Seismic Tests of a Pile-Supported Structure in Liquefiable Sand Using Large-Scale Blast Excitation

Kamijho Naotaka [1)], Saito Hideaki [1)], Kusama Kazuhiro [2)], Kontani Osamu [2)] and Nigbor Robert [3)]

1) Power Engineering R&D Center, Tokyo Electric Power Co., 4-1 Egasaki, Tsurumi-ku, Yokohama 230-8510 JAPAN
2) Kobori Research Complex Inc., 6-5-30, Akasaka, Minato-ku, Tokyo 107-8502 JAPAN
3) Civil Engineering Department, University of Southern California, Univ. Park, KAP210, Los Angeles, CA 90089 USA

ABSTRACT

Extensive, large-amplitude vibration tests of a pile-supported structure in a liquefiable sand deposit have been performed at a large-scale mining site. Ground motions from large-scale blasting operations were used as excitation forces for vibration tests. A simple pile-supported structure was constructed in an excavated 3m-deep pit. The test pit was backfilled with 100%-water-saturated clean uniform sand. Accelerations were measured at the pile-supported structure, in the sand in the test pit and in the adjacent free field. Excess pore water pressures in the test pit and strains of one pile were also measured.

Vibration tests were performed with six different levels of input motions. The maximum horizontal acceleration recorded at the adjacent ground surface varied from 20 Gals to 1353 Gals. These alternations of acceleration provided different degrees of liquefaction in the test pit. Sand boiling phenomena were observed in the test pit with larger input motions. This paper outlines vibration tests and investigates the test results.

INTRODUCTION

In current design practice for reactor buildings in Japan, a reactor building is required to be constructed by a direct foundation on a firm shallow rock layer. Because there are few such locations, it is very difficult to find suitable locations.

Pile foundations have become very popular for ordinary buildings, including high-raise buildings in Japan. Pile foundations are very flexible because piles can be founded on deep or shallow supporting layers by simply adjusting their lengths. If pile foundations can be introduced in construction of nuclear facilities, the number of suitable sites will be increased. However, before pile foundations can be used in nuclear facilities, it is very important to experimentally demonstrate their applicability. Since very strong earthquake motions are employed for designing nuclear facilities, understanding of dynamic nonlinear soil-pile-structure interaction including liquefaction of surrounding soil layers need to be incorporated to structural design of pile foundations.

The objectives of this experimental research are (1) to achieve a better understanding of the dynamic nonlinear behavior, including liquefaction, of soil-pile-structure interaction systems under severe ground motions and (2) to investigate a nonlinear response analysis method and a structural design method for pile foundation structures. To meet those objectives, seismic tests were conducted on a pile-supported structure in a liquefiable sand deposit using ground motions from large mining blasts at Black Thunder Mine, Wyoming USA.

This paper outlines seismic tests and investigates test results. The simulation analyses of seismic tests and investigation of a structural design method for pile foundations are presented in a separate paper entitled "Simulation Analyses of Seismic Tests of a Pile-Supported Structure in Liquefiable Sand Using Large-Scale Blast Excitation" [1] in this conference, SMiRT-16.

VIBRATION TEST METHOD USING GROUND MOTIONS CAUSED BY MINING BLASTS

The vibration test method using ground motions caused by mining blasts is shown schematically in Figure 1. Common ways for performing vibration tests of structures are Shaking Table Tests, Forced Vibration Tests and Earthquake Observations. These methods are very useful in many ways. However, none are capable of shaking a large-scale soil-pile-structure system at large amplitude. The vibration test method using ground motions caused by mining blasts has the following advantages over the conventional test methods.

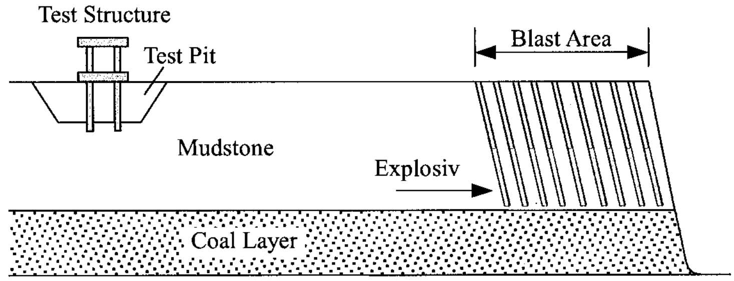

Figure 1 Vibration Test Method at Mining Site

- Large-scale test structures can be used for the test.
- Ground motions of various amplitudes can be generated in accordance with distances from the blast area.
- Three-dimensional effects and perfect soil-structure interaction in the actual ground can be considered.

Seismic tests of pile-supported structure in a liquefiable sand deposit were conducted at Black Thunder Mine of Arch Coal, Inc. Black Thunder Mine is one of the largest coal mine in North America and is located in northeast Wyoming, USA. Since its operation is very active, there were many opportunities to have large ground motions at the test site.

At the mine, there is an overburden (mudstone layers) over the coal layers. The overburden is dislodged by large blasts called "Cast Blasts" and the rubble is removed by huge earthmoving equipment. After the coal surface is exposed, smaller blasts called "Coal Shots" are applied to loosen coal layers. The coal is then mined out by truck and shovel operation. The ground motions caused by Cast Blasts were used for seismic tests conducted in this research. The smaller Cast Blasts or Coal Shots were used for checking and calibrating instrumentation.

OUTLINES OF SEISMIC TESTS

A sectional view and a top view of the test pit and the pile-supported structure are shown in Figure 2 and Figure 3, respectively. A 12x12-meter-square test pit was excavated 3-meter deep with a 45-degree slope, as shown in Figure 2. A waterproofing layer was made of high-density plastic sheets and was installed in the test pit in order to maintain 100% water-saturated sand.

Details of the pile-supported structure are shown in Figure 4. Four piles were made of steel tube. Pile tips were closed by welding. Piles were embedded 70cm into the mudstone layer. The top slab and the base mat were made of reinforced concrete and were connected by H-shaped steel columns. The construction schedule was determined so that the structure under construction received the least influence from mining blasts.

Instrumentation is shown in Figure 5. Accelerations were measured of the structure and one of the four piles. Accelerations in the sand deposit and ground surrounding the free field were also measured in array configurations. Axial strains of the pile were measured to evaluate bending moments. Excess pore water pressures were measured at four levels in the test pit to investigate liquefaction phenomena. Sensors embedded in the test pit were sealed and protected against water-sand mixture. Great care was taken in preparing pore pressure transducers. Each transducer was installed in a plastic casing and the casing was wrapped in silica sand and glass fiber sheet for protection. The air in front of the transducer diaphragms was removed to ensure accurate measurements. This treatment was done by heating and vacuuming in a water-filled glass container [2].

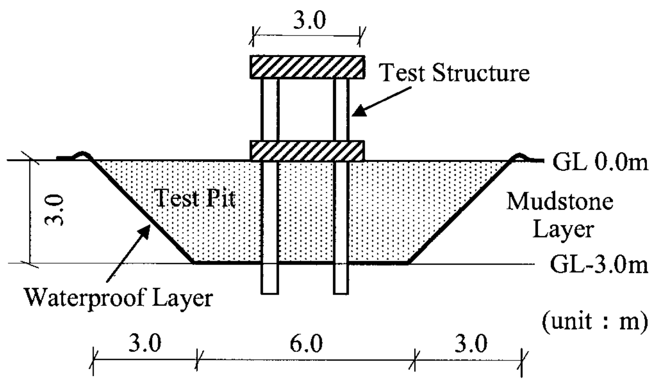

Figure 2 Sectional View of Test Pit

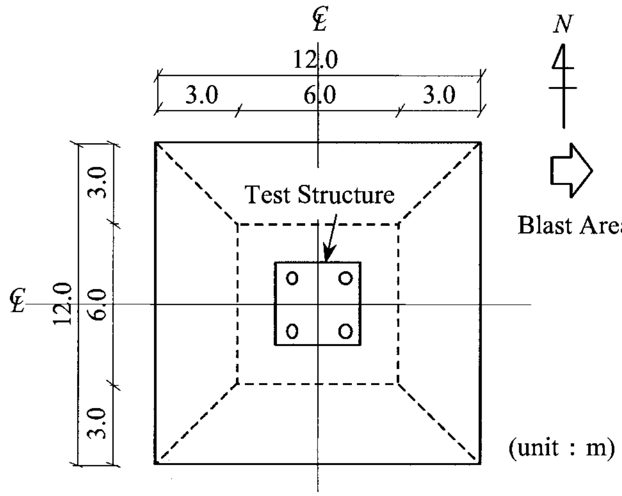

Figure 3 Top View of Test Pit

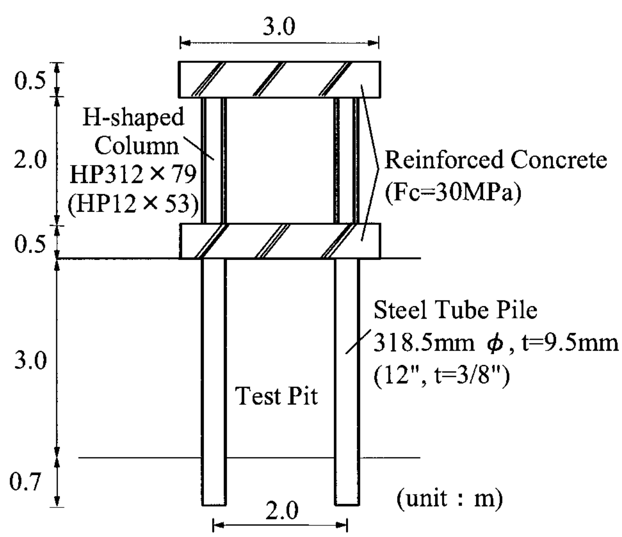

Figure 4 Details of Pile-Supported Structure

PS measurements were conducted in the test site to investigate the physical properties of the soil layers. PS measurement results are shown in Figure 6. The overburden consisted of several layers of siltstone or mudstone. The shear wave velocity at the test pit bottom was about 200 m/s and this increased to 500 to 700 m/s with increasing depth. Core soil

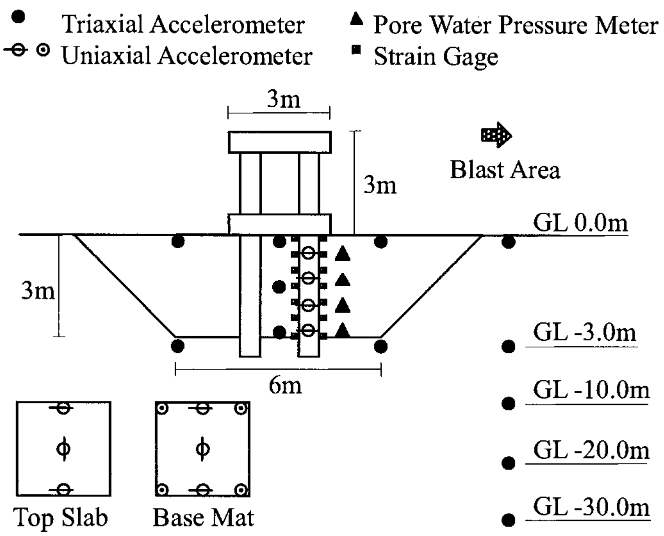

Figure 5 Instrumentation

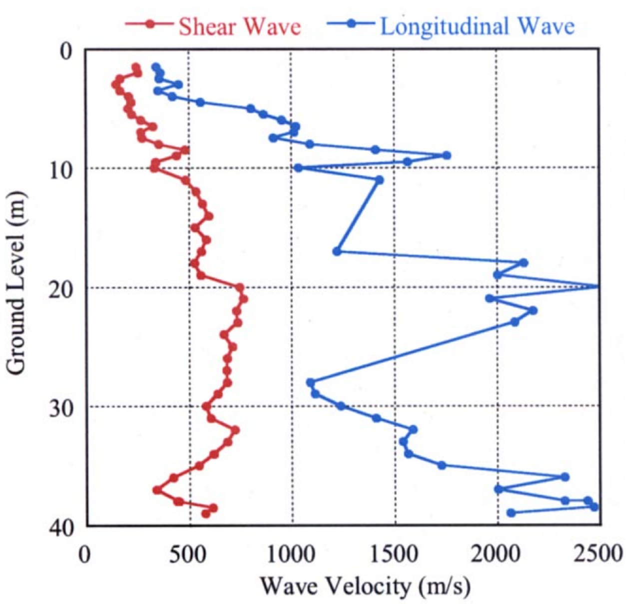

Figure 6 Results of PS measurement

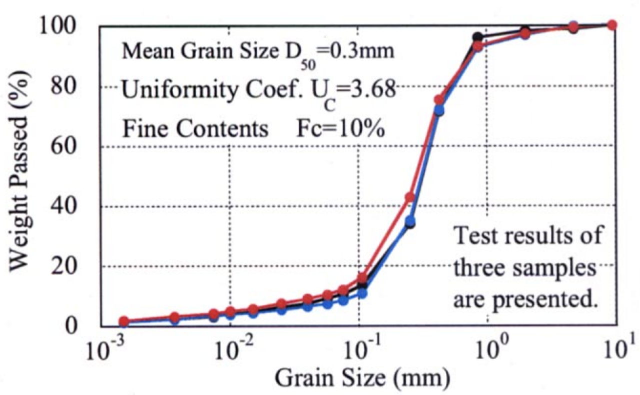

Figure 7 Grain Size Distribution of Sand

samples were collected for laboratory tests.

The grain size distribution of the backfill sand is shown in Figure 7. The sand was found near Black Thunder Mine. Great care was taken in backfilling the test pit with the sand, because the sand needed to be 100% water-saturated and air had to be removed in order to ensure a liquefiable sand deposit.

Figure 8 shows the installation of the waterproof layer. Figure 9 shows the completed pile-supported structure and the test pit. The water level was kept at 10 cm above the sand surface throughout seismic tests to prevent dry out of the sand deposit.

SEISMIC TEST RESULTS

Seismic tests were conducted on the pile-supported structure six times. The locations of the blast areas for each test are shown in Figure 10. The blast areas were about 60m wide and their lengths depended on the mining schedule.

The results of the seismic tests are summarized in Table 1. The maximum horizontal acceleration recorded

Figure 8 Installation of Waterproof Layer

Figure 9 Completion Test Structure and Test Pit

on the adjacent ground surface varied from 20 Gals to 1353 Gals depending on distance from the blast area to the test site. The closest blast was only 90m from the test site. These differences in the maximum acceleration yielded responses at different levels and liquefaction in of different degrees. Sand boiling phenomena were observed in the test pit with larger input motions. This is one of the most advantageous features of the test method employed in this project, although the input motions were not controlled mechanically or electrically.

In this paper, three tests indicated by yellow highlights in Table 1 were chosen for detailed investigations, because those tests provided three different phenomena in terms of liquefaction of the sand deposit as well as in terms of dynamic responses of the structure. Horizontal accelerations in the EW direction are discussed hereafter.

Measurement Records at Free Field and Sand Deposit

The maximum accelerations recorded in the adjacent free field in vertical array configurations are compared for three tests in Figure 11. The amplification tendencies from GL-32m to the surface were similar in the mudstone layers for three tests. The maximum accelerations recorded through the mudstone layers to the sand deposit are compared for three tests in Figure 12. There was a clear difference among the amplification trends in the test pit. Test-1 showed a similar amplification trend to that of the mudstone layers as shown in Figure 11. Test-5 showed less amplification in the sand deposit. Test-3 showed a large decrease in acceleration in the test pit because of severe liquefaction of the sand deposit.

Acceleration records at the sand surface, the free field surface and GL-32m are compared for Test-1 (Small Input Level) in Figure 13. The response spectra from these records are also shown in the figure. The same set of acceleration records and these response spectra are shown in Figure 14 for Test-5 (Medium Input Level) and in Figure 15 for Test-3 (Large Input Level).

As can be seen from Figure 13 for Test-1, over all the frequency regions, the responses at the sand surface were greater than those at the free field surface, and the responses at the free field surface were greater than those at GL-32m. From Figure 14 for Test-5, the responses at the sand surface and the free field surface were greater than those at GL-32m over all frequency regions. The responses at the sand surface became smaller than those at the free field surface for the period less than 0.4 seconds due to in a certain degree of liquefaction of the sand. From Figure 15 for Test-3, the responses at the sand surface became much smaller than those at the free field surface and even smaller than those at GL-32m. These responses reductions in the test pit were caused by extensive liquefaction over the test pit, because shear waves could not travel in the liquefied sand.

Measurement Records of Structure

Figure 16 compares the maximum recorded accelerations of the pile-supported structure and in the test pit for three tests. As can be seen for Test-3, there were differences in maximum response between the pile-supported structure and the sand deposit, which means that the pile and surrounding sand did not behave in the same manners. In Test-3, unlike in the other cases, the maximum acceleration decreased as motions traveled upward.

Table 1 Summary of Seismic Tests

Level of Input Motions	Test #	Distance (m) *	Max. Acceleration **		
			EW	NS	UD
Small	Test-1	3000	20	28	29
	Test-2	1000	32	84	48
Medium	Test-5	500	142	245	304
Large	Test-3	140	579	568	1013
	Test-4	180	564	593	332
Very Large	Test-6	90	1217	1353	3475

*: distance from blast area to test site

**: at the ground level of adjacent free field (Gals)

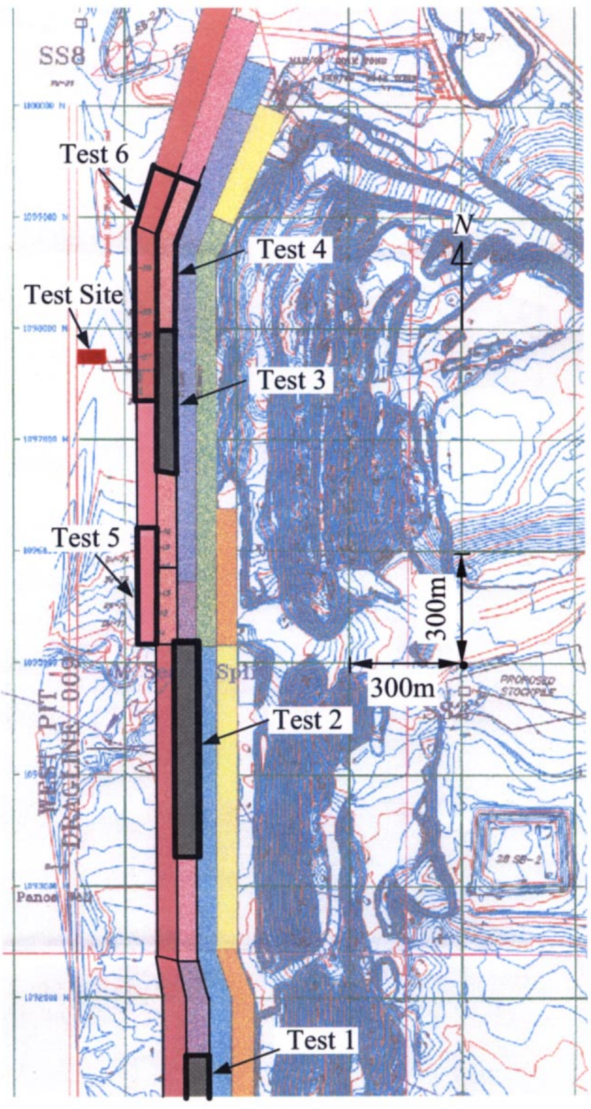

Figure 10 Locations of Blasts in Seismic Tests

The maximum bending moment distributions of the pile are shown in Figure 17. The bending moment took its maximum value at the pile head for all cases. However, the moment distribution shapes differed and the inflection points of curves moved downward in accordance with the input motion levels, in other words, the degrees of liquefaction in the test pit. Figure 18 compares the acceleration records at the top slab, the base mat and GL-3m of the pile for Test-1 (Small Input Level) . The response spectra from these records are also shown. The same set of acceleration records and these response spectra are shown in Figure 19 for Test-5 (Medium Input Level) and in Figure 20 for Test-3 (Large Input Level).

As can be seen from Figure 18 for Test-1, the maximum accelerations increased as motions went upward. For all frequency regions, the responses at the top slab were greater than those at the base mat, and the responses at the base mat were greater than those at GL-3m of the pile. The first natural period of the soil-pile-structure system was about 0.2 seconds under the input motion level of Test-1. From Figure 19 for Test-5, the maximum accelerations increased as motions went upward. For almost all frequency regions, the responses at the top slab were greater than those at GL-3m of the pile. The responses at the base mat were greater than those at GL-3m of the pile for periods greater than 0.2 seconds and were similar to those at GL-3m for periods less than 0.2 seconds. The peaks in response spectra were at about 0.3 seconds, and were shifted by 0.1 seconds from those of Test-1. For Test-3, the maximum accelerations decreased as motions went upward, which were different from those of the other two tests. The responses at the top slab and the base mat became smaller than or similar to the responses at GL-3m of the pile. Compared with the other two tests, it became difficult to identify peaks corresponding to natural periods of the soil-pile-structure system from response spectra diagrams. The structure responses from the three tests described above indicate that soil nonlinearity and liquefaction greatly influence the dynamic properties of pile-supported structures.

Excess Pore Water Pressure Ratio

The changes of excess pore water pressure ratios are shown in Figure 21. The excess pore water pressure ratio is the ratio of excess pore water pressure to initial effective stress. In Test-1, the maximum ratio stayed around zero, which means that no liquefaction took place. In Test-5, the ratios rose rapidly, reaching around one at GL-0.6m and GL-1.4m after the main vibration was finished. Ratios at GL-2.2m and GL-3.0m were about 0.7 and 0.5. The measurement showed that the liquefaction region was in the upper half of the test pit. In Test-3, ratios at all levels rose rapidly, reaching around one, which indicates extensive liquefaction over the entire region. The large fluctuations in pressure records during main ground motions were caused by longitudinal waves.

Evaluation of Natural Frequencies and Damping Factors of Soil-Pile-Structure System

Using measured ground motion inputs and structure responses, vibration properties of the soil-pile-structure system were identified by fitting test records to the single-input-multi-output ARX model (the auto-regressive model) [3]. The soil-pile-structure system was modeled by a simple lumped mass model, as shown in Figure 22. Acceleration records at the test pit bottom were used as input motions, and acceleration records of the base mat and the top slab were regarded as output motions in this investigation.

The alternation of natural frequencies and damping factors evaluated with time are shown for the first natural mode of the system in Figure 23. The frequencies of the first mode were decreased by ground motions and these values were varied in accordance with input motion levels. The first natural frequencies were around 7 Hz for all tests before subject to the ground motions. For Test-3, the frequency was decreased by half after the ground motions. The damping factors of the first mode were increased by the ground motions and these values were varied in accordance with the input motion levels. For Tets-1, the damping factor was less than 7%. For Test-3, the damping factor was considerably higher at 20 to 40%.

During extensive liquefaction in the test pit, the natural frequency of the soil-pile-structure system was decreased because the sand lost its stiffness, however, the damping factor was increased considerably because of the nonlinear behavior of liquefied sand.

CONCLUSIONS

(1) Seismic tests were conducted of a pile-supported structure in a liquefiable sand deposit six times using ground motions from large mining blasts. Nonlinear responses of the soil-pile-structure system at different levels were obtained for various levels of liquefaction in the test pit.

(2) The maximum horizontal acceleration recorded at the adjacent ground surface varied from 20 Gals to 1353 Gals depending on distance from the test site to the blast areas. This is one of advantages of the vibration test method employed in this project.

(3) In the adjacent free field, motions were amplified from GL-32m to the ground surface, regardless of input motion levels. In the test pit, amplification or reduction of motions depended upon input motion levels. Motions were amplified at small input levels and decreased at large input levels from the bottom to the surface of the test pit.

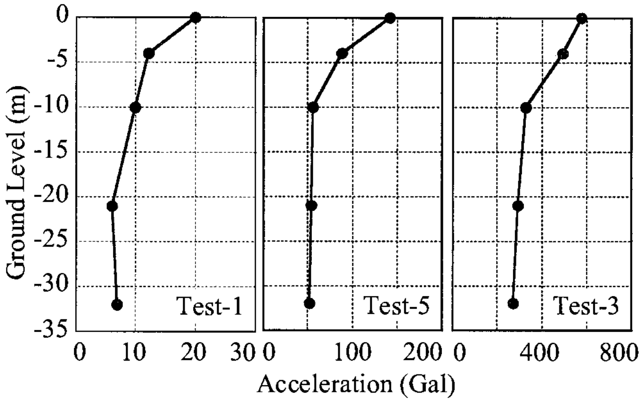

Figure 11 Max. Acc. in Vertical Array at Free Field

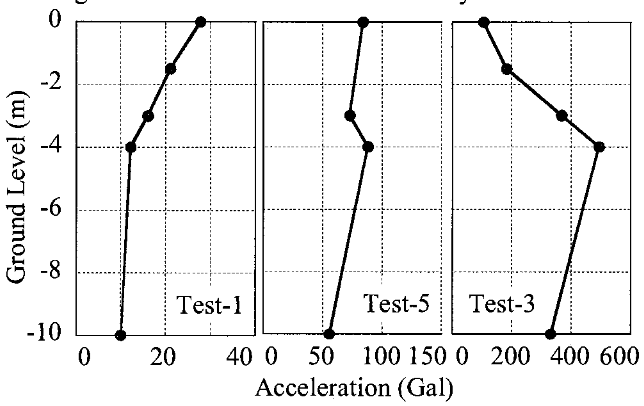

Figure 12 Max. Acc. through Mudstone Layers to Test Pit

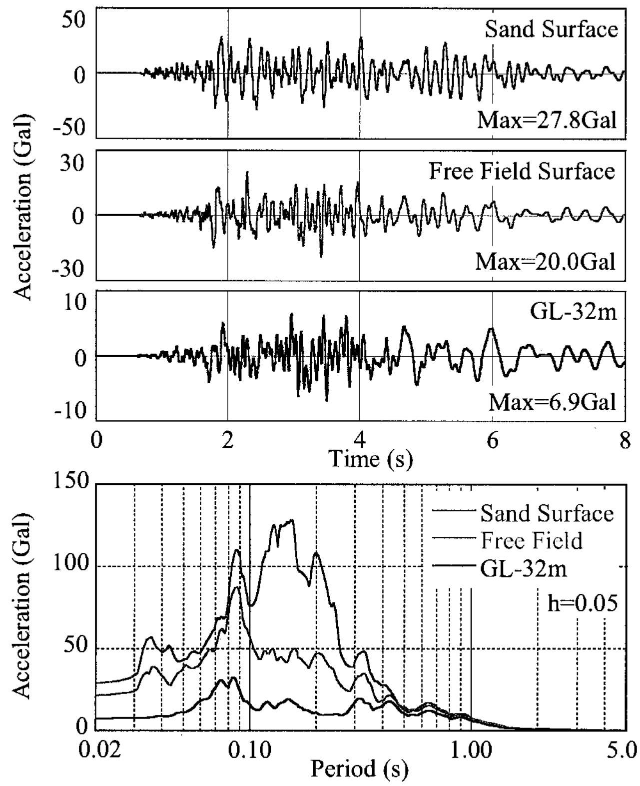

Figure 13 Acceleration Records of Test-1 (Small Input Level)

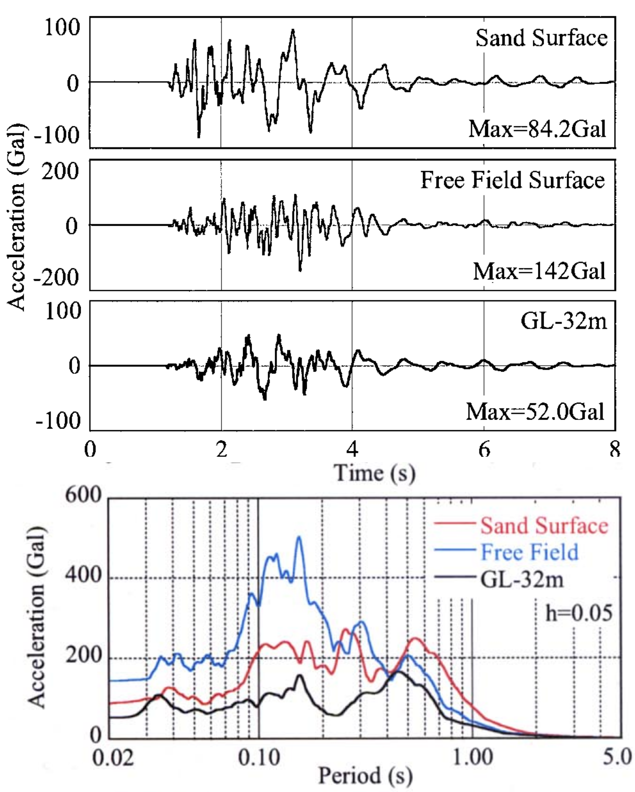

Figure 14 Acceleration Records of Test-5 (Medium Input Level)

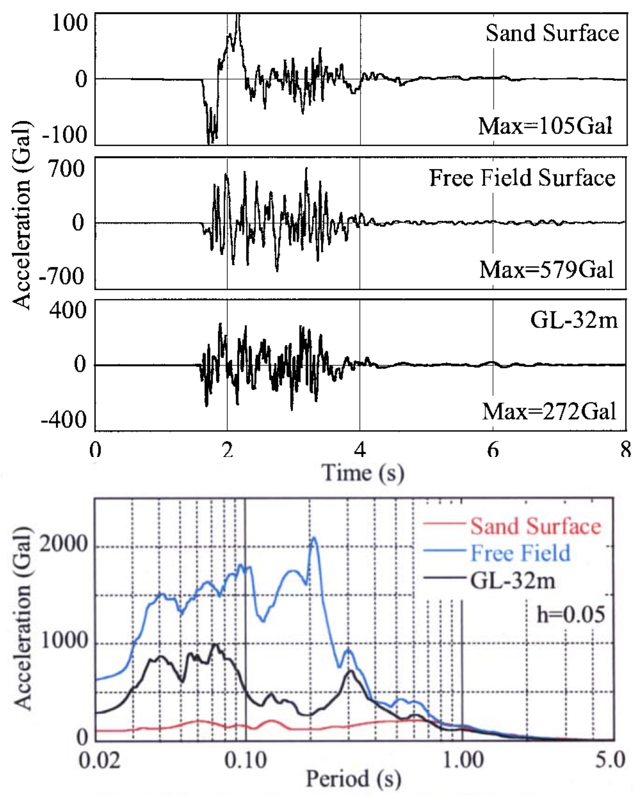

Figure 15 Acceleration Records of Test-3 (Large Input Level)

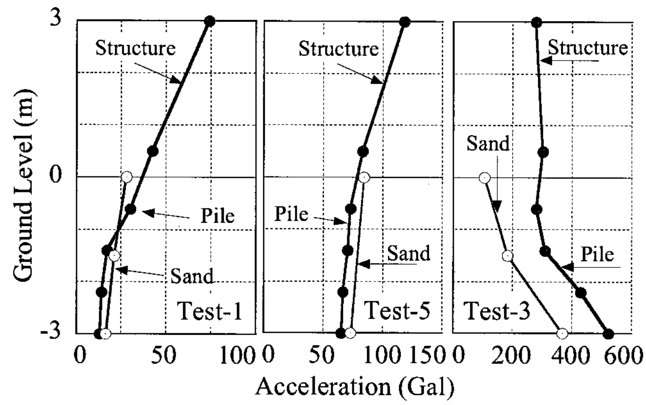

Figure 16 Max. Acc. at Sand Deposit and Test Structure

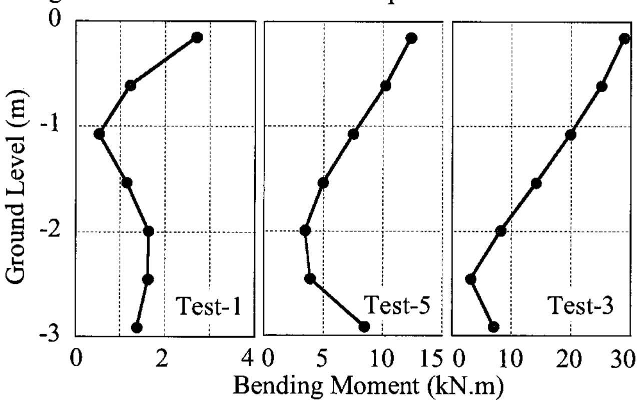

Figure 17 Maximum Bending Moment Distribution

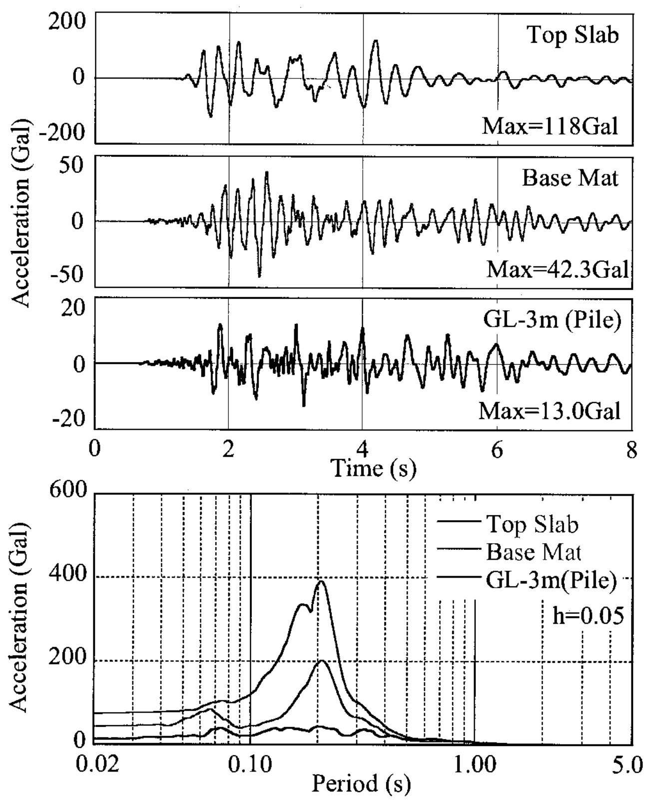

Figure 18 Acceleration Records at Test Structure
(Test-1 : Small Input Level)

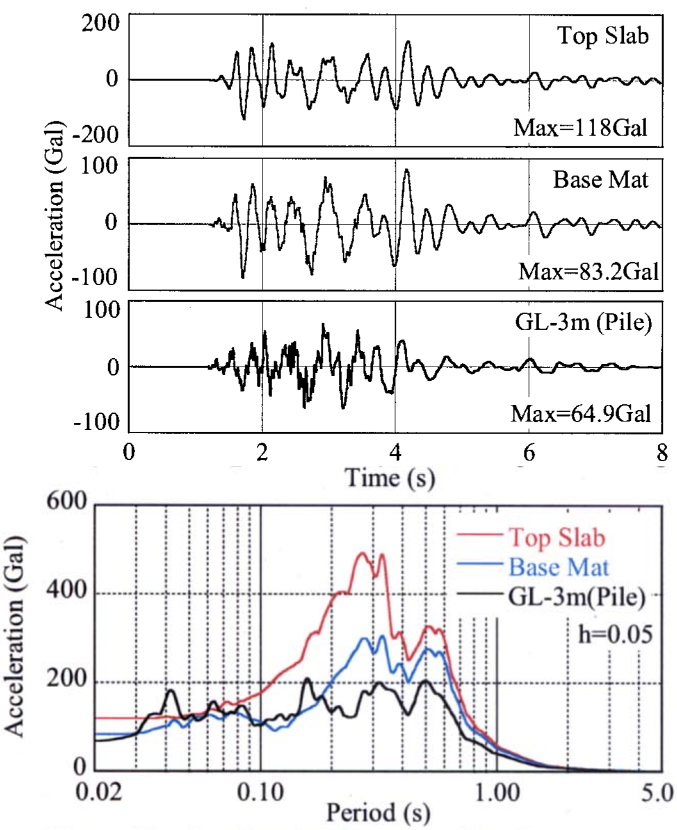

Figure 19 Acceleration Records at Test Structure
(Test-5 : Medium Input Level)

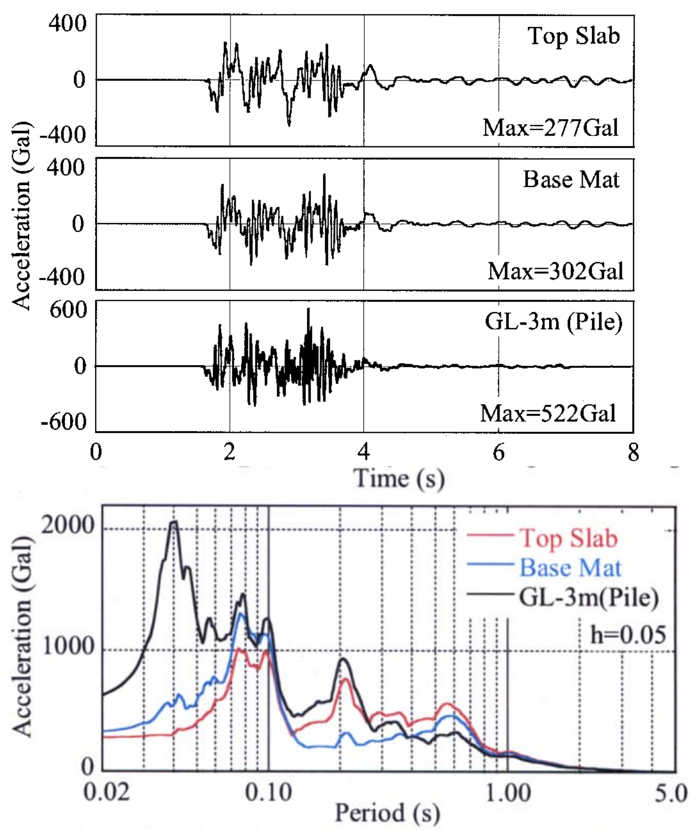

Figure 20 Acceleration Records at Test Structure
(Test-3 : Large Input Level)

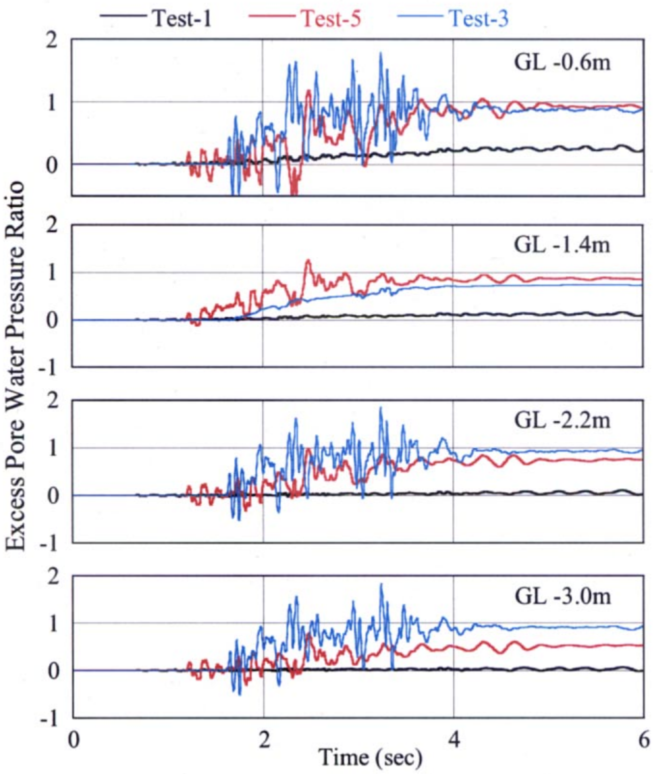

Figure 21 Excess Pore Water Pressure Ratio

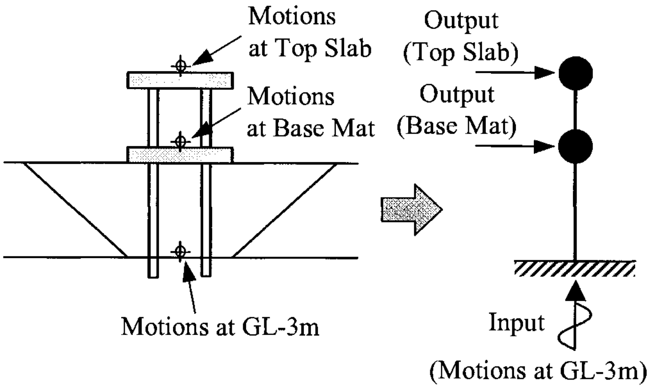

Figure 22 Model for Identifying Vibration Properties of Soil-Pile-Structure System

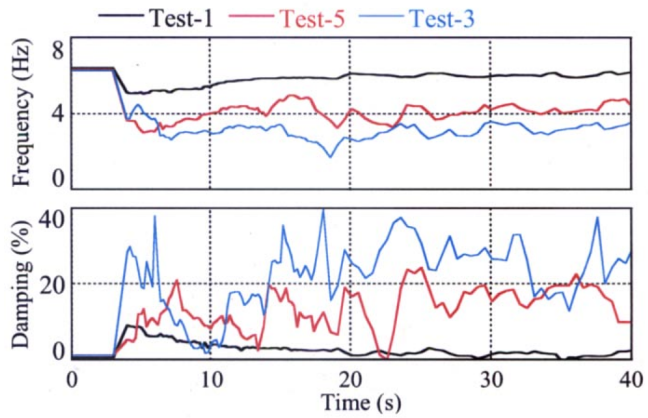

Figure 23 Evaluated Natural Frequencies and Damping

(4) Generation of pore water pressures depended upon input motion levels. Liquefaction started from the shallow part and extended to the deeper part of the test pit, and finally the test pit was completely liquefied as in Test-3.
(5) Bending moments were a maximum at the pile heads, regardless of input motion levels. However, the moment distribution shapes varied and the inflection points of the distribution curves moved downward in accordance with input motion levels, in other words, the degrees of the liquefaction in the test pit.
(6) The vibration test method employed in this experimental research was found very useful and effective for investigating the dynamic behavior of large model structure under severe ground motions.

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