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PILE RESPONSE CHARACTERISTICS OF LIQUEFIED SOIL LAYERS IN SHAKING TABLE TESTS OF A LARGE SCALE LAMINAR SHEAR BOX

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ABSTRACT

To better understand the causes of pile damages during earthquakes such as Hyogoken-Nanbu Earthquake, shaking table tests of soil-pile-structure interaction models were done using a large scale laminar shear box. Because the pile response is affected by both the ground motion and the structure's inertial forces, three models were tested: a soil-pile model and two soil-pile-structure models. For the latter models, superstructures with long and short natural periods were tested separately. Through comparisons among the three cases, the influences on the pile response due to the inertial force of the superstructure for the long and short natural periods were clarified and properties of the subgrade reactions in liquefied ground were determined.

KEYWORDS

Liquefaction, Shaking table test, Laminar shear box, Soil-pile-structure interaction, Earthquake, Ground motion, Spectrum ratio, Natural period, Inertial force, Subgrade reaction

INTRODUCTION

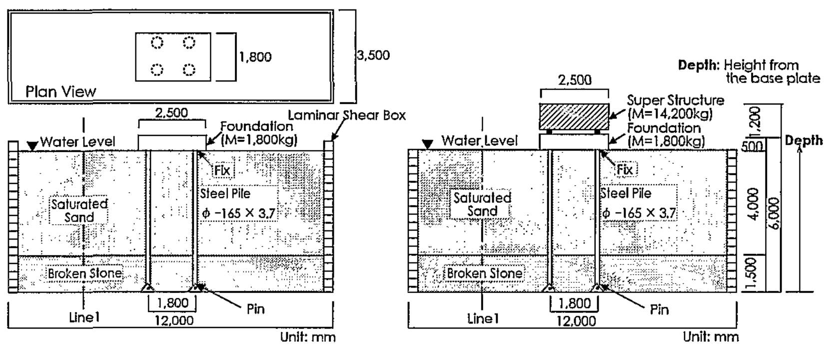
The purpose of this study is to clarify the characteristics of the pile response in the liquefied ground during a large earthquake. There have been several field investigations on the pile damage during Hyogoken-Nanbu Earthquake and the corresponding analytical studies. (Fujii et al.,1998, Yahata et al.,1998) Also, shaking table tests have been used to simulate the effects of earthquakes on concrete piles (Tamura et al., 2000). In the present study, shaking table tests of soil-pile-structure were carried out using a large scale laminar shear box in order to reproduce the pile response and the pile damage in the liquefied ground. As the pile damage is closely related to the ground motion and the inertial forces of the superstructure, three parametric models were used in the test: a soil-pile model to investigate the influence of the ground motion, and two kinds of soil-pile-structure models having superstructures with the long and short natural periods separately to study the influence of the inertial forces.

MODELS AND SHAKING TABLE TESTS

The models are explained in Fig.1 and the test conditions are described below.

Because the pile response is generated by both ground motions and the structure's inertial forces, the soil-pile model and two soil-pile-structure models were tested. Each test model has the same foundation supported by four steel piles. The details of the models are outlined as follows.

1. A soil-pile model for estimating the pile response due to the liquefied ground motions. This is case A1.
2. Two soil-pile-structure models with different natural periods, for investigating the pile behavior influenced by the inertial forces in the liquefied ground; the natural period of the structure in case AL is 0.8 sec, whereas that for case AS is 0.2 sec.
3. The masses of the superstructure and the foundation were 14200 kg and 1800kg, respectively. Therefore, the inertial force contribution from the foundation is assumed to be negligible.



Section View of soil-pile model (A1 model)

Section View of soil - pile - structure model (AL and AS models)

Fig.1 Test models

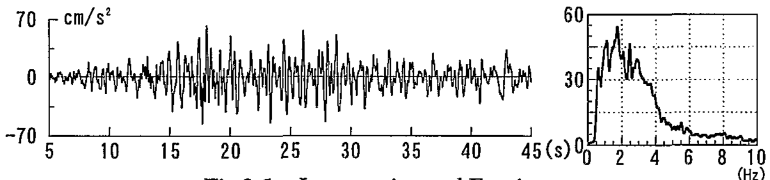


Fig.2-1 Input motion and Fourier spectrum

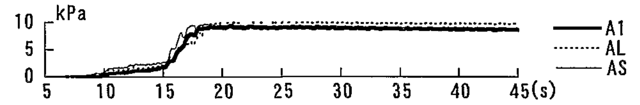


Fig.2-2 Pore Pressure at 4.5m depth

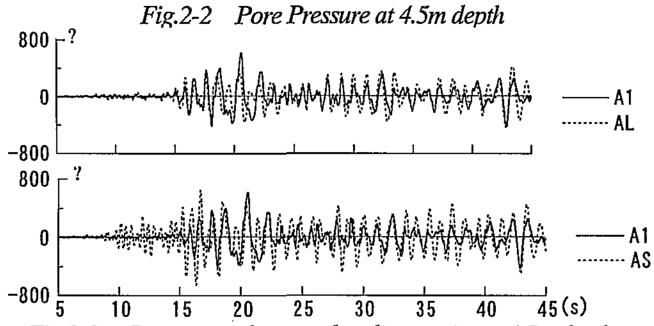


Fig.2-3 Comparison between bending strains at 4.5m depth

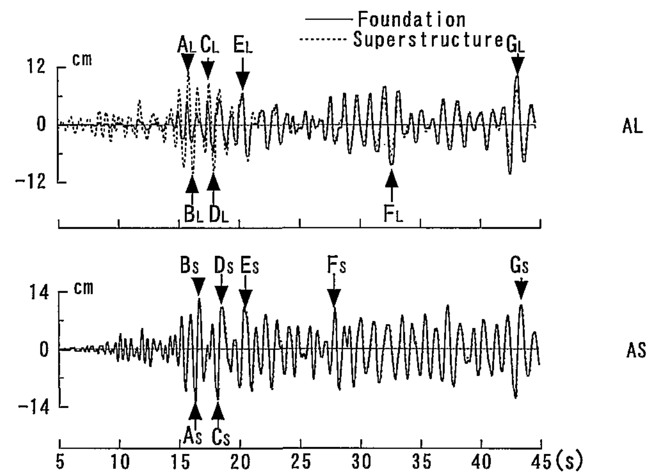


Fig.2-4 Foundation and superstructure displacements

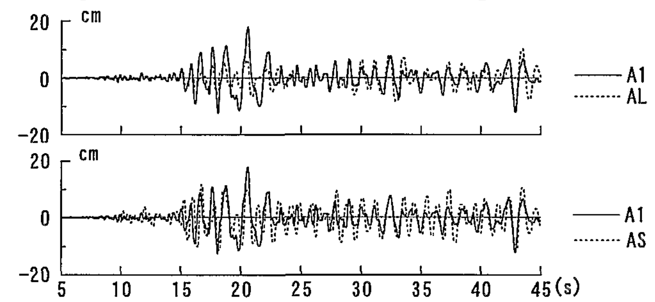


Fig.2-5 Foundation displacements

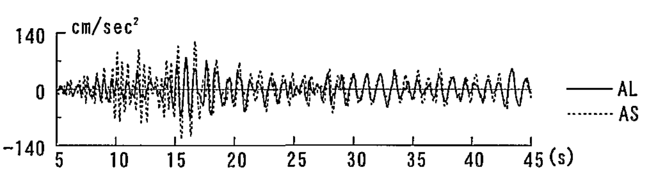


Fig.2-6 Superstructure accelerations

Fig.2 Time histories

4. The superstructure for AL was supported by isolation rubbers and viscous dampers which were set up on the foundation and for the case of AS, they were laminar rubber bearings, isolation rubbers and viscous dampers.
5. The pile had a 16.52cm diameter with a 0.37cm wall thickness, the flexural rigidity of the pile, EI, was 1259kNm^2. The pile heads were fixed tightly to the foundation and the pile tips had pin joints connected to the base plate of the large laminar box.
6. Four steel piles were used to keep the pile response within an elastic range during the tests.
7. There were two layers in the ground to simulate the pile responses affected by the boundary between the liquefied sand and the broken stone. These layers correspond to the reclaimed fill and the underlying alluvial clay in the reclaimed land where the piles were damaged during Hyogoken-Nanbu Earthquake.

The effect of the inertial force in the pile response was determined by comparing AL and AS with A1. Through the comparison between the pile responses of AL and AS, the effects from two types of inertial forces were observed.

The accelerometers and pore pressure gauges were set up along Line 1 in Fig.1 for measuring the liquefaction ground response, and the strain gauges were installed along the outside length of the pile for measuring the pile response. The ground and the pile displacements were evaluated from the accelerometer measurements, and the relative displacements between the pile and the ground along Line 1 were obtained by a similar procedure. The shear forces of the pile were evaluated from the strain gauge measurements.

As for the shaking table tests, a large scale laminar shear box with a base of 12m×3.5m and height 6.0m shown in Fig.1 was used and Rinkai92, which is a synthetic ground motion in the Tokyo bay area, was used for the input motion in the shaking table tests. These tests were done using several different amplitudes of the input motion. The test result obtained from the case with a 60cm/s^2 input motion shown in Fig.2-1 is presented in this paper. The results obtained from the shaking tests are as follows.

TIME HISTORIES

The pore pressures at the 4.5m depth rose gradually between 10 and 15sec (hereafter called Period 1) for all three cases. The pore pressure then rose rapidly between 15 and 19sec (hereafter called Period 2), and then reached the maximum value, that is, hydrostatic pressure: the pore pressure at which the complete liquefaction occurs. This is shown in Fig. 2-2. The qualitative behavior for all three cases were similar; thus, the differences between the three ground models, A1, Al and AS, might be slight.

At the 4.5m depth, the bending strain for AL is smaller than that of A1 within Periods 1 and 2 shown in Fig.2-3; however, it becomes greater than A1 after about 25sec. As for the relation of the period between A1 and AL, a very small difference is found which may tend to reduce the amplitude of AL. Conversely, it for AS is typically larger than that of A1 before 15sec. The large amplitudes in AS before 15sec are generated from the inertial force of the superstructure. For AS, the inertial force produces a significantly greater bending strain amplitude during Periods 1 and 2 as compared to A1. Conversely, AL has a smaller amplitude than A1 during the same time periods; however, AL and AS are similar after 40sec.

Fig.2-4 shows the foundation and superstructure displacements for AL and AS. The amplitude of the superstructure response is greater than that of the foundation only before 20sec for AL, whereas the superstructure response is almost the same to that of the foundation at nearly all the times for AS. Therefore, the inertial force of AS may be produced from the natural period of the soil-pile-structure interaction system during the test, which has a decreasing period with increasing pore pressure as described later. As for the inertial force of AL, it is initially resulted from the response for the natural period of the superstructure and then from that in the interaction system which can be regarded as one rigid mass system because both responses of the foundation and the superstructure are almost the same after nearly 20sec.

Seven times at which there are large amplitudes in the pile responses for the superstructures in AL and AS are marked A-G in the figures. A-D points occur in Period 2, whereas E point is in the initial period of the complete ground liquefaction shown in Fig.2-2 and F-G points are long times after the complete ground liquefaction.

Fig.2-5 compares the foundation displacements between AL and A1, and between AS and A1. The relation between AL and A1 corresponds to the trend in the bending strain shown in Fig.2-3. However, for AS and A1, comparing the results of the bending strain in Fig.2-3 to Fig. 2-5, Fig 2-5 shows a slight difference between AS and A1 before 20sec, and thereafter, the relative relation between AS and A1 becomes similar to that shown in Fig.2-3.

As the acceleration amplitude of AS for the superstructure shown in Fig.2-6 is greater than that for AL within Periods 1 and 2, the discrepancy between both cases decreases with increasing time after Period 2. Therefore the amplitudes due to the inertial force of the superstructure become similar after 19sec for AL and AS.

The study of the time histories is summarized as follows.

Although there is a large discrepancy between the bending strain of A1 and AS during Periods 1 and 2, the response periods in the bending strain of AL are close to those for the case of A1 at all the times, and the amplitude for AL is smaller than that for the case of A1 within Period 2. The discrepancy between the responses of AL and AS decreases after 40sec. The general trend in the foundation displacements for three models corresponds to that for the bending strains after Period 2.

SPECTRUM RATIOS

Firstly, Fourier spectrum of the input motion is shown in Fig.2-1.
The spectrum ratios of the superstructure to the foundation, shown in Fig.3-1, are the results of AL and AS with natural frequencies of 1.5 Hz (0.8 sec) and 5 Hz (0.2 sec), respectively. Four spectrum ratios of the superstructure and the foundation to the input motion are shown in Fig.3-2 for AL. From left to right, the time periods are 1 through 4; hereafter Period 3 is 19-30 sec, and Period 4 is 30-45sec.
Periods 3 and 4 are the times when the pore pressure at the 4.5m depth first reached its maximum value and thereafter, respectively. The first peak for the superstructure near 1.5 Hz in Period 1, which is not seen clearly and is a different frequency from that of the foundation, agrees approximately with that in Fig.3-1, and then it shifts to lower frequencies gradually with increasing time. The first peak for the foundation during Period 1 is at 3 Hz. This peak is generated from the ground; it decreases from 3 Hz to below 1 Hz during Periods 3 and 4.

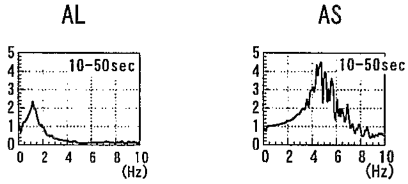


Fig.3-1 Spectrum ratios of superstructure to foundation

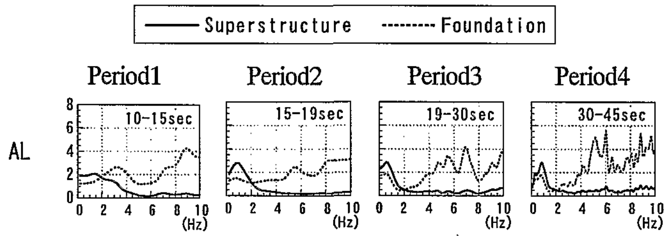


Fig.3-2 Spectrum ratios of superstructure and foundation to input motion for AL

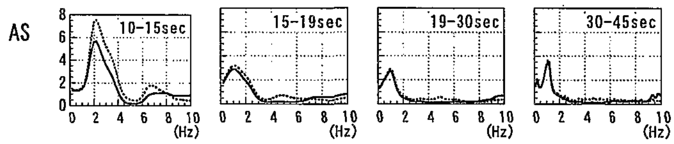


Fig.3-3 Spectrum ratios of superstructure and foundation to input motion for AS

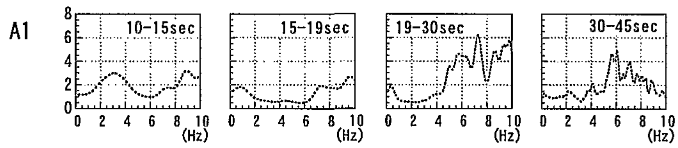


Fig.3-4 Spectrum ratios of foundation to input motion for A1

For the case of AS shown in Fig.3-3, the first natural frequency in Period 1 is at 2 Hz and shifts to a lower frequency near 1 Hz in Period 2, which is similar to the case for AL; however, the first natural frequencies of the superstructure coincide with those for the foundation in the four spectrum ratios. As already described, the first natural frequency is not resulted from that of the superstructure but from the interaction. Although the spectrum ratios for the superstructures of AL and AS in Period 1 are significantly different, they are nearly the same in Periods 2 and 3.

The spectrum ratio of A1 shown in Fig.3-4 during Period 1 is nearly the same as that for the foundation of AL in Fig.3-2; therefore, it for AL is probably resulted from ground motion. During Periods 3 and 4, there is an appreciable discrepancy between the foundation responses in AL and A1 cases below 2 Hz. Whereas the first peak for AL corresponding to the response due to the interaction is seen in Period 4, it is not seen for A1. Through this analysis, the influences due to the interaction were found to be limited to frequencies below 3 Hz. Therefore, these frequencies are filtered out hereafter to focus the study on the influence on the pile responses due to the inertial force of the superstructure after Period 1. Both low- and high-pass filters for 3Hz are used.

BENDING STRAIN DISTRIBUTIONS OF THE PILES

Seven comparisons of the bending strain distributions of AL and A1, representing times A-G, and similarly, for AS and A1 are shown in Fig.4. For these plots, the low-pass filter was used; however, the same

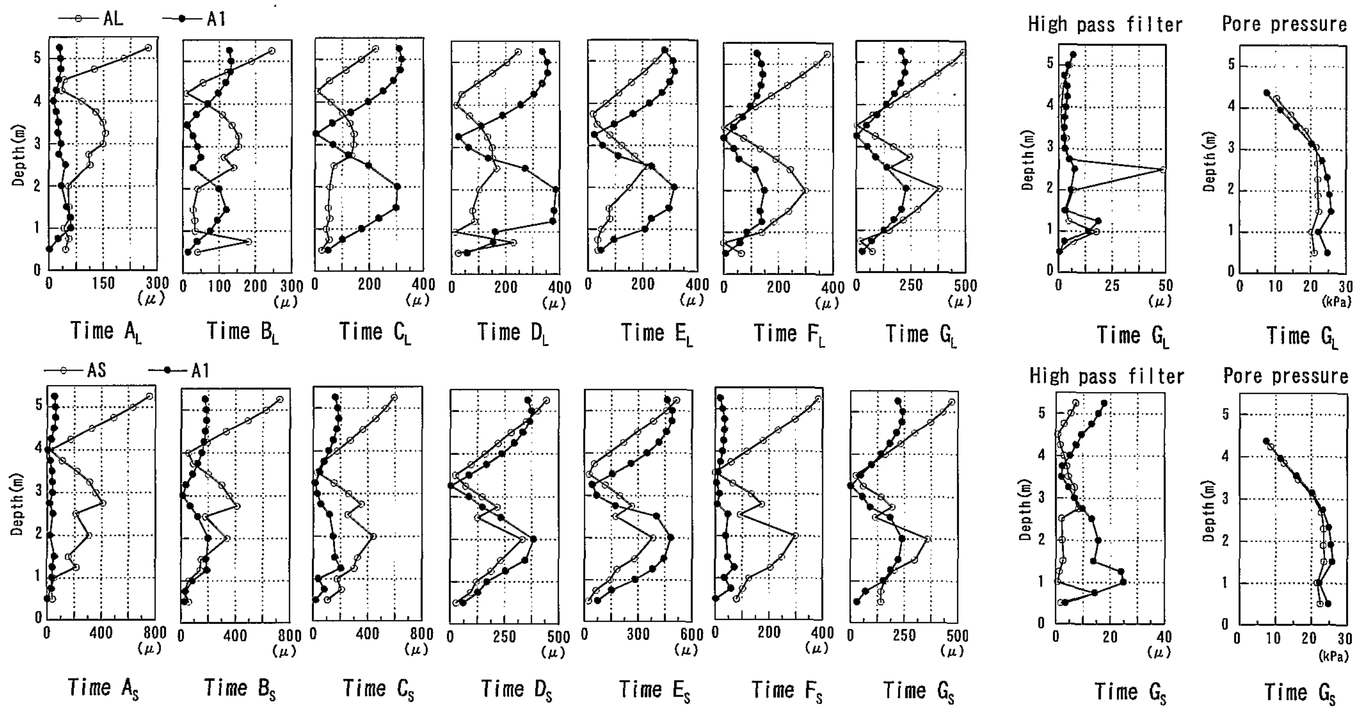


Fig.4 Bending strain distributions and pore pressure distributions

Table1 Large amplitude for three models

	Position	Time
A1	Pile head	E_S
	Deep depth	E_S
AL	Pile head	A_L,F_L,G_L
	Deep depth	F_L,G_L
AS	Pile head	A_S,B_S,E_S,G_S
	Deep depth	E_S,G_S
Deep depth; 2.0m		A–D ; Period2
		E ; Period3
		G ; Period4

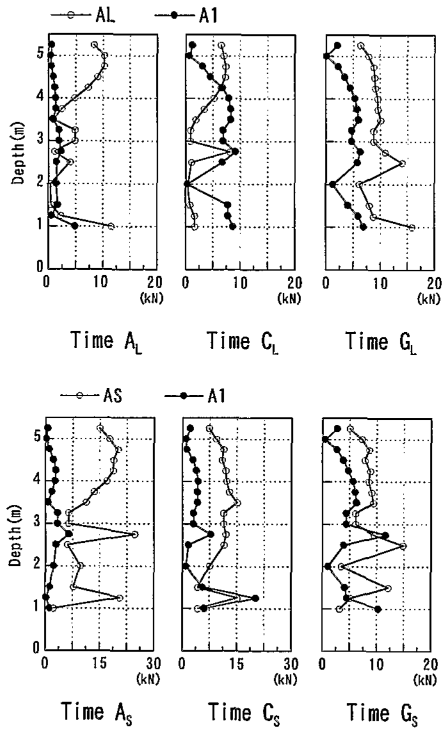


Fig.5 Shear force distributions

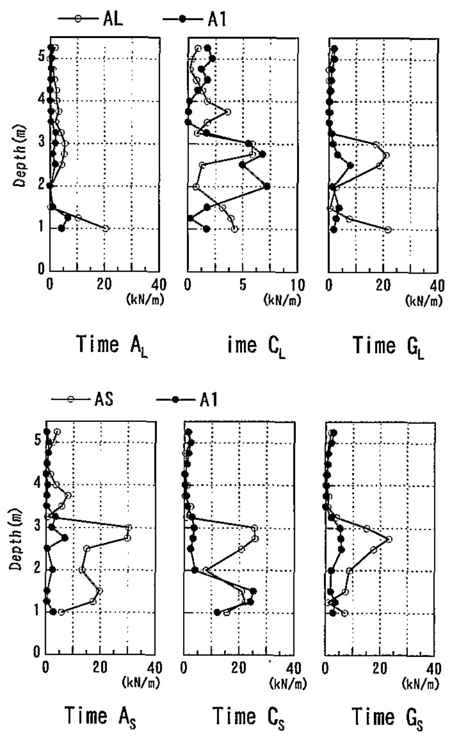


Fig.6 Subgrade reaction distributions

plots using the high-pass filter is shown for time G. The pore pressure distributions at time G are also shown. The superstructure displacements showed the large amplitudes at each time from A to G in Fig.2-4. These points are subdivided further as follows:

A-D: times during Period 2,
  A_L-D_L: times for the case of AL
  A_S-D_S: times for the case of AS

E: time in the beginning of Period 3,
  E_L: time for the case of AL
  E_S: time for the case of AS

F: times during Periods 3 and 4,
  F_L: time for the case of AL during Period 4
  F_S: time for the case of AS during Period 3

G: times during Period 4,
  G_L: time for the case of AL
  G_S: time for the case of AS

The letters A-G without L and S indicate the times for both AL and AS.

As the pile responses are different between AL and AS during Period 2, the large amplitudes occur at slightly different times; for instance, time D_L is close to time C_S, and time F_L is a far from time F_S. However, three cases for times B, E, and G are almost the same in both models. From Fig.4, it is found as follows. The bending strains are greatly influenced by the inertial forces for the full length of the pile at all the times. The distribution properties in both AL and AS are similar at times A and B, and their inertial forces produce the large amplification

of the bending strain. A particular phenomenon appears in the latter half of Period 2 at times C_L and D_L; here the amplitudes for AL become significantly smaller than those for A1. Decreasing amplitudes are also observed in AS at time D_S, but the effect is smaller than that for AL.
The distributions of AL and AS at times E, F, and G depend strongly upon the inertial force and have similar trends; hence, it is during Period 2 that significant differences between AL and AS appears. The large amplitudes suggest that the pile damages occurred during an earthquake such as Hyogoken-Nanbu Earthquake and the large amplitudes for each case are summarized in Table 1.

For times G_L and G_S, the high-pass filter cases, all the amplitudes are small and the distribution tendencies of AL are similar to those for A1. Therefore, neglecting response contributions from frequencies above 3 Hz should be acceptable for investigating the influence due to the inertial force.
The pore pressure distribution at time G indicates that the half depth of the liquefaction layer above 3 m became completely liquefied, and the other half, from 3 m to 1.5 m, was gradually liquefied with an average pore pressure ratio of approximately 70%. Discrepancies between the three cases are small. The comparisons among three test models concerning the pile response in the liquefied ground discussed here are effective because of the similar ground models.

SHEAR FORCE AND SUBGRADE REACTION DISTRIBUTIONS OF THE PILE

The shear force and the subgrade reaction in Figs. 5 and 6 were derived from the bending strains. These distributions at times A, C, and G are shown. Whereas the amplitudes of the shear force are large for AL and AS from the surface to the depth near 3m at time A, the distribution amplitudes become more nearly uniform at time G because of the degrading effective stresses in the ground. The distributions at time C_L are significantly affected by the inertial force for AS, and the boundaries at the depths near 3m and 1.5m. The depth 3m corresponds to the bottom level of the complete liquefaction ground and the depth 1.5m is the boundary between the two layers.

The subgrade reaction distributions have the following characteristic properties: the complete liquefaction layer above 3m yields only very small amplitudes, whereas the partially liquefied layer from 3 to 1.5m produces complex distributions which are significantly influenced by both boundaries at the 3m and 1.5m depths. The slight discrepancy between AL and A1 seen near the surface at time C_L can partly be explained by the disturbance due to the inertial force which causes the effective stress of the ground to drop precipitously during liquefaction. The amplitudes of AL are smaller than those for AS at times A_L and C_L; however, the amplitudes for AL generally approach those for AS at time G_L.

SUBGRADE REACTION COEFFICIENT

The relative displacements between the ground (along Line 1 in Fig.1) and the pile are compared in Fig.7 for the 4.5m depth. To clarify the relationship between the subgrade reaction and the relative displacement, three periods, S_1, S_2, and S_3, are chosen. These periods are short time periods within Periods 2, 3, and 4. Fig. 7 shows that the amplitudes during these three periods are large. The amplitude of AL is smaller than that for A1 during S_1 and S_2, which supports the analysis of Fig.2-3. The discrepancy between AL and AS decreases with increasing time after S_2, and then it becomes slightly greater once again during S_3. The relationships between the subgrade reaction and the relative displacement at the 4.5m and 2.5m depths are shown in Fig.8 during S_1, S_2, and S_3. The relationships for the relative velocity are also shown.

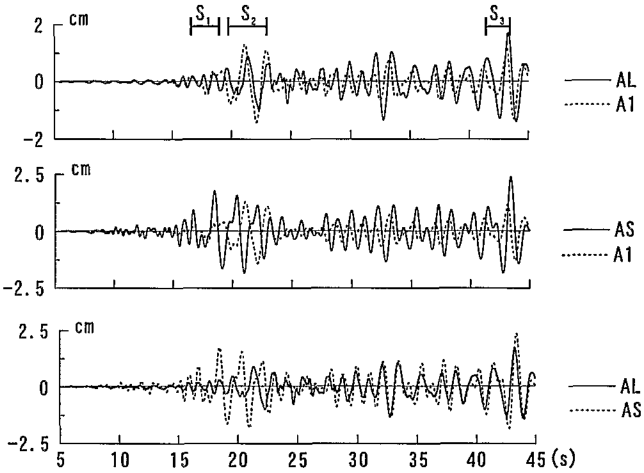


Fig.7 Time histories of relative displacements at 4.5m depth

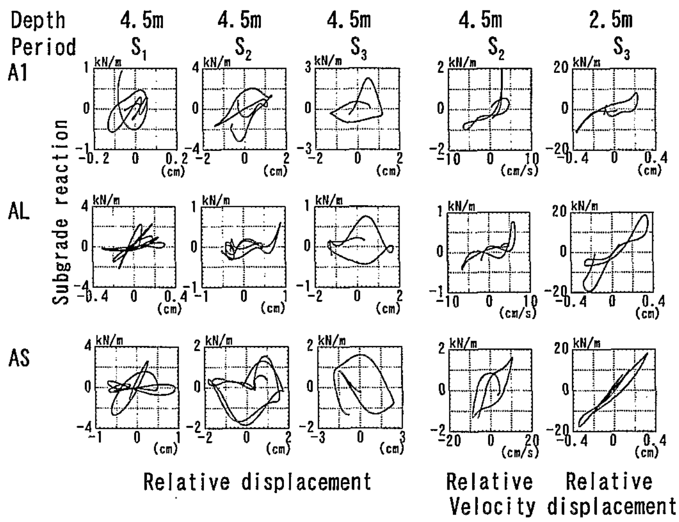


Fig.8 Relationships between subgrade reaction and relative displacement and velocity at 4.5m and 2.5m depths

The subgrade reaction coefficients at the 4.5m depth decreases with rising pore pressure during S_1. These coefficients can not be estimated from the relationship during S_2 and S_3 because of invisible correlation. After the complete liquefaction during S_2, the relationships between the subgrade reaction and the relative velocity become correlative and their general trends of A1 and AL are similar. On the other hand, at the shallower depth of 2.5m, the subgrade reaction coefficients are still relatively large because the pore pressures did not reach the maximum value shown in Fig.4 and the effective stress still remained enough.

PROPERTY OF GROUND MOTION

The small amplitude of the subgrade reaction above 4m at time C_L for AL in Fig.6 can be explained if the inertial force produces a degrading effective stress in the ground near the pile head. A discussion of this is presented below. The shear force of AL at the 4.5m depth due to the

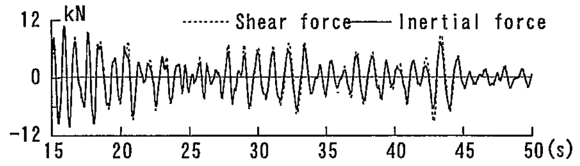


Fig.9-1 Shear force and inertial force for AL

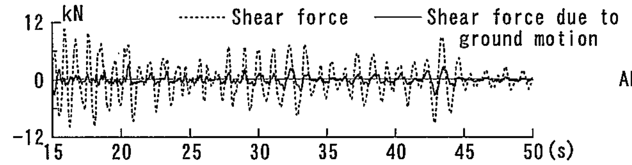


Fig.9-2 Shear force of test and shear force due to ground motion for AL

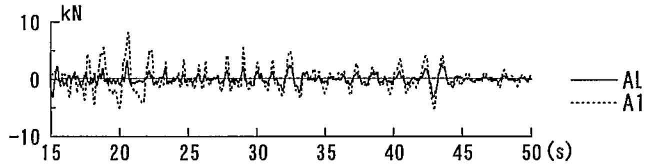


Fig.9-3 Shear force for A1 and shear force due to ground motion for AL

Fig.9 Time histories of shear force and inertial force at 4.5m depth

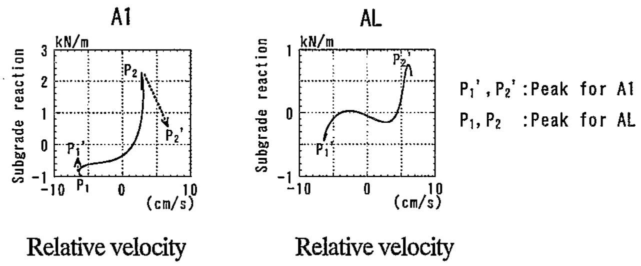


Fig.10 Relationships between subgrade reaction and relative velocity for small period in S_3 at 4.5m depth

ground motion shown in Fig. 9-2 is estimated by assuming that the contribution of the ground motion is the discrepancy between the shear and the inertial forces shown in Fig. 9-1. From Fig.9-2, the shear force due to the ground motion has very small amplitude. However, the amplitude for AL having the superstructure was approximately estimated by subtracting the inertial force from the shear force in the test, therefore the comparison between the shear forces due to the ground motions for A1 and AL is done as shown in Fig.9-3. It indicates that both waves have similar trends, but the amplitudes at each peak for AL are smaller than those for A1. This phenomenon suggests that the degrading effective stress for AL near the pile head is associated with the influence of the inertial force.
Fig.10 draws half loops of the relationship from the peak to the peak during S_2 shown in Fig.8 corresponding to time C_L for A1 and AL. These configurations are approximately similar and both peaks, P_1' and P_2', for AL correspond to those, P_1 and P_2, for A1, respectively. The amplitudes of the relative velocity and the subgrade reaction at the peak P_2' for AL are larger and smaller than those at the peak P_2 for A1, respectively. This trend is similar to the relation between P_1' and P_1. The smaller amplitude of the subgrade reaction for AL in Fig.10 agrees with the tendency observed in Fig.9-3 at each peak.

CONCLUSION

By comparing the test results among the three cases, the observations can be summarized as follows.

The inertial force for the case of AL, the long period case, reduced the bending strain amplitude during Period 2 while the pore pressure was rising. On the other hand, for the case of AS, it amplified the bending strain. The influences of the inertial force of AL and AS became similar after the pore pressure reached the maximum value, because both responses were generated due to the natural periods of the interaction system having one rigid mass.
The large amplitudes of the bending strain were found at the depth near the pile head and the depth near 3m and their appearing times were different among three cases. The large amplitudes might be associated with the pile damages during a large earthquake such as Hyogoken-Nanbu Earthquake.
The shear force distributions for AL at time C_L during Period 2 were strongly influenced not only by the inertial force but also by the boundaries of the soil layers in the ground. Similar tendency was also seen in the subgrade reaction distributions.
The correlative relationship between the subgrade reaction and the relative displacement disappeared after the pore pressure reached the maximum value, on the other hand it appeared for the case of relative velocity after that.
The amplitude of the shear force due to the ground motion for AL was approximately evaluated through the tests and the comparison of these shear force between AL and A1 indicated the degrading effective stress for AL near the pile head in the liquefied ground at each peak influenced by the inertial force.
Compared with the case of the short period AS, the pile behavior for AL was characteristic in the liquefied ground and much attention should be paid to the pile property at the natural period in the interaction system which varied as the amplitude of the pore pressure increased.

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