From the bending moment and the axial force distributions, the combined group piles were seen to resist external force by bending stiffness compared to the other cases.

Future studies will include: (1) an investigation of the lateral and horizontal mechanical behavior more from stress and the displacement of the ground, (2) a real scale FEM analysis and an investigation of the influence of batter piles and (3) the development of a new combining method.

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