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SHAKING TABLE TEST OF INSULATED PILE FOUNDATION FOR EFFECTIVE UTILIZATION OF EXISTING PILE

H. Kashiwa[(1)], S. Ohmura[(2)], H. Nakagawa[(3)], S. Nakai[(4)]

[(1)] *Senior Research Officer, National Institute for Land and Infrastructure Management, MLIT, kashiwa-h92ta@mlit.go.jp*
[(2)] *Research Engineer, Building Research Institute, ohmura@kenken.go.jp*
[(3)] *Senior Research Engineer, Building Research Institute, hiroto-n@kenken.go.jp*
[(4)] *Professor Emeritus, Chiba University, nakai@faculty.chiba-u.jp*

Abstract

While the motivation for rebuilding in the old city is increasing in Japan, in many cases of demolishing buildings, the pile foundation remains underground as existing piles. If existing piles can be used effectively in the design of a new building, it will be extremely advantaged to reconstruct the building in terms of cost and environment. There are various construction methods to use existing piles in design, and the bearing mechanism of existing piles depends on the method. While a simple method is desired, several researchers have been exploring the feasibility of a special type of foundation (Jang et al. [1]; Sekiguchi et al. [2]; Yamamoto et al. [3]; Nakagawa et al. [4]), named an insulated pile foundation, which consists of a raft foundation and a set of piles installed in a ground without being connected to the raft and may be applied to the effective use of existing piles. However, the bearing mechanism in which existing piles bear the building along with the soil seems complicated, especially during an earthquake when existing piles are subjected to not only the weight of the building but also the seismic inertial force combined with vertical and lateral load. To develop a new design method that can make effective use of existing piles by the insulated pile foundation concept, it is necessary to clarify the bearing mechanism. Therefore, shaking table tests using model specimens were conducted for several types of ground models.

Only the ground near the footing, the existing piles, and the structure is modeled in a series of tests because the interaction behavior between the existing piles and the footing is focused. Sandy soil in dry condition is used to the ground model in the tests. The ground model is set in a rigid soil box for each test. The ground model has 1040mm in length and 740mm in width and 230mm in depth. The existing pile is modeled as an aluminum pipe which has 30mm in diameter and 210mm in length. The existing pile foundation model is composed of 16 model piles. The pile model is fixed at the bottom of the soil box and is covered with a steel cap at the top. The structure model is composed of a steel mass, steel foundation, and lamina steel springs. The model has about 170kg in weight and the width of the foundation is 350mm.

The major findings obtained from a series of model tests under limited conditions are summarized as follows. 1) The settlement of the foundation occurs during excitation regardless of the existence or absence of the existing piles, and the residual settlement displacement of the foundation with the existing piles is almost the same as that without the existing piles. On the other hand, the residual rotational displacement of the foundation with the existing piles is significantly smaller than that without the piles in the test with large input amplitude. 3) The behavior of superstructure during excitation is affected by the local nonlinearity around the foundation which depends on the existence of existing piles. 4) The distance between the bottom of the foundation and the top of the existing piles become smaller by settlement of the building, the axial load on the existing piles increases when the overturning moment increases. As a result, the tilting of the building with the existing piles during excitations is reduced. Therefore, the existing piles can be expected to bear the axial force even if the footing and the existing piles are insulated.

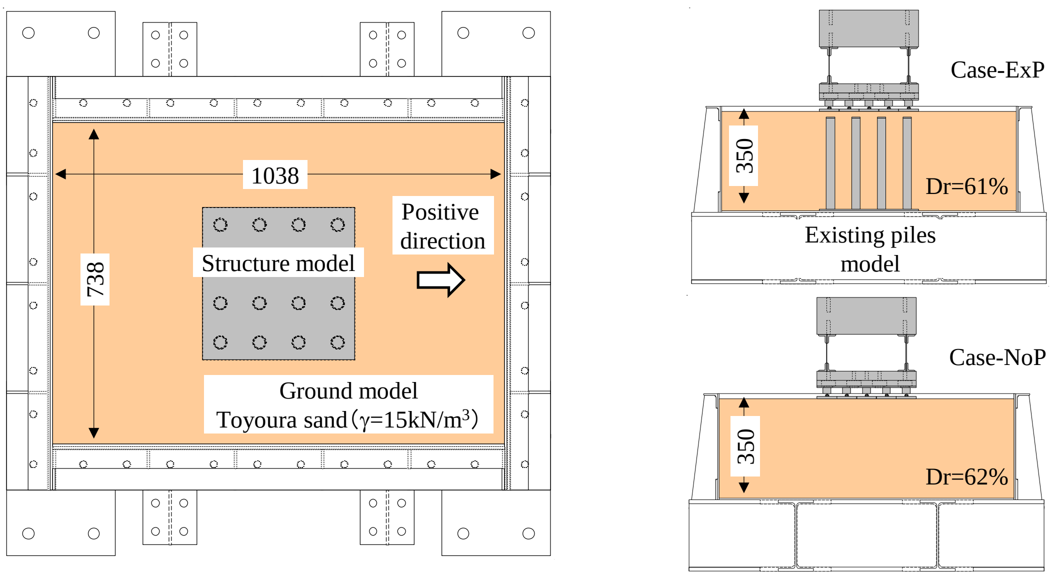
Keywords: soil-structure interaction; insulated pile foundation; shaking table test; sandy soil

1. Introduction

While the motivation for rebuilding in the old city is increasing in Japan, in many cases of demolishing buildings, the pile foundation remains underground as existing piles. If existing piles can be used effectively in the design of a new building, it will be extremely advantaged to reconstruct the building in terms of cost and environment. There are various construction methods to use existing piles in design, and the bearing mechanism of existing piles depends on the method. While a simple method is desired, several researchers have been exploring the feasibility of a special type of foundation (Jang et al. [1]; Sekiguchi et al. [2]; Yamamoto et al. [3]; Nakagawa et al. [4]), named an insulated pile foundation, which consists of a raft foundation and a set of piles installed in a ground without being connected to the raft and may be applied to the effective use of existing piles. However, the bearing mechanism in which existing piles bear the building along with the soil seems complicated, especially during an earthquake when existing piles are subjected to not only the weight of the building but also the seismic inertial force combined with vertical and lateral load. To develop a new design method that can make effective use of existing piles by the insulated pile foundation concept, it is necessary to clarify the bearing mechanism. Therefore, shaking table tests using model specimens were conducted for several types of ground models.

2. Experimental procedures

Tests are conducted using a rigid soil tank. As shown in Fig. 1 (a), the rigid soil tank has 1038mm length, 738mm width, and 350mm depth and is fixed on the shaking table. Two types of tests are conducted, namely, ExP(existing pile) case and Nop(no pile) case. Exp case has a ground model, a spread foundation building model, and existing piles in the ground model. Nop case does not have existing piles, but otherwise is the same as Exp case. The test apparatus is designed only the ground around the foundation because the interaction behavior between the existing piles and the footing is focused.



(a) Plan of rigid tank (b) Two types of specimen

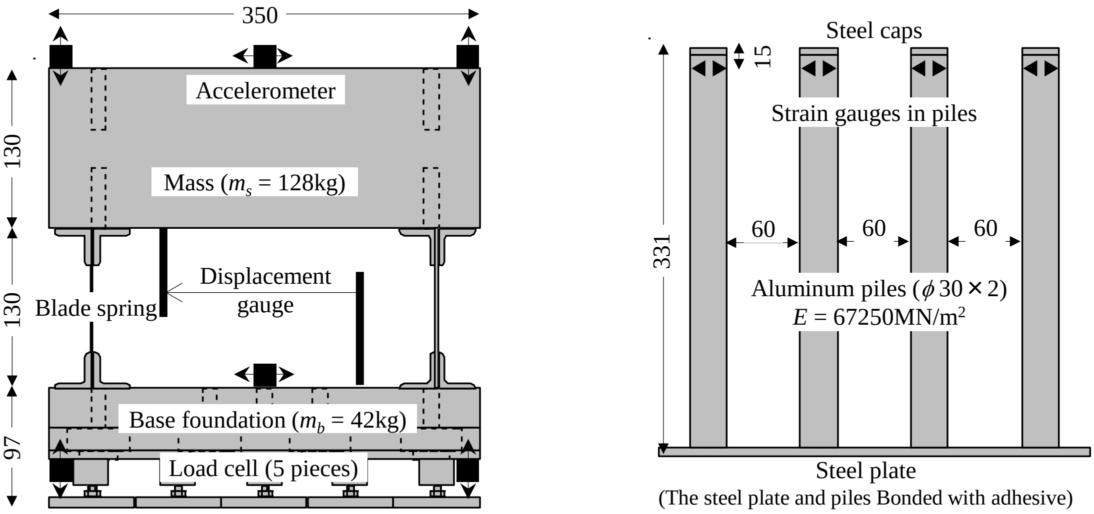
Fig. 1 – Setup of test shaking table tests and test (unit: mm)

The ground model is set in the tank. The model ground is consisted of Toyoura sand. The specific gravity, the maximum void ratio, and the minimum void ratio of Toyoura sand are 2.65, 0.95, and 0.58, respectively. The model soil preparation was summarized as follows; 1) The layered soil segmented into 4 layers is put in the tank softly by using the container bag carried by crane. The layered soil was consisted of

3 layers of 100mm depth and one layer of 50mm depth. 2) The surface of the layered soil is smoothed by using a trowel and compacted by using a vibrator. 3) The depth of the layered soil is measured at the top of the tank. And then, the relative density of the layered soil was calculated.

As shown in Fig. 2 (a), the spread foundation building is designed to behave as a SDOF system with a flexible base condition, as shown in Fig. 3. The building is consisted of an upper mass, 4 blade springs, and a base foundation. The base foundation have five load cells at the bottom and the distribution of subgrade reaction can be measured with 1/5 resolution. Horizontal and vertical acceleration of the mass and the base foundation, story drift and horizontal and vertical displacement of the mass and the base foundation can be measured by accelerometers and non-contact displacement gauges. Mass of the upper mass m_s is 128kg, and mass of the base foundation m_b is 42kg (contained mass of load cells), respectively. The natural frequency f_1 is 12Hz.

As shown in Fig. 2 (b), an existing pile is modeled as an aluminum pipe which has 30mm in diameter and 331mm in length. The dry sand is filled in the space between the bottom of the base foundation and the top of piles which is about 20mm. The existing piles are composed of 16 model piles. The existing piles are bonded to a steel plate with adhesive and the plate is put on the bottom of the tank. The tops of piles are covered with steel caps.



(a) Structure model (The natural frequency is 12Hz) (b) Existing piles

Fig. 2 – Details of Specimen (unit: mm)

Table 1 shows test cases of input motion for the shaking table tests. The input motion is the scaled sine wave acceleration, which consists of 5 principle waves with a rising and falling wave before and after. The frequency of sine wave f_{inp} is changed each 2Hz from 4Hz until 20Hz. Several maximum accelerations of the input motion are applied in these tests. Input amplitudes (namely, I.A.) are 1.0, 2.0, 4.0, and 6.0m/s^2. In the cases of 1.0, 2.0, and 4.0 m/s^2, a method to input excitation continuously is adopted with increasing frequency, and in the case of 6.0 m/s^2, the structure model is replaced and the surface of the ground model is smoothed for each excitation of different frequency. This paper shows the test results in the cases of 1.0, 2.0, and 4.0m/s^2.

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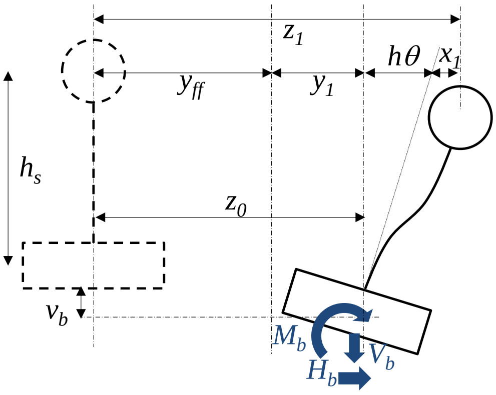


Fig. 3 – A SDOF structural model considered with soil-structure interaction

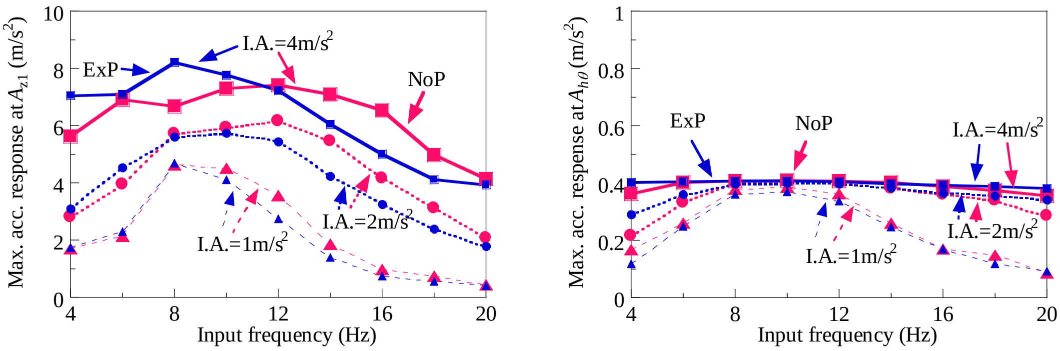
Table 1 – Cases of input motion

Input case name	Input Amplitude	Details
1) Sine wave	$1m/s^2$	Continuous oscillations with increasing frequency (f_{inp}= 2, 4, 6, 8, 10, 12 , 14, 16, 18, 20Hz)
	$2m/s^2$	
	$4m/s^2$	
2) Sine wave	$6m/s^2$	Single oscillation with changing frequency, respectively (f_{inp}= 2, 4, 6, 8, 10, 12 , 14, 16, 18, 20Hz)

3. Test results and discussion

3.1 Maximum response of structure

Fig. 4 shows the maximum acceleration responses of mass in a horizontal direction for each I.A. plotted against the input frequency. As shown in Fig. 4(a), the acceleration response of the structure has peaked at a frequency of 8 to 12Hz with input amplitude I.A.=1.0 and $4.0m/s^2$. Therefore, the natural frequency of the soil-structure interaction system is estimated to be 8 to 12Hz in these cases. On the other hand, the maximum acceleration response from 4 to 12Hz is little change in the case with input amplitude I.A.=$4.0m/s^2$. As shown in Fig. 4(b), the rotational component of the acceleration response has peaked with input amplitude I.A.=$4.0m/s^2$. If the maximum value of the rotational component is almost constant for a building without an embedded part, it is suggested that a slip behavior occurs between the foundation and the ground or the overturning moment reaches the maximum resisting moment by weight of the structure model. The rotational component has an almost constant value in all frequency ranges with input amplitude I.A.= $4.0m/s^2$. Therefore, the test result with I.A.=$4.0m/s^2$ is under the condition where slip or lifting behavior of the foundation occurs.



(a) Absolute acceleration : A_{z1} (b) Rotational component : $A_{h\theta}$

Fig. 4 – Maximum acceleration responses of the mass(at mass point) for each I.A. vs input frequency

3.2 Residual displacement of foundation

Fig. 5 shows the residual settlement vb and rotation displacement q of the foundation after each frequency excitation plotted against the I.A. and the input frequency. The residual settlement and rotation displacement are based on the start of the tests. As shown in Fig. 5(a), the residual settlement displacement of ExP case is almost the same as that of NoP case, so it can be seen that the residual settlement of the foundation occurs during excitation regardless of the existence or absence of the existing piles. The residual settlement increases significantly with low-frequency excitations (4.0 - 10.0Hz) at each input amplitude. Furthermore, the larger the input amplitude is, the larger the residual settlement displacement occurs. However, the residual settlement displacement with the input amplitude from 1.0 to 4.0 m/s^2 is within the distance between the bottom of the foundation and the top of the existing piles. As shown in Fig. 5(b), the residual rotational displacement of ExP case is almost the same as that of Nop case with the input amplitude 1.0 and 2.0 m/s^2. On the other hand, residual rotational displacement of Exp case with the input amplitude 4.0 m/s^2 is smaller than that of NoP case. Therefore, it is suggested that the existing piles prevent the tilting of the foundation.

Photo 1 shows the settlement and tilt behavior of the foundation with the input amplitude I.A. = 4.0m/s^2. The white broken line in each photo represents the initial position of the upper surface of the base plate before I.A.=4.0 m/s^2 exicitations and the red line represents the bottom line of the base plate after excitations. It can be seen that the base plates located outer side (left side of Photo 1(b-2)) is embedded in the ground model.

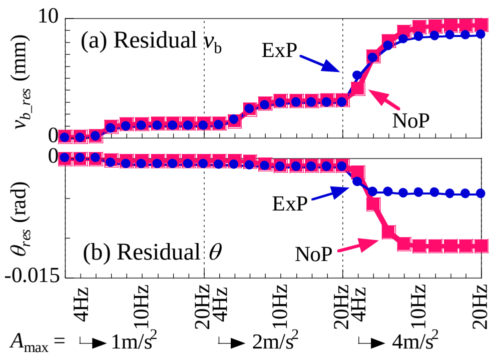


Fig. 5 – Residual settlement and rotational displacement of the foundation after each frequency excitation

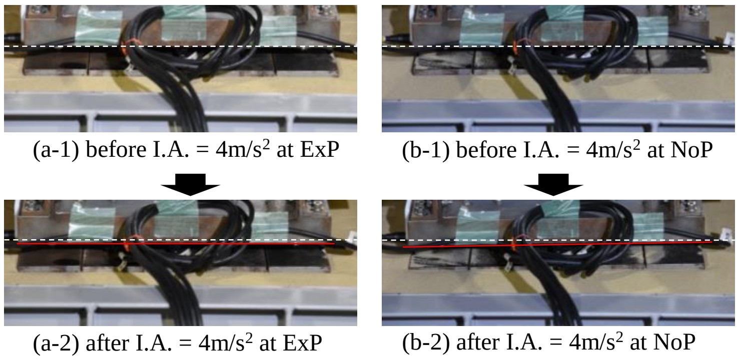
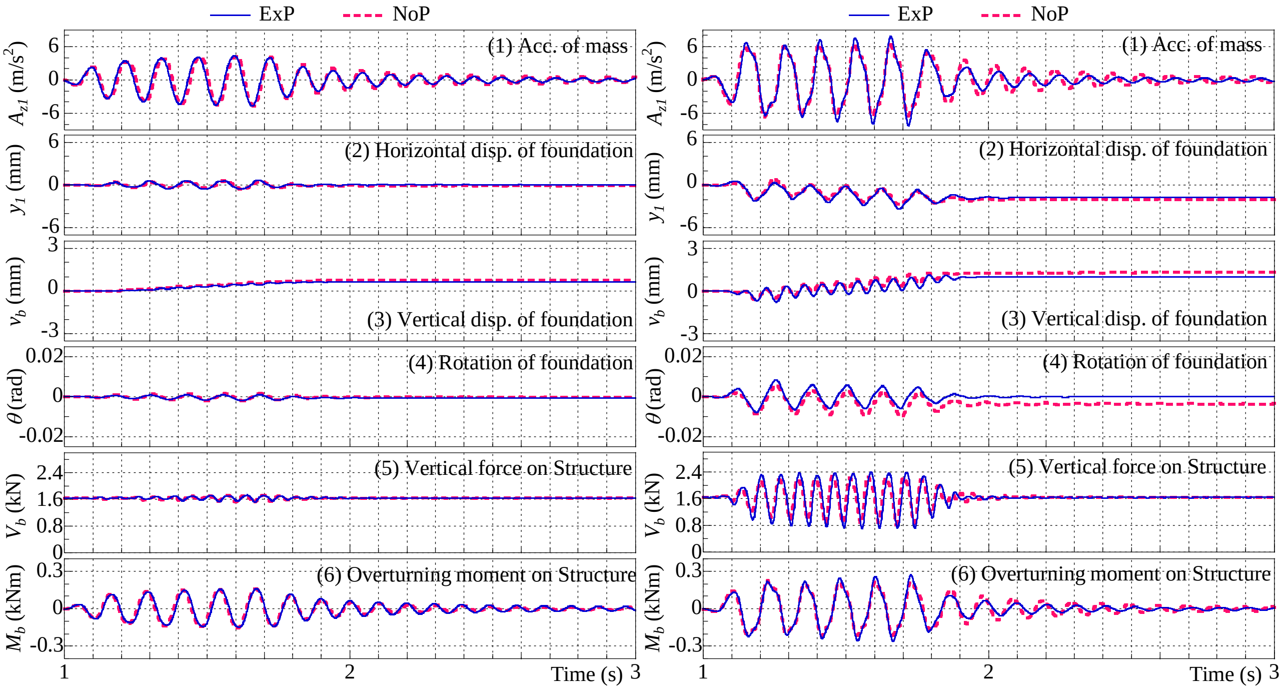


Photo 1 – Settlement and tilt behavior of foundation with input amplitude I.A. = 4.0m/s^2
(white broken line : initial position before excitations, red line : position after excitations)

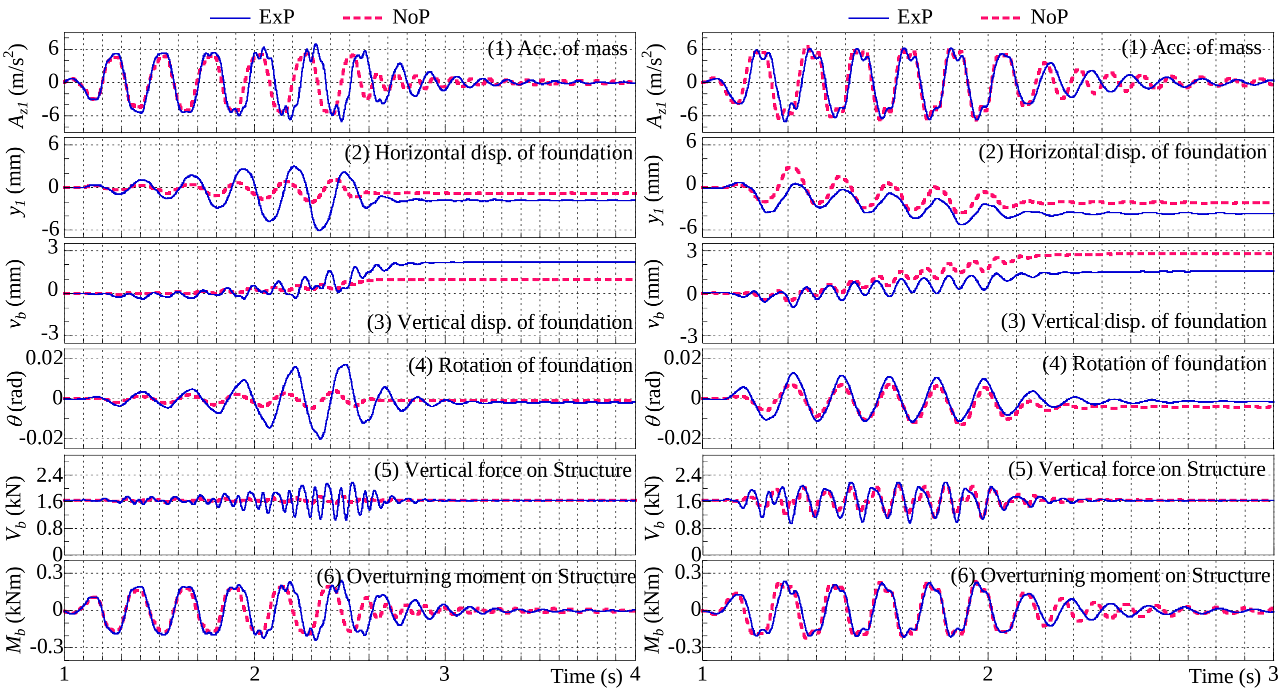
3.3 Response of structure

The time histories of Exp case and Nop case with input frequency f_{inp} = 8.0Hz are compared and shown in Fig. 6 with the input amplitude 1.0m/s^2 and 4.0m/s^2, respectively, (1) shows the acceleration of mass, (2) shows the horizontal displacement, (3) shows the vertical displacement of foundation, (4) shows the rotational displacement, (5) shows the sum of the subgrade reaction (vertical force) acting on the foundation, and (6) shows the sum of the overturning moment acting on the structure. In the results with I.A.=1.0m/s^2, shown in Fig.6(a), all of the time histories of ExP case are almost the same as that of NoP case. As shown in Fig.6(a-3), the baseline of the vertical displacement of foundation is shifted linearly during the building is oscillated seen in Fig.6(a-1). This behavior is observed even if the input amplitude increases, as shown in Fig.6(b-1) and (b-3). However, increasing the input amplitude increases the vertical displacement amplitude and the residual vertical displacement. Also, the same behavior is observed in the rotational displacement and the shift of the baseline of ExP case is smaller than that of NoP cases. In addition, it can be seen that when the input amplitude increases, the waveform of the acceleration response of mass and the overturning moment change, in Fig.6(1) and (6), the residual displacement in the horizontal direction occurs, in Fig.6(2), and the oscillation of the subgrade reaction occurs at twice the frequency of input motion, in Fig.6(5).



(a) I.A. = 1.0m/s^2 (b) I.A. = 4.0m/s^2

Fig. 6 – Comparison of time histories between Exp case and Nop case with input frequency f_{inp} = 8.0Hz

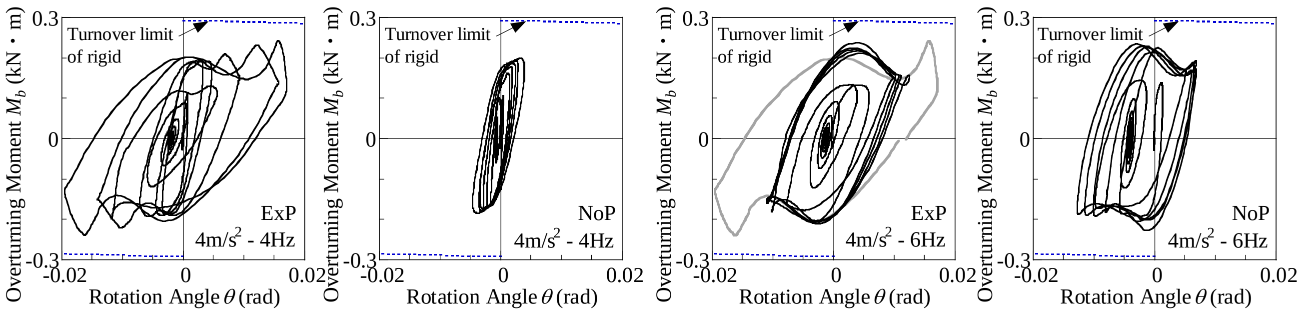


(a) f_{inp} = 4.0Hz (b) f_{inp} = 6.0Hz

Fig. 7 – Comparison of time histories between Exp case and Nop case with input amplitude I.A. = 4.0m/s^2

As shown in Fig.6, it can be seen that the baseline shift of the vertical displacement or the rotational displacement of the foundation during the excitation of the structure causes the residual settlement and tilt of the foundation. It is suggested that the amount of the residual settlement and the residual tilt of the foundation are related to the oscillation characteristics of the structure. The time histories of ExP case and Nop case with input amplitude 4.0m/s^2 are compared and shown in Fig. 7 with the input frequency 4.0 and 6.0Hz, respectively, when the amount of increase in the residual settlement or the residual tilt is remarkable as shown in Fig.5. As mentioned in Fig.4, the baseline of the horizontal displacement of the foundation is shifted during the oscillation of the structure as shown in Fig.7(b), and it is considered that the slip behavior occurs between the foundation and the ground. Small vibrations at peaks of the acceleration responses and the overturning moments acting on the structure appear with the input frequency 4.0Hz of ExP cases, in Fig.7(a-1) and (a-6), and that of 6.0Hz of NoP cases, in Fig.6(b-1) and (b-6). The responses of the vertical displacement and the rotational displacement are large when the small vibration at the beak becomes remarkable in Fig.7(a-3), (a-4), (b-3), and (b-4). In addition, it can be seen that the oscillation of the subgrade reaction appears at the same time, in Fig.7(a-5) and (b-5).

Fig. 8 shows the comparison of overturning moment and the rotation angle relationships between Exp and Nop with the input frequency 4.0Hz and 6.0Hz, and the input amplitude 4.0 m/s^2. The thin line in ExP case of Fig.8(b) is the relationships of the maximum displacement cycle of ExP case in Fig.8(a). The blue broken line in these figures are the overturning moment and the rotation angle relationship of a rigid body on a rigid base. The overturning moment in the relationship of Exp case with f_{inp} = 4.0Hz has the several peaks in one cycle, are higher at first, then decrease and increase again as shown in Fig.8(a), ExP case. It is considered that this behavior is caused by the higher mode response by lifting of the foundation(Meek [5]). The region of the decrease expands with each cycle of the excitation. The same behavior observed the relationship of NoP case with f_{inp} = 6.0Hz as shown in Fig.8(b). In addition, the relationship of ExP case with f_{inp} = 6.0Hz is almost contained in the maximum displacement cycle with f_{inp} = 4.0Hz and affected by the previous excitation. Furthermore, the decreasing behavior of the overturning moment occurs significantly earlier than the skeleton curve represented the overturning of the rigid body. It is considered that the local non-linearity in the ground around the foundation affects these behaviors.



(a) f_{inp} = 4.0Hz (b) f_{inp} = 6.0Hz

Fig. 8 – Comparison of the overturning moment - the rotation angle relationships between Exp and Nop with the input frequency 4.0Hz and 6.0Hz (I.A. = 4.0m/s^2, the thin line in ExP case of Fig.(b) is the same as the result of Fig.(a))

Fig. 9 shows the time histories of the average subgrade reaction to the load cell on the foundation and the axial force of the existing pile located outer side with input amplitude 4.0m/s^2. The bearing capacity q_u is given by

$$\begin{aligned} q_u &= (0.5-0.2C_{test})\gamma\,(B/1.0)^{-1/3}\,N_r\,BC_{test} \\ N_r &= (N_q-1)\tan(1.4\phi) \\ N_q &= (1+\sin\phi)/(1-\sin\phi)\exp(\pi\tan\phi) \end{aligned} \quad (1)$$

where γ: unit weight(kN/m^3), B: width of foundation (=0.35m), N_r, N_q: bearing coefficient, ϕ:friction angle of ground model(35degree), C_{test}: contact ratio between foundation and ground.

The contact ratio is evaluated by dividing the range of 0.0 to 1.0 into 5 divisions from the value of the load cells. When the average pressure of the load cell is less than 1.0% of the average pressure of the structure, it is defined that the load cell has separated from the ground. The average subgrade reaction of NoP case with input frequency 4.0Hz is about half of the bearing capacity. That with input frequency 6.0Hz is approaching the bearing capacity, and the residual rotational displacement occurs as shown in Fig.7(b). On the other hand, that of ExP cases with input frequency 4.0Hz and 6.0Hz is approaching about 80% of the bearing capacity. However, the axial force of piles arises at the same time of the average subgrade reaction and the residual rotation displacement is smaller than that of NoP case as shown in Fig.5 and Fig.7(b). It is considered that the distance between the bottom of the foundation and the top of the existing piles become smaller by settlement of the structure, the axial load on the existing piles increases when the overturning moment increases. As a result, the tilting of the building with the existing piles during excitations is reduced. Therefore, the existing piles can be expected to bear the axial force even if the footing and the existing piles are insulated.

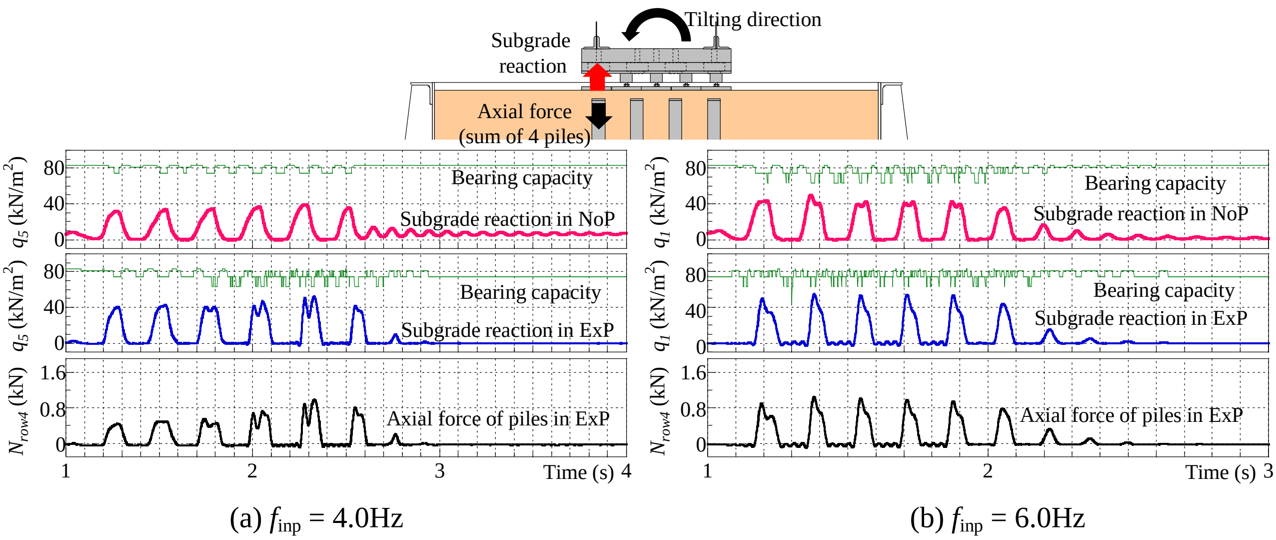


Fig. 9 – Time histories of average subgrade reaction to load cell on foundation and axial force of piles located outer side with input amplitude I.A. = 4.0m/s^2

4. Conclusions

The major findings obtained from a series of model tests under limited conditions are summarized as follows.
1) The settlement of the foundation occurs during excitation regardless of the existence or absence of the existing piles, and the residual settlement displacement of the foundation with the existing piles is almost the

same as that without the existing piles. On the other hand, the residual rotational displacement of the foundation with the existing piles is significantly smaller than that without the piles in the test with large input amplitude. 3) The behavior of superstructure during excitation is affected by the local nonlinearity around the foundation which depends on the existence of existing piles. 4) The distance between the bottom of the foundation and the top of the existing piles become smaller by settlement of the building, the axial load on the existing piles increases when the overturning moment increases. As a result, the tilting of the building with the existing piles during excitations is reduced. Therefore, the existing piles can be expected to bear the axial force even if the footing and the existing piles are insulated.

5. Acknowledgement

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