EXPERIMENTAL STUDY ON THE SOIL-PILE-STRUCTURE INTERACTION BY SHAKING TABLE TESTS USING LARGE-SCALE LAMINAR BOX

Taro NAKAGAWA[1], Masaru TANAKA[2], Takeshi FUJIMORI[3], Toshiaki HATORI[4] And Kaeko YAHATA[5]

SUMMARY

The estimation of the behavior when the structure which has pile foundation on the soft ground was exposed to the dynamic effects of earthquakes is very important for seismic design. This paper showed the results of the behavior of pile foundation by the shaking table tests using large scale laminar box. On the other hand, the simplified method to estimate the behavior of the structure with the pile foundation during earthquake was considered by authors. This paper outlines the characteristics of soil-pile interaction displayed in the tests and evaluates the efficiency of the method as shown by the test results. In the studies, four models were employed: embedded foundation, two piles and a one-story structure (MODEL A); embedded foundation and two piles (MODEL B); non-embedded foundation, two piles and a one-story structure (MODEL C); and non-embedded foundation and two piles (MODEL D). The test models were 1/4-scaled compared with the prototype. The input motion was RINKAI92H, and it was normalized to 100Gal and 200Gal. The load distribution tendencies in the piles and the embedded foundation from the structure which was main investigation of this paper was performed employing models A and B. From the response spectrum on the tests, the characteristic of the vibration of the models were confirmed. The load distribution was studied using the test and the analytical results. In consideration of the investigation of the load distribution on the tests and analyses, the analytical model was made, and the earthquake response analyses were performed using the present method. The applicability of the present method was confirmed from the results on the tests and frequency response analyses.

INTRODUCTION

The estimation of the behavior when the structure which has pile foundation on the soft ground was exposed to the dynamic effects of earthquakes is very important for seismic design. This paper showed the characteristics of the vibration of the models on the shaking table tests using large scale laminar box. The analytical investigations were also performed by the proposed method[1].

PURPOSE ON THE TESTS

- The purpose was to understand the behavior of the structure models which have pile foundation when they were exposed to the dynamic effects of earthquakes.
- The study to understand the load distribution between the embedded foundation and piles was performed.

1 Technical Consultancy Department, Osaka Regional Office, Fujita Corporation, JapanEmail: nakagawa@fujita.co.jp
2 Technical Research Institute, Araigumi Corporation, JapanEmail: masa01@mba.sphere.ne.jp
3 Vibration Engineering Department, Technical Research Institute, Obayashi Corporation, JapanEmail: fujimori@tri.obyashi.c
4 Nuclear Power Division, Technical Research Institute, Toda Corporation, JapanEmail: toshiaki.hatori@toda.co.jp
5 Structual Dynamics, Technical Research Institute, Kajima Corporation, JapanEmail: kaeko@katri.kajima.co.jp

The analytical investigation by the proposed method which was based on the substructure method[2]-[5] was performed. And a little non-linearity was taken into consideration on the analyses. The tests was used to investigate the accuracy of this simplified method.

OUTLINE OF THE TESTS

The models were 1/4 scaled compared with medium-rise building. The time was 1/5 scaled. The time was originally 1/2 scaled based on law of similarity, but the time was modified to be 1/5 scaled because that the rigidity of the soil was higher than normal soil. Figure 1 showed the details of the model employed in the shaking table tests and the large scale laminar box. The measurements of the laminar box used in the shaking table tests were 3100 mm(w), 11600 mm(l), and 4000 mm(h). In the tests, the structures were displayed the lumped one mass model. The structure was supported by the fully embedded foundation and the two end bearing piles. The observe points as shown in the Figure 1 were the points which the accelerometers were set up. Table 1 showed the pile profile. The soil model was made by the following process. The Kasumigaura-sand was spread homogeneously at the thickness of 20cm, and the soil was predicted by the vibration plate. Figure 2 showed the G/G_0-gamma and h-gamma curve of the soil employed in the tests. Figure 3 showed the investigation models on the tests.
The investigation models were showed as followings.

- Embedded foundation, two piles and a one-story structure. (MODEL A)
- Embedded foundation and two piles. (MODEL B)
- Non-embedded foundation, two piles and a one-story structure. (MODEL C)
- Non-embedded foundation and two piles. (MODEL D)

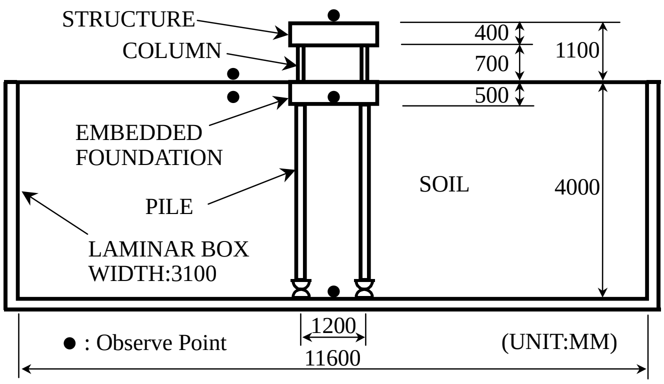


Figure 1:Test Model

Table 1:Pile Profile

Pile Number	2
Pile Section	40 cm×9.8 cm
Pile Moment of Second Order	3137 cm^4

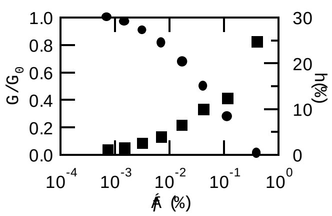


Figure 2:Relation between G/G_0 and gamma,

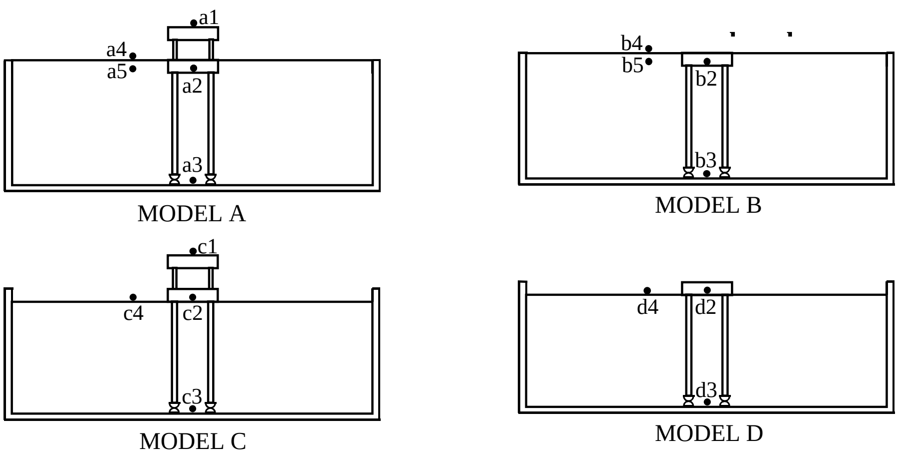


Figure 3:Test and Analytical Model

TEST RESULUTS

Figure 4 showed the acceleration time history on the shaking table at the MODEL A in the case of 100Gal RINKAI92H input motion. The acceleration time history on the shaking table was observed at the point a3 as shown in Figure 3.

Figure 5 showed the spectrum ratio of the top of the structure against the shaking table (a1/a3, Total System), and the spectrum ratio of the foundation against the shaking table (a2/a3, Soil-Pile System) in the case of 100Gal input motion. The a1,a2 and a3 herein were the points which accelerometers were set up as shown in Figure 3 and so on. Figure 5 also showed the spectrum ratio of the top of the structure against the foundation (a1/a2, Structure System), and the spectrum ratio of the soil system against the foundation (a4/a2, Soil System). The first resonance frequencies of the Total System and the Soil-Pile System as shown in Figure 5 were both 7Hz. And the first resonance of the Structure System and the Soil System were both 10Hz. From these result, it was understood that the structure and the foundation vibrated in a body. Therefore the inertia force of the structure was estimated taking into consideration both the inertia force of the structure and the foundation in the case of 100Gal input motion.

Figure 6 showed the acceleration time history on the shaking table at the MODEL A in the case of 200Gal input motion.

Figure 7 showed the spectrum ratio of the top of the structure against the shaking table (a1/a3, Total System), and the spectrum ratio of the foundation against the shaking table (a2/a3, Soil-Pile System) in the case of 200Gal input motion. Figure 7 also showed the spectrum ratio of the top of the structure against the foundation (a1/a2, Structure System), and the spectrum ratio of the soil against the foundation (a4/a2, Soil System). As shown in Figure 7, the first resonance frequencies of the Total System and the Soil-Pile System were both 6Hz, and the first resonance frequencies of the Soil System and the Structure System were 8Hz and 10Hz.

Figure 8 showed the time history of the inertia force of the structure and the shear force of the piles at the MODEL C in the case of 100Gal and 200Gal input motion. The inertia force of the structure was obtained using the acceleration of the point c1 as shown in Figure 3, and the shear force of the piles which was obtained from the measured value of the strain gauges. The inertia force of the structure and the shear force of the piles had a good agreement as shown in Figure 8.

Figure 9 showed the time history of the inertia force of the structure, the shear force of the piles, and the earth pressure of the embedded foundation at the MODEL A in the case of 100Gal and 200Gal input motion. The inertia force of the structure and the shear force of the piles and the earth pressure of the embedded foundation had a good agreement as shown in Figure 9. Therefore it was obvious that the good measurement of the strain of the piles and the earth pressure of the embedded foundation was performed.

Figure 10 showed the time history of the inertia force of the structure and the shear force of the piles at the MODEL A in the case of 100Gal and 200Gal input motion. The shear force of the piles showed that the value of the shear force at the MODEL B deducted from the value of the shear force at the MODEL A at each time step. The time history of the inertia force of the structure and the shear force of the piles had same phase as shown in Figure 10.

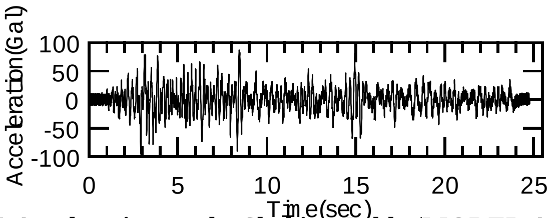


Figure 4:Acceleration on the Shaking Table (MODEL A, 100Gal Input)

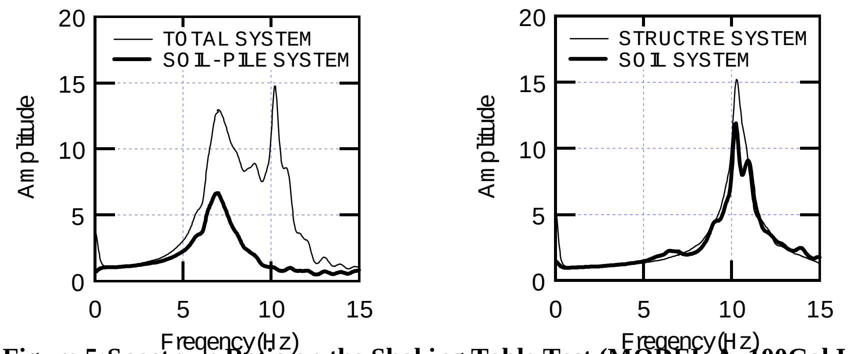


Figure 5:Spectrum Ratio on the Shaking Table Test (MODEL A, 100Gal Input)

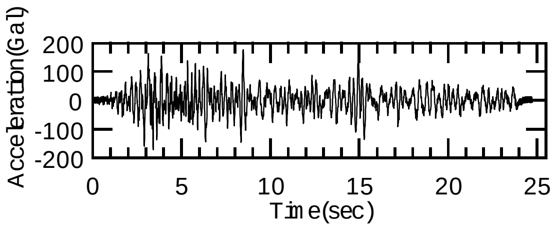


Figure 6:Acceleration on the Shaking Table (MODEL A, 200Gal Input)

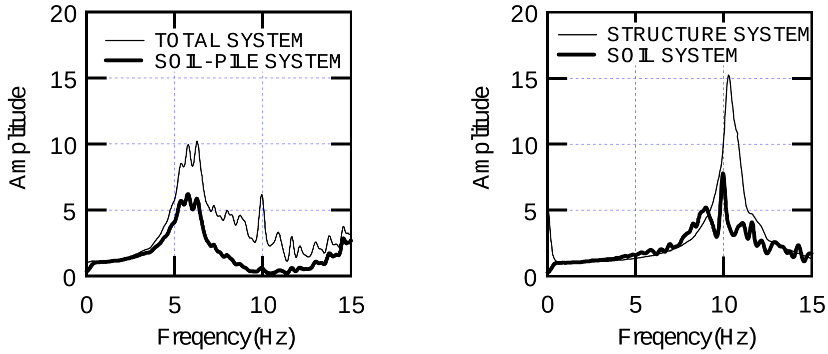
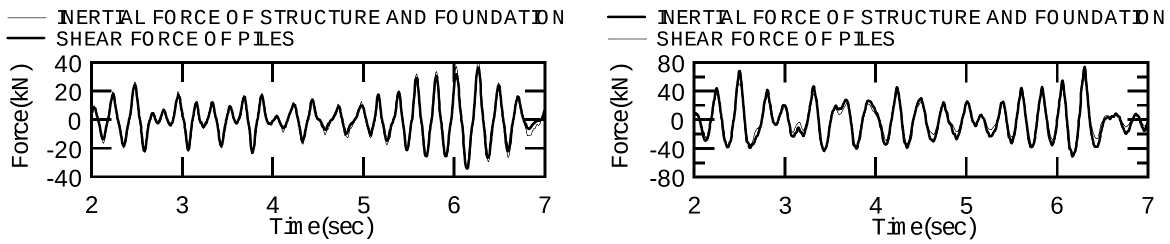
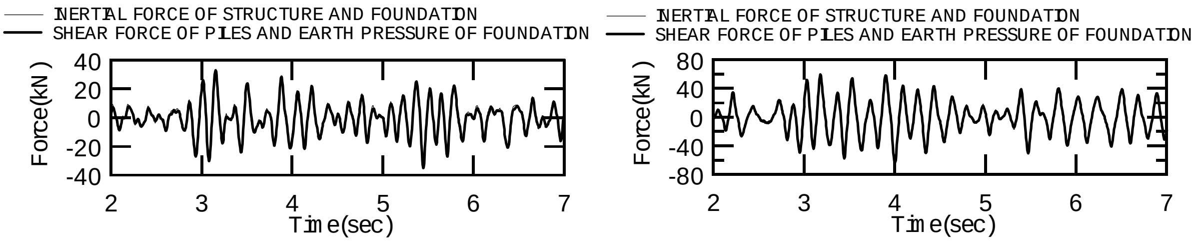


Figure 7:Spectrum Ratio on the Shaking Table Test (MODEL A, 200Gal Input)



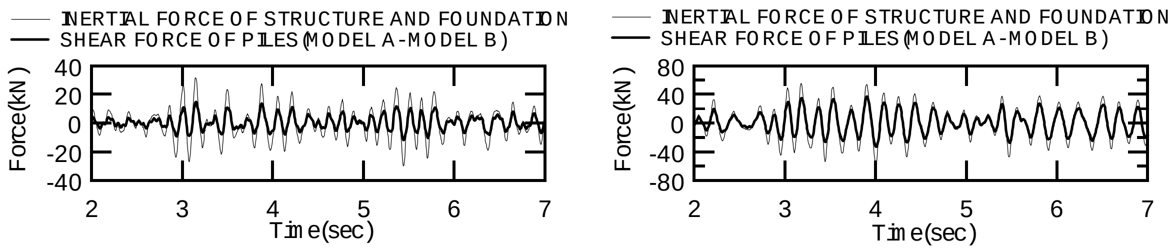
(a) 100Gal Input **(b) 200Gal Input**

Figure 8:Inertia Force of the Structure and Shear Force of the Piles (MODEL C, 100,200Gal Input)



(a) 100Gal Input **(b) 200Gal Input**

Figure 9:Inertia Force of the Structure, Shear Force of the Piles and Earth Pressure of the Embedded Foundation (MODEL A, 100,200Gal Input)



(a) 100Gal Input **(b) 200Gal Input**

Figure 10:Inertia Force of the Structure and Shear Force of the Piles (MODEL A, 100,200Gal Input)

EXPERIMENTAL EXAMINATION OF THE TEST RESULTS

Figure 11 showed that the load distribution of the embedded foundation. The load distribution was the value which was that the shear force of the piles deducted from the inertia force of the structure and divided by the inertia force of the structure. The amplitudes of lateral load distribution within the piles and the embedded foundation due to inertial force was 0.65 and 0.35 in the case of the 200Gal input motion as shown in Figure 11. The load distribution was 0.5 and 0.5 in the case of the 100Gal input motion. The load distribution of the embedded foundation was reduced in the case of the 200Gal input motion compared with the case of 100Gal input motion. The investigation of this factor was shown as following.

Figure 12 showed the G/G_0-gamma curve of the sand soil which was employed in the tests and the sand soil obtained from the soil survey of the real ground. The black points were the value of the tests sand soil and solid and dotted lines were the G/G_0-gamma relation of the real sand soil in Chiba and Yokohama. The reduction ratio of the stiffness of the tests sand soil was greater than that of real sand soil as shown in Figure 12. The excessive reduction of the stiffness of the tests sand soil was the factor that the load distribution was reduced in the case of 200Gal input motion.

Figure 13 showed the time history of the inertia force of the structure and the shear force of the piles at the MODEL A in the case of 100Gal and 200Gal input motion picked up from 3.0second to 4.0second. The shear force of the piles had the different character from the inertia force of the structure especially in the case of 100Gal input motion as shown in Figure 13. The separation of the piles from the surrounding soil was assumed because of these wave shape. The separation of the piles from the surrounding soil in the case of 100Gal input motion was the factor that the load distribution was reduced in the case of 200Gal input motion.

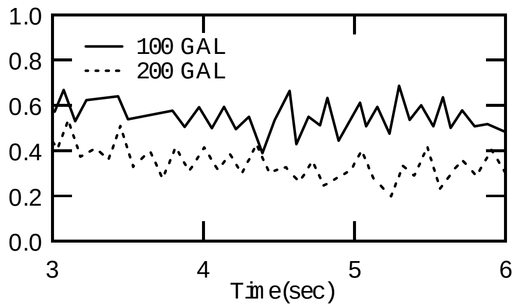


Figure 11:Load Distribution to the Embedded Foundation (MODEL A)

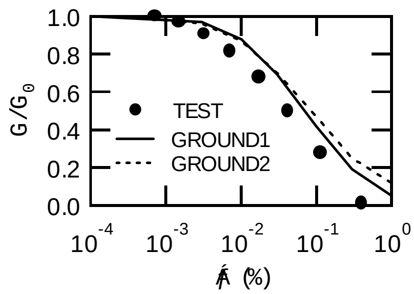


Figure 12:Relation between G/G_0 and gamma (Test and Real Ground)

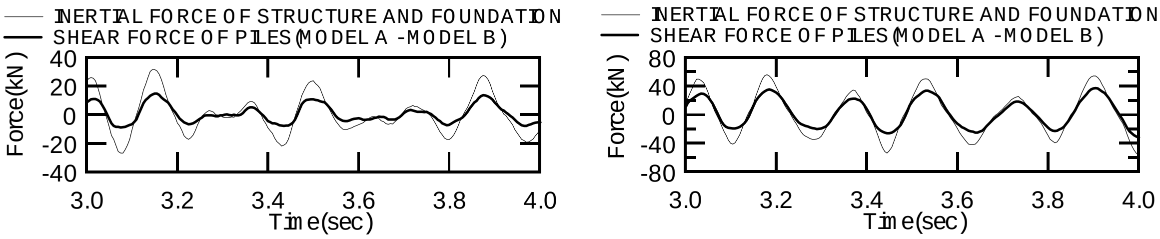


Figure 13: Inertia Force of the Structure and Shear Force of the Piles (MODEL A, 100, 200Gal Input)

ANALYTICAL EXAMINATION OF THE TEST RESULTS

The load distribution of the inertia force of the structure to the embedded foundation and the piles was analytically investigated. Moreover these analytical results and the test outcomes were used as a guide in the earthquake response analyses. The analytical method was the present simplified method by authors based on the substructure method.

The analytical models were that the embedded foundation, two piles and a one-story structure (MODEL A), and embedded foundation and two piles (MODEL B). The models were made based on the law of similarity and 1/4 scaled compared with medium-rise building. The input motion employed in the analyses was RINKAI92H which was normalized to 200Gal.

The soil model was made to adjust the first resonance frequency of the test results in the case of 200Gal input motion by the inversion analysis based on the equivalent linear analysis. The G/G_0-gamma and h-gamma curve employed by the analyses were shown in Figure 2. The impedance function of the piles and the input motion which were employed in the earthquake response analyses were computed at the elastic half space. And the impedance function of the embedded foundation was computed at the homogeneous soil over bedrock. Figure 14 showed the soil model. By trial and error, the coefficient of the subgrade reaction of the stratification ground was established taking into consideration the dependence of confined compression to adjust the coefficient of the subgrade reaction of the homogeneous soil at the center of the layered deposits.

Figure 15 showed the impedance function of the embedded foundation and the piles. Figure 15 also showed the impedance function of the embedded foundation obtained using the inertia force and the exciting force from the result of the excitation test at the MODEL B. The coefficient of subgrade reaction used for computation of the impedance function was the average V_s value of the neighborhood ground surface as shown in Figure 14. The real part of the impedance function of the analytical result generally had an agreement with the test result. The imaginary part of the impedance function of the analytical result was fairly small in comparison with the test result. This was due to the decrease of the effect in the cause of the separation of the piles from the surrounding soil, and the reduction of the stiffness of the local soil ground.

Figure 16 showed the real part of the impedance function of the embedded foundation and the total impedance. The ratio of the impedance function of the embedded foundation against the total impedance was 0.35 at the 6Hz which was the first resonance frequency of the Total System. This value had a good agreement with the load distribution from the test result as shown in Figure 12.

Figure 17 showed the acceleration time history wave by the present method and the test result in the case of 200Gal input motion. As a result, the result by the present method generally had a similar tendency with the test result, however the peak value was somewhat greater than that of test result.

Figure 18 showed the amplitude ratio of the Total System obtained by the present method. The damping coefficients were 5% at the structure, and 10% at the soil ground. In the analysis, the following assumption was introduced. The imaginary part of the impedance function which was employed for the frequency response analysis was reduced. This was due to that the radiation damping was reduced because that the laminar box was not the half space, and that the separation of the piles from the surrounding soil and the reduction of the stiffness of the local soil ground were given rise to. As a result, the amplitude ratio by the present method generally had a good agreement with the test result as shown in Figure 18.

Figure 19 showed the velocity spectrum ratio of 3% by the present method had a good agreement with the test result. The analytical results also had a good agreement with the test results as shown in Figure 19.

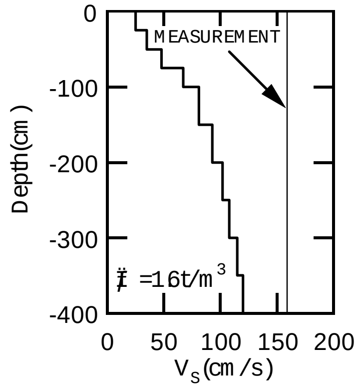


Figure 14:Analytical Soil Model

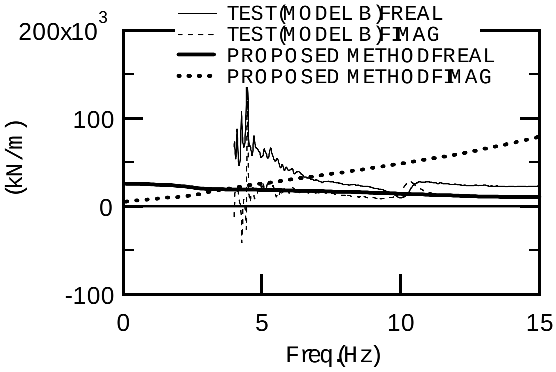


Figure 15: Impedance Obtained by the Test and Analytical Result

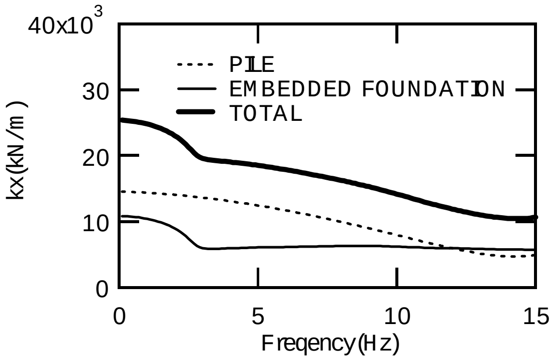
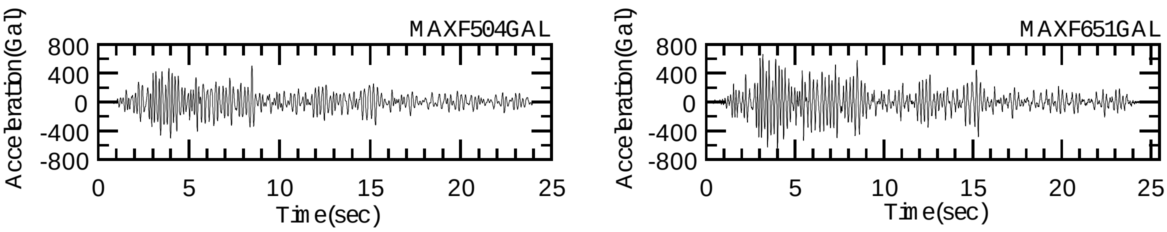


Figure 16: Real Part of Impedance by the Proposed Method



a) Test Result **b) Present Method**

Figure 17:Response Acceleration on Top of the Structure (Model A, 200Gal Input)

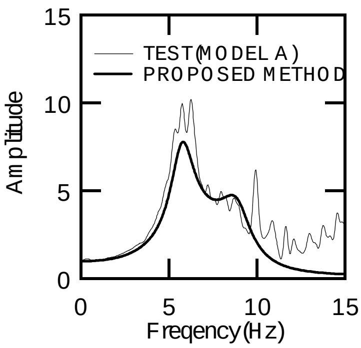


Figure 18: Spectrum Ratio Obtained by the Test and the Analytical Result (200Gal Input)

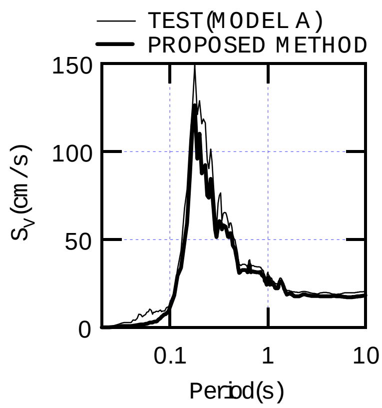


Figure 19: Response Spectrum (h=0.03, 200Gal Input)

CONCLUSION

This paper showed the details of the shaking table tests, and investigated the behavior of the model which had the structure with pile foundation during earthquake. The load distribution tendency in the embedded foundation and piles was studied. The applicability of the present method to the shaking table tests was confirmed. As the results, the following things were obtained.

1. From the test result, the amplitudes of the lateral load distribution within the piles and the embedded foundation due to inertial force was 0.35 and 0.65 in the case of the 200Gal input motion. The load distribution was 0.5 and 0.5 in the case of the 100Gal input motion.
2. The investigation of the factors of the value of the load distribution in the case of 100Gal and 200Gal input motion were showed. One was the excessive reduction of the stiffness of the tests sand soil in the case of 200Gal input motion, moreover the other was the separation of the piles from the surrounding soil in the case of 100Gal input motion.
3. From the response spectrum on the tests, the characteristic of the vibration of the models were confirmed.
4. The impedance function of embedded foundation and of piles were computed. The real part of the impedance function of the analytical result generally had an agreement with the test result. The imaginary part of the impedance function of the analytical result was fairly small in comparison with the test result.
5. In consideration of the investigation of the load distribution on the tests and analyses, the analytical model was made, and the response analyses were performed using present method.
6. The applicability of the present method was confirmed from the results on the tests and frequency response analyses.

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