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LIQUEFACTION COUNTERMEASURE METHODS USING A COMBINATION OF PILES AND RAFT FOUNDATIONS

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Saturated loose sandy ground is easily liquefied and damaged during earthquake shaking. In recent years, seismic design that takes into account liquefaction has become required in various kinds of standard specifications. Some countermeasures for liquefaction have been developed, including soil improvement techniques and seismic reinforcement using piles. This paper reports on liquefaction countermeasure methods using a combination of piles and raft foundations. Raft foundations with sallow soil improvement could reduce the differential settlement of building. The piles could share parts of lateral loading during sand liquefaction and reduce the shear deformation of the ground surrounded by piles. The purpose of this research is to understand the lateral-loading share ratio of piles and shear-deformation reduction rate of ground with different pile spacings. It will attempt to solve engineering questions on designing piles foundations against sand liquefaction, both in simplified terms and in terms of providing a basic understanding for appropriate analytical platforms. The performance of piles in liquefying ground under lateral loading is a complex problem, so to simplify it, our research is two-fold: 1) the lateral-loading share ratio of piles, and 2) shear deformations reduction rate of ground. This paper focuses on the first part: the lateral-loading share ratio of piles.

Keywords: Liquefaction countermeasure method, Piles, Lateral loading, Numerical analysis, Lateral-loading share ratio, Pile spacing.

1 INTRODUCTION

Many buildings are damaged by ground liquefaction during and after earthquakes. Embankment with sandy soil construction is a common example, which further expands the liquefaction damage. Some methods, such as seismic reinforcement and ground improvement, have been developed as liquefaction countermeasure methods (Ishigawa et al. 2011). In this study, a new liquefaction countermeasure method using a combination of piles, raft foundations and ground improvements as a new composite foundation is considered. This method differs from other existing liquefaction countermeasure methods used to restrain the level of liquefaction and reduce damage.

Combination of raft foundation and ground improvement could reduce the differential settlement of the building (Huang et al. 2012). Piles can shoulder the parts of lateral loading and reduce the shear deformation of the ground that occurs during an earthquake. In order to simplify the study, problems of pile behavior in the ground during liquefaction is divided into two issues. First, studying the variation in the loading share ratio when pile spacing is changed. Second, studying the reduction rate of the ground-shear deformation with the pile spacing is changed. In this paper, the first issue of this research is presented.

2 LIQUEFACTION COUNTERMEASURE METHOD USING A COMBINATION OF PILES AND RAFT FOUNDATION

This "liquefaction countermeasure method using a combination of piles and raft foundation" has 3 elements: raft foundation, grid-pattern soil improvement layers (preventing differential settlement), and pile groups (intended to support the load of the building). Figure 1 shows the schematic diagram of this method.

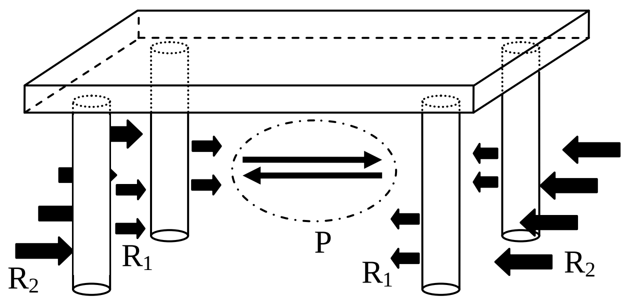


Figure 1. Schematic diagram of liquefaction countermeasure.

Lateral loading P will occur in the ground during an earthquake. It is the sum of the reaction force R_1 occurring around the piles, and force R_2 transmitted to the ground behind the piles. In another words, if the total loading share of the transmitted force to the ground behind the poles, and the reaction force of the piles, are equal to 1, the dynamic can be written as the following equation:

$$1 = R_1/P + R_2/P \tag{1}$$

It is conceivable that the loading share ratio of piles will decrease with an increase in pile spacing. It is necessary to consider the relationship between the pile spacing and the loading share ratio. It is possible to reduce the damage level of liquefaction when the ground is confined with a large loading share ratio of piles.

3 ANALYTICAL MODEL

A horizontal cross section of the piles in Figure 1 is clipped to clarify the relationship between the lateral-loading share ratio of the piles and the pile spacing. The piles are arranged symmetrically, and the analytical model is drawn as shown in Figure 2. The pile diameter is D and pile spacing is d. In this analysis, the unit pile diameter is set to 1m. Figure 3 shows an example of the element meshing of the model (d = 7D), used in this analysis with a two-dimensional finite element method. The analytical area is only the ground, and by assuming that this is the location to install the piles, the boundary can be drawn along the circumference of the piles. All the nodes are fixed on this boundary, and the reaction forces of these nodes are derived as the share loading of piles.

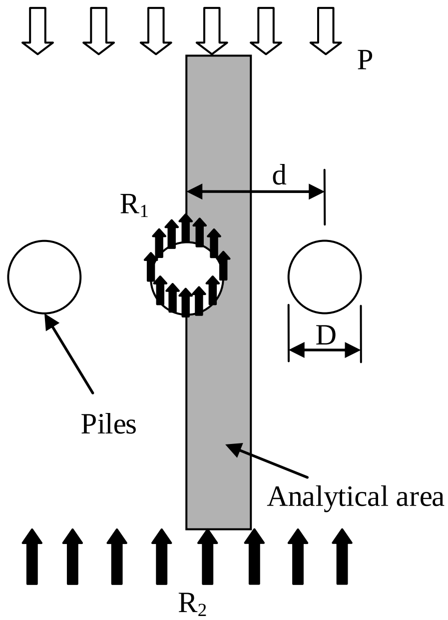


Figure 2. Analytical model.

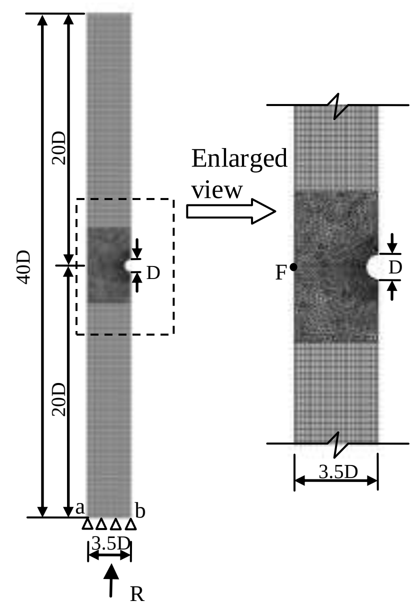


Figure 3. Element meshing (d = 7D).

4 CASE OF ANALYSIS

As shown in Table 1, elasticity modulus Es, Poisson's ratio ν, adhesion c and the internal friction angle φ are used for the soil characteristics. Three different ground conditions are assumed: soft ground (Case A), intermediate ground (Case B), and hard ground (Case C). The elasticity modulus of the ground, the internal friction angle, and the adhesive strength are increased in the order of (A), (B), (C), and the ground became strong and hard. N value is assumed to be about 20 for normally consolidated sand ground. The internal friction angle φ of the soil was set by the equation of Osaki (Architectural Institute of Japan 2001) in the case of (B). The elasticity modulus is assumed based on the empirical equation E = 1.4N (*ibid*). Adhesion c is assumed to be the value of an extent corresponding to common ground.

Table 1. Case parameter of ground.

	E(kN/m^2)	ν	C(kN/m^2)	φ(deg.)
Soft ground（A）	10000	0.3	5	30
Intermediate ground（B）	30000	0.3	10	35
Hard ground（C）	150000	0.3	20	40

The parameter of pile spacing d is assumed as shown in the Table 2. A total of 24 analysis cases were performed in combination with the parameters of pile spacing and soil characteristics. The analyses were carried out with elastic-plastic elements which were applied with a standard Drucker-Prager failure criterion of the ground.

Table 2. Cases of analysis.

	Soft ground（A）	**Intermediate ground（B）**	**Hard ground（C）**
d=2D	(A)-①	(B)-①	(C)-①
d=3D	(A)-②	(B)-②	(C)-②
d=4D	(A)-③	(B)-③	(C)-③
d=5D	(A)-④	(B)-④	(C)-④
d=7D	(A)-⑤	(B)-⑤	(C)-⑤
d=10D	(A)-⑥	(B)-⑥	(C)-⑥
d=20D	(A)-⑦	(B)-⑦	(C)-⑦
d=30D	(A)-⑧	(B)-⑧	(C)-⑧

5 INFLUENCE OF BOUNDARY CONDITIONS

The influence of boundary conditions decreases as distance increases from the piles' center (lower end a-b of the model in Figure 3), and the reaction force R_1 converges to a constant value and the influence become small. The analytical model's boundary was set at a distance of 20 times the piles' diameter from the piles' center. To confirm the influence of the boundary, the case (A) -②and (A) -⑥ were used. The lateral-loading share ratio of the piles were calculated when the boundaries were set gradually away from the piles' center. Then the convergence of the influence of boundary could be examined by the relationship between the lateral-loading share ratio of the piles and the distance from the piles' center.

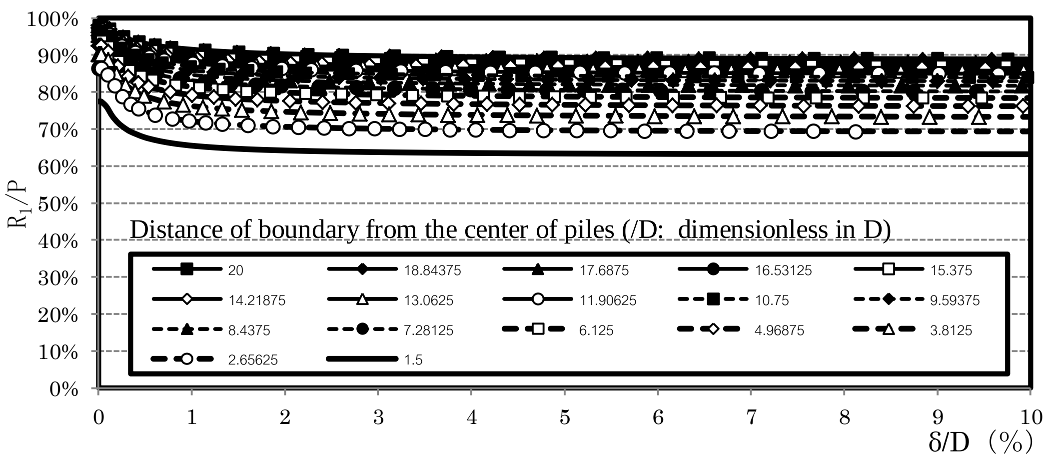


Figure 4. The relationship between the lateral-loading share ratio of the piles (R1 / P) and the relative deformation of the ground (δ/D).

Figure 5 shows the relationship between the distance of boundary from the center of piles (/D: dimensionless in D) and the lateral-loading share ratio of case (A)-②, when the relative deformation of the ground is 10%. The lateral-loading share ratio of piles indicated the smallest value of about 63% when the boundary surface closest to the piles' center (1.5 times the piles' diameter) and relative deformation of ground (δ / D) was 10%. The lateral-loading share ratio of piles increased gradually when the boundary surface moved away from piles' center. It was 84% when the boundary surface moved 10.8 times the piles' diameter away from piles center; this ratio increased only 5% to 89% when boundary surface was separated by 20 times the piles' diameter from the piles' center. It tends to converge at this point. Different ground-condition cases (case (B) - ② and (C) - ②) have the same trend.

Figure 6 shows the relationship between the boundary distance from the center of the piles and the lateral-loading share ratio of case (A)-⑥, when the relative deformation of ground is 10%. Same as in case (A)-②, the lateral-loading share ratio of piles was at the smallest value when the boundary surface was closest to the piles' center (3.5 times the piles' diameter). The curve is not fully converged, regardless of the point where the boundary surface is 20 times piles diameter away from piles center, but it seems that an increase in the lateral-loading share ratio of piles after this point will effect little change. Therefore, the boundary surfaces of all cases are set to 20 times the piles' diameter from the piles' center.

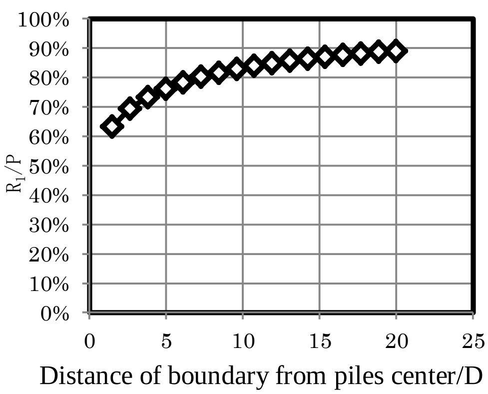


Figure 5. The relationship between the lateral-loading share ratio and the distance from the center of piles in case (A)-② (δ/D=10%).

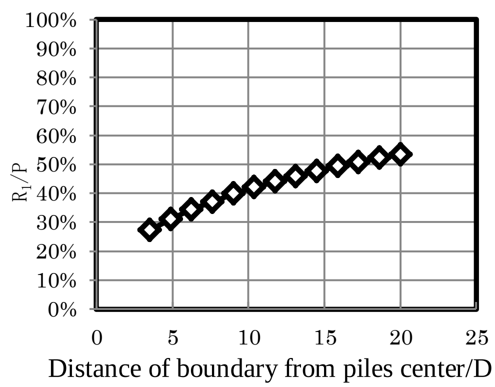
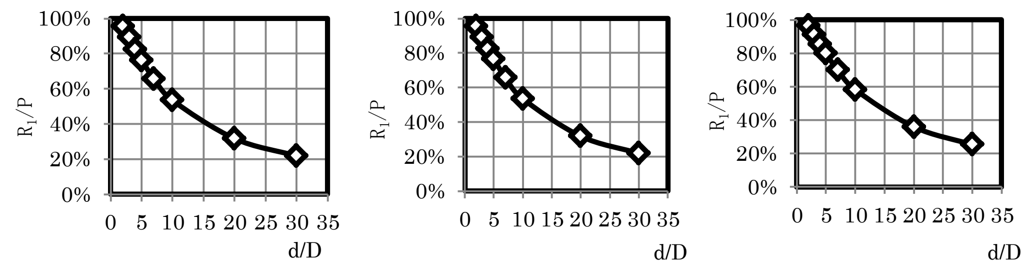


Figure 6. The relationship between the lateral loading share ratio and the distance from the center of piles in case (A)-⑥ (δ/D=10%).

6 DISCUSSION OF THE RESULTS

Figure 7 (A) shows the relationship between the pile spacing and lateral-loading share ratio in case (A) when the relative deformation of ground (δ / D) is 10 %. The lateral-loading share ratio was nearly 96% when the pile spacing was 2 times the piles' diameter. The lateral-loading share ratio of piles increased gradually as the pile spacing decreased, indicating a relatively small amount of load transmitted to the ground behind the piles. Lateral-loading share ratios were 73% and 53% when pile spacing was 5 times and 10 times the piles' diameter. The lateral-loading share ratio of the piles were exactly 100% when piles are closely arranged, and the ratio decreased only 4% even if half the number of piles (d = 2D) were used. Therefore, this is a very economical and efficient method.



(1) Case-(A) (2) Case-(B) (3) Case-(C)

Figure 7. The relationship between pile spacing and lateral-loading share ratio (δ / D=10%).

Figures 7 (2) and (3) also show the relationship between the pile spacing and the lateral-loading share ratio of the piles, when the relative deformation of ground is 10% in different ground condition cases (B) and (C) respectively. All of the curves in Figure 7 show almost the same shape and tendency. It means that the lateral-loading share ratio of the piles is almost the same when relative deformation is 10% even in different ground conditions. Therefore it is unnecessary to consider the effect of soil characteristics when using this method.

In this paper, we investigated the relationship between the lateral-loading share ratio of the piles and the pile spacing using the finite-element method analysis. The confining effect of shear deformations of ground by piles will be examined in future research.

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