DYNAMIC BEHAVIOR OF PILE FOUNDATION IN LIQUEFACTION PROCESS - SHAKING TABLE TESTS UTILIZING BIG SHEAR BOX

Hatsukazu MIZUNO[1], Michio SUGIMOTO[2], Toshihiro MORI[3], Masanori IIBA[4] And Tsutomu HIRADE[5]

SUMMARY

The paper presents shaking table tests utilizing big shear box to clarify pile foundation behavior in liquefaction process. It is, in principle, impossible for liquefaction process to satisfy similitude ratios in reduced models of prototype water-saturated sands in centrifugally accelerated field. Therefore, we carried out shaking table tests in near-to fullscale models of water-saturated sands and piles to break through the above-mentioned bottle neck. The effect of ground water table depth on liquefaction and pile behavior is examined. In a case of low ground water table, the liquefaction is not so severe and bending moments of piles is remarkably reduced.

INTRODUCTION

This study was conducted as a part of a project titled "Development of technology for earthquake disaster prevention in large metropolitan areas" (1992-1996 fiscal year) in collaboration with researchers and engineers of universities and private companies[Ministry of Construction, 1997]. Our missions in the project are to clarify seismic actions to building foundations and/or substructures, and to develop the seismic design method of the building foundations and/or substructures through incorporating dynamic soil-structure interaction based on real phenomena. On halfway of the project, we encountered the 1995 Hyogoken-nanbu earthquake, and found a lot of seismic damage of piles. Shaking table tests utilizing big shear box were planned and prepared before the earthquake.

Two targets of our missions are a proposal of design model of buildings incorporating dynamic soil-structure interaction, and shaking table tests of pile foundations utilizing a big shear box. One target are as follows:

1) a proposal of evaluation method on internal stresses of pile foundations based on an extended sway and rocking model (extended SR model) in the linear region of soil properties.

2) a proposal of evaluation method on internal stresses of pile foundations based on the Penzien model (lumped mass model) in the linear and nonlinear region of soil properties, including detailed discussion of evaluation of several constants in the model.

3) the numerical comparison between the extended SR model and the Penzien method in seismic action evaluation.

4) verification through the comparison with the results of more rigorous analyses and shaking table tests on soil grounds.

[1] *Building Research Institute, Ministry of Construction, 1 Tatehara, Tsukuba, Ibaraki, Japan*
[2] *Research and Development Institute, Takenaka Co., 1-5, Ohtsuka, Inzai, Chiba, Japan*
[3] *Institute of Construction Technology, Kumagai Gumi Co., LTD, 1043 Onigafuchi, Tsukuba, Ibaraki, Japan*
[4] *Building Research Institute, Ministry of Construction, 1 Tatehara, Tsukuba, Ibaraki, Japan*
[5] *Building Research Institute, Ministry of Construction, 1 Tatehara, Tsukuba, Ibaraki, Japan*

The paper is related with another of the targets, and presents the results and discussions of the shaking table tests of the pile foundations utilizing the big shear box of about 6m, 11.6m and 3Am in height, length and width, respectively. It is, in principle, impossible for liquefaction process to satisfy similitude ratios in reduced models of prototype water-saturated sands in centrifugally accelerated field. A main reasons for using the big shear box is to carry out the experiment in near-to fullscale models of water-saturated sands and piles. The shaking table used in the experiment is large shaking table (maximum specimen weight is 500 tonf) of National Research Institute for Earth Science and Disaster Prevention, Scientific Technology Agency.

DYNAMIC PROPERTIES OF SOIL

Kasumigaura sand was used for the test soil model. Table 1 shows soil properties. Figure 2 shows equivalent shear stiffness and equivalent damping factor derived from the dynamic triaxial test (a confining pressure : 0.5kgf/cm2). The shaking table test of surface-dry sand deposit (depth: 3.48meters), when a big shear box was not completed and 4 meters high, clarified dynamic properties of the soil. Random excitations with maximum acceleration of 60 gals was done. Figure 2 presents Fourier spectrum ratio of ground surface to bottom with fundamental natural mode shape. In the case of surface-dry sand, the mode shape is linear. That means that shear stiffness of soil deposits is proportional to a square root of overburden pressure of soil, namely to a square root of depth. If the shear stiffness is constant with depth, its fundamental mode shape is concave downward in a shape of cosine function. If the shear stiffness is proportional to depth, its fundamental mode shape is convex upward, and motion near to the soil surface increases.

TABLE1 SOIL PROPERTIES

Test item	Result
density (g/cm^3)	2.718
gravel fraction (%)	0.8
sand fraction (%)	94.8
silt fraction (%)	3.5
clay fraction (%)	0.9
uniformity coefficient	3.01
D50 (mm)	0.311
natural water content	5.71

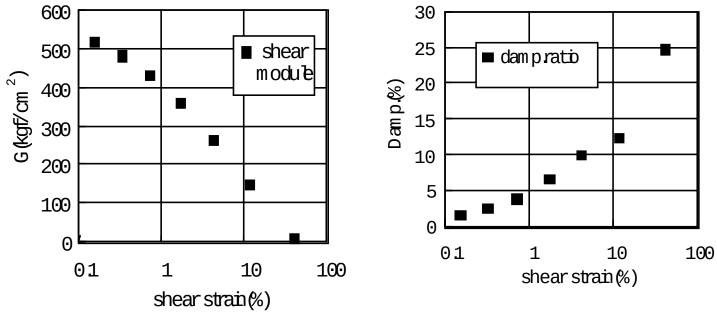


Fig.1 Equivalent Shear Modules & Damping

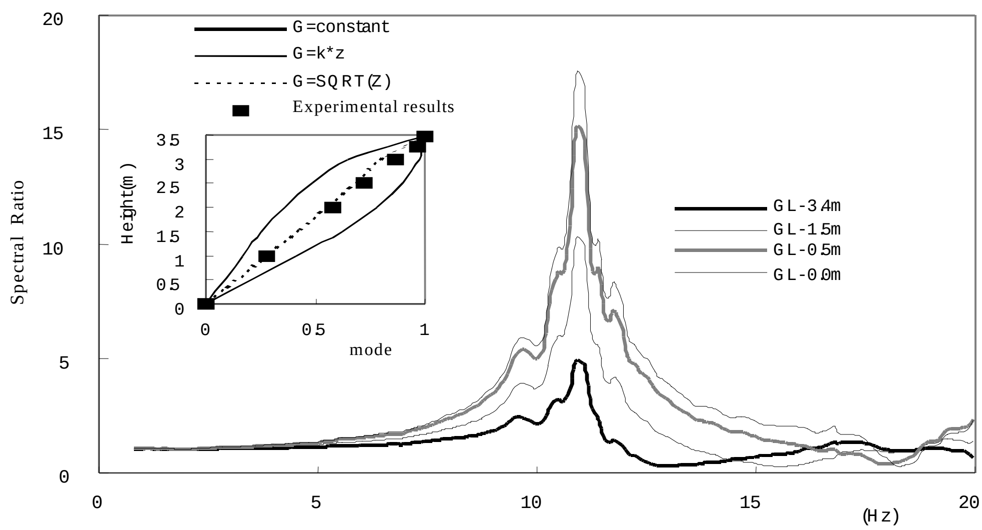


Fig.2 Spectral Ratio on Random Wave(60gal)

TABLE2 TEST SERIES AND OBJECTS

<table>
<tr><th rowspan="3">Test Case
&
Test Ground
Condition</th><th colspan="4">Shaking Table Test(O:input)</th><th rowspan="3">Static
Load
(before
shake
table)</th><th rowspan="3">Oscil-
later Test</th><th rowspan="3">Object</th></tr>
<tr><th rowspan="2">Ran-
dom
30gal</th><th colspan="3">Earthquake wave ,gal
(Port island GL-32m,Ns)</th></tr>
<tr><th>500</th><th>200</th><th>re-500</th></tr>
<tr><td rowspan="2">Case1
Drop of Sand into
Water, water
level G.L.</td><td rowspan="2">$O_{2,5}$</td><td>O_3</td><td></td><td></td><td rowspan="2">$O_{1,4}$</td><td rowspan="2">O_7
At
dissipation</td><td rowspan="2">check the liquefaction
seismic behavior of
ground & foundations</td></tr>
<tr><td colspan="3">O_6*350gal,time scale=1/2</td></tr>
<tr><td>Case2
Produced by
boiling,
water level G.L.</td><td>$O_{2,6}$</td><td>O_3</td><td></td><td>O_7
*600
gal</td><td>$O_{1,5}$</td><td>O_4
At
dissipation</td><td>seismic behavior of
ground & foundations
(compare Case1)</td></tr>
<tr><td rowspan="2">Case3
Reproduced by
boiling,
water level G.L.</td><td rowspan="2">$O_{3,7,9}$</td><td>O_4</td><td>O_8</td><td>O_{10}</td><td rowspan="2">$O_{2,6}$</td><td rowspan="2">$O_{1,5}$
Before
earthquake
wave</td><td rowspan="2">reappearance of
seismic behavior of
ground & foundations
(compare Case2)</td></tr>
<tr><td colspan="3">measured dissipation</td></tr>
<tr><td rowspan="2">Case4
Reproduced by
boiling with
drain,
water level G.L.</td><td rowspan="2">$O_{2,4,6}$</td><td>O_3</td><td>O_5</td><td>O_7</td><td rowspan="2">O_1</td><td rowspan="2"></td><td rowspan="2">seismic behavior of
ground & foundations
under the drain
(compare Case3)</td></tr>
<tr><td colspan="3">measured dissipation</td></tr>
<tr><td rowspan="2">Case5
Reproduced by
boiling,
water level G.L.-
1.4m</td><td rowspan="2">$O_{2,6,7}$</td><td>O_3</td><td>O_6</td><td>O_8</td><td rowspan="2">$O_{1,5}$</td><td rowspan="2">O_4
At
dissipation</td><td rowspan="2">seismic behavior of
ground & foundations
at low water level
(compare Case2,3)</td></tr>
<tr><td colspan="3">measured dissipation</td></tr>
</table>

Oindex : Test Order

SHAKING TABLE TESTS OF PILE FOUNDATION

Test Cases and Setup

The dimensions of soil deposit in the big shear box used in the experiment are about 6m, 11.6m and 3.lm in height, length and width, respectively. A model of pile foundation is made of steel and is 40cm, 10cm and 5.82m in width, thickness and length, respectively. Table 2 shows a series of the experiment cases with their and aims. The experiments includes shaking table tests of earthquake random excitations, static pulling tests and oscillator tests. Oscillator tests are reported in a companion paper titled “Oscillator Tests of Pile Foundation in dissipation Process of Excess Pore Water Pressure After Liquefaction” (Abstract Reference No. 1744/5/A)[Hirade T. et al. ,2000]. In the cases 1, 2 and 3, the aims are to clarify the behavior of pile foundation during liquefaction, and to check soil deposit making, namely dropping sand into water and boiling. In the case 4, the aim is to investigate the effect of a countermeasure against liquefaction, one of excess pore water pressure dissipation method (vertical drains). In the case 5, the aim is to clarify the effect of low ground water table on liquefaction and pile behavior. In each case, an earthquake excitation with 500gals peak acceleration and a random excitation with 30gals peak acceleration were carried out. A NS component acceleration record at GL-32m depth at Port Island, Kobe during 1995 Hyougoken-nanbu earthquake was used in earthquake excitation. Figure 3 represents setup and measurement points in the experiments. A ground water level of all cases and a position of vertical drains in case 4 are added to the figure. In the soil deposit, accelerometers and excess pore water transducers were installed on lines G-1 to G-5. Accelerometers, excess pore water transducers and earth pressure transducers (on the both sides perpendicular to vibration direction) were set on pile (P-1). Strain gauges were attached on pile surfaces (P-1 and P-2) to measure bending moments and shear forces. Accelerometers and displacement transducers were installed in the foundation and the shear box.

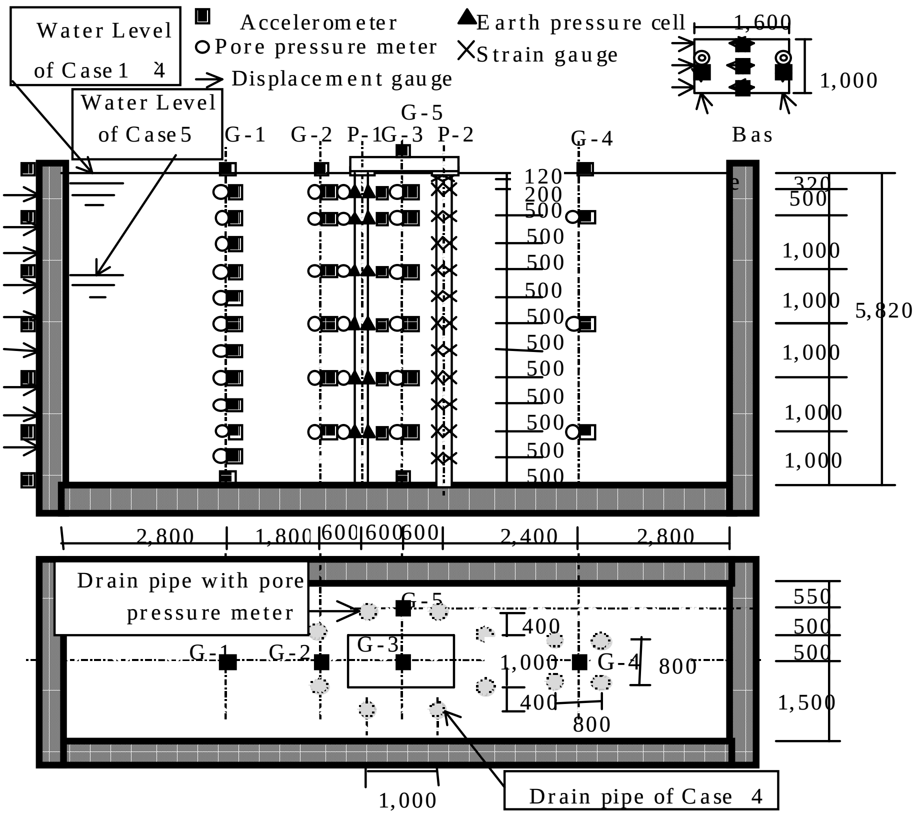


Fig.3 Outline of Test Specimen and Measurement

TABLE3 GROUND CONDITION

Test Case	Surface Level(m)	Dry density (g/cm^3)	Void ratio	Wet density (g/cm^3)	Relative density (%)	Water Level(m)
1	5.82	1.50	0.81	1.95	38.7	surface
2	5.65	1.59	0.71	2.00	63	surface
3	5.54	1.62	0.68	2.02	71.7	surface
4	5.52	1.62	0.67	2.03	73.3	surface
5	5.39	1.66	0.64	2.05	83.3	surface-1.4

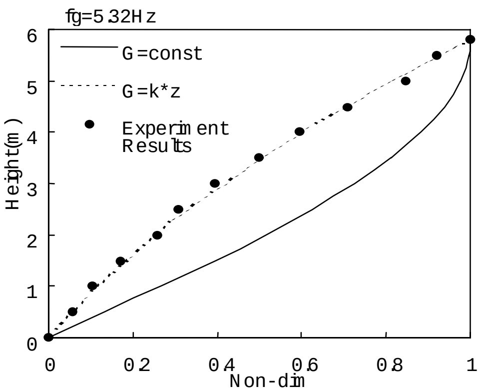


FIG.5 VIBRATION MODE

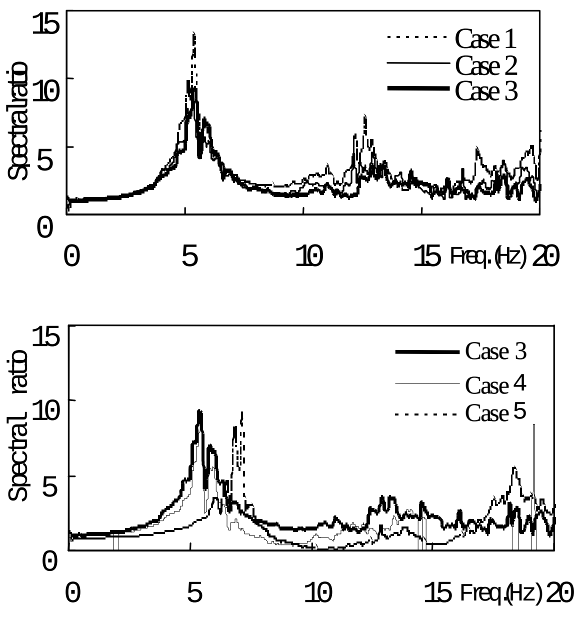


Fig.4 Spectral Ratio due to Random Wave(30gal)

Dynamic Properties and Fundamental Natural Mode of Water-Saturated Soil

Figure 4 shows spectral ratios (surface /bottom) of Cases 1, 2 and 3 under random excitation (max. acceleration 30 gals) before 500gals earthquake excitations. Predominant frequencies of soil ground are about 5.3 - 5.6 Hz in Cases 1 – 4 and 6.85 Hz in Case 5. The fundamental natural mode of Case 1 is presented in Fig. 5. The mode shape is convex upward and utterly different from that of surface-dry sand as shown in Fig. 2. As stated in the mode of surface-dry sand deposit, this means that shear stiffness of the water-saturated soil is proportional to overburden pressures. The difference seems to be mainly derived from effective overburden pressure.

LIQUEFACTION PHENOMENA UNDER EARTHQUAKE EXCITATION

Comparison by Production Method of Soil Deposit

The test soil deposit of Case 1 is made of by dropping sand into water, and those of the other Cases by sand boiling utilizing high water pressure from bottom of the shear box. Time histories of main measuring points in Cases 1 and 2 are illustrated in Fig. 6. The difference between Case1 and Case2 in the process of excess pore water pressure increase is very little, except for excess pore water increase at the point less than 2m from the soil bottom. The maximum response distribution of accelerations, excess pore water pressures and pile bending moments in Cases 1, 2 and 3 are drawn in Fig. 7. Comparison of the results between Case 2 and case3 leads that reproduction of the test soil by sand boiling is good, except for pile bending moments due to difference of soil ground density.

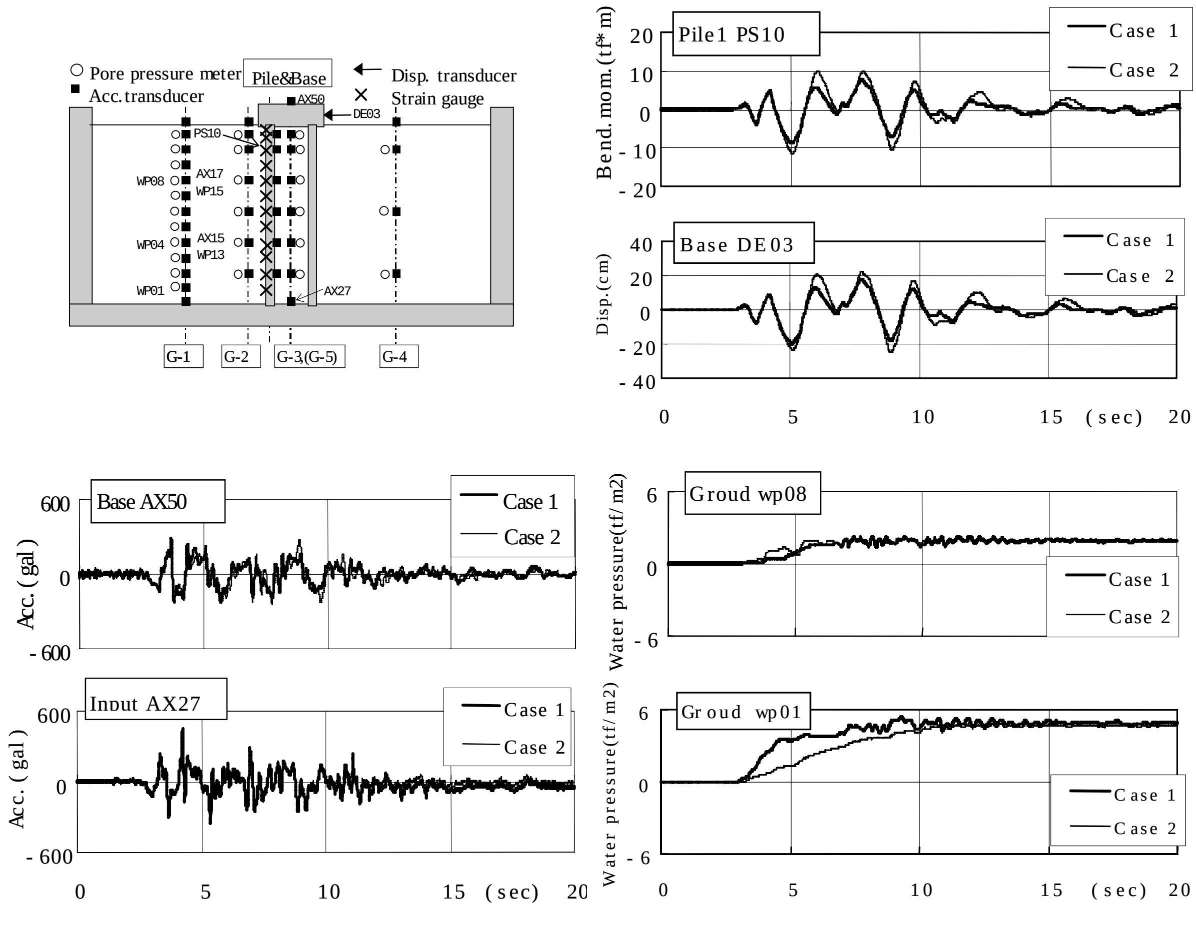


Fig.6 Time History due to Earthquake Excitation(Case1,2)

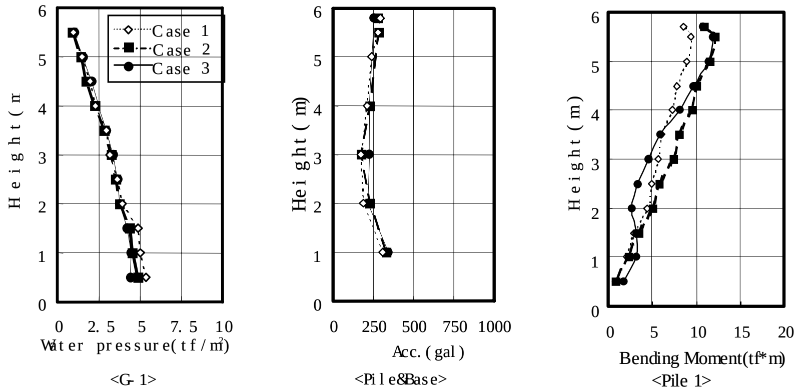


Fig.7 Max. Distribution of Pore Water Pressure, Acceleration and Bending Moment(Case1-3)

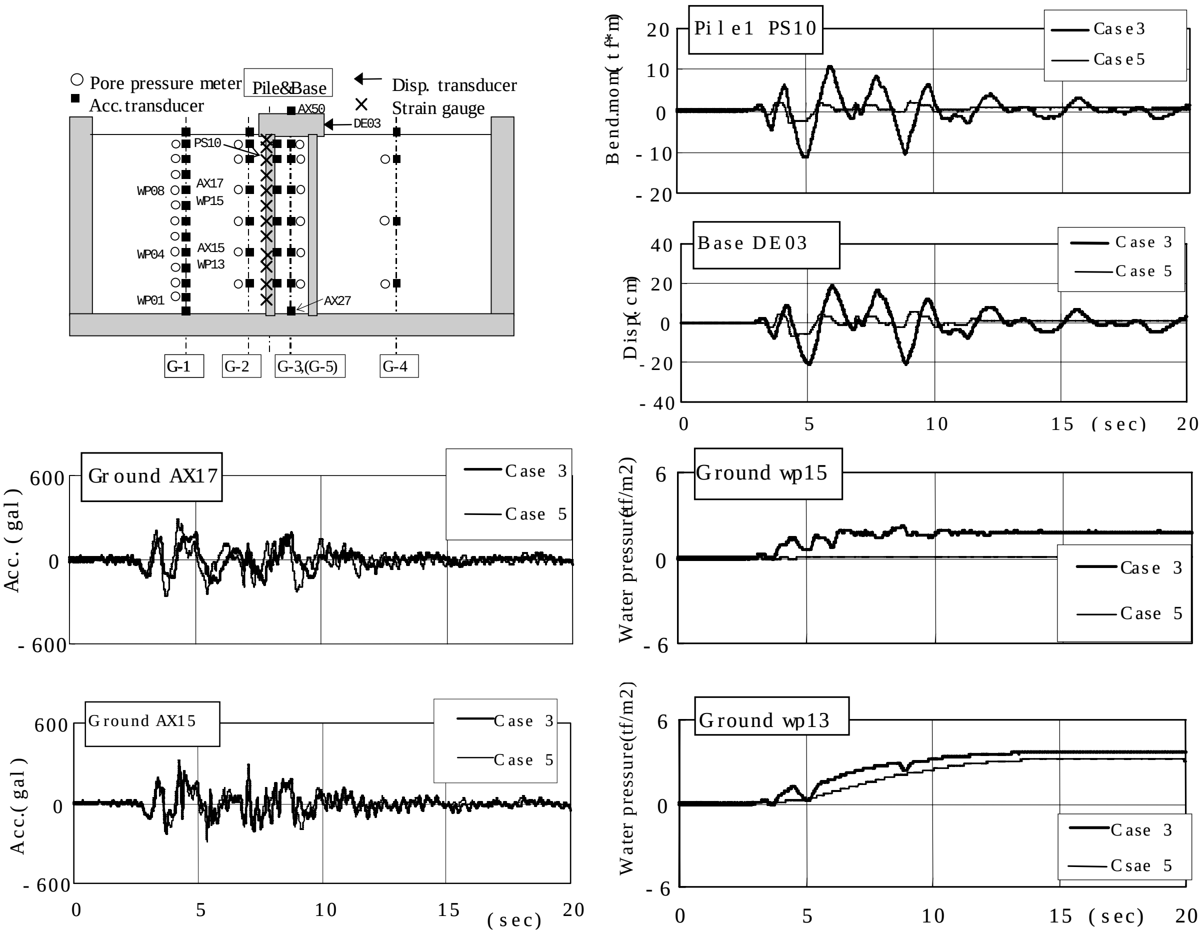


Fig.8 Time History due to Earthquake Excitation(Case3,5)

Effects of Low Ground Water Table and Vertical Drains

The time histories of responses and the distribution of maximum responses in Cases 3 and 5 are shown in Figs. 8 and 9, respectively. The ground water levels are at the soil surface and 1.4m in depth from the surface in Cases 3 and 5, respectively. In Case 3, all of the soil deposit is saturated. The increase amount of excess pore water pressures in saturated soil of Case 3 is larger than that in soil of Case 5. In Case 5, there is little increase of excess pore water pressures in non-saturated soil layers above ground water table. The maximum acceleration of soil deposit in Case 5 is a little larger than that in Case 3. On the contrary, the maximum pile bending moment of piles in Case 5 is remarkably smaller than that in Case 4. Because in Case5, the decrease of the effective stress and the shear stiffness is small in the non-saturated soil near to the surface, the displacement responses of soil deposit becomes small. The displacement of the shear box in Case 5 is about one fourth of that in Case 3. The difference of pile bending moments is very similar to the difference of the displacement of shear box. From comparison of responses between Cases 3 and Case 4, the excess pore water pressure and its build-up process, the acceleration of foundation and the pile bending moment show similar responses. The effects of reducing on increase amounts of excess pore water pressure by vertical drains is very small under the 500 gals earthquake excitation in the experiment. However, in the dissipation process of the excess pore water pressures after the excitation, the dissipation rate is 4 times by vertical drains, as shown in Fig. 10.

Behavior of Piles

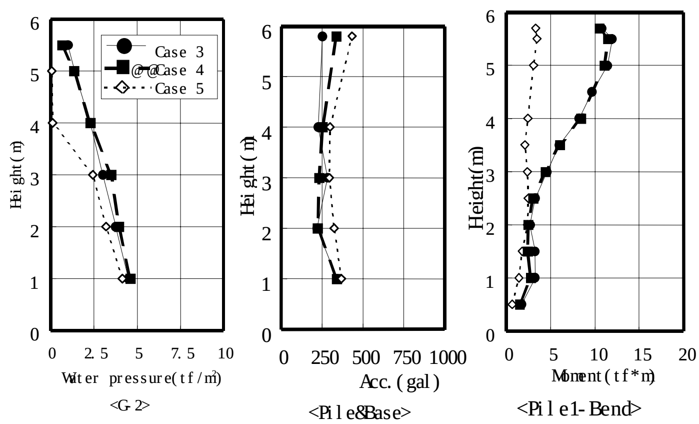


Fig.9 Comparison of Max. Response Distribution with Ground Water Level(Case3-5)

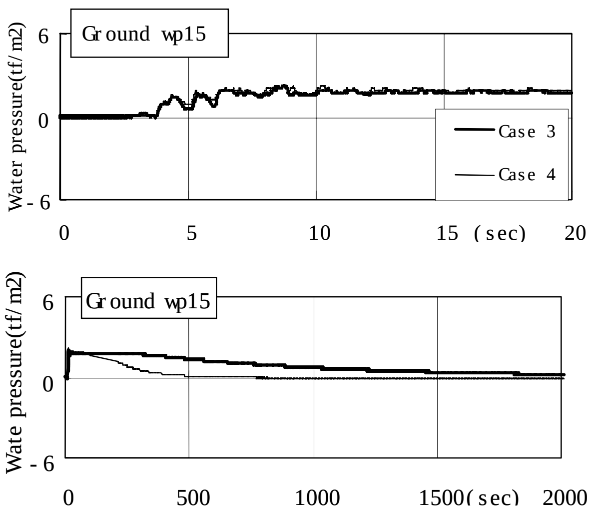
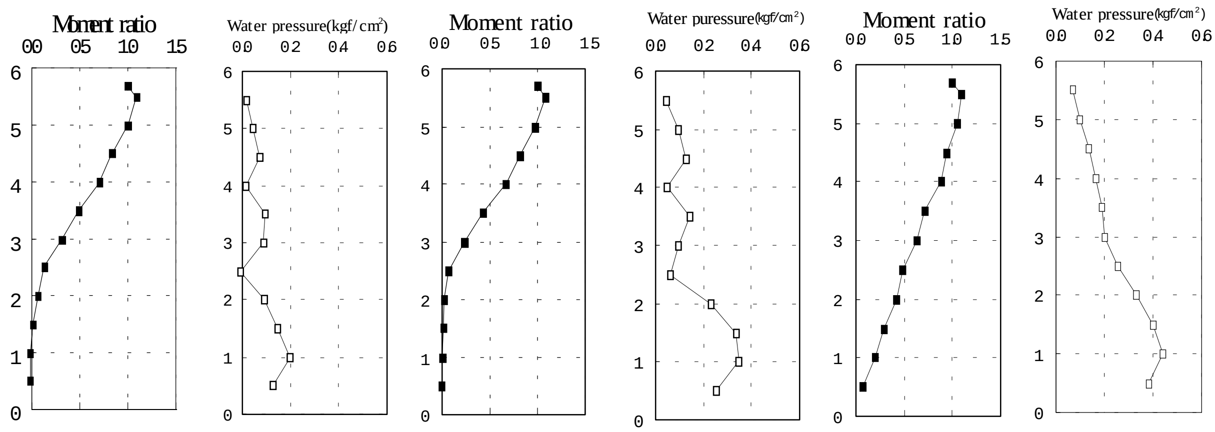


Fig.10 Pore Water Pressure During Dissipation with and without Drains(Case3,4)

The distribution of pile bending moment and excess pore water pressures at several stages of excess pore water pressure level are shown in Fig. 11. At early stages of build-up process of excess pore water pressures, pile bending moments at the points near to the soil surface become large, but the moments at the points 2.5meters nearer to the bottom are still small. This means that enough subgrade reactions to piles still exist in deeper soil layers. With the progress of liquefaction process in whole soil deposit, bending moment distribution of piles changes into a linear shape.

CONCLUDING REMARKS

The concluding remarks are summarized as follows;



3.70(s) 4.19(s) 5.96(s)

Fig.11 Distribution of Bending Moment Ratio & Pore Water Pressure at Several Times During Liquefaction (Case1)

(1) At early stages of liquefaction, behavior of pile foundation is influenced by inertial force, and with progress of liquefaction, is much affected by soil motion. At complete liquefaction stage, pile foundation behaves with soil in the same direction.

(2) Effects of low ground water table on pile behavior is large, and makes pile bending moment remarkably small.

REFERENCES

Iguchi M. et al. (1997),"Evaluation of Seismic Behavior of Pile Foundation and Seismic Action on Piles by Shaking Table Test of Large-scale Shear Box", Summary of annual meeting of Architectural institute of Japan, pp.369-396 (in Japanese)

Mizuno H. et al. (1998),"Seismic Behavior of Pile foundation on Liquefaction by Shaking Table Tests of Large Scale Shear box", The fifth dynamic interaction symposium of structure and ground, pp.169-174 (in Japanese)

Ministry of Construction (1997), "Reports of a subcommittee of the design for earthquake resistance (building part) in the Development of Technology for Earthquake Disaster Prevention in Large Metropolitan Areas", annual reports of 1997(in Japanese)

Hirade T. et al. (2000), " OSCILLATOR TESTS OF PILE FOUNDATION IN DISSIPATION PROCESS OF EXCESS PORE WATER PRESSURE AFTER LIQUEFACTION", 12WCEE,companion paper (1744/5/A)