CENTRIFUGE TESTS ON PILE FOUNDATION-STRUCTURE SYSTEMS AFFECTED BY LIQUEFACTION-INDUCED SOIL FLOW AFTER QUAY WALL FAILURE

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ABSTRACT :

The paper investigates experimentally the behavior of a structure-footing-four piles system under the action of seismic shaking causing liquefaction of a critical soil layer and subsequent soil flow towards a laterally displacing quay-wall. A series of innovative centrifuge tests explore in parametric fashion the role of this pile foundation in the response of the system. The response is recorded in 38 channels providing time histories of acceleration, displacement, excess pore water pressure, pile axial and bending strains, and earth pressure. The results provide significant quantitative information and qualitative insight on the behavior of this realistically complex soil-foundation-structure system.

KEYWORDS: Centrifuge test, Soil liquefaction, Liquefaction-induced soil flow, Quay wall, Pile foundation

1. INTRODUCTION

Soil liquefaction may cause significant damage to structures, especially when lateral soil flow takes place. Such flow (which often takes the form of "lateral spreading") was triggered along river banks and sea coasts behind quay-walls in Kobe during the 1995 Great Hanshin Earthquake. (Tazoh, et al., 2002, 2001)

Numerous studies have been published in the last decade on lateral flow failures induced by soil liquefaction. Numerical and experimental studies focused on the damage mechanism of structures and on the external forces induced by the soil flow on deep foundations. Many important structures exist along and near waterfronts in Japan, and their safety in the next major earthquake must be secured. Thus, the study of liquefaction-induced soil flow, together with remedial measures to mitigate the damage, is a crucial earthquake engineering issue. (Tazoh, et al., 1996)

In this study, a series of centrifuge tests was conducted to shed light on the seismic performance of pile-foundation-structure systems located behind quay-walls, arising from the large displacement or collapse of these walls and the ensuing soil flow. Furthermore, remediation using batter piles is proposed, and the effectiveness of this measure is examined parametrically.

2. CENTRIFUGE TESTING

To investigate quantitatively the effect of quay-wall collapse on the seismic performance of

pile-foundation-structure systems, we compare two cases: one in which the quay-wall collapses and triggers flow of the soil, and one in which the wall remains standing displacing almost elastically. We also investigate qualitatively the effectiveness of remedial measures by comparing the behavior of structures with and without remediation.
Each test for each model is carried out under nearly identical conditions with respect to input motions, soil liquefaction, and quay-wall collapse. Note, however, that it is impossible to achieve complete similarity between tests, due to the difficulty of reproducing failure events of soil and quay-walls.
Therefore, some innovative ideas must be adopted in the centrifuge testing. In this study, a partition is placed at the center of the soil container, and two quay-walls with two models of the pile-foundation-structure behind each quay-wall are installed parallel to the partition. One quay-wall is fixed to the base of the soil container and the other is left "floating" (unattached to the base). The difference between the responses of the two pile-foundation-structures represents the effect of the amount of movement of the quay-wall on the seismic performance of the system. In these tests the loading is of a kinematic nature: quay-wall collapse induces soil flow failure, thereby loading the pile-foundation-structure system.
Batter piles are proposed as a remedial measure against damage caused by liquefaction-induced soil flow. Batter piles can be used with little or no additional expense, no special design, and hardly any difficulty in construction. In these centrifuge tests, a partition is placed at the center of a soil container with two models in each side: a vertical-pile-foundation-structure and a batter-pile-foundation-structure. These are installed parallel to the partition behind a quay-wall with free tip-end, which will be collapsed in the tests. All tests were conducted at centrifugal acceleration of 30 g on a 1/30-scale model.

3. EFFECT OF QUAY-WALL COLLAPSE ON THE SEISMIC PERFORMANCE OF THE PILE FOUNDATION

The experimental model used in the tests is shown in Figure 1. Both quay-walls consist of sheet piles, either fixed to the base of the soil container or terminated in the stiff base layer, i.e. unattached to the base. A laminar box is used as a soil container to allow shear deformation of the deposit as in the free field.
The soil in the container is divided into two parts: "A-side", where the quay-wall is fixed to the base, and "B-side" where the quay-wall is unattached. Three tests are carried out by changing the distance from the quay-wall to the structure. Table 1 shows the distances of these cases.
The soil deposit consists of four soil layers: the first, third, and fourth soil layers are non-liquefiable; the second is liquefiable. The thickness and relative density of each soil layer are shown in Table 2.
Thirty-eight monitoring channels were installed, with the sensors comprising accelerometers, pore water pressure transducers, strain gauges, non-contact displacement meters, and earth pressure cells. Moreover, numerous colored beads were embedded in the soil layers to visually identify the soil deformation at the final stage.
Photograph 1 shows the condition after the test of Case 1. The recorded excess pore water pressure in the liquefied soil layer at the almost free field sensor PP2 (GL-90mm, prototype: 2.7m), is shown in Figure 2. The two time histories recorded in A-side and B-side, showing the accumulation and dissipation of excess pore water pressure, are very similar. Thus, there is no difference between the two sides with respect to the liquefaction occurrence and evolution. Liquefaction started at around 4sec at the depths of GL-90mm (prototype -2.7m). The peak acceleration value of the input motion (Case 2) is 258gal and the significant duration is about 8 seconds. The measurements were continued for sufficient time after the end of excitation, to fully capture the evolution of the liquefied-induced soil flow. Note in Figure 2 that the time axis from 15 to 1200sec is at 1/8 of the scale from 0 to 15sec.
The relative displacements between quay-wall and footing for A-side and B-side of Case 2 are plotted in Figure 3. Furthermore, for comparing among the three cases, the relative horizontal displacements of the footings [Disp(BF) – Disp(AF)] are divided by the relative horizontal displacements of the quay-walls [Disp(BY) – Disp(AY)] and the influence factor α is defined as follows:

$$\alpha = \frac{Disp(BF) - Disp(AF)}{Disp(BY) - Disp(AY)} = \frac{relative\ horizontal\ displacement\ of\ footing}{relative\ horizaontal\ displacement\ of\ quaywall}$$

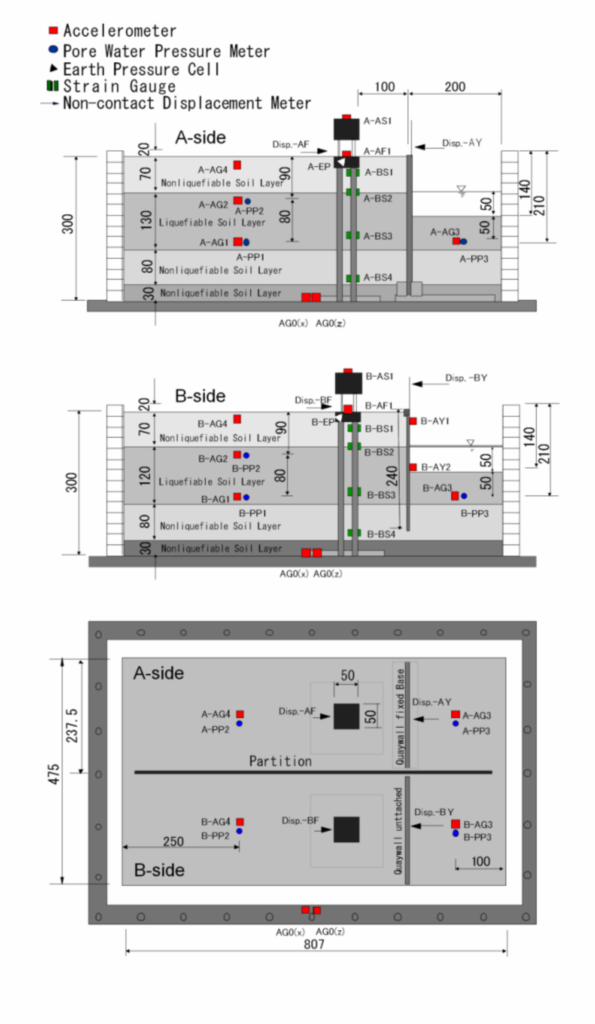

Figure 1. Longitudinal sections and plan of the 1/30-scale centrifuge model of Case 2 (scale unit: mm, for the prototype dimensions: multiply by 30)

Table 1. Three cases of the tests

Case	Distance from the quay-wall to the pile-foundation-structure
Case 1	200mm (prototype: 6.0m)
Case 2	100mm (prototype: 3.0m)
Case 3	50mm (prototype: 1.5m)

The influence factor α represents the horizontal displacement of the footing to unit horizontal displacement of the collapsed quay-wall. It is plotted in Figure 4. In this figure, the time histories from 0 to 4sec of Cases 1 and 2, and also from 0 to 400sec of Case 3, have been omitted, because in these intervals the factor α becomes infinity (the denominators vanish).

It can be clearly seen that the influence factor α is largest in Case 3 (the distance from the quay-wall to the footing L=50mm, prototype L=1.5m), followed by Case 2 (L=100mm, prototype L=3m) and Case 1 (L=200mm, prototype L=6m). This implies that the shorter the distance from the quay-wall to the footing, the stronger the effect of the collapse of the quay-wall.

The influence factor α, at the final stage of the 1200sec, is summarized in Table 3. The physical meaning of the influence factor α is that if the quay-wall displaces 1m forward, the pile-foundation located at the distance 1.5m from the quay-wall will move 0.17m forward (residual displacement).

Table 2. Soil profiles of the soil layers

Soil layer	Thickness	Soil profile	Liquefiable
1st soil layer	70mm (2.1m)	Silica sand No. 8, Dr=50%	Non- liquefiable (above water table)
2nd soil layer	120mm (3.6m)	Silica sand No. 8, Dr=50%	Liquefiable
3rd soil layer	80mm (2.4m)	Toyoura sand Dr=90%	Non- liquefiable
4th soil layer	30mm (0.9m)	Silica sand No. 3	Non- liquefiable

( ): prototype dimensions

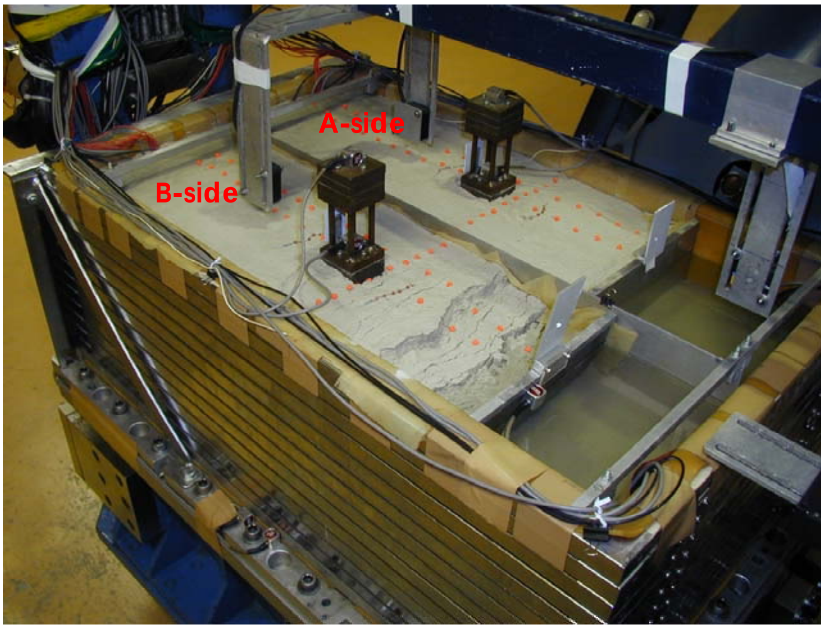

Photo 1. Condition after the test (Case 1)

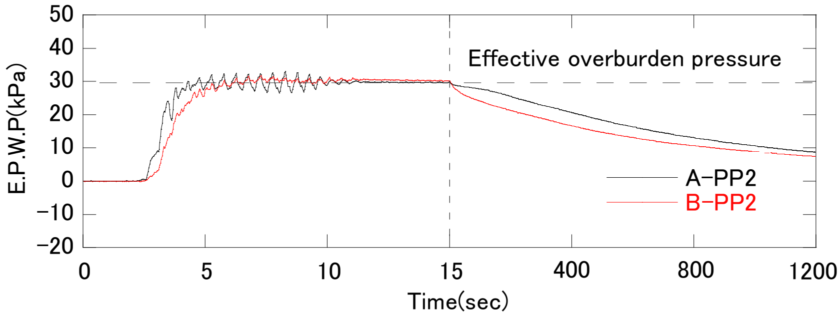

Figure 2. Excess pore water pressure records in the second soil layer (Case 2)

Table 3. Influence factor α at the final stage of 1200sec

Case	Influence factor α
Case 1 (L=200mm, prototype=6m)	0.07
Case 2 (L=100mm, prototype=3m)	0.09
Case 3 (L=50mm, prototype=1.5m)	0.17

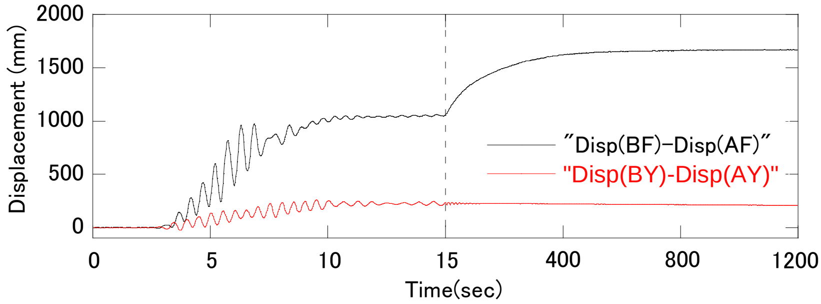

Figure 3. Relative horizontal displacements of quay-walls and footings in A-side and B-side (Case 2)

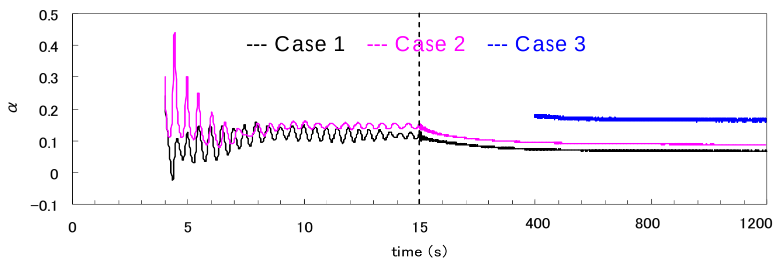

Figure 4. Influence factor α of Case 1 to 3. Effect on the horizontal displacement of the footing to unit horizontal displacement of the collapsed quay-wall

Figure 5 compares the time histories of the bending strains of the piles for Case 2. In addition, the differences between the strains at B-side and A-side at 1200sec of the final stage are shown in Table 4. The influence factor β, which represents the effect on pile strains of the collapse of the quay-wall (at t = 1200sec), is calculated as shown in Table 4. Incidentally, the influence factor β (absolute value) is obtained as follows:

$$\beta = \mathrm{abs}\left|\frac{pile\ strain\ (B\ side) - pile\ strain\ (A\ side)}{pile\ strain\ (A\ side)}\right|$$

Note that strains in the A-side piles are quite small compared with those in the B-side piles. It therefore appears that the influence of the displacement of the quay-wall on pile strains is extremely large. The influence factor β increases clearly in inverse proportion to the distance from the quay-wall to the footing.
Remedial measures against liquefaction-induced soil flow usually focus either on reinforcement of the pile-foundation-structures themselves, using additional piles, or soil improvement such as using vibro-floatation and other techniques. However, it is important to also strengthen the quay-walls to prevent their collapse during strong shaking, in addition to reinforcing the structures.

4. EFFECT OF THE REMEDIAL MEASURE AGAINST LIQUEFACTION-INDUCED SOIL FLOW

Several remedial techniques against liquefaction-induced soil flow have been proposed in the past. In this study, we proposed batter piles as a remedial measure, and examined its effectiveness by means of centrifuge tests.
Four tests are carried out as shown in Table 5, by changing the distance from the quay-wall to the pile-foundation-structures and the pile inclination angle.
The model for Case 32 is shown in Figure 6. A partition is placed at the center of the soil container, and a quay-wall with two models of the pile-foundation-structure behind the quay-wall is installed parallel to the partition. The tip-end of the quay-wall remains unattached to the base of the soil container. The soil container is divided into two parts: A-side and B-side where the vertical pile foundation and the batter pile foundation are installed, respectively.

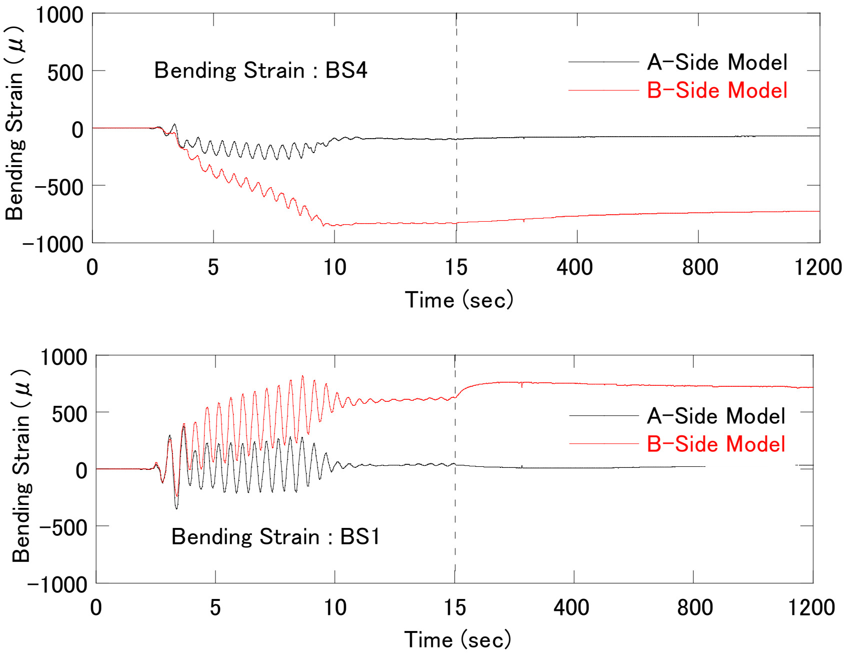

Figure 5. Comparison between the bending strains of the pile-heads and pile-tips at A-side and B-side (Case 2)

Table 4. Influence factor β (Effect on pile strains of the collapse of the quay-wall at 1200sec) (Case 2)

Case 2		B-side	A-side	B-side –A-side	β_{axial}
Axial Strain (μ)	BS1	-77.4	-20.7	-56.7	2.7
	BS4	-99.2	-16.8	-82.4	4.9
Case 2		B-side	A-side	B-side – A-side	$\beta_{bending}$
Bending Strain (μ)	BS1	716.0	35.9	680.1	18.9
	BS4	-724.0	-70.7	-653.3	9.2

$\beta_{bending}$ at Pile-head: BS1 of Case 1, 2, 3

	Case 1	Case 2	Case 3
$\beta_{bending}$ at Pile-head: BS1	5.7	18.9	46.2

Table 5. Four tests of the remedial measure with batter piles

Case	Distance from quay-wall to pile-foundation	Inclination angle of batter piles (degree)
Case 31	200mm (prototype: 6m)	10
Case 32	100mm (prototype: 3m)	10
Case 33	50mm (prototype: 1.5m)	10
Case 34	100mm (prototype: 3m)	5

Figure 7 shows the time histories of the horizontal displacements of the quay-wall (Disp-Y), and the footings in A-side (Disp-AF) and B-side (Disp-BF). The effectiveness of the batter piles in reducing the horizontal displacements of the foundation is clear.

Figure 8 compares the time histories of the axial bending strains in the vertical and batter piles for Case 32. The effectiveness of the batter piles is again quite clear.

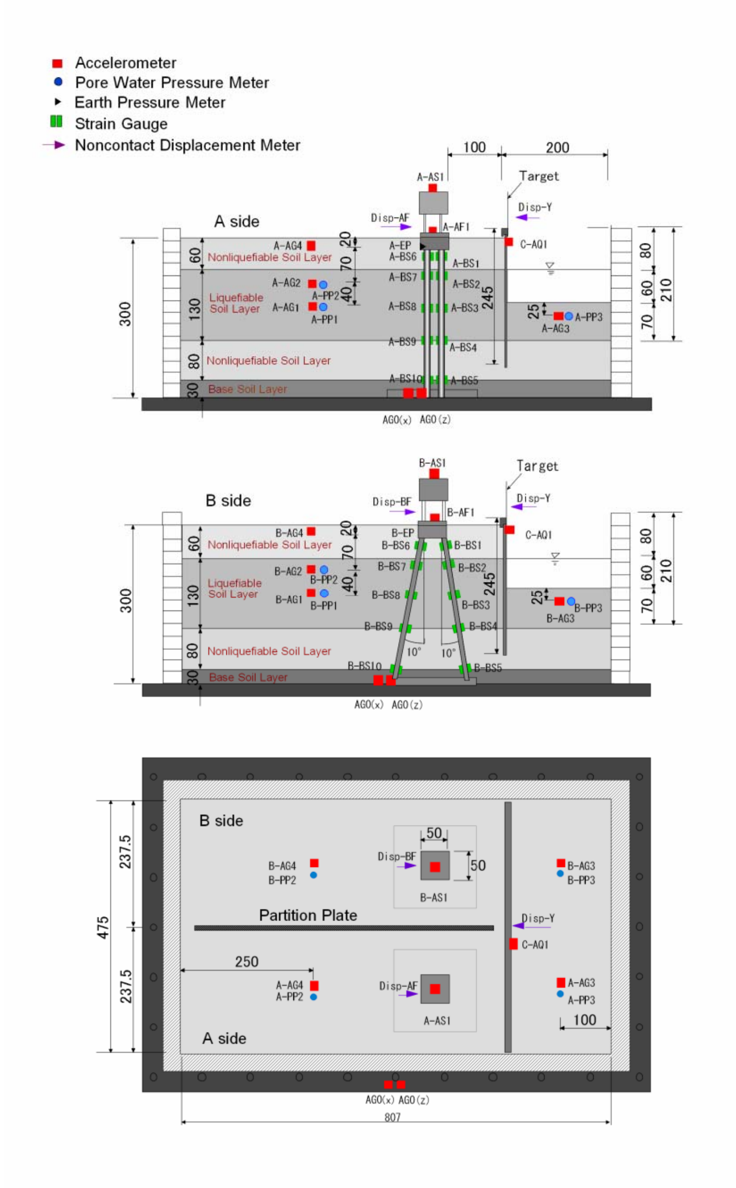

Figure 6. Longitudinal sections and plan of the 1/30-scale centrifuge model of Case 32 (scale unit: mm)

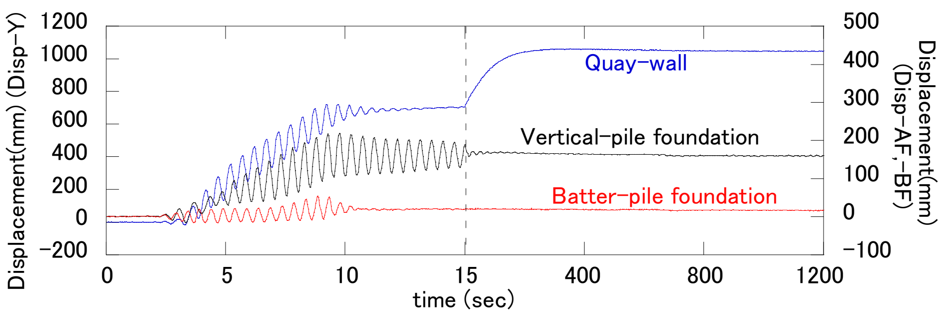

Figure 7. Time histories of the horizontal displacements of the quay-wall (Disp-Y), and the footings of the vertical piles in A-side (Disp-AF) and of batter piles in B-side (Disp-BF)

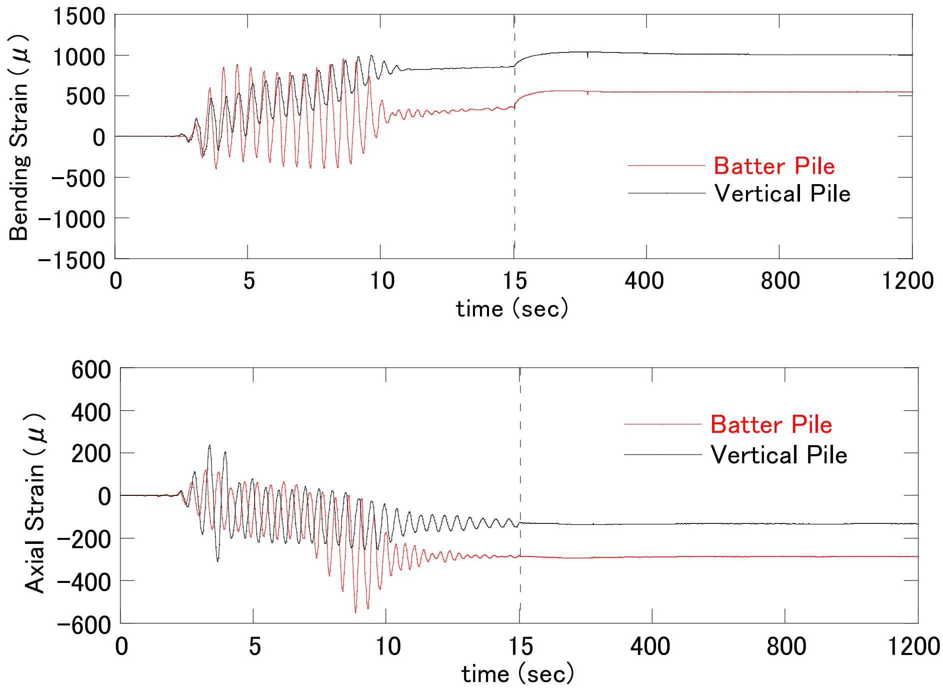

Figure 8. Comparisons between the time histories of the axial and bending strains of the vertical and batter piles at the pile-head: BS1 (Case 32)

5. CONCLUSIONS

The main conclusions of the study are:

1) The shorter the distance from the quay-wall, the stronger the effect of the collapse of the quay-wall on the pile foundation.
2) Pile distress is affected by the lateral displacement and failure of the quay-wall. To mitigate severe damage to pile-foundation-structures constructed in the vicinity of quay-walls, one must ensure that quay-wall displacements are kept to a minimum, even after the soil has liquefied.
3) Batter piles are clearly effective in restricting horizontal displacement of the foundation in a liquefied soil flow environment. The disadvantages of such piles are the larger axial forces in the piles.
4) It is very important to strengthen quay-walls to prevent large displacements in soil, in addition to other reinforcement measures of the structures themselves. In any case, batter piles deserve serious consideration as a means of defending against large soil displacements.

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