Physical modeling and evaluation of pile foundations retrofitted with sheet piles as a measure against liquefaction

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ABSTRUCT

Physical model tests were conducted to examine seismic performance of the retrofit with sheet pile walls for the pile foundations on liquefiable ground. Test results reveal that the sheet pile wall isolates the soils adjacent to the piles from the surrounding soils and mitigates the liquefaction and soils deformation in the wall, resulting in significant reduction in the maximum bending moment and shear force in piles. However the pile foundation with the long sheet piles that are rigidly connected to the pile cap makes the dynamic responses of the superstructure larger, since the rigid pile-sheet pile composite foundation restrains the sway motion of the pile cap and makes the rocking motion of the foundation dominant. Considering all the various factors together, the retrofit with the long sheet piles without connection to the pile cap may be recommended.

1. INTRODUCTION

Kobe Earthquake in 1995 caused bridge piers and bridges to collapse, resulting in the worst damage due to natural causes recorded in Japan since Kanto Earthquake in 1923. This motivated us to work, with a sense of urgency, on seismic- resistant measures for bridges to prevent them from collapsing and to make their piers resistant to earthquakes in preparation for a large earthquake—such as the Tokai Earthquake, the East Nankai and Nankai Earthquake, and the Tokyo Metropolitan Epicentral Earthquake—that is expected to occur sometime within the next three decades. An example of such measures is the three-year program to reinforce the seismic resistance of bridges serving emergency transportation roads.

Seismic-resistant measures for foundations have not been developed as much as those for other structural materials because only a few cases of damage caused by impaired foundations have been reported[1)]. Another barrier is that because construction conditions are so restrictive, measures to improve seismic-resistance require large-scale construction work.

Some bridges built on old design standards prior to the Hyogoken-Nambu Earthquake have foundations that need the same reinforcement as other structural materials, such as those that do not meet the seismic-resistant performance stipulated in new standards; those that are now found, as a result of a change in the liquefaction test, to have very weak foundations at the time of liquefaction; and those that now have a relatively inadequate bearing force in their foundations due to the bridge's piers having had their seismic resistance reinforced.

Accordingly, many existing bridges are potentially unable to withstand a large seismic motion. Therefore, developing seismic-resistant reinforcement methods that take cost and restrictive work conditions into consideration is indispensable to developing seismic-resistant reinforcement for foundations.

In this research, we adopted the method of installing sheet piles around a pile foundation in liquefied ground and proved the seismic-resistant reinforcement effect of this method.

2. CHARACTERISTICS OF PILE FOUNDATION RETROFITTING USING SHEET PILES

In this experiment, we used a seismic-resistant reinforcement method whereby sheet piles were installed up to a predetermined height around existing bridge piers in liquefied ground. The research shown below represents the reinforcement method that builds walls around existing pile foundations.

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Shioi et al.[2)] proposed a method to install sheet piles around an existing pile foundation and solidify the area enclosed by the sheet piles, and confirmed an increase in the horizontal bearing force of the foundation and a decrease in the pile's section force. Fujikawa et. al[3)] devised a structure in which continuous underground walls are arranged, and confirmed through three-dimensional liquefaction analysis that controlling the shear deformation of the ground inhibits excess pore pressure and decreases a pile's section force

The seismic-resistant reinforcement method using sheet piles we selected in this research is expected to realize the following results:

- Increase a foundation's horizontal bearing force
- Alleviate the effect of ground displacement on piles
- Inhibit liquefaction by restraining shear deformation of the soil within the sheet piles

The method has the following characteristics from the viewpoint of construction. Little constrain is imposed by the limited space available below the beam during construction due to the use of small construction machines including press-in pile drivers. It only needs a small construction area because the sheet piles can be used as temporary earth retention devices. In addition, the space for construction is not constrained by neighboring structures or structures under the ground, because the area occupied by a foundation will not increase much after reinforcement.

3. SUMMARY OF THE EXPERIMENT

3.1 Objective Bridge and Experiment cases

Fig.1 shows the bridge pier and the foundation that we used for the experiment. Measuring 12.2 meters tall, this pier is part of a bridge that has five spans made of continuous steel beam I. The foundation is a cast-in-place pile, and three piles 27.5 meters long and 1.2 meters in diameter are arranged vertically and horizontally. The shaved load of the upper structure is 6203 kN. The foundation has the structure shown in Fig.1, which we based on the foundation shown in Reference 4).

We carried out four experiments, including one that did not yield a measurement, as shown in Fig.2. The

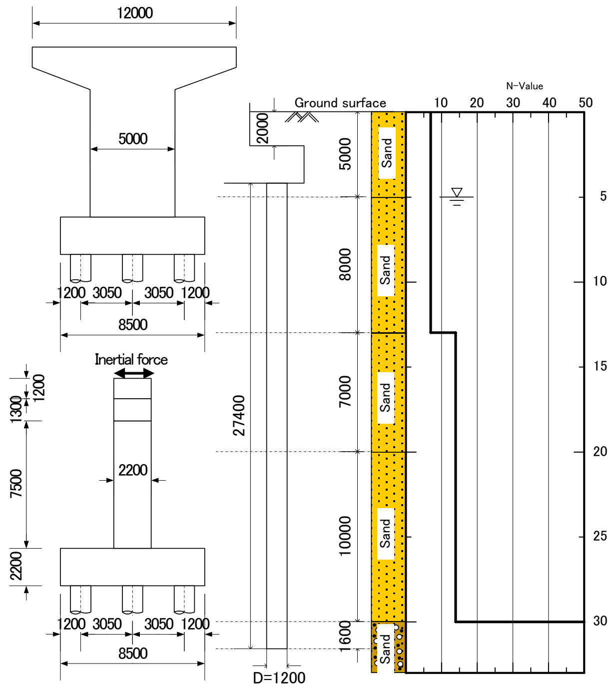


Fig.1 Target bridge substructure and soil profile

structure of the model foundation is shown in Fig.3. The layer that is completely liquefied is a saturated sand layer in which Dr=60%. We conducted three experiments by changing the connection conditions between the sheet piles and the footing, as well as the length of the sheet piles.

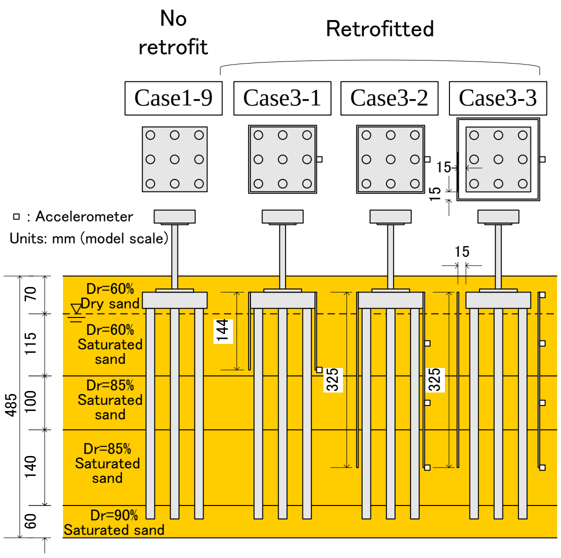


Fig.2. Test conditions

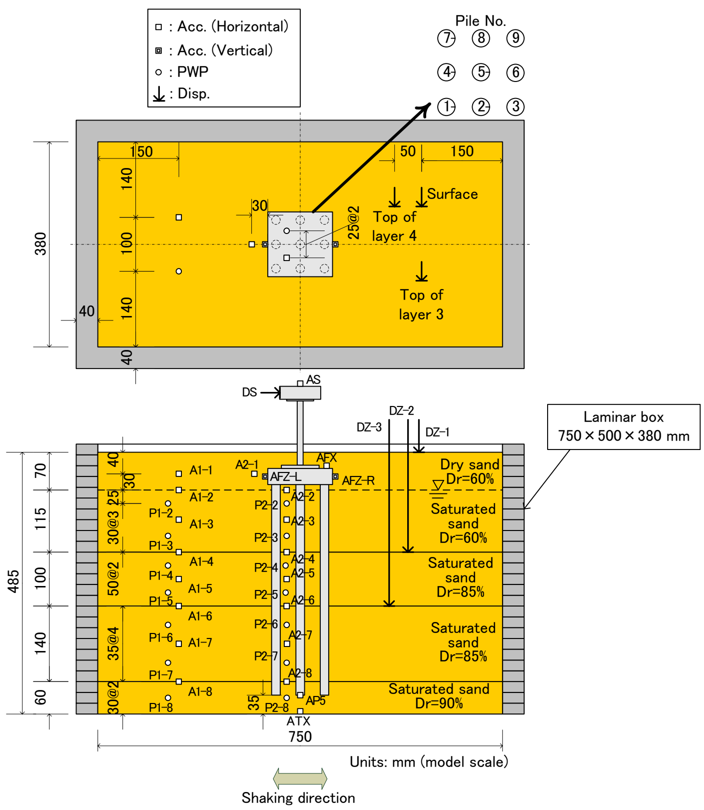


Fig.3. Centrifuge model package and locations of instrumentation (Case1-9)

Photo.1. Model piled bridge pier with sheet pile walls (Case3-1)

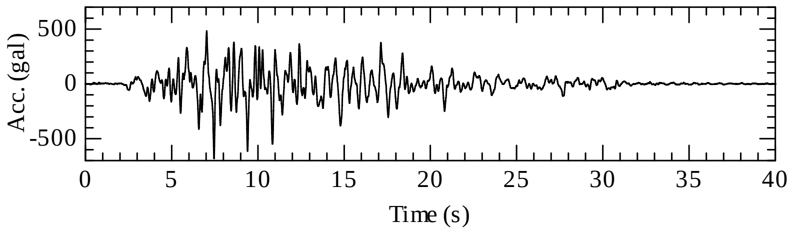


Fig.4. Input earthquake motion (in prototype scale)

3.2 Experiment method

We selected the dynamic centrifuge model test using a large dynamic centrifuge loading test apparatus belonging to the Public Works Research Institute. The centrifuge model test enabled us to conduct an experiment having the same stress state as the original case by imparting centrifuge acceleration to a geometrically miniaturized model.

Fig.3 illustrates the description of the experiment model, and Picture 1 shows the model of the pier foundation of Case 3-1. We used a 1/70-scale model and conducted the experiment in a 70G centrifuge field. We used silica sand obtained from Toyoura Keiseki Kogyo for the model ground, and constructed model ground having the same composition as described in Fig.3 inside the shear earth tank.

We set the relative density so that the rate of shear force R_{L120} where axial strain amplitude DA is 5% after 20 repeat counts equals the triaxial strength R_L estimated by the N value of the ground for the experiment. We constructed the saturated sand layer in which Dr=90% by means of compaction, and other sand layers using the air falling method, and used a metrose water solution, which has 70 times the viscosity of water, to create the saturated sand. We used aluminum pipes with a 1.5 mm wall thickness and an outside diameter of 16 mm for the model piles. The edge of the model pile was set deep in the supporting layer, and the pile head was connected to the footing by means of rigid joins.

The footing was set deep in the dry sand layer, and we placed the bridge pier model, which has a rigidity equivalent to the yield rigidity, and a spindle that weighs as much as the upper structure, on the footing. The sheet pile is equivalent to Type III, and we used 0.8 mm thick aluminum plates. In Cases 3-1 and 3-2, we bolted sheet piles on all sides of the footing. In Case 3-3, however, we installed sheet piles 15 mm away from the circumference of the footing. The sensor arrangement is as shown in Fig.2 and 3.

We assumed Level 2 seismic motion (Type II) for the input waveform to the vibration table, and used the waveform in Fig.4, which is seven-tenths of estimated bedrock outcrop motion at JMA Kobe in Kobe Earthquake.

All the following values were converted to those for the original scale.

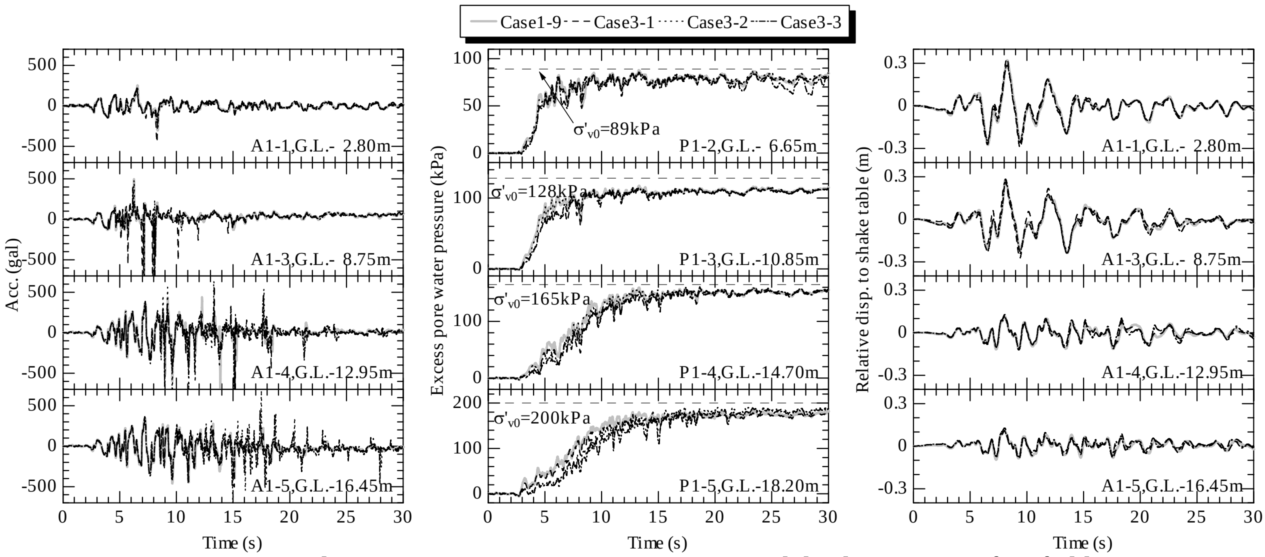


Fig.5. Accelerations, excess pore water pressures and displacements at free field

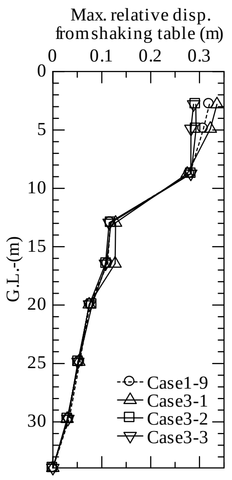


Fig.6. Maximum displacement profiles at free field

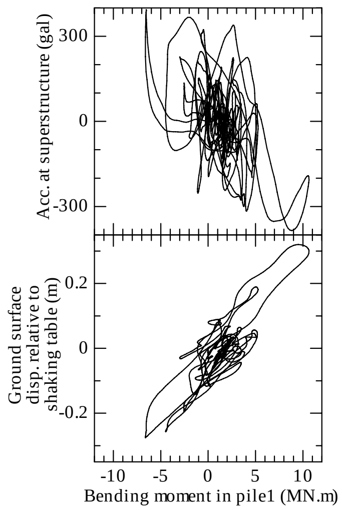


Fig.7. Hysteresis curves between bending moment in pile1 and acceleration at superstructure, ground surface displacement

4. RESPONSE OF FREE FIELD GROUND AND EFFECT OF INERTIAL FORCE FROM SUPERSTRUCTURE AND GROUND DISPLACEMENT ON PILE FOUNDATION

To observe the responses of the free ground, we put the time history of its displacement relative to velocity, excess pore pressure, and vibration table in a position away from the bridge pier that was slightly affected by the structure in Fig.5. The depth distribution of the maximum displacement on the ground is shown in Fig.6. In this report, we transformed the measured acceleration waveforms using the Fourier transform and integrated them using a high-pass filter around 0.2 Hz in the frequency domain to get displacement waveforms.

Acceleration values A1-1 and A1-3 and excess pore pressure values P1-2 and P1-3 indicate that the Dr=60% saturated sand layer almost reached the initial effective overburden stress σ'_{v0} in about 9.3 seconds and the response of acceleration became smaller, informing us that the Dr=60% saturated sand layer was liquefied in about 9.3 seconds.

At the same time, we learned that liquefaction created a great deal of shear deformation between G.L.-8.75 m and G.L.-12.95 m because we could observe a great difference in the maximum displacement between them.

The Dr=85% saturated sand layer almost reached the initial effective overburden stress σ'_{v0} in about 13 seconds, as indicated by excess pore pressure values P1-4 and P1-5, but a spikelike waveform due to cyclic mobility could be observed after 13 seconds, as indicated by acceleration values A1-4 and A1-5. As shown in Fig.6, large ground deformation such as that caused by liquefaction did not occur deeper than G.L.-12.95 m, which means the rigidity of the soil did not decrease much

As for the difference in ground response, we could observe a small difference in displacement near ground level, but the ground response in each case was almost the same. Fig.7 shows the moments of bend of the pile head of untreated pile 1, the acceleration values of the upper structure, and the relative displacement of the vibration table and the ground.

This informed us that the influence of ground displacement against the pile foundation was dominant because when ground displacement reached the maximum value, the bending moment of the pile head reached nearly the maximum value, and because ground displacement showed higher linearity than the bending moment of the pile head and the upper structure.

From the observation results noted above, we conclude that the reinforcement method tried in this experiment is effective with regard to ground displacement.

5. EFFECT OF RETROFITTING USING SHEET PILES

5.1 Excess pore pressure inside sheet piles

To study the effect of inhibiting liquefaction of the ground inside the sheet piles, we put the free ground in the liquefied layer G.L.-6.65 m, excess hydraulic pressure values immediately below the footing P1-2 (outside the sheet piles) and P2-2 (inside the sheet piles) in Fig.8.

P2-2 in untreated Case 1-9 increased a little more slowly than P1-2, but caught up with it in about 7 seconds, indicating that they were liquefied at the same time (in about 9.3 seconds).

In the three treated cases, however, excess pore pressure increased faster in P1-2 than in P2-2, showing the effect of sheet piles in inhibiting liquefaction. However, we need to further examine the data to explain qualitative trends, because the rise of excess pore pressure was slower in Case 3-1 than in Case 3-2, despite the fact that the sheet piles are shorter in Case 3-1 than in Case 3-2.

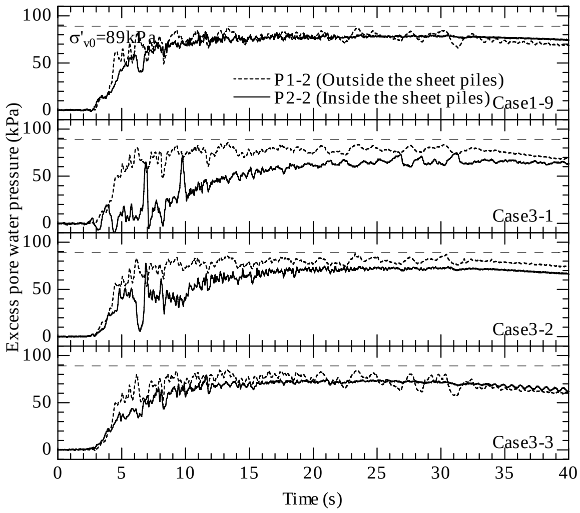


Fig.8. Excess pore water pressures in liquefied soil

5.2 Sectional force in piles

Fig.9 shows the distribution of the maximum bending moment and maximum shearing force of Pile 1. The dash line indicates the position of the bottom of the sheet piles in each case. We interpolated the distribution of bending strain against the depth direction measured each time using the three-dimensional spline function.

The shearing force of the untreated pile in Case 1-9 recorded a maximum bending moment of 11.1 MNm and a maximum shearing force of 1.89 MN in each head and at G.L.-11.55 m. As we explained in the previous chapter, a lot of shear deformation occurred between G.L.-875 m and 12.95 m. This indicates that the shear deformation of the ground caused the maximum shearing force at this depth.

We compared the maximum bending moment of the pile head in the three cases in which the sheet piles were installed with that of untreated Case 1-9, and found that the longer the sheet piles, the more the bending moment was reduced. However, in Case 3-3, where the sheet piles were not connected to the footing, the effectiveness of the sheet piles were reduced. The same trend was observed in the pile's shearing force.

As compared with Case 1-9, the shearing force in the three cases where the sheet piles were installed decreased around G.L.-11.55 m. This, it can be presumed, is because the sheet piles inhibited the shearing forced of the soil within the sheet piles and alleviated the action on the piles. As we mentioned in *5.4*, because Case 3-3 where the sheet piles were not connected to the footing had greater acceleration of the upper structure than Case 1-9 (Fig.12), its bending moment was reduced.

Therefore, the main factor that enables the sheet piles to reduce the pile's section force is not inertial force, but the alleviation of ground deformation.

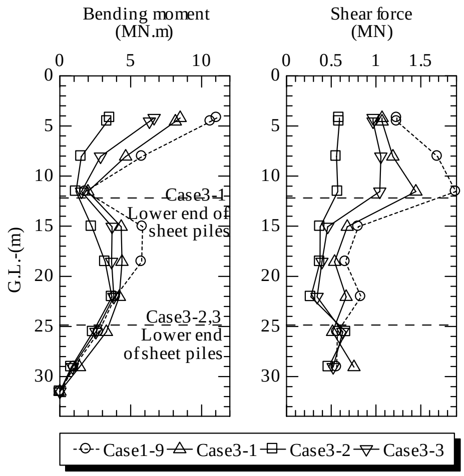


Fig.9. Profiles of maximum bending moment and shear force in pile

5.3 Horizontal displacement and rotation angle at pile cap

Fig.10 shows the time history of the relative displacement of the footing against the ground level. Although the footing of the three treated cases recorded a slightly larger lateral displacement than that of untreated Case 1-9, no significant difference was observed among the three cases where sheet piles were installed.

Fig.11 shows the time history of the lateral displacement of the upper structure position created by the rotation of the footing. We calculated the values by multiplying the height of the bridge pier by the rotation angle, which we calculated from the values measured by the vertical acceleration meter installed on both ends of the footing. Data were not recorded in Case 3-1 because of incorrect installation of the acceleration meter.

Case 3-2 where the footing is connected to the sheet pile had a higher rotation angle in the basement than untreated Case 1-9. In addition, the increase of rotation angle was alleviated in Case 3-3 where the footing was not connected to the sheet piles.

At the same time, as the acceleration of the upper structure (Fig.12) shown in (4) indicates, the waveforms of all cases were similar despite the agreement in phase. This leads us to conclude that the inherent vibration characteristics of the foundation did not change greatly.

As mentioned above, however, judging from the fact that the balance between sway and locking of the foundation changed, installing the sheet piles changed the deformation mode of the foundation.

5.4 Response of Superstructure

We examined the acceleration and displacement of the upper structure because reinforcement of the foundation would change the response of the upper structure. The inertial force of the upper structure affects the safety of bridge piers and supports, and relative displacement with the upper structure affects safety with regard to the bridge collapsing.

Fig.12 shows the time history of acceleration of the upper structure, and Fig.13 illustrates the time history of the relative displacement of the upper structure against the ground level. As compared with untreated Case 1-9, acceleration increases as the sheet pile become longer, and it did not increase in Case 3-3 where the sheet piles were not connected to the footing. The same trend can be observed in the lateral displacement of the upper structure.

As we mentioned in (3), the rocking of the foundation is far better with the installation of the sheet piles, and the rotation angle of the footing closely resembles the waveform difference of lateral displacement. This can be taken as indicating that the major factor that enables the installation of the sheet piles to markedly increase the response of the upper structure is the rocking of the foundation.

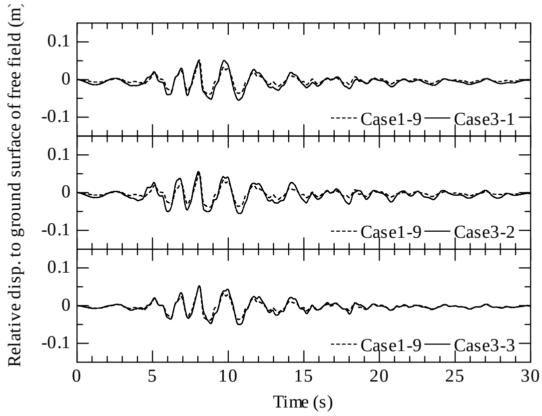


Fig.10. Horizontal displacements at pile cap

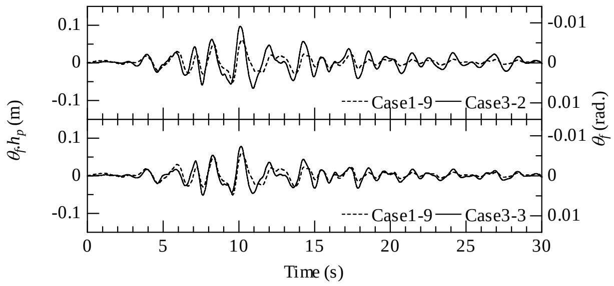


Fig.11. Rotations of pile cap (q_f : rotation angle of pile cap, h_p : height of pier)

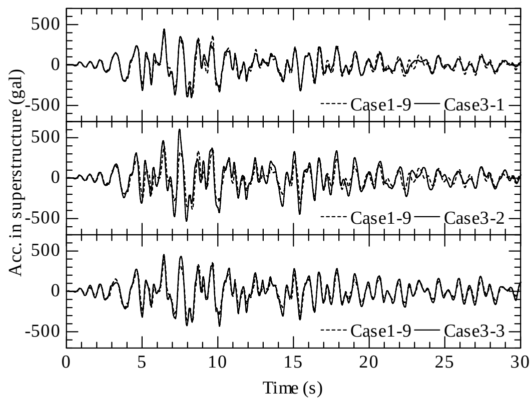


Fig.12. Accelerations in superstructure

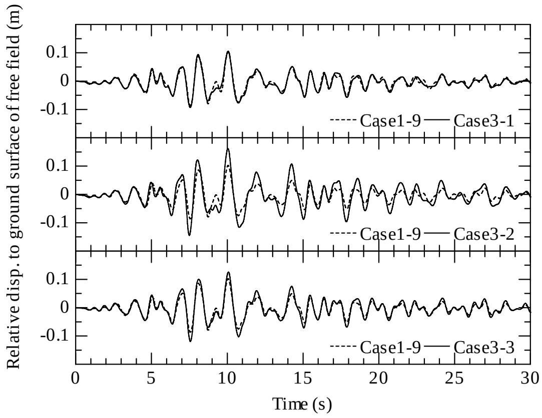


Fig.13. Displacements at superstructure

5.5 Effect of retrofitting using sheet piles

Fig.14 shows the ratios of the maximum response values of each case to the untreated case. The results indicate that although making the sheet piles longer contributes to alleviating the section force of the pile material, the acceleration and displacement of the upper structure increases and adversely affects the safety of the entire bridge and materials other than the foundations.

At the same time, if the connection between the sheet piles and the footing is released, the adverse effect on the upper structure is alleviated despite the fact that the effect to decrease the section force of the pile decreases. As we mentioned in (4), the reinforcement of the foundation by sheet piles increases the response of the upper structure because the installation of the sheet piles changes the deformation mode of the foundation and makes it possible for the rocking to increase.

The factor that enables reinforcement by installing sheet piles to make the locking of the foundation bigger can be assumed to be as follows. Fig.15 shows the conceptual diagram of the deformation of the bridge pier foundation that can be imaged from the structural characteristics. When inertial force and ground deformation are affective, the deformation mode of the bridge pier foundation will be as shown in Fig.15(a). Because the sheet piles and the footing are connected. and the steel sheets are set deep in a relatively hard layer with small deformation mode in Case 3-2, the large amount of ground deformation in the layer above the liquefied layer exceeds the deformation mode where the footing, steel sheets, and the inside soil combine in an integrated manner. (Fig.15(b))

In this way, Case 3-2 has a greater locking value of the foundation than Case 1-9. Because the sheet piles and the footing are not connected in Case 3-3, the vertical shearing force that the sheet piles affect on the foundation is transmitted to the soil inside the sheet piles, making the effect on the deformation in Case 3-3 not as great as that in Case 3-2.

In addition, as indicated in Fig.16, which shows the maximum displacement distribution, the distribution of Case 3-3 is more like the maximum ground displacement than that of Case 3-2. This indicates that the deformation of the sheet piles in Case 3-3 has a better sway mode than that of Case 3-2.

This is because the sheet piles between levee crown G.L.-2.1 m and around G.L.-8.75 m are liable to have local deformation due to a lack of connection between the sheet piles and the footing. This is why Case 3.3 has a lower value of ground locking of the foundation than Case 3.2, showing the deformation as shown in Fig.15(c).

As shown above, serious consideration needs to be given to bridge pier foundations and the support realized by reinforcement when using sheet piles for reinforcement.

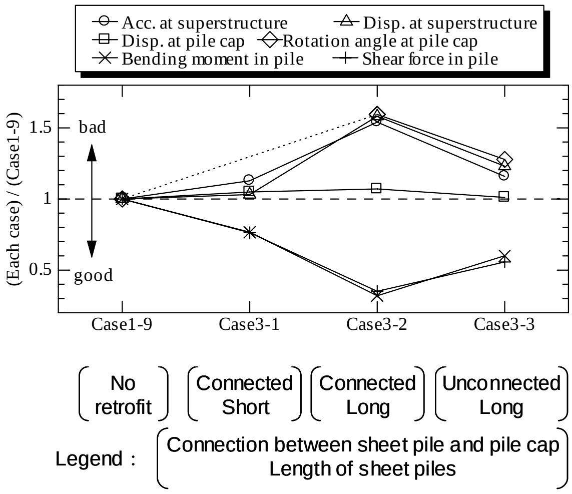
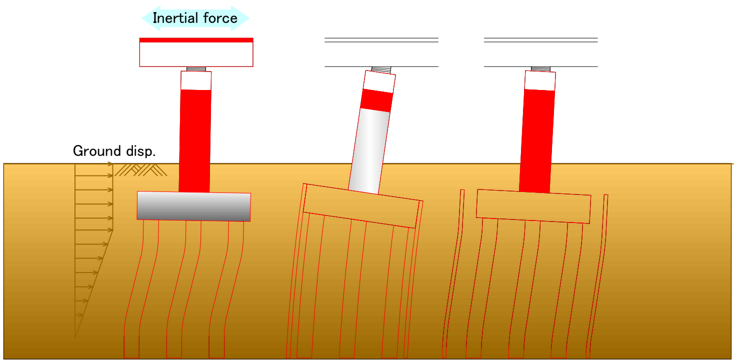


Fig.14. Effects of retrofitting using sheet piles



(a) Case1-9 (b) Case3-2 (c) Case3-3

Fig.15. Vibration modes of foundation

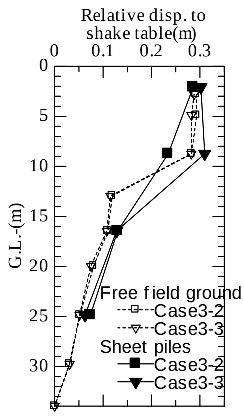


Fig.16. Profiles of maximum displacement of sheet pile

6. CONCLUSION

In this research, we examined by means of experiments the seismic-resistant effect of sheet piles on a bridge pier foundation inside liquefied ground and obtained the following conclusions:

(1) In this experiment, ground displacement was more influential than the inertia force in the upper structure against the section force of the pile.

(2) Sheet piles can inhibit liquefaction of the ground inside the piles to a certain degree.

(3) Seismic-resistant increases the section force of the pile, and the longer the sheet piles, the bigger the effect. On the other hand, the acceleration and lateral displacement of the upper structure grows bigger and adversely affects the safety of the bridge foundations and may cause the bridge to collapse. If the connection between the sheet piles and the footing is released, the effect to decrease the pile becomes weaker and the increase in the response of the upper structure is alleviated.

(4) The major factor that enables seismic resistance to decrease a pile's section force is believed to be that the sheet piles inhibit shear deformation inside the sheet piles and the effect on the pile is alleviated.

(5) We confirmed that the response of the upper structure increases after reinforcement because locking of the foundation increases. The factor that enables the locking of the foundation to increase is that the sheet piles and pile foundation combined affect rigidly in an integrated manner.

In the future, we need to concentrate in detail on the reinforcement effect of sheet piles by setting up models and parameters to conduct analytical reviews, and by changing the specifications of the sheet piles.

REFERENCES

1) Japan Society of Civil Engineers, the Earthquake Engineering Committee: Liquefaction by Level 2 Seismic Motion, June 2003 (in Japanese)

2) Yukitake Shioi, Nobuhiro Segawa, Koichi Inagawa, and Koji Kato: Developing seismic-resistant method in combination with improvement of the ground for structures with pile foundation (In-Cap method), Collected papers of the 7th symposium on seismic-resistant design of structures including bridge piers based on retained proof strength in the time of earthquake, held by Japan Society of Civil Engineers, pp. 307-314, 2004 (in Japanese)

3) Satoshi Fujikawa, Kiyoshi Fukutake, Akira Otsuki, Yoshiaki Yoshimi, and Koichi Nakamura: Three-dimensional analysis of the prevention of liquefaction of the pile-ground system using a continuous underground wall, the 9th Symposium of Japan Association for Earthquake Engineering, pp. 991-996, 1994 (in Japanese)

4) Japan Road Association: Example of design calculation for the case that has ground unstable in a level 6 earthquake, Materials on seismic-resistant design of road bridge, March 1997 (in Japanese)

5) Seismic-Resistant Technology Research Center, Public Works Research Institute, Ministry of Land, Infrastructure and Transport, Experimental Research of Seismic-Resistant Design Method of underground structure in consideration of a large-scale earthquake, Summary Report of the Results of Experimental Research by Vibration Research Section, No. 22, pp. 19-20, March 2001 (in Japanese)