13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 332

CORRELATION BETWEEN INERTIAL FORCE AND SUBGRADE REACTION OF PILE IN LIQUEFIED SOIL

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SUMMARY

Shaking table tests have been conducted to clarify the characteristics of the subgrade reaction, and the relation between the inertial force and the subgrade reaction in non-liquefied and liquefied soil. Several experimental findings are: 1) The subgrade reaction mainly acts as a reaction force in the non-liquefaction state, while in the liquefaction state, it mainly acts as an external force in loose and medium sand, and as a reaction force in dense sand. 2) The maximum shear force on a pile to which the soil acts as a reaction force occurs at the pile head at the maximum inertial force. However the maximum shear force on a pile on which the soil acts as an external force occurs at the layer boundary. Its occurrence time is at the inertial force maximum in loose sand, and at the subgrade reaction maximum in medium sand. 3) The maximum inertial force and the maximum subgrade reaction do not act on the pile simultaneously in the same direction independently of the soil condition. According to the response displacement method, it is the superfluous design that the maximum inertial force and the maximum subgrade reaction act on the pile simultaneously in the same direction.

1. INTRODUCTION

Pile foundations were severely damaged by soil liquefaction and lateral spreading during the 1995 Hyogoken-Nanbu Earthquake. Pile damage was observed not only at pile heads but also at pile portions close to the interface between liquefied and non-liquefied strata.[1)~3)]

The dynamic behaviors of piles are greatly affected by both the inertial force of the superstructure and the lateral ground force (subgrade reaction) acting on the piles, which must be taken into account in their anti-seismic design. The authors have clarified the relationships between subgrade reaction and relative displacement/velocity in the liquefaction state.[4) 5)]

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This study was carried out to examine the correlation between inertial force and subgrade reaction. Shaking table tests were performed on pile foundation models in liquefiable sand deposits with four relative densities and in non-liquefied deposits. The input motions to the shaking table were various earthquake waveforms and various input acceleration levels.

2. EXPERIMENTAL PROCEDURE

2.1 Test model and measuring sensor locations

Shaking table test model and measuring sensor locations are shown in Figure 1. The laminar container[4] used in the experiments consisted of 25 identical vertically stacked frames 2 cm high. The width, depth, and height of the laminar container inside were 1.0, 1.0, and 0.5 m, respectively. The scale of the experiment model set the similarity ratio to 25 according to the similarity law[6].

A soil model was constructed in the laminar container with an unprecedented two-layer composition comprising an upper liquefiable soil and a lower non-liquefiable silicone rubber. The characteristics of the upper liquefiable sand are shown in Table1, and the grain size distribution curve is shown in Figure 2. A pile foundation model made of nine acrylic tubes (a 3×3 pile group) with a steel superstructure was installed in this soil model. The length, outer diameter, inter diameter and flexural rigidity of the acrylic tube were 490, 20, 17 mm and 13.9Nm^2, respectively. The piles were rigidly connected to the steel superstructure at the head and pin supported at the tip. The total weight of the superstructure was 151N. The accelerations, pore water pressures, and displacement were measured, as well as the pile bending strains. The bending strains were measured at the three center piles parallel to the excitation direction. The strain measurements were made at 12 points on each pile. Pile C is examined in this paper.

Shaking table test cases are shown in Table 2. The tests were conducted under two input waveforms, several input acceleration levels, and four relative densities of upper saturated sand. A particular model with water in place of the upper saturated sand was tested for comparison with a normal model with saturated sand. The input waveforms, the simulated earthquake motion[7] (RINKAI92H, hereafter named R wave) were developed to simulate an earthquake in the southern part of Japan's Kanto region and the

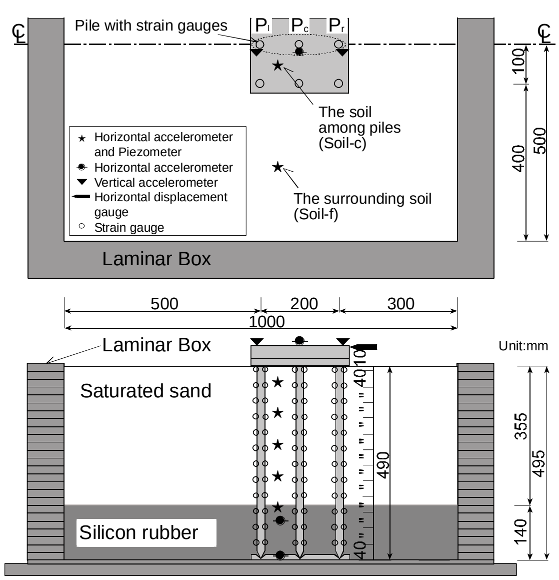


Figure 1 Shaking table test model and measuring sensor locations

Table 1 Characteristics of sand

Specific gravity of soil density	ρ_s (g/cm^3)	2.66
Dry density	ρ_d (g/cm^3)	Dr=50% 1.52
		Dr=65% 1.54
		Dr=80% 1.57
		Dr=95% 1.60
Maximum dry density	ρ_{dmax} (g/cm^3)	1.65
Minimum dry density	ρ_{dmin} (g/cm^3)	1.37

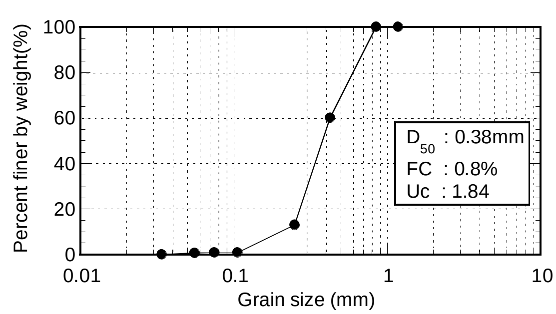


Figure 2 Grain size distribution curve

Table 2 List of test cases

Relative Density Dr (%)	Input wave	Maximum Input Acc. Level(cm/s^2)
65	RINKAI92H	10-680
	PORT ISLAND	10-680
50, 65, 80, 95	RINKAI92H	500
water	RINKAI92H	500

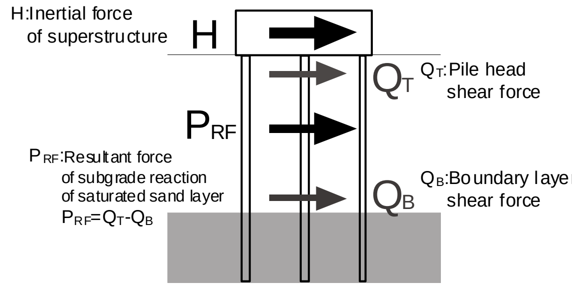


Figure 3 Schema of forces acting on piles

earthquake motion[8)] (hereafter named PI wave) observed in Port Island (G.L.-32 m) during the 1995 Hyogoken-Nanbu Earthquake, were applied by reducing the time axis to one-fifth according to the similarity law and changing the input acceleration level.

2.2 Forces acting on piles and evaluation of physical quantities

Forces acting on piles during an earthquake comprise both the subgrade reaction (P_{RF}) and the inertial force (H) of the superstructure, as shown in Figure 3. The physical quantities used in this paper were obtained as follows.

(1) Inertial force, displacement and average pore water pressure ratio of soil

The inertia force was obtained by multiplying the foundation acceleration by the foundation mass. The soil displacements were obtained by integrating the acceleration of the soil, and the average pore water pressure ratio was obtained by averaging the pore water pressure ratios for each depth.

(2) Bending moment, shear force, subgrade reaction and pile displacement

Pile bending moments were obtained by multiplying the curvature by the flexural rigidity of the pile. The shear forces and subgrade reactions of the pile were obtained by differentiating the bending moments, and the pile displacements were obtained by integrating the curvatures using simple beam theory. The resultant subgrade reaction (P_{RF}) in saturated sand layer was obtained by subtracting the boundary layer shear force (Q_B) from the pile head shear force (Q_T).

3. EXPERIMENTAL RESULTS

3.1 Effects of input acceleration level and input waveform

(1) Response time histories

The response time histories of inertial force, pile head displacement, shear force at the pile head and the boundary layer, subgrade reaction, pore water pressure ratio at 19cm depth and input acceleration under R wave and PI wave are shown in Figure 4.

This section compares the R waves for input accelerations of $160cm/s^2$ and $680cm/s^2$. The pore water pressure ratio U_f/σ_{v0}' for the R wave for an input acceleration of $160cm/s^2$ is about 0.5, and the material is not completely liquefied. Inertial force H, pile head shear force Q_T, and subgrade reaction P_{RF} indicate the vibration behavior for this input acceleration. The pile head shear force Q_T is larger than the boundary layer shear force Q_B. The excess pore water pressure ratio U_f/σ_{v0}' for the R wave for the input acceleration of $680cm/s^2$ reaches 1.0, where the material is completely liquefied. After complete liquefaction, the long-period component is mainly contained in the inertial force H and the pile head displacement δ_{PH}. Although the input acceleration is 4 times higher for both R waves, the pile head

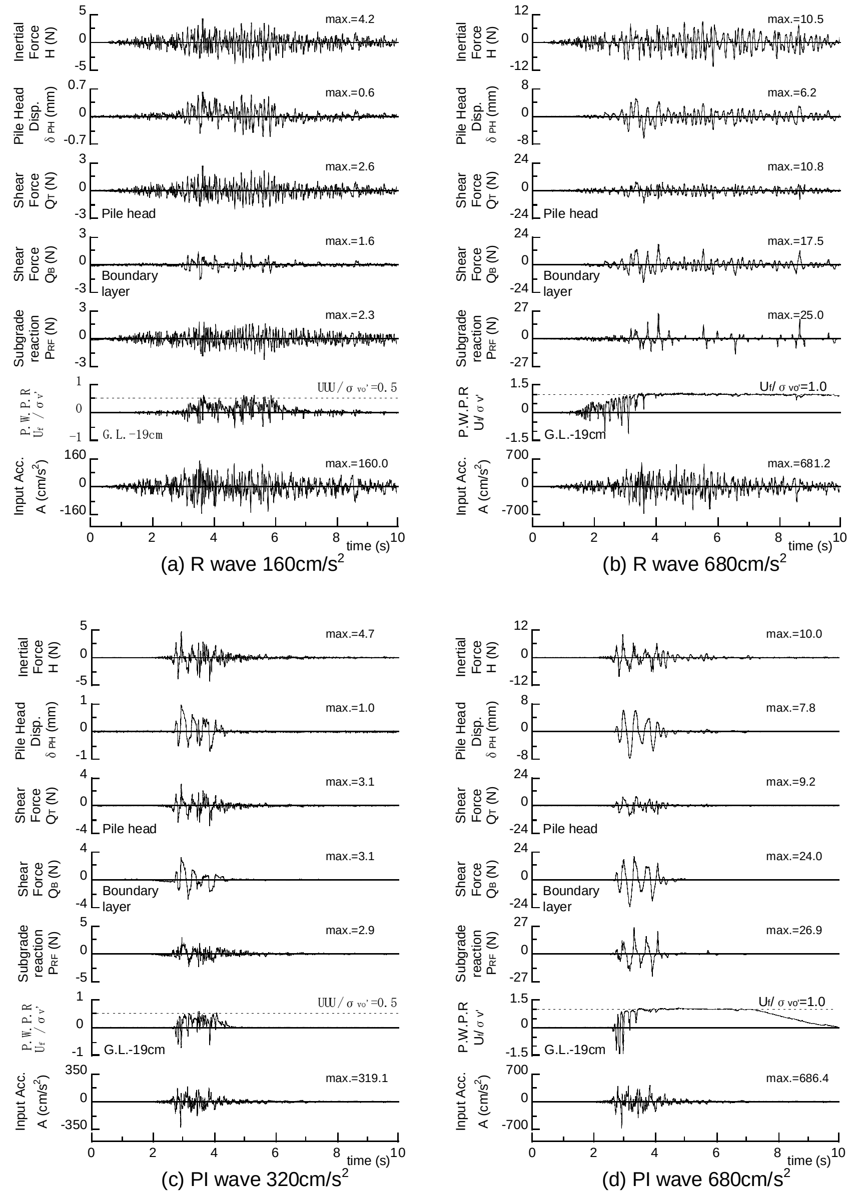


Figure 4 Response time histories at soil, superstructure and pile

displacement δ_{PH} becomes 10 times larger. The boundary layer shear force Q_B is far larger than the pile head shear force Q_T. The subgrade reaction P_{RF} shows a pulse-like response, and its amplitude is far larger than that of the inertial force H. The tendency of the input acceleration level is approximately similar even for the PI wave.

This section compares the R and PI waves for an input acceleration of 680cm/s^2 at which the input waveform differs. The pore water pressure ratios U_f/σ_{v0}' of both input waveforms reach 1.0, and the material is completely liquefied. It is different in rising in the pore water pressure ratio of PI wave in a moment, while it gradually rises with increase in input acceleration in that of R wave. Although the maximum inertial force H is almost the same for both input waveforms, the pile head displacement δ_{PT} of the PI wave is larger than that of the R wave, and the period is also long. Although the inertial force H and

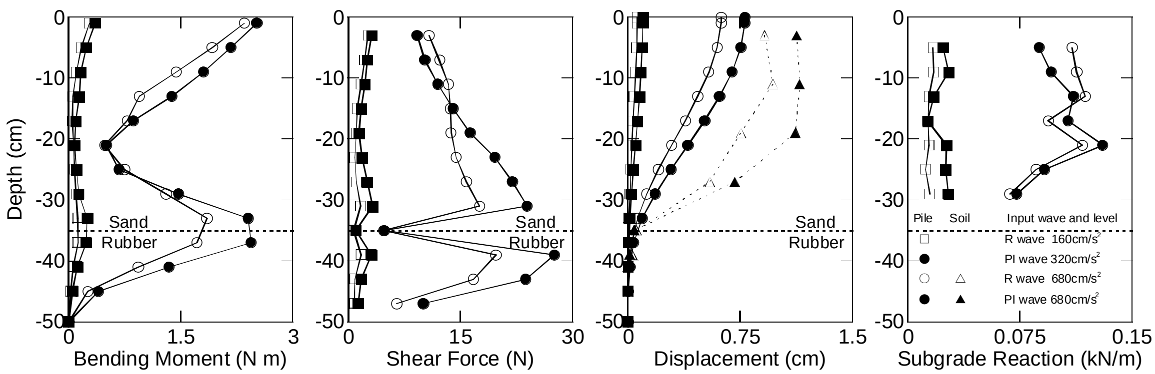


Figure 5 Maximum distributions of pile stresses and soil displacements

the subgrade reaction P_{RF} are almost the same for both input waveforms, the boundary layer shear force Q_B of the PI wave is by far larger than that of the R wave.

(2) Maximum distributions of pile stresses and soil displacements

Maximum distributions of pile stresses and soil displacements for the 4 cases shown in Figure 4 are shown in Figure 5. For the R wave, for an input acceleration of 160cm/s^2 and for the PI wave for an input acceleration of 320cm/s^2, which is in the non-liquefaction state, the bending moments and the shear forces become large at the pile head.

For the R wave and PI wave, for an input acceleration of 680cm/s^2, which is in the liquefaction state, the bending moments become large at the pile head and the boundary layer, and the shear forces show triangular distributions. Due to the liquefaction, the displacement of the soil and the pile at the pile head greatly increases from the near boundary layer. The maximum bending moments and shear forces at the pile head are almost the same for both input waves, while those of the PI wave at the layer boundary are far larger than those of the R wave, as shown by the response time histories in Figure 4.

(3) Relation between inertial force and pile head displacement

The relationships between the inertial force H and the pile head displacement δ_{PH} of the 4 cases shown in Figure 4 are shown in Figure 6. As shown, the linear response of the particular model with water in place of the upper soil layer is shown by a dotted straight line.

For the R wave for an input acceleration of 160cm/s^2 and for the PI wave for an input acceleration of 320cm/s^2, which are the non-liquefaction states, the hysteresis loops become of ordinary shape and the maximum displacement occurs when the inertial force reaches a maximum. The inclination of the inertial force and the pile head displacement are larger than when the upper layer is water, and the soil acts as a reaction force to the pile.

For R and PI waves for an input acceleration of 680cm/s^2, which show the liquefaction states, the pile head displacement mainly tends to increase with decreasing inertial force, and to increase with inclination where the upper layer is water. For the former, the soil acts as an external force on the pile due to liquefaction, and for the latter the soil becomes like water.

The pile head displacement for the R wave for an input acceleration of 680cm/s^2 almost coincides with the case where the upper layer is water, when the inertial force becomes a maximum. However, for the PI

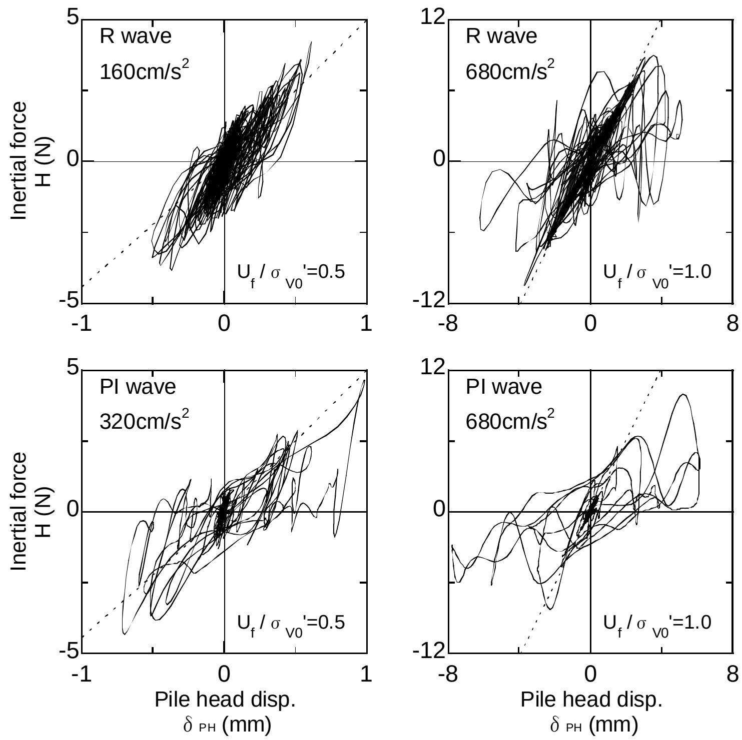


Figure 6 Relations between the inertial force and the pile head displacement

wave for an input acceleration of $680cm/s^2$, the displacement at the pile head is larger than when the upper layer is water. The maximum subgrade reactions were almost the same for both input waveforms. The pile stresses for the PI wave were also larger than those for the R wave, as shown in Figure 5. This is because the occurrence time of the large inertial force and the large subgrade reaction for the PI wave was in agreement.

(4) Relation between subgrade reaction and inertial force normalized by maximum inertial force

The relationships between the subgrade reaction P_{RF} and the inertial force H of the 4 cases shown in Figure 4 are shown in Figure 7. The inertial force H/H_{max} and the subgrade reaction P_{RF}/H_{max} are normalized by the maximum inertial force H_{max}. The sign of the subgrade reaction is shown as positive for the condition of external force on the pile. In Figure 7, the maximum inertial force H_{max} is shown in mark ○, the maximum subgrade reaction P_{RFmax} is shown in mark □, and the maximum shear force at the boundary layer Q_{Bmax} is shown in mark △. The sum of the maximum subgrade reaction P_{RFmax} and the maximum inertial force H_{max} is shown by the oblique dotted line, and the maximum inertial force(=1.0) is shown by the broken line. The sum of the maximum subgrade reaction P_{RFmax} and the maximum inertial force H_{max} corresponds to the boundary layer shear force Q_{Bmax}.

For the R wave, for an input acceleration of $160cm/s^2$ and for the PI wave for an input acceleration of $320cm/s^2$, which are non-liquefaction states, the relations between the inertial force and the subgrade reaction have negative correlation for both waveforms, and the soil acts as a reaction force to the pile. The maximum subgrade reaction P_{RFmax} (mark □) and the maximum inertial force H_{max}(mark ○) do not act simultaneously. The subgrade reaction P_{RF} is comparatively small when the maximum shear force occurs at the boundary layer Q_{Bmax}(mark △) occurs.

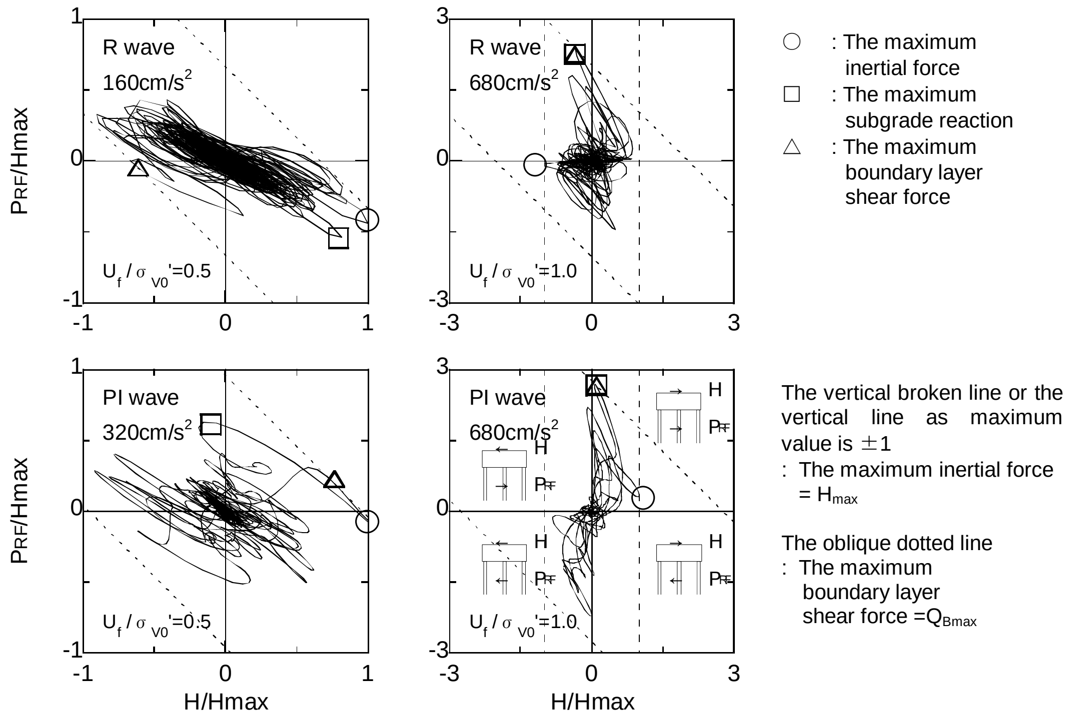


Figure 7 Relations between the subgrade reaction and the inertial force normalized by maximum inertial force

For the R and PI waves, for an input acceleration of 680cm/s^2, which are non-liquefaction states, only the subgrade reaction increases for both waveforms, and the soil acts as an external force on the pile due to soil liquefaction. The maximum subgrade reaction P_{RFmax} (mark □) and the maximum inertial force H_{max}(mark ○) do not act simultaneously. The occurrence of the maximum shear force of boundary layer Q_{Bmax}(mark △) agrees with the occurrence of the maximum subgrade reaction P_{RFmax} (mark □).

3.2 Effects of soil density

(1) Response time histories

The response time histories of the inertial force, pile head displacement, shear force at the pile head and boundary layer, subgrade reaction, pore water pressure ratio at 19cm depth and input acceleration under R wave for 4 cases at which the relative density of the soil changed, are shown in Figure 8.

The pore water pressure ratios U_f/σ_{v0}' reach 1.0 for all relative densities of the soil. Although in the pore water pressure U_f/σ_{v0}' ratio of relative densities of 65, 80 and 95%, the effect of the cyclic mobility is remarkable, it is not almost occurred in that of 50%.

The short period component of the inertial force H increases with increasing relative density of the soil. The inertial force H shows a pulse-like response due to the effect of the cyclic mobility, except where the relative density is 50%. For a relative density of 65%, the amplitude of the inertial force H is smallest, and that of the displacement at the pile head δ_{PH} is largest. For a relative density of 65%, the amplitude of the inertial force H is smallest, and that of the displacement at the pile head δ_{PH} is largest. However, for a relative density of 95%, the inertial force amplitude H is largest, and that of the displacement at the pile head δ_{PH} decreases to half of the relative density at 65%. The boundary layer shear Q_B are larger than at the pile for relative densities of 50 and 65%, and the shear forces are reversed for densities of 80 and 95%.

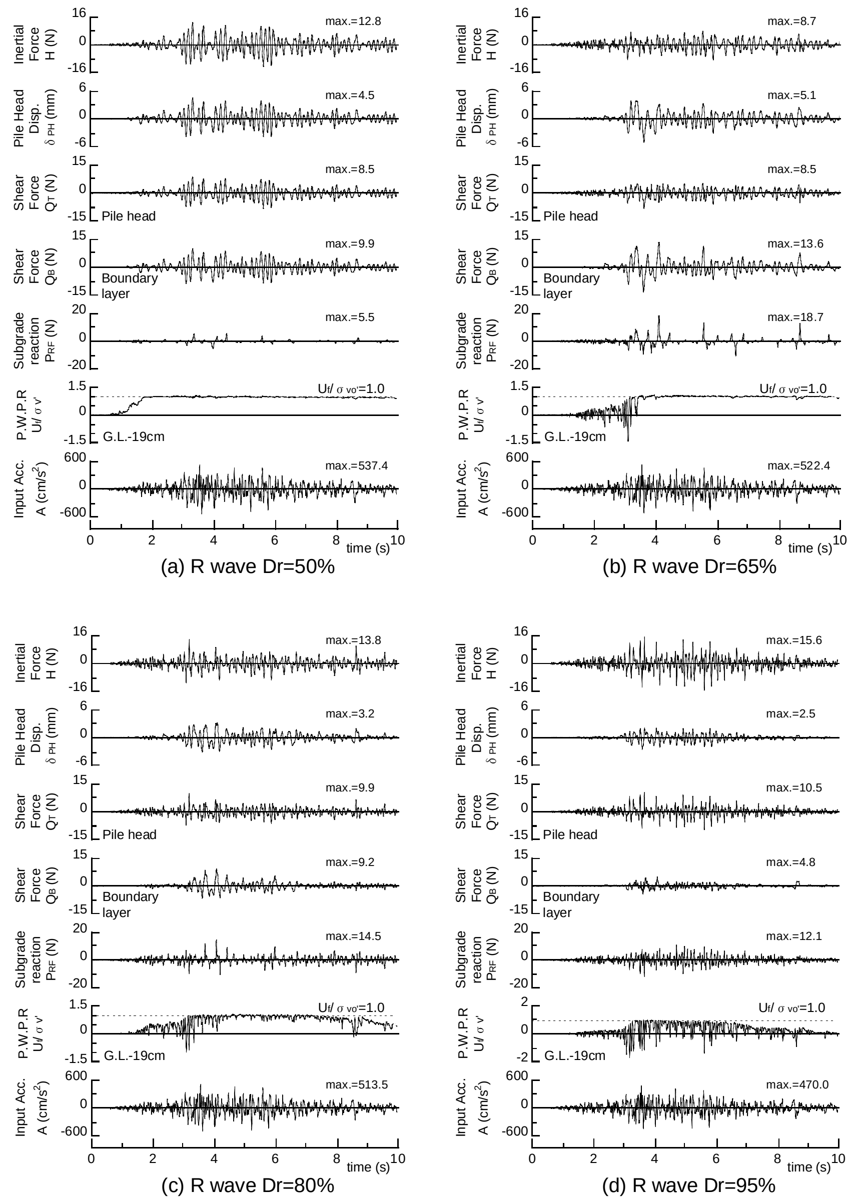


Figure 8 Response time histories at soil, superstructure and pile

The boundary layer shear force Q_B for a relative density of 95% is about 1/2 of that at the pile head. The subgrade reactions P_{RF} show pulse-like responses due to the effect of cyclic mobility at all relative densities. Pulse-like responses of the subgrade reaction due to the effect of cyclic mobility are sporadically occurred in the relative densities of 50 and 65%, while in the relative densities of 80 and 95%, its are intermittently occurred.

(2) Maximum distributions of pile stresses

Maximum distributions of pile stresses for the 4 cases in Figure 8 are shown in Figure 9. The bending moments increase at the pile head and at the boundary layer, and decrease with increasing relative density at the boundary layer. The shear forces for relative densities of 50 and 65% have triangular distributions. The shear forces for relative densities of 80 and 95% have a triangular distribution similar those for 50

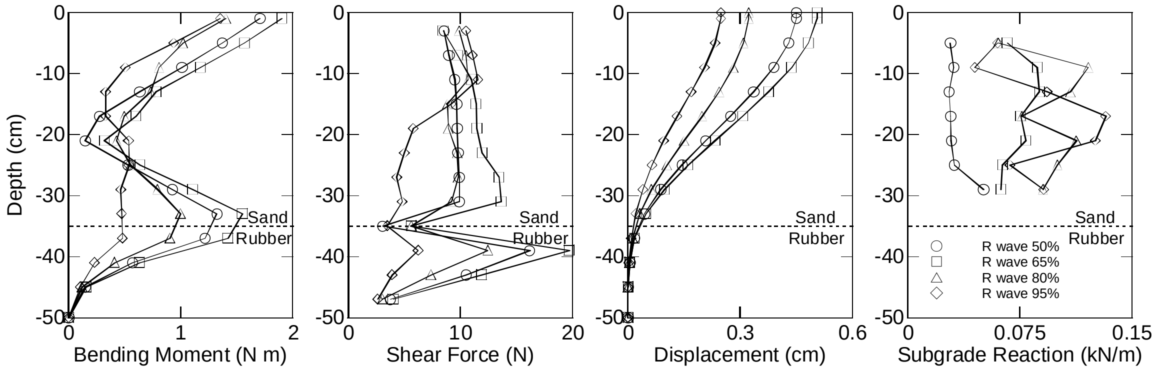


Figure 9 Maximum distributions of pile stresses

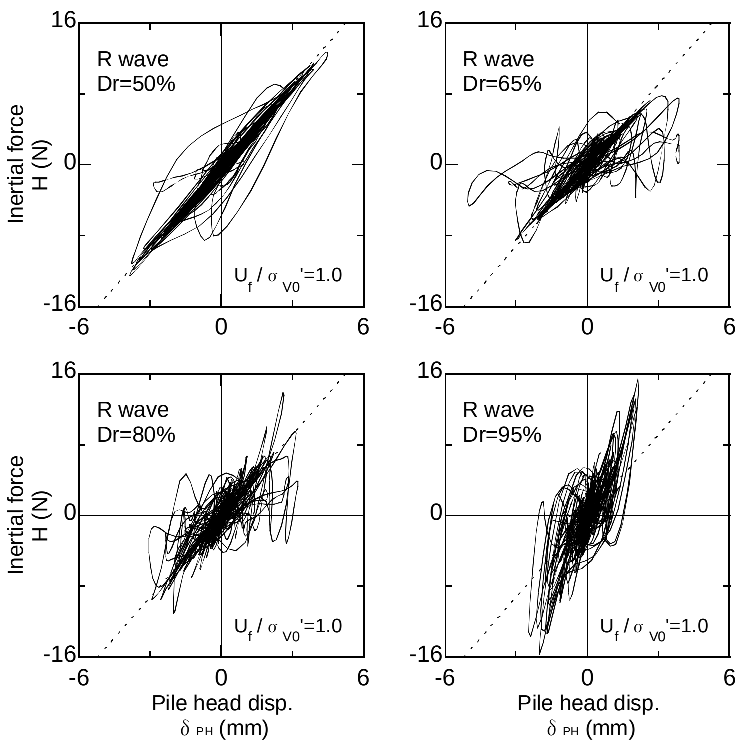


Figure 10 Relations between the inertial force and the pile head displacement

and 65% from the surface to about 10cm below the surface, and decreases below about 10cm. Although the subgrade reactions scatter a little with depth, they increase with tend to increase with relative density.

(3) Relation between inertial force and pile head displacement

The relationships between the inertial force H and the pile head displacement δ_{PH} for the 4 cases in Figure 8 are shown in Figure 10. The dotted straight line has the same meaning as in Figure 6.

The pile head displacement for a relative density of 50% increases with inclination when the upper layer is water. Therefore, in loose sand, the soil becomes almost like water due to the liquefaction. The inclination of the inertial force and the pile head displacement for a relative density of 65% is smaller when the upper layer is water, and in the medium sand, the soil mainly acts as external force on the pile due to liquefaction. The inclination of the inertial force and the head displacement for a relative density of 95% is larger than when the upper layer is water, and in the dense sand, the soil mainly acts as reaction force to the pile in spite of liquefaction. The hysteresis loop for a relative density of 80% becomes characteristic for the relative densities of 65 and 95%. The characteristics of the force that acts on the pile in the liquefaction state are different due to the relative density of the soil.

(4) Relation between subgrade reaction and inertial force normalized by maximum inertial force

The relationships between the subgrade reaction P_{RF} and the inertial force H for the 4 cases in Figure 8 are shown in Figure 11. The mark and line have the same meaning as in Figure 7.

In the relation between the subgrade reaction and the inertial force for the relative density of 50%, only the inertial force increases, and the maximum subgrade reaction P_{RFmax} (mark □) and the maximum inertial force H_{max}(mark ○) do not act simultaneously. The occurrence of the maximum boundary layer shear force Q_{Bmax} (mark △) coincides with the occurrence of the maximum inertial force H_{max} (mark ○). In the relation between the subgrade reaction and the inertial force for a relative density of 65 %, only the subgrade reaction increases, and the soil mainly acts as external force on the pile. The maximum subgrade reaction P_{RFmax} (mark □) and the maximum inertial force H_{max}(mark ○) do not act simultaneously. For a relative density of 95%, the relation between the subgrade reaction and the inertial force becomes negative, and the soil acts as a reaction force to the pile. The maximum subgrade reaction P_{RFmax} (mark □) and the maximum inertial force H_{max} (mark ○) do not act simultaneously. The relation between the subgrade reaction and the inertial force for a relative density of 80% becomes characteristic of the relative densities of 65 and 95%.

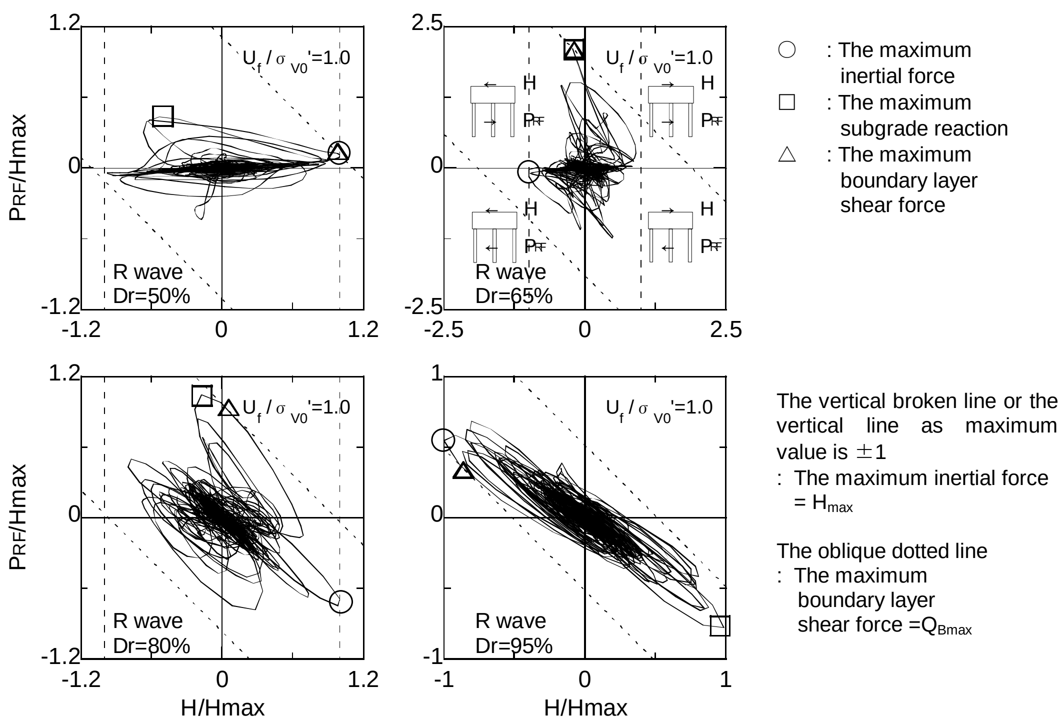


Figure 11 Relations between the subgrade reaction and the inertial force normalized by the maximum inertial force

4. RELATION AMONG INERTIAL FORCE, SUBGRADE REACTION AND SHEAR FORCE

4.1 Relations among inertial force, subgrade reaction and input acceleration

The relations between the inertial force H/H_{max}, the subgrade reaction P_{RF}/H_{max}, and the input accelerations at the maximum inertial force H_{max} and the maximum subgrade reaction P_{RFmax}, and the relation between the average pore water pressure ratios and the input acceleration are shown in Figure 12. The inertial force H/H_{max} and subgrade reaction P_{RF}/H_{max} are normalized by the maximum inertial force H_{max}. In Figure 12, the R wave is shown as a dotted line with ○ or ● marks, and the PI wave is shown as a solid line with □ or ■ marks. Furthermore, the inertial force is shown as positive at the occurrence of the maximum inertial force, and the subgrade reaction is shown as positive at the occurrence of the maximum subgrade reaction.

The average pore water pressure ratios for the R wave begin to increase from the low input acceleration levels, and it is mostly liquefied over about 300cm/s^2. The average pore water pressure ratios for the PI wave rise slowly at low input acceleration levels, and the soil is mostly liquefied over about 400cm/s^2. Therefore, the tendencies are different for the relation between the subgrade reaction and the inertial force for non-liquefaction and liquefaction state.

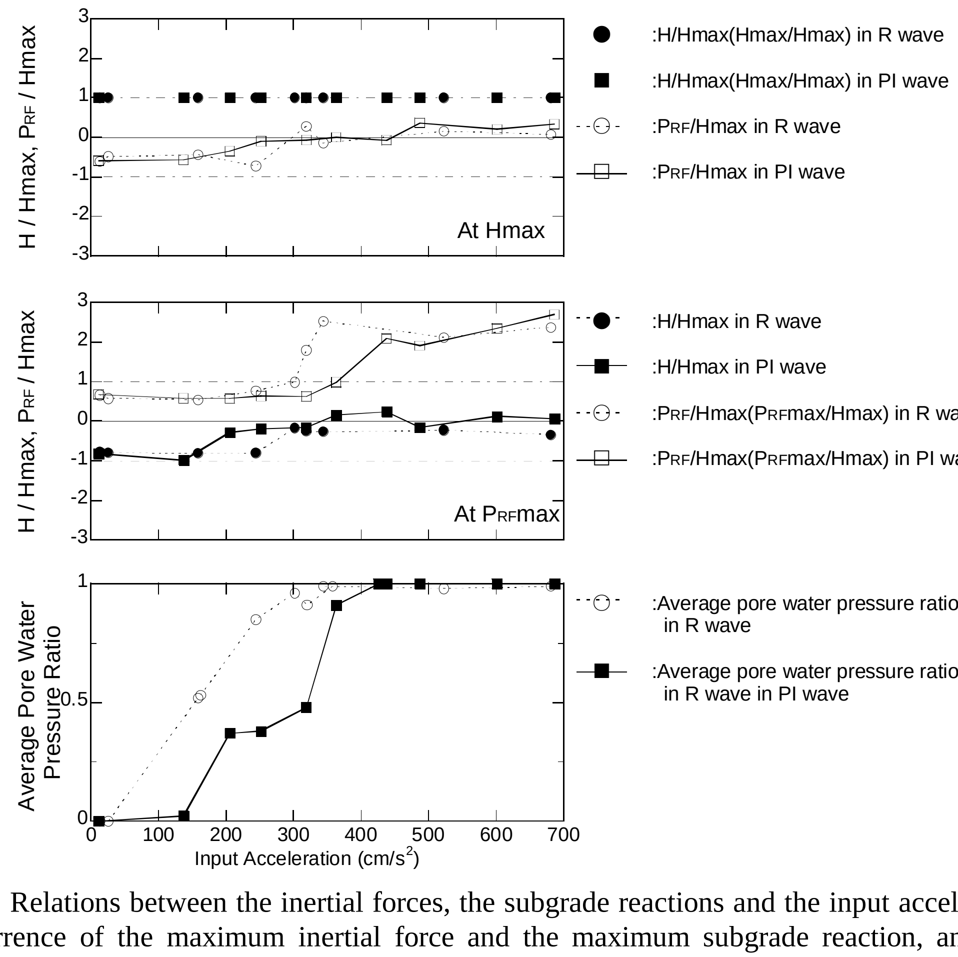


Figure 12 Relations between the inertial forces, the subgrade reactions and the input accelerations at the occurrence of the maximum inertial force and the maximum subgrade reaction, and relation between the average pore water pressure ratios and the input accelerations

At the maximum inertial force H_{max} in the non-liquefaction state, the subgrade reactions P_{RF}/H_{max} act in reverse for the inertial forces $H/H_{max}(=H_{max}/H_{max})$, and the soil acts as a reaction force to the pile. However, at the maximum inertial force in the liquefaction state, the subgrade reactions P_{RF}/H_{max} are comparatively small for the inertial forces $H/H_{max}(=H_{max}/H_{max})$. At the maximum subgrade reaction P_{RF}/H_{max} in the non-liquefaction state, the inertial forces H_{max} act in reverse for the subgrade reactions $P_{RF}/H_{max}(=P_{RFmax}/H_{max})$. However, at the maximum subgrade reaction P_{RF}/H_{max} in the liquefaction state, the inertial forces H_{max} are comparatively small for the subgrade reactions $P_{RF}/H_{max}(=P_{RFmax}/H_{max})$. Therefore, the maximum inertial force and the maximum subgrade reaction do not act on the pile simultaneously in the same direction independently of non-liquefaction and liquefaction states.

The characteristics of the maximum subgrade reaction caused by the difference between R wave and PI wave are examined. There is no difference under an average pore water pressure ratio of about 0.5 for both input waveforms, while the maximum subgrade reactions of the R wave become larger than those of the PI wave from an average pore water pressure ratio of about 0.5 to under 1.0 due to the difference in rise quantities of the average pore water pressure ratios. The maximum subgrade reactions in the R wave after liquefaction become almost constant, and in the PI wave, they gradually increase. Therefore, the pile stresses deep in the PI wave after liquefaction become larger than those in the R wave.

4.2 Relations among inertial force, subgrade reaction and soil density

The relations between the inertial force H/H_{max}, the subgrade reaction P_{RF}/H_{max}, and relative density of the soil at the maximum inertial force H_{max} and the maximum subgrade reaction P_{RFmax} are shown in Figure 13.

At the maximum inertial force H_{max} for relative densities of 50 and 65%, the subgrade reactions P_{RF}/H_{max} are comparatively small for the inertial force H/H_{max} $(=H_{max}/H_{max})$ as well as in the liquefaction state of Figure 12. However, at the maximum inertial force H_{max} for relative densities of 80 and 95%, the subgrade

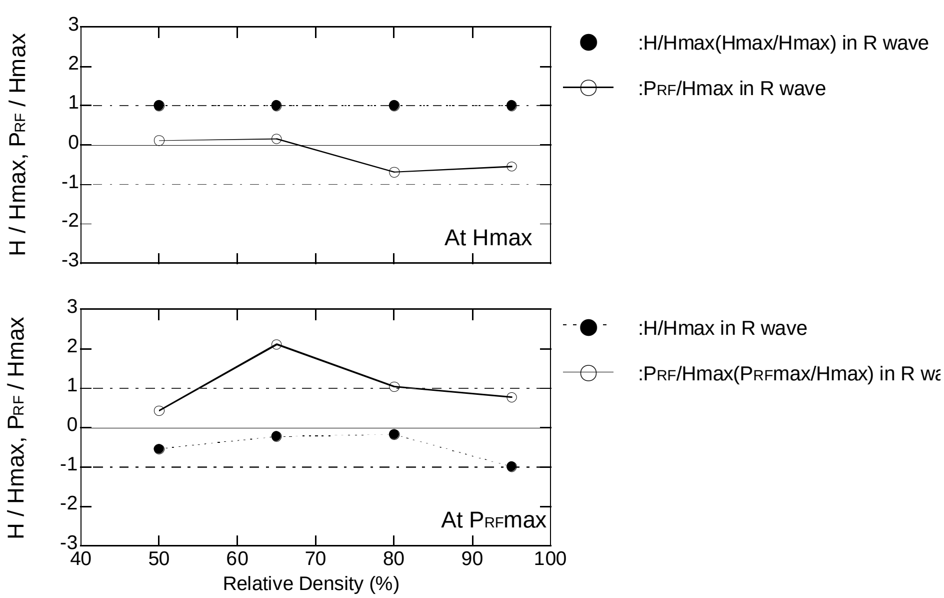


Figure 13 Relations between the inertial forces and the subgrade reactions and relative densities at the occurrence of the maximum inertial force and the maximum subgrade reaction

reactions P_{RF}/H_{max} act in reverse for the inertial forces H/H_{max} ($=H_{max}/H_{max}$), and the soil acts as a reaction force to the pile as well as in the non-liquefaction state of Figure 12. At the maximum subgrade reaction P_{RFmax}/H_{max} for all relative densities, the inertial forces act in reverse for the subgrade reactions. Therefore, the maximum inertial force and the maximum subgrade reaction do not act on the pile simultaneously in the same direction independently of the relative density of the soil.

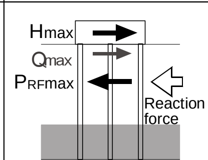
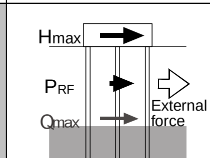
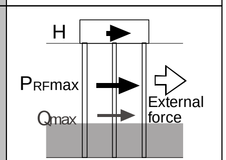
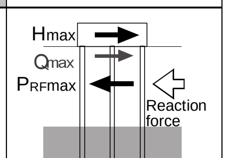
4.3 Position/time of maximum pile shear force, and inertial force-subgrade reaction relationship

The position and time of the maximum pile shear force, and the inertial force-subgrade reaction relationships are shown in Table 3.

In the non-liquefaction state, the maximum shear force occurs at the pile head, when the inertial force becomes a maximum. The maximum inertial force and the maximum subgrade reaction affect in reverse, because the soil acts as a reaction force to the pile.

In the liquefaction state, the soil acts as either a reaction or an external force to the pile due to the difference in relative density of the soil. Therefore, the position and time of the maximum pile shear force is different due to the difference in relative density of the soil. Although the soil acts as an external force on the pile in loose sand, since the ground behaves like water due to the liquefaction, the effect of the subgrade reaction as an external force is small, and that of the inertial force is large. Therefore, the maximum shear force occurs at the layer boundary when the inertial force becomes a maximum. Since the soil strongly acts as an external force in medium sand, the maximum shear force occurs at the boundary layer when the subgrade reaction becomes a maximum. Since the soil mainly acts as a reaction force to the

Table 3 Position and time of the maximum shear force of the pile, and the inertial force-subgrade reaction relationship

Soil condition	Relative density	Characteristic of subgrade reaction	Maximum shear force of a pile		Relation between H and P_{RF}		The schema of forces acting on piles
			position	time	P_{RF}/Hmax at Hmax	H/Hmax at P_{RF}max	
Non -liquefaction	All	Reaction force	Pile head	At occurrence of Hmax	$-P_{RF}$max/Hmax	-Hmax/Hmax	
Liquefaction	Loose	External force	Boundary layer	At occurrence of Hmax	small	-H/Hmax	
	Medium	External force	Boundary layer	At occurrence of P_{RF}max	small	small	
	Dense	Reaction force	Pile head	At occurrence of Hmax	$-P_{RF}$max/Hmax	-Hmax/Hmax	

pile in the dense sand, the maximum pile shear force occurs at the pile head when the inertial force becomes a maximum.

The maximum inertial force and the maximum subgrade reaction do not act on the pile simultaneously in the same direction independently of the soil condition. According to the response displacement method, it is the superfluous design that the maximum inertial force and the maximum subgrade reaction act on the pile simultaneously in the same direction.

5. CONCLUSIONS

The concluding remarks of this study are as follows:

1) The subgrade reaction mainly acts as a reaction force in the non-liquefaction state, while in the liquefaction state, it mainly acts as an external force in loose and medium sand, and it acts as a reaction force in dense sand.
2) The maximum shear force on a pile to which the soil acts as a reaction force occurs at the pile head at the maximum inertial force. However the maximum shear force on a pile on which the soil acts as an external force occurs at the layer boundary. Its occurrence time is at the inertial force maximum in loose sand, and at the subgrade reaction maximum in medium sand.
3) The maximum inertial force and the maximum subgrade reaction do not act on the pile simultaneously in the same direction independently of the soil condition. According to the response displacement method, it is the superfluous design that the maximum inertial force and the maximum subgrade reaction act on the pile simultaneously in the same direction.

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