FULL-SCALE MODEL TEST FOR EARTHQUAKE-RESISTANCE REINFORCEMENT OF PILE FOUNDATION USING GROUND SOLIDIFICATION BODY

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ABSTRACT :

The necessity of earthquake resistant reinforcement for structural foundations in large-scale earthquakes is rising. Especially, earthquake resistance reinforcement methods for pile foundations for bridges and buildings and pipeline networks for water, sewage, gas etc. are limited by various unfavorable construction conditions. Urano, Adachi, Mihara and Kawamura proposed a new method for earthquake resistance reinforcement applicable to either new or existing pile foundations, which was confirmed by model shaking table test under 1g gravitational field and the numerical simulation analysis. The proposal method aims to increase the stiffness of the pile foundation by the effect of a two layered Rahmen structure by the reinforcing body made in the ground. This paper shows a full scale field test of the proposed method and its numerical simulations that were conducted to examine deformation characteristics of the reinforced foundation and the effect of the reinforcement. Based on the test results, applicability of the proposed reinforcement method for a pile foundation has been confirmed.

KEYWORDS: Pile foundation, Earthquake Resistance Reinforcement, Ground Solidification, Lateral loading test, Vibration test

1. INTRODUCTION

In recent years, re-evaluating the earthquake level on an aseismic design, preparing existing structures and their foundations ready against the supposed coming large-scale earthquake have raised the necessity of earthquake resistance reinforcement method. Actually, reinforcement methods for pile foundations are limited due to construction restrictions such as site and space. To deal with that problem, the authors proposed a new type of earthquake resistance reinforcement method, which is applicable even for existing pile foundations. In this method, ground solidification technique is adopted in construction of a solidified body in the ground surrounding a portion of the pile group, which is in combination with the piles and footing resulting in a two-layer Rahmen structure strongly reinforcing the pile foundation against the earthquakes. The effectiveness of the method had previously been confirmed by model shaking table tests under 1g gravitational field and numerical simulation (Adachi 2002). This paper reports about a full-scale model test carried out for investigating the construction performance and quality of the proposed method at actual scale level of pile foundation.

2. OUTLINE OF FULL SCALE MODEL TEST

Outline of the pile foundation and ground used in the experiment are shown in Figure 1. This newly constructed pile foundation for experiment consists of four steel pipe piles, which are 406.4 mm in outer diameter, 9.5 mm in thickness and 10.0 m in length, being arranged at 2.0 m spacing. Material properties of steel pipe piles are tabulated in Table 1. Pile installation was carried out by the method of inner pre-boring and tip grouting (cement milk spraying agitation technique). The pile heads were fixed with 0.5 m length embedded in a reinforced concrete footing of 3.8 m x 3.8 m x 0.6 m dimension. On the outer surface of two of the steel pipe piles, strain gauges and their protectors (L-shape steel) were set up beforehand. Moreover, a 5 cm-thick styrene foam layer was layout at the bottom of the footing to eliminate the friction between the concrete and soil.
As for the ground conditions, beneath a 2 m thick surface fill layer, there exist a 5 m thick soft loam and clay layer with SPT N-value of 1 followed by a 1.5 m thick clay of SPT N-value of 5~10, which are underlain by a sand layer of SPT N-value of 40. The pile tips were embedded about 1 m in the sand layer. The reinforcement body was constructed by ground solidification treatment to bind the pile group at its middle length, so that together with the footing they form a 2-layer Rahmen structure, thank to its restraining effect the pile foundation rigidity is enhanced.
The reinforcement body, being almost the same to the footing in horizontal dimension, was situated between the depths of 3.2 m ~ 5. 2m (2.0 m thick). It was structured by spraying cement milk at 12 spots within a prescribed periphery using high-pressure jet-grouting method, which was capable for obliquely construction. The design strength of the reinforcement body is 1 MN/m^2. Image of the created formation within the ground is shown in Figure 2, while Figure 3 demonstrates its cross-section and the structure construction sequence.
For the purpose of confirming mechanical behavior, effectiveness and construction ability of this reinforcement method during application, three testing scopes included in this study are:

1. Lateral loading tests,
2. Vibration tests,
3. Observation of excavated reinforcement body.

Outline of each experiments as well as the test results are described hereafter.

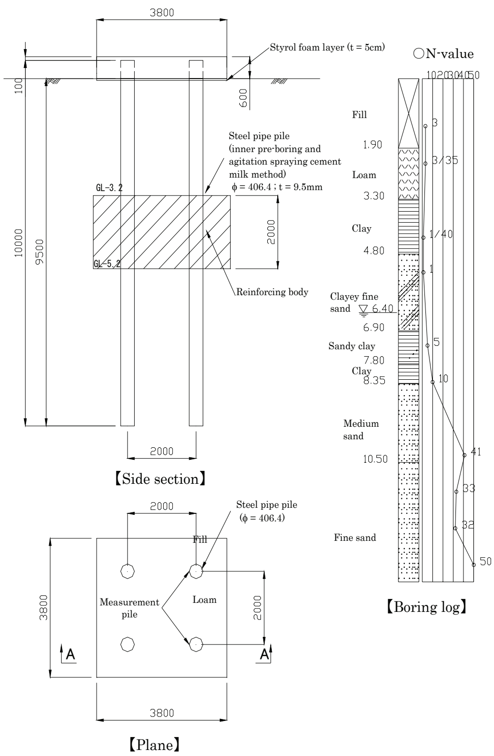


Figure 1 Full-scale model test outline

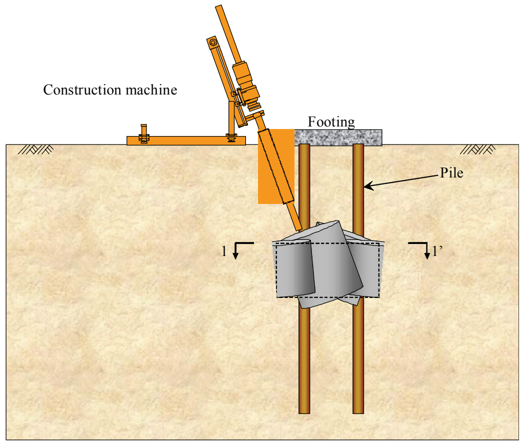


Figure 2 Situation of construction of reinforcement body.

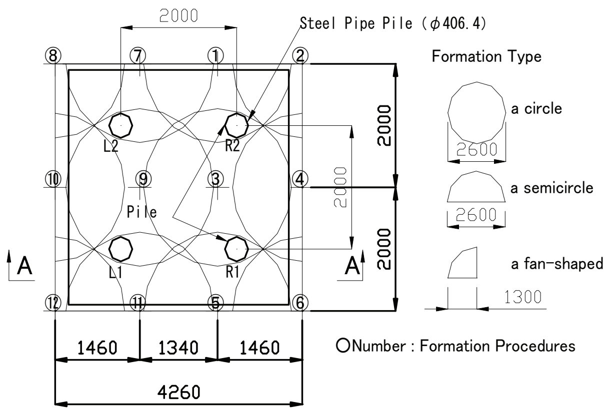


Figure 3 Reinforcement body cross-section (1-1') And formation procedures

Table 1. Material properties of steel pipe pile.

Steel pipe pile φ406.4mm, t=9.5mm, L=10.0m		
Section area	A (m^2)	0.011846
Geometrical moment of inertia	I (m^4)	0.000233
Geometrical moment of area	Z (m^3)	0.001149
Young modulus	E (kN/m^2)	2.1×10^8
Bending rigidity	EI (kN/m^2)	4901.1

3. LATERAL LOADING TESTS

3.1. Test Outline

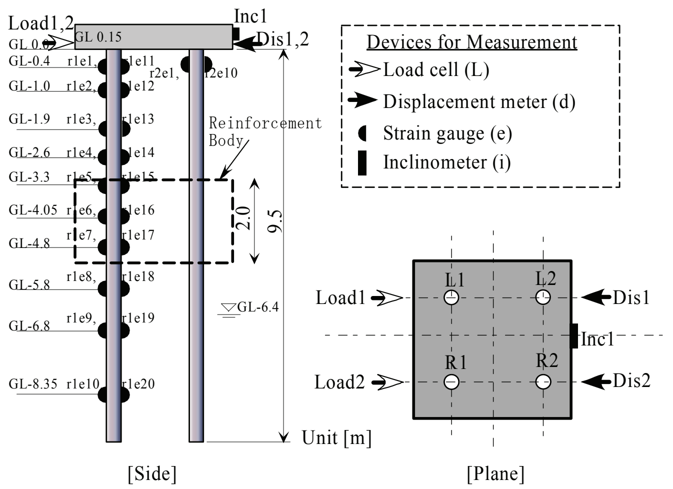
Lateral loading tests were performed before and after construction of reinforcement body to compare the behaviors of the pile foundation. For lateral loading, two oil pressure jacks were used to apply uniaxial load in multi-cycle loading style (JGS 1983).

Instrumentation with displacement transducer, inclinometer, load cell and strain gauges for measurements in lateral loading tests is shown in Fig. 4. One set of strain gauge was setup on one pile on the push-in side, while 10 sets are on another pile on the pull-out side.

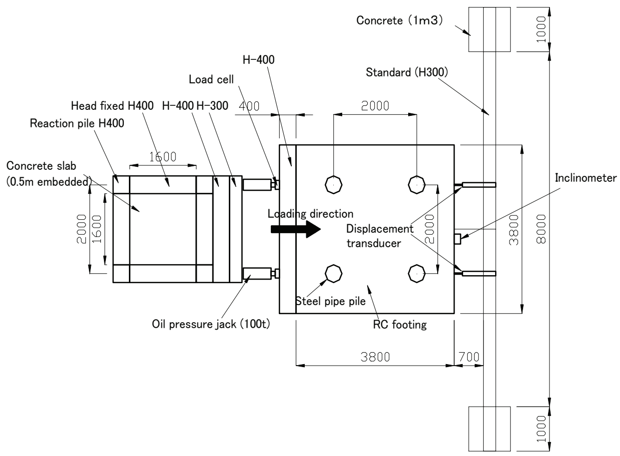
3.2. Test Results

3.2.1 Load - Displacement Relationship

Load - Time curves and Load - Lateral displacement curves of the pile head from lateral loading tests before and after reinforcement are presented together in Figures 5 & 6, respectively, for comparison. The maximal load before and after reinforcement was 600 kN and 787.5 kN, respectively. Compared to 17.2 mm of lateral displacement of the footing at the moment of maximal loading in the test before reinforcement, the displacement after reinforcement was reduced to 4.8 mm only. Thus after reinforcement, even when approaching the maximal load of about 200 kN higher than before reinforcement, the load - displacement relationship still showed almost linear elastic behavior. Actually, according to the inclinometer equipped on the side surface of the footing, the footing inclination angle at the moment of 600 kN load intensity was +0.0956 degree and + 0.0608 degree in the tests before and after reinforcement, respectively (rotation in the direction of loading is signed as "+").



(a)Arrangement of devices for measurement



(b)Loading test instrumentation(Plane)

Figure 4 Outline of lateral loading test

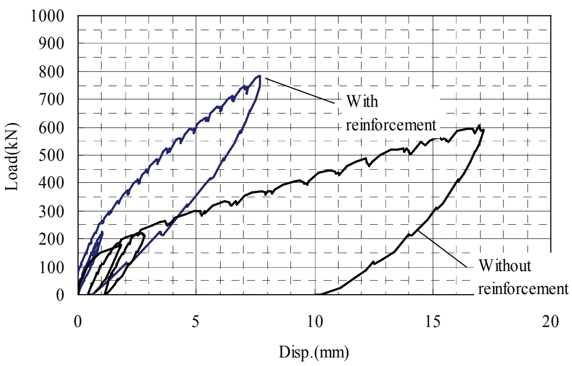


Figure 5 Load - Time curves

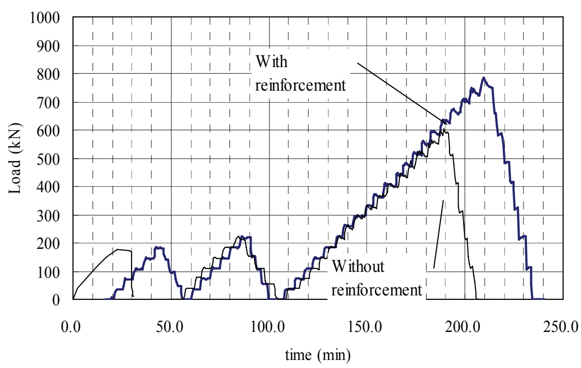


Figure 6 Load - Displacement curves.

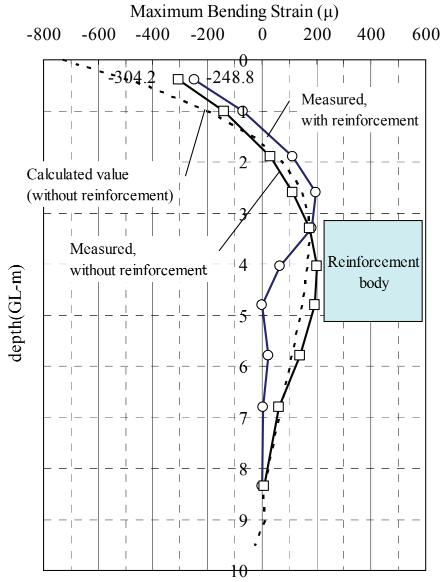
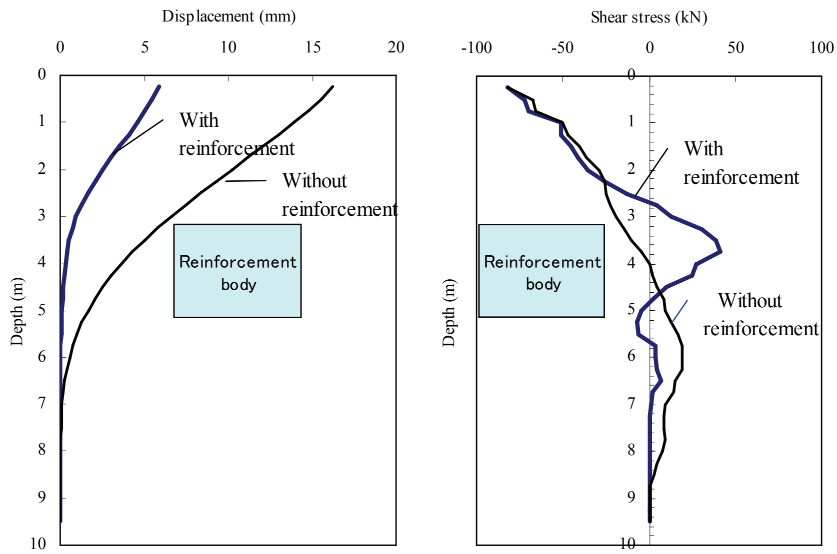


Figure 7 Bending strain distribution (under load intensity of 600 kN).



(a) Lateral displacement distribution (b) Shear stress distribution

Figure 8 Distributions of lateral displacement and shear stress in accordance to bending strain distribution (under load of 600 kN).

3.2.2 Bending strain distribution

Bending strain distribution before reinforcement under load intensity of 600 kN is shown in Figure 7. Also combined in the same figure is calculated bending distribution without reinforcement of an elastic beam above foundation level under pile head fixed condition (Chang method). The results of test without reinforcement showed a generally good agreement with calculated values. After reinforcement, due to confining effect of the reinforcement body set at the middle part of the piles, bending strain was reduced near the pile head, but inversely increased near the end of reinforcement body. However, for the lower part of the pile (beneath the reinforcement body depth), bending strain was almost not occurred. Such behavior is considered due to the effect of two layer Rahmen structure formed by setting the reinforcement body to relate the pile foundation and the footing. Using elastic flexible curve equation from bending strain distribution shown in Figure 7, numerical integration and differentiation were performed, and calculated results of pile lateral displacement distribution and shear force distribution are presented in Figure 8. In calculation, micro incremental interval of depth, dx = 0.25m, was adopted in picking up the values of the strain curve. As shown in Figure 8, by setting up reinforcement body, up to the depth of GL -3.0m, the pile lateral displacement largely decreased. Also in this case, the shear force near the top of the reinforcement body has been increased compared to that before reinforcement. Because of that, for actual design, thoroughly consideration of the shear stress in adjusting the thickness and position of the reinforcement body is necessary.

3.3. Analysis based on Beam-Spring System Model

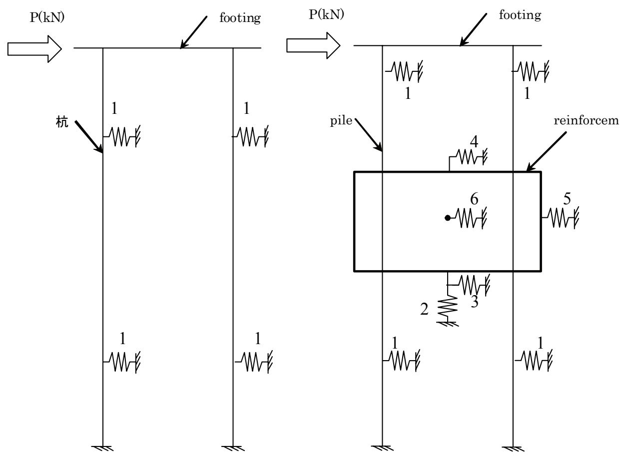
To investigate a simple design technique for this reinforcement method, it was attempted to estimate the results obtained from lateral loading test by beam-spring system modeling (Ohtsuka 2001).

3.3.1 Modelong

An analysis model based on beam - spring system is shown in Figure 9. In this model, elastic beam elements were used for simulating piles and footing. Material properties for piles are tabulated in Table 2. It was assumed the footing as rigid beam with stiffness of 100 times higher than that of steel pipe pile. For the ground, the springs were considered of 6 types numbered from 1~6 as shown in Figure 9, respectively. According to data of previous pile lateral loading test, the spring index in horizontal direction of piles was found suitably evaluated by a power function ($y^{-1/2}$) of lateral displacement y (Nishi 1987 , AIJ 2002) as expressed by following equation (1), in which horizontal subgrade reaction coefficient was used for non-linear spring.

$$K_h = K_{ho} * (\alpha,y)^{-1/2} \tag{3.1}$$

Where: K_h is horizontal subgrade reaction coefficient (kN/m^3);
K_{ho} is standard horizontal subgrade reaction coefficient (kN/m^3);
y is non-dimensional lateral displacement (adopting the lateral displacement of the pile from the test, in unit of cm, $\alpha,y > 0.1$);



Without reinforcement With reinforcement
1) Spring in horizontal direction of pile
2) Spring in normal direction to bottom surface of the reinforcement body
3) Shear spring to the bottom surface of the reinforcement body
4) Shear spring to the top surface of the reinforcement body
5) Spring in horizontal direction to the front surface of the reinforcement body
6) Shear spring to the side surface of the reinforcement body

Figure 9 Analysis model

Table 2 Material properties for piles (beam elements)

Steel pipe pile ϕ 406.4 t = 9.5 L =10m		
Sectional area	A (m^2)	0.011846
Sectional moment inertia	I (m^4)	0.000233
Sectional coefficient	Z (m^3)	0.001149
Young modulus	E (kN/m^2)	2.1 x 10 ^{8}
Bending rigidity	EI (kN·m^2)	4901.1

Table 3 Physical properties of reinforcement body (horizontal strain)

Reinforcement body (cement solidified treated bo		
Volume unit weight	(kN/m^3)	15.0
Young modulus	E (kN/m^2)	1.5 x 10 ^{6}
Elastic shear modulus	G (kN/m^2)	5.5 x 10 ^{5}
Poisson ratio		0.35

Table 4 Analysis cases

Analysis cases		Conditions
1	Non-reinforced	α = 1.0
2	Non-reinforced	α = 0.5
3	Reinforced	α = 1.0
4	Reinforced	α = 0.5

α is correction coefficient of non-dimensional displacement amount y
The correction coefficient α was adopted in the function $y^{-1/2}$ so that the required spring constant would better express the test results. Value of K_{ho} was calculated based on N-value according to the method found in AIJ(2002). Horizontal subgrade reaction coefficient used in the analysis is presented in Figure 10. In this figure, since lateral displacement under non-reinforcing and reinforcing condition were different from each other, therefore the subgrade reaction coefficient under reinforcing condition had become greater compared to that under non-reinforcing condition by taking into consideration of the function $y^{-1/2}$. Different values calculated based on various ordinary design standards such for AIJ(2002), JRA(2002) or RTRI(2000) are compared in the same figure. Furthermore, the vertical spacing of horizontal springs of piles was set at maximum about 0.4m, which is the same as in the pile diameter. Beside that, the pile spacing of 5D as in full-scale model test was found too large to consider about effect of pile group on lateral ground spring constant, and would not used in this analysis.
Therefore, in order to directly simulate such condition in the analysis model, the reinforcement body was modeled by elastic material with plane strain elements as shown in Table 3. The transverse side of plane strain elements was assumed the same as the footing width. In order to represent an interaction with the surrounding ground, vertical, lateral and shear springs were set up at the periphery of the reinforcement body (indicated by number 2~ 6 in Figure 9). For setting the reinforcement body, the ground spring value was calculated in accordance with the calculation method of horizontal subgrade reaction coefficient for spread foundation (JRA(2002)). Here, the shear spring constant Ks was estimated equal to 1/3 of horizontal spring constant. For convenience, normal springs in horizontal and vertical directions (No.2 & 5) of reinforcement body were set at the node points on front surface of loading direction and bottom surface with the value in proportion to the area, and shear springs (No.3, 4 & 6) were set each at the center of upper, lower and side surfaces (not in the same direction of loading) of the reinforcement body.

Analysis cases are summarized in Table 4.

3.3.2 Analysis Results and Discussions

Distribution of lateral displacement and bending moment at loading intensity 600kN are presented in Figure 11. For correction coefficient $\alpha = 1.0$, calculated lateral displacement and bending moment were 20% and 30%, respectively, higher than that from the test results for both non-reinforcing and reinforcing conditions. In this case, by paying attention on estimation of horizontal subgrade reaction coefficient and adjudgment of α, finally it was able to reproduce the test results for both non-reinforcing and reinforcing conditions with $\alpha = 0.5$. Consequently, by modeling based on beam-spring system shown in Figure 9, the design procedure of the proposed reinforcement method with reinforcement body has been judged effective. Actually, in estimation of ground spring value under reinforcing condition influences such as from setting of reinforcement body should also be examined in details.,

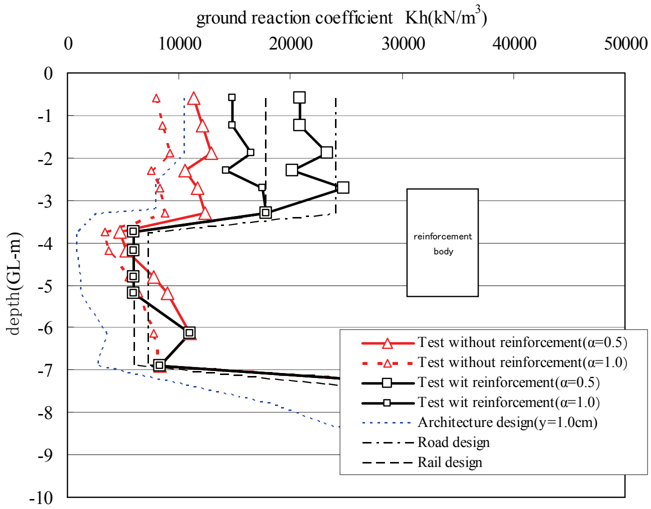


Figure 10 Comparison of ground reaction coefficient(at loading intensity of 600kN)

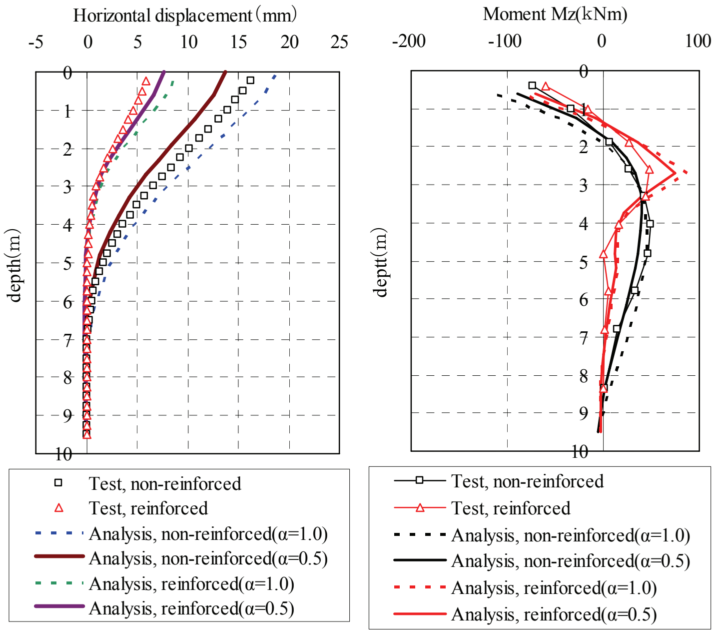


Figure 11 Analysis results (at loading intensity of 600kN)

4. VIBRATION TESTS

4.1. Test Outline

Vibration test is carrying out to clarify vibration characteristics of the actual structure (Inoue 1996).For the purposes of understanding vibration characteristics of actual structures, which in this case are vibration amplitude and natural frequency of the pile foundation, full-scale model vibration tests were conducted before and after reinforcement. In these tests, using the full-scale pile foundation model shown in Figure 12, a vibration generator with maximal vibration force of 40 kN was set up at the center of the upper surface of the footing, which created sinusoidal waves of frequency from 1 to 15 Hz. Vibrations were applied in horizontal and vertical directions. Vibration conditions are summarized in Table 5. For measurement, micro-displacement meters and accelerometers were arranged on the upper surface of the footing as shown in Figure 12.

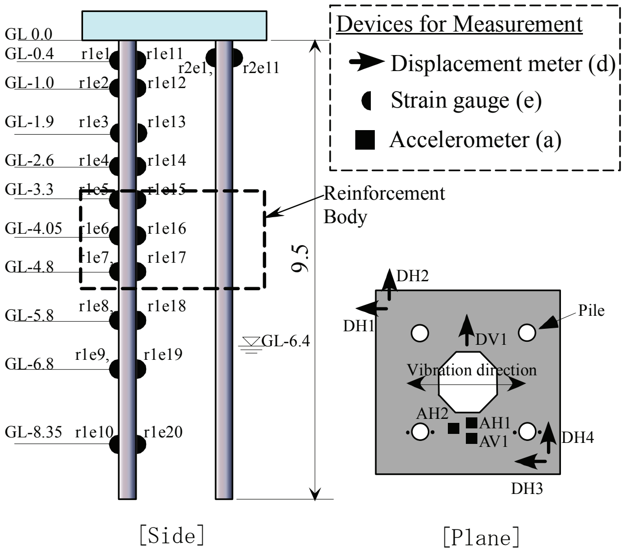


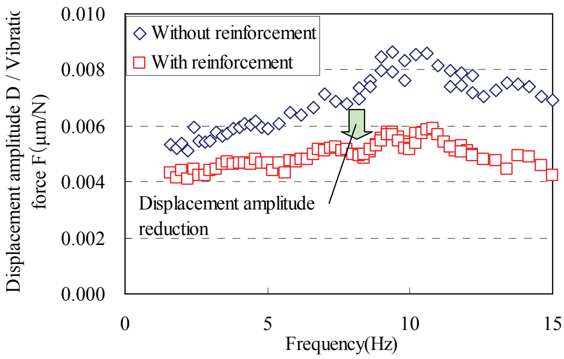
Figure 12 Vibration test equipment.

Table 5 Vibration conditions

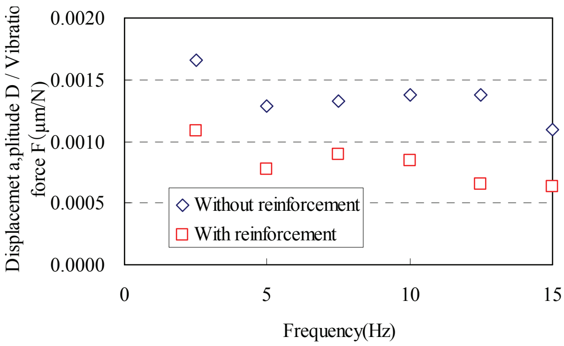
Vibration frequency		1~ 15 Hz
Vibration frequency pitch:	Horizontal vibration	0.2 – 0.4 Hz
	Vertical vibration	2.5 Hz
vibration moment	Horizontal vibration	40 Nm (1.0 ~ 10.0 Hz) 20 Nm (10.0 ~ 12.2 Hz) 5 Nm (10.0 ~ 12.2 Hz)
	Vertical vibration	20 Nm (2.5 ~ 15.0 Hz)

4.2. Test Results

Relationship between vibration frequency and the normalized displacement vibration amplitude to vibration force is plotted in Figure 13. The plotted data were obtained from the result of the first test among two tests conducted after reinforcement. According to beforehand test, the natural frequency of the pile - footing combination (without the ground) was 1.6 Hz before reinforcement and 2.1 Hz after reinforcement. Beside that, the natural frequency of the ground was about 3.1 Hz according to microtremor measurement. If only look at Figure 13, confirmation about variation of natural frequency of the pile foundation structure is difficult, because it is unable to clearly identify the natural frequencies before and after reinforcement. However, in all frequencies (1 ~ 15 Hz), a decrease in displacement vibration amplitude after reinforcement compared to that before reinforcement can be seen. This is considered due to reinforcing effect of the reinforcing body to the pile foundation structure in enhancing its rigidity. Reduction ratio of displacement vibration amplitude after reinforcement to that before reinforcement is plotted in Figure 10. It is clear from this figure that the displacement was reduced for 20 ~ 30 % under horizontal vibration, and 30 ~ 40% under vertical vibration.

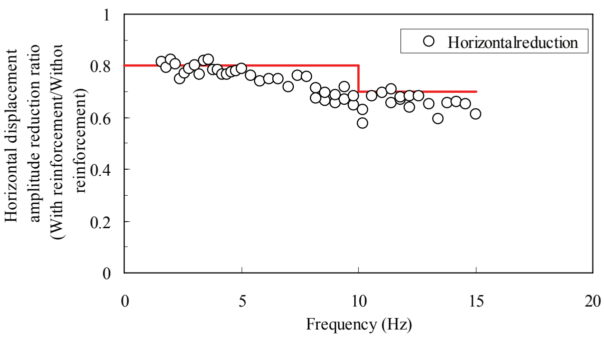


(a) Horizontal vibration

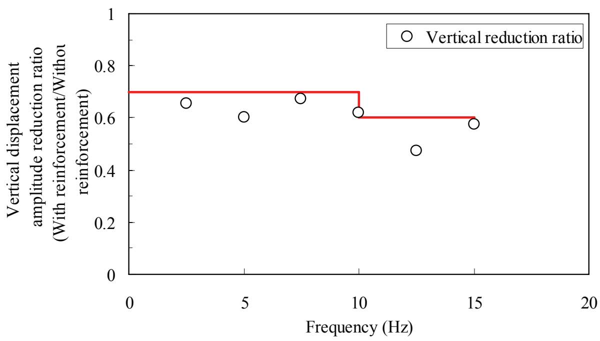


(b) Vertical vibration

Figure 13 Resonance curve



(a) Horizontal vibration



(b) Vertical vibration

Figure 14 Displacement amplitude reduction ratio

5. OBSERVATION OF REINFORCEMENT BODY FROM EXCAVATION

After completion of lateral loading tests and vibration tests, the reinforcement body was excavated to observe its ready form as well as its quality.
To enable observation of the outer shape and side surface of the reinforcement body, excavation up to the ground level of GL -3.5 m was performed. Excavation situations are shown in Photos 1 and 2. Observation indicated that the initially designed horizontal dimension of 3.8m x 3.8m was satisfied, and the joining between the pile and the reinforcement body was in good adherence. Collection of continuous core along depth was carried out at 3 spots as shown in Figure 15 and the thickness of the reinforcement body was confirmed. It was understood that, a homogenous reinforcement body has been constructed within the depth from GL - 3.2m to GL - 5.2m. The status of the collected cores is shown in Photo 3.
Unconfined compression tests were performed on specimens of collected cores to examine their strength

characteristic. The loading was conducted by compression at constant strain of 1%/min. Results of compression tests on specimens of four weeks aging cores are shown in Table 6. It was found that the obtained strength considerably surpassed the designed compressive strength of 1.0MPa. Furthermore, mean value of moist density ρt was 1.48g/cm^3.

Photo 1 Situation of excavated reinforcement body

Photo 2 Situation of excavated reinforcement body (pile surrounding status).

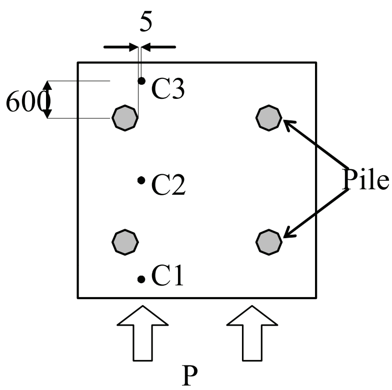


Figure 15 Load versus axial strain curves

Table 6 Mean value of unconfined compression tests (four weeks).

Compression strength q_u	4.4 MPa
Elastic coefficient E_{50}	1460 MPa

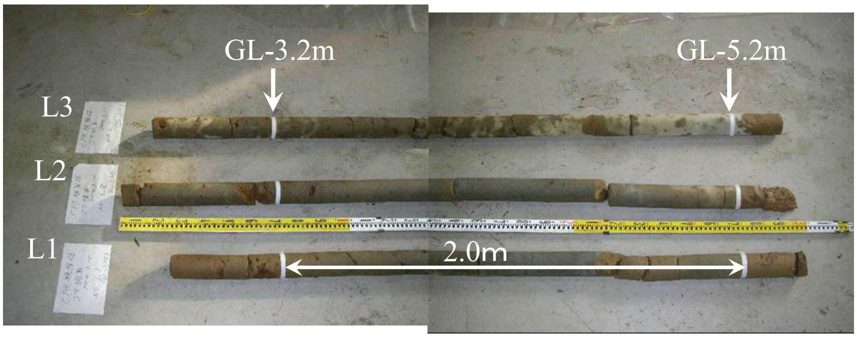


Photo 3 Core gathering positions(C1,C2,C2)

6. CONCLUSIONS

By conducting full-scale model test of earthquake resistance reinforcement method on actual scale pile foundation using ground solidification technique, following points are made clear.

1) Comparing the behaviors of the pile foundation under lateral loading (at load intensity of 600 kN), bending moment and displacement after reinforcement were reduced compared to those before reinforcement, which confirms the reinforcing effect of the proposed method.
2) It was confirmed that numerical analysis by spring-beam model could generally reproduce the behaviors of the pile foundation before and after reinforcement as in lateral loading test.
3) As shown by vibration test results, with applying vibration frequency from 1 to 15 Hz, displacement was reduced for 20-30% during horizontal vibration and 30-40% during vertical vibration, which suggest about displacement suppression effect of the reinforcement method.
4) By excavation of reinforcement body for observation, it was confirmed that the reinforcement body and the piles are well adhered as planned. Moreover, from the results of compression tests it is understood that the attained strength of the reinforcement body essentially satisfied the design value.

Therefore, it is concluded that this new reinforcement method is highly applicable to actual structures. Based on these data, following work would be conducting detailed investigation on influences of various specifications such as ground conditions, pile foundations and reinforcement body in order to establish a simple design method.

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