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E-DEFENSE SHAKING TABLE TESTS ON THE BEHAVIOR OF A PILE-FOUNDATION STRUCTURE IN LARGE-SCALE MODEL GROUND UNDER MULTI-DIMENSIONAL MOTIONS

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ABSTRACT

To investigate the behavior of a pile foundation under multi-dimensional earthquake ground motions, a total of 80 shaking table tests of large-scale models of non-liquefiable sand deposits with a pile-foundation structure were performed at the E-Defense testing facility. The models were prepared in a cylindrical shear box 8m in diameter and 6.5m in height, which were as large as currently possible in order to produce actual phenomena under earthquake ground motions on the table. This paper describes a part of the 80 tests, which involved the testing of the models of three types of pile-foundation structures having different natural periods applied to two-dimensional horizontal shaking to evaluate the influence of a superstructure's inertial force and ground deformation on the pile foundation. The test results explain that the behavior of the pile foundation of a long period structure is mainly dominated by ground deformation, while that of a short period structure is affected predominantly by the superstructure's inertial force as well as ground deformation.

Introduction

Many mega cities in Japan are located on soft ground along the sea or large rivers. When a structure is built on such soft ground, a foundation to support it is needed due to the ground's lack of bearing capacity. Most structures with foundations in Japan employ a pile foundation because of its advantages concerning construction cost and schedule.

Since a pile foundation has relatively small horizontal rigidity, it tends to be damaged by its superstructure's inertial force and/or ground deformation due to the large horizontal motions of ground and structure that an earthquake induces. Such damage of a pile foundation can produce inclination or settlement of its superstructure, causing problems concerning its use in spite of the fact that the superstructure itself has functionally survived. From this point of view, assuring the seismic performance of a pile foundation during and after an earthquake is one of the important factors in terms of geotechnical earthquake engineering disciplines.

Many case histories regarding pile foundations damaged by large earthquakes have been reported and studied so far. However, the process leading to failure of a pile foundation under

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earthquake ground motions has still not yet been ascertained because no data observed during the process has been obtained in actual earthquakes. In other words, it is difficult to say that the failure mechanism of a pile foundation, that rational methods of earthquake resistant design need, is understood without evaluation of the data obtained in actual earthquake situations.

In order to contribute to the development of rational methods of earthquake resistant design concerning a pile foundation based on an understanding of its failure process due to earthquake-induced ground motions, the authors carried out a research project involving various tests of ground models with a pile-foundation structure as large as currently possible at the E-Defense large-size shaking table facility to observe the behavior of a foundation under shaking and obtain data (Tabata and Sato 2006). This paper describes a part of the project's results obtained from tests of the models of non-liquefiable sand deposits with three types of pile-foundation structure applied to horizontal and two-dimensional excitation, in order to investigate the influence of a superstructure's inertial force and ground deformation on a pile foundation. In this paper, to discuss the fundamental aspects of the influence, the horizontal displacement of a pile head are especially focused.

Outline of the tests

E-Defense shaking table

The tests were performed by the E-Defense shaking table. E-Defense is the name of a full-scale three-dimensional earthquake testing facility operated by the National Research Institute for Earth Science and Disaster Prevention (Ohtani et al. 2003; Tabata and Kajiwara 2009). Figure 1 shows an illustration and photo of the E-Defense shaking table and Table 1 presents its specifications. The table is 20m long and 15m wide, and can reproduce the various

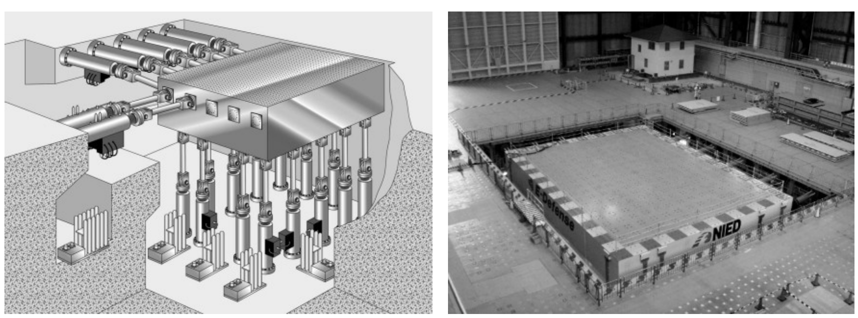

Figure 1. Illustration and photo of the E-Defense shaking table.

Table 1. Specifications of the E-Defense shaking table.

Table size	20m x 15m	
Loading capacity	12MN	
Maximum performance*	Horizontal (x and y)	Vertical (z)
acceleration	900gal	1500gal
velocity	2m/s	0.7m/s
displacement	±1m	±0.5m
allowable moment	150MNm	40MNm

* at the maximum load

3-D ground motions recorded in the 1995 Hyogoken-Nambu earthquake for a 12-MN specimen by 10 horizontal and 14 vertical actuators.

Models

For the tests, the models were prepared in a cylindrical shear box. Figure 2 shows an illustration of one of the models in the shear box. The shear box shown in Fig. 3 is 8m in diameter and 6.5m in depth, and is formed by 40 laminar rings that can only move horizontally. In the shear box, a 6.4m-high non-liquefiable deposit consisted of Albany silica sand compacted to a relative density of 70%. The properties of the sand are presented in Table 2, and the grain-size distribution of the sand is shown in Fig. 4 that demonstrates a similarity to that of Toyoura sand.

As shown in Fig. 2, the model had a pile-foundation structure at the center of the deposit. The structure consisted of a 28-ton superstructure, 10-ton footing, pile foundation, and four

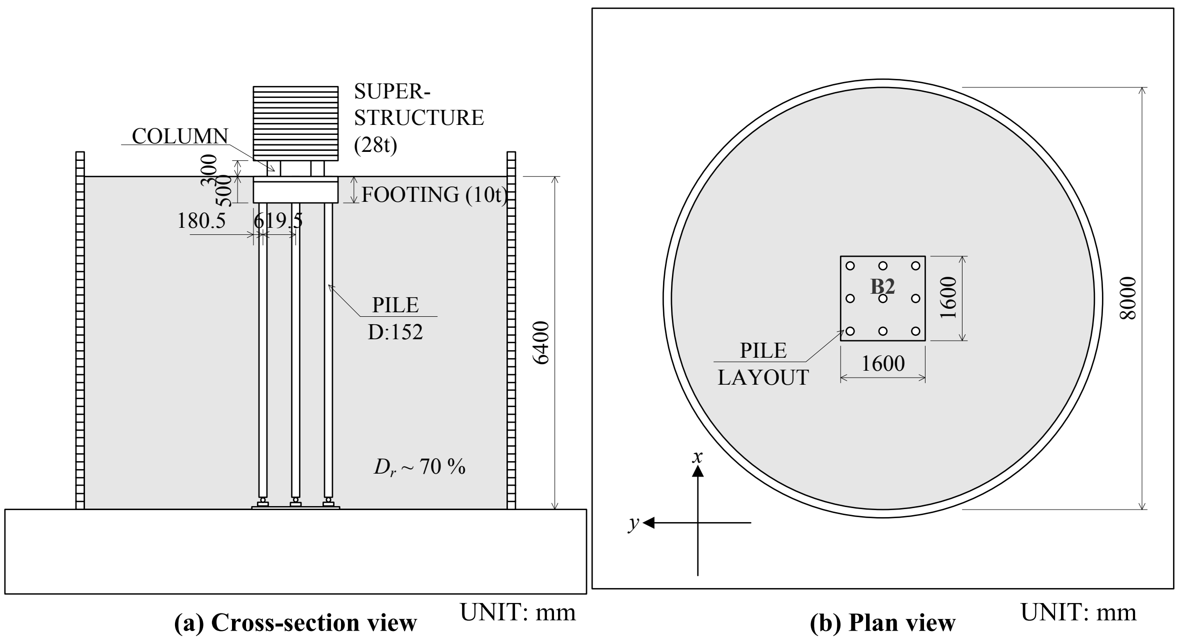

Figure 2. Illustration of one of the models and the coordinate system in the tests: (a) Cross-section and (b) plan views.

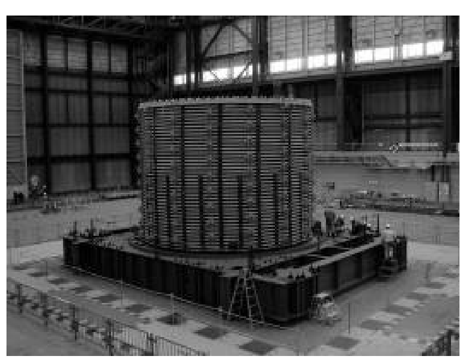

Figure 3. Photo of the cylindrical shear box.

30cm-high columns between the superstructure and footing. The pile foundation consisted of 9 hollow steel piles 5.7m long, 152mm in diameter and 2mm thick. Each pile was fixed at the top on the footing and pinned at the tip to the box's bottom plate. The four columns between the superstructure and footing were replaceable in order to change the natural period of the structure.

Measurement sensor installation

A total of 857 measurement sensors listed in Table 3 were installed with the models. Accelerometers, velocity and displacement transducers, earth pressure transducers and strain gauges on the piles monitored the behavior of the structure. To observe the behavior of the deposit, accelerometers were installed at different levels of the deposit. In addition, to obtain the

Table 2.   Properties of Albany silica sand.

Density of soil particles	$\rho_s = 2.63$ g/cm^3
Maximum void ratio	$e_{max} = 0.783$
Minimum void ratio	$e_{min} = 0.513$
Mean grain size	$D_{50} = 0.20$ mm
Uniformity coefficient	$U_c = 1.64$
Coefficient of curvature	$U'_c = 1.13$

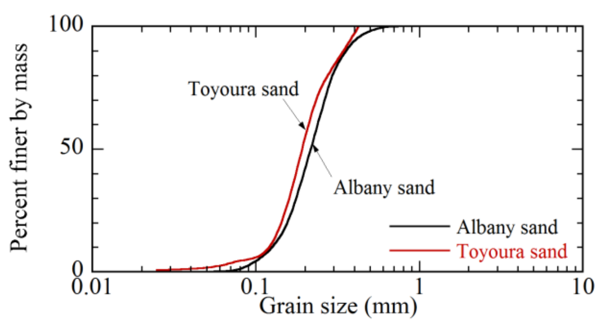

Figure 4.   Grain size distributions of Albany silica sand and Toyoura sand

Table 3. Measurement sensors installed with the models.

Type of sensor	Ground	Piles	Superstructure and footing	Columns between superstructure and footing	Container	Total
Strain gauge		476		48		524
Accelerometer	63	28	24		82	197
Veolcity transducer			4			4
Displacement transducer	2		11		24	37
Earth pressure transducer		52	16			68
Load cell		27				27

horizontal displacements of different levels of the deposit, displacement transducers measured the displacements of the laminar rings.

Testing program

In the entire research project, a total of 80 shaking table tests were performed for five types of model with different natural period structures applied to three types of input motions based on different ground motion recordings in 1-D, 2-D and 3-D.

Out of the 80 tests, only three cases are discussed in this paper as follows: Case 1 for the structure with a natural period shorter than the deposit's predominant period (short period structure), Case 2 for the structure with a natural period longer than the deposit's (long period structure), and Case 3 for the structure having a footing and pile foundation without the superstructure (no superstructure). In Case 1, in order to give the structure a shorter natural period than the deposit's predominant period, rigid steel columns were placed between the superstructure and footing. Similarly in Case 2 for the long period structure, columns of vibration isolation rubbers were used instead of rigid steel columns. Note that the short and long period structures were the same shape and weight: the only difference was that their natural periods were changed by the four columns between the superstructure and footing. In Case 3, since no superstructure and columns were placed on the footing, there was no influence of inertial force from the superstructure on the behavior of the structure.

These models were shaken under the 2-D horizontal input motions set to the maximum acceleration of approximately 0.8m/s^2 based on ground motions recorded at the Takatori Station in the 1995 Hyogoken-Nambu earthquake (Nakamura et al. 1996). Figure 5 shows the time

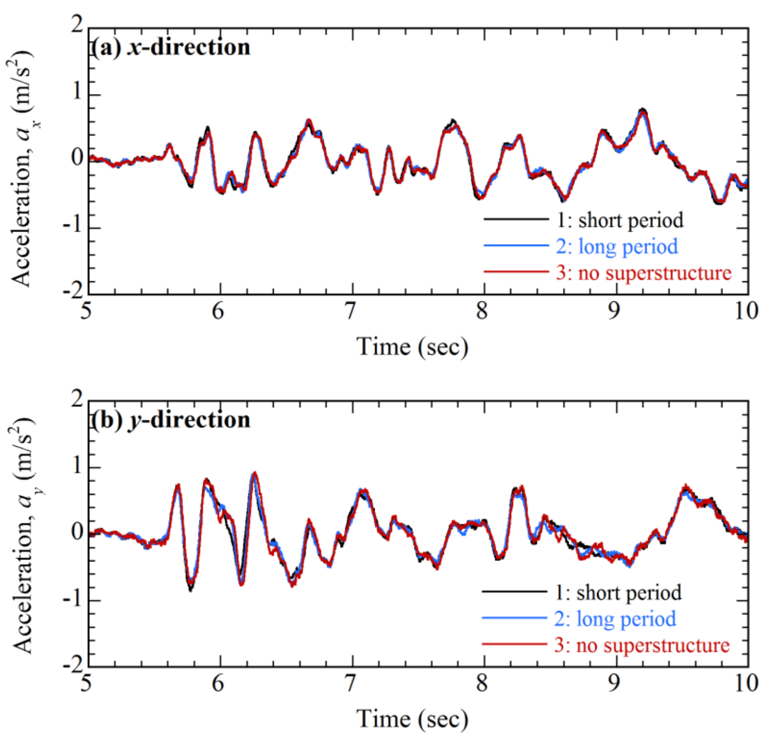

Figure 5. Comparison between the acceleration time histories of the table motions in (a) *x*- and (b) *y*-directions.

histories of the table accelerations, indicating that the input motions in three test cases were almost identical.

Test results

Behaviors of the superstructure and footing

To clarify the difference between behaviors of the short and long period structures, Fig. 6 presents the time histories of horizontal displacement in the *y*-direction of the superstructure and footing in Cases 1 and 2. In Case 1 for the short period structure in Fig. 6a, the displacement of the superstructure is relatively larger than that of the footing, while both phases are similar. In Case 2 for the long period structure in Fig. 6b, the displacement of the superstructure is larger than that of the footing and the period of its repetitive change is longer.

Influence of ground deformation and the superstructure's inertial force on the structure

To evaluate the influence of ground deformation and the superstructure's inertial force on a pile-foundation, comparisons of the ground displacement, superstructure's inertial force and displacement of the footing that is identical to pile heads are explained as follows.

Figure 7 shows the time histories of horizontal displacement in the *y*-direction of the footing and ground at the same level of the footing in Cases 1 and 2. In Case 2 for the long period structure in Fig. 7b, the footing and ground have almost the same displacements. In Case 1 for the short period structure in Fig. 7a, although the displacement of the footing indicates

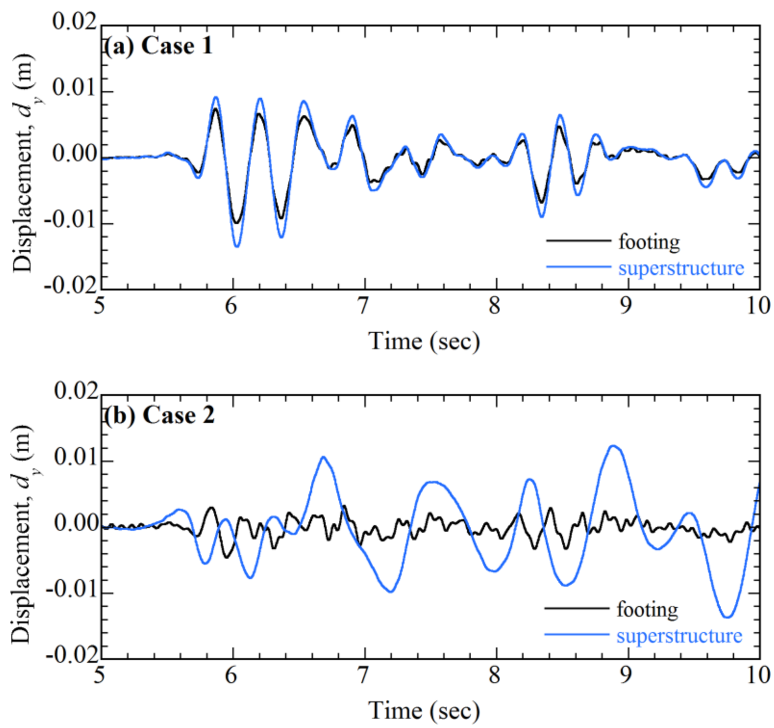

Figure 6. Horizontal displacement time histories of the superstructure and footing in (a) Case 1 and (b) Case 2.

similar behavior with that of the ground, it is larger, especially at the peaks of the displacement. Based on this observation, it can be said that the displacement of the footing of the long period structure is mainly dominated by ground deformation, while that of the short period structure is affected not only by ground deformation but also by another factor that in this case could be the superstructure's inertial force.

Figure 8 shows the time histories of the horizontal inertial force of the superstructure and footing, and horizontal displacement of the footing in *y*-direction in Cases 1 and 2. In Case 1 for the short period structure in Fig. 8a, since these changes and phases show almost the same trends, the inertial force affects the displacement of the footing rather than that of the ground as explained above and shown in Fig. 7a. In other words, the influence of the inertial force on the displacement of the footing is more predominant than that of the ground. In contrast, the inertial force in Case 2 for the long period structure in Fig. 8b has less correlation with the displacement of the footing than in the case of the short period structure. This fact implies that the inertial force has less influence on the displacement of the footing than the ground deformation. Indeed, as shown in Fig. 9, in Case 3 for the structure with no superstructure, in which it is assumed that there is no influence from the inertial force of the superstructure, the displacement of the footing is similar to the case for the long period structure.

Bending strains of the center pile

The bending strains of a pile for three types of structure are discussed here by focusing on the center pile labeled as B2 in Fig. 2b.

Figure 10 shows the time histories of bending strains of Pile B2 in *y*-direction at a depth of 15cm

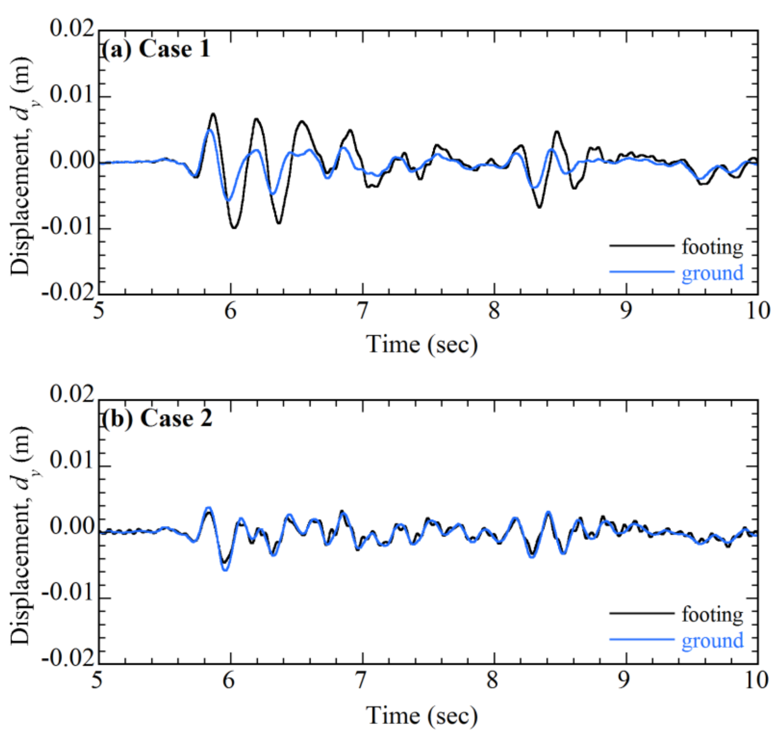

Figure 7. Horizontal displacement time histories of the footing and ground at the same level of the footing in (a) Case 1 and (b) Case 2.

from the pile head in Cases 1-3. The bending strain of the short period structure is larger than those in the other cases especially at around 6-7 seconds, while the bending strain of the long period structure has almost the same tendency as that of the structure with no superstructure. Figure 11 shows the bending strain distributions of Pile B2 in *y*-direction when each strain at 15cm from the pile head becomes maximal in Cases 1-3. In the cases for both the long period structure and the structure with no superstructure, similar strain distributions are found: the strain becomes the maximum at the pile head, decreases with depth and is not or only a little observed below 1.5m. The distribution of the short period structure is quite different from the others: the strain is the largest at the pile head, changes to the opposite bending and becomes the minimum around 1m deep, and returns to zero below 3m. These observations indicate that the inertial force induced by the superstructure has a greater influence on the bending behavior of a pile than

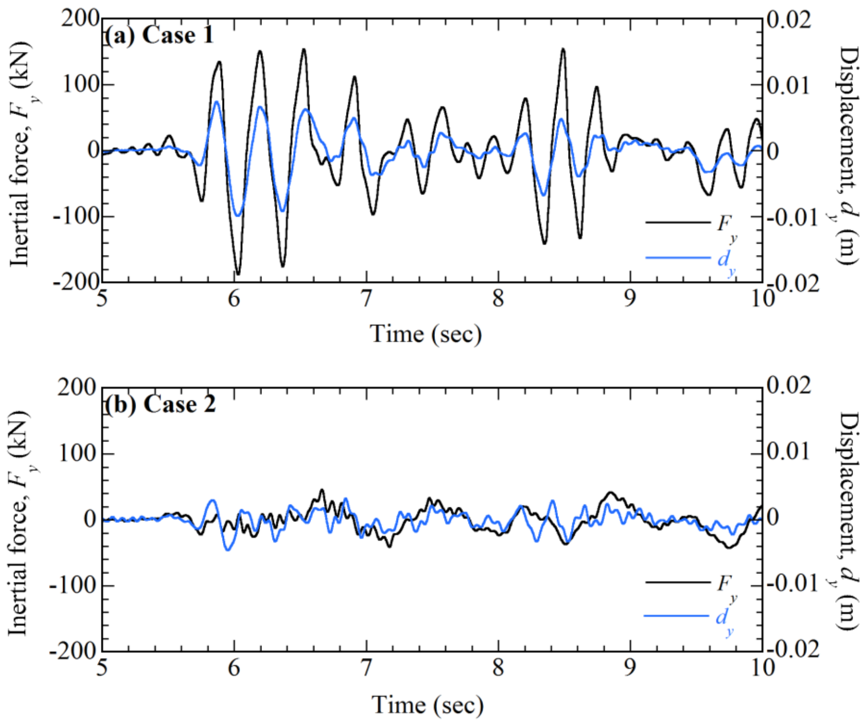

Figure 8. Time histories of horizontal inertial force induced by the superstructure and footing and horizontal displacement of the footing in (a) Case 1 and (b) Case 2.

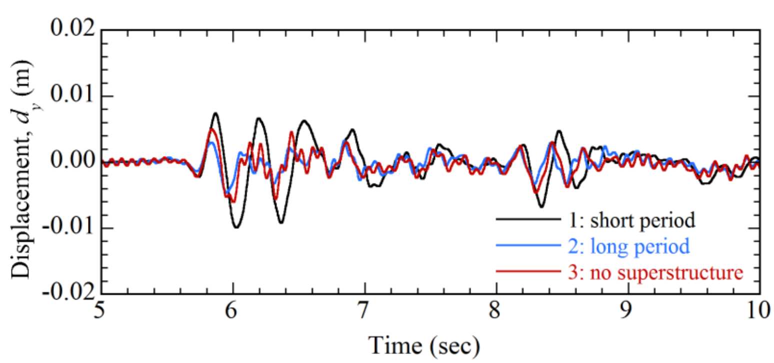

Figure 9. Horizontal displacement time histories of the footing in Cases 1-3.

the ground deformation.

Conclusions

In order to investigate the influence of a superstructure's inertial force and ground deformation on a pile foundation, E-Defense shaking table tests were carried out on the large-scale sand ground models of three types of pile-foundation structures with different natural periods. This paper particularly focuses on the horizontal displacement of a pile head to discuss the fundamental aspects of the influence. According to the test results, it is found that the behavior of the pile foundation of the structure with a natural period longer than the deposit's predominant period is mainly dominated by ground deformation and has only a small influence on its superstructure's inertial force. On the other hand, the behavior of the pile foundation of the structure with a shorter natural period is predominately affected by the superstructure's inertial force as well as ground deformation.

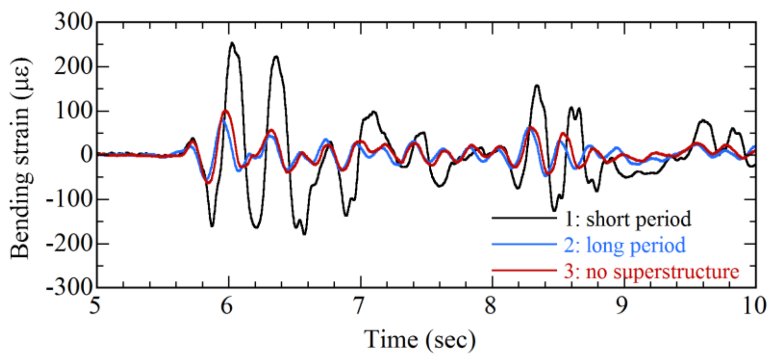

Figure 10. Bending strain time histories of Pile B2 in Cases 1-3.

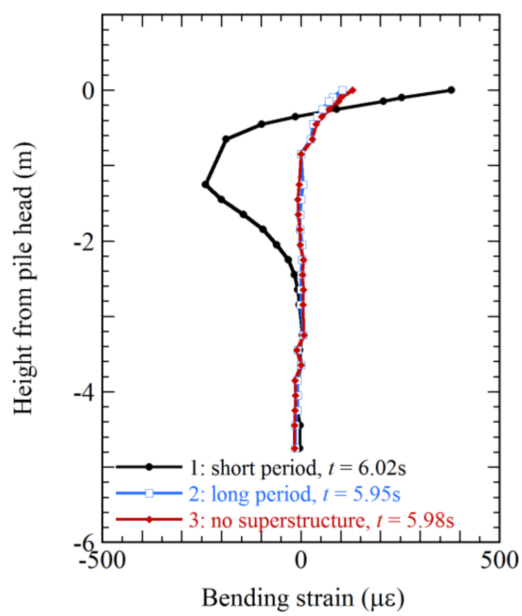

Figure 11. Bending strain distributions of Pile B2 in Cases 1-3.

Acknowledgments

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