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PERFORMANCE EVALUATION OF THE NEWLY-DESIGNED ASEISMATIC GRAVITY QUAY WALLS BY SHAKING TABLE TESTS

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SUMMARY

Shaking table tests and pseudo-static analyses were performed on the newly-developed aseismatic quay walls, namely the Hybrid caisson quay wall and the Piled caisson quay wall, to ascertain the seismic stability of the structures. The L-shaped Hybrid caisson quay wall, constructed by extending the bottom plate of gravity quay wall through the backfill soil, is expected to give economical benefits because this wall has a reduced cross sectional area but constant aseismatic efficiency. The Piled caisson quay wall, designed to penetrate through the foundation ground of low bearing capacity, is expected to save extra labors needed to improve poor ground. The test results showed that although the Hybrid caisson quay wall is a good earthquake resistant structure, the increase in the protruding length of the bottom plate did not proportionally increase the aseismatic capacity of the wall. In the Piled caisson quay wall, the caisson should be penetrated to a considerable depth for the wall to become aseismatically effective.

INTRODUCTION

Many caisson-type quay walls in Kobe were destroyed by the 1995 Hyogoken-Nambu Earthquake. Since then, various aseismatic gravity quay walls such as the Hybrid caisson quay wall and the Piled caisson quay wall were introduced (Shiozaki et al. [1]; Goda et al. [2]; Kim [3]). The Hybrid caisson quay wall is composed of slabs made of steel-concrete composite, and bulkheads made of stiffened steel plates. The steel members are used to extend the footing, which are easy to install in deep water and at poor subsoil conditions and are effective in improving the seismic stability of the wall. The Piled caisson quay wall is constructed by attaching an upturned bucket to the bottom of a typical caisson quay wall. Using such piled caisson wall brings many benefits, for example, material savings and short installation time. However, the

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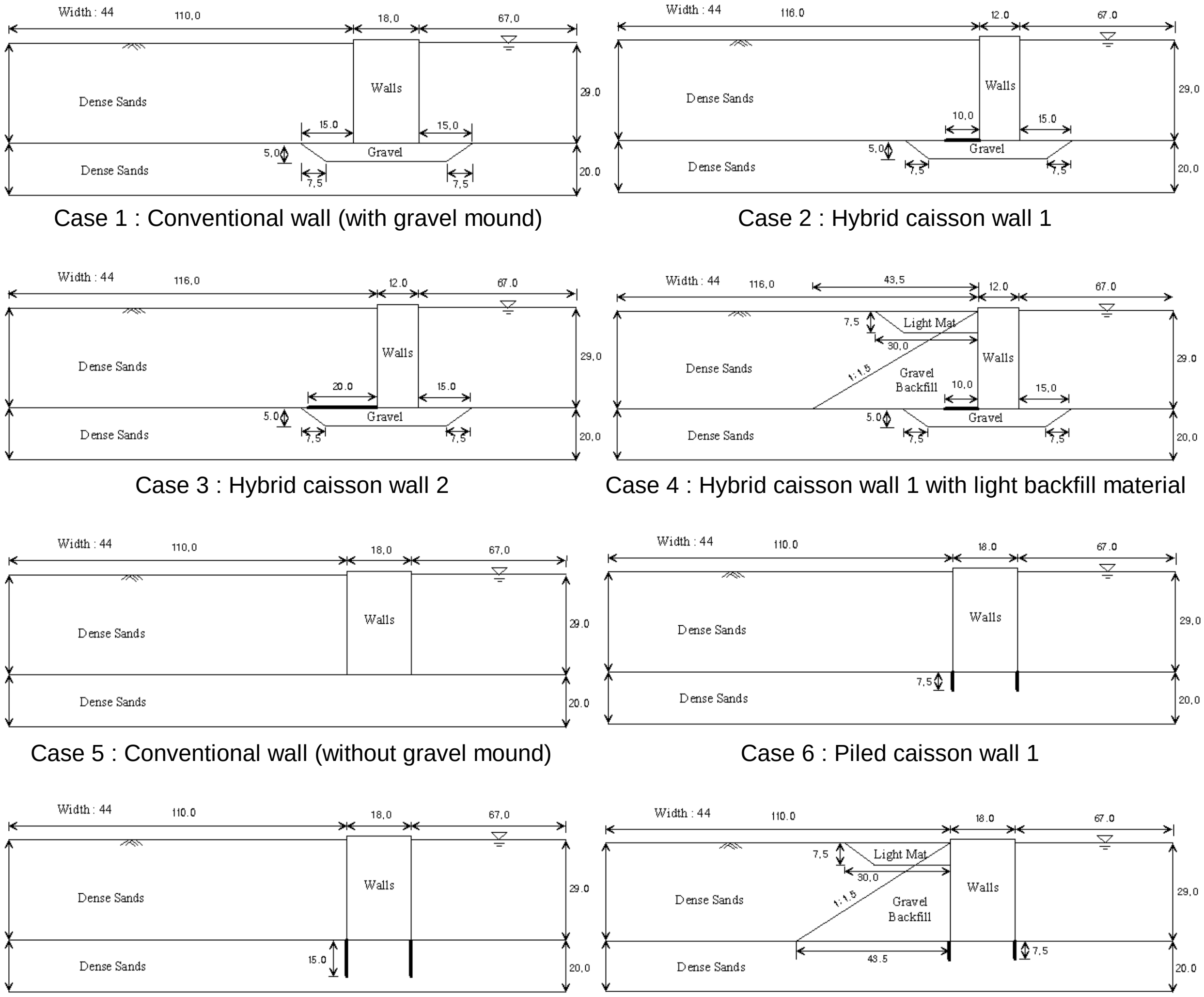
seismic performances of these walls, when the dimensions of the protruding bottom plate of the Hybrid caisson quay wall and the penetration depth of the foundation pile are varied, respectively, have not been verified yet. To this end, a series of shaking table tests and pseudo static analysis were performed in this study to ascertain the seismic stability of the structures with the shapes of these walls. In addition, the influence of backfill soils on the seismic behavior of quay wall was verified by shaking table tests on these walls, after a part of the backfill soil was replaced by light materials and gravel (Kim [3]).

TESTING PROCEDURES

Eight different testing models of a quay wall as shown in Fig. 1 were used. They were classified into three different types, conventional gravity quay wall (Cases 1 and 5), Hybrid caisson quay wall (Cases 2, 3 and 4) and Piled caisson quay wall (Cases 6, 7 and 8). The dimensions of the conventional wall in Cases 1 and 5 were 18cm wide, 42cm long and 30cm high. The difference between Case 1 and Case 5 is the installation of a gravel mound at the bottom of the wall. The quay wall in Case 2 was 12cm wide with a 10cm-long extended footing base as shown in Fig. 1. The wall in Case 2 was designed to have an identical sliding safety factor by pseudo static analysis with that of the conventional wall in Case 1 as shown in Table 1. The extended footing base of the wall in Case 3 was two times as long as that of wall in Case 2. For Piled caisson quay walls, two unturned buckets having a diameter of 18cm were attached to the bottom of the conventional gravity quay wall (Cases 6, 7 and 8). Since the foundation pile (i.e., upturned bucket) penetrated through the ground, a gravel mound was not installed. For the Cases 6 and 7, the penetration depth of the foundation pile was 7.5cm and 15.0cm, respectively, as shown in Fig. 1. For the Cases 4 and 8, a part of backfill soils was replaced by light materials and gravel.

The wall and the foundation base were made of steel. The unit weight of the wall was 2.4t/m^3. The average size of the sands (D_{50}) was 0.32mm and C_u was 1.53. The maximum and the minimum dry unit weights were 1.66 and 1.40t/m^3, respectively. Uniform gravels, whose size varies between 3mm and 5mm, were used for gravel backfill and mound. The saturated unit weight of the light material in Cases 4 and 8 was 1.25t/m^3, and it had a uniform particle size of about 1cm. Since the objective of these tests was to analyze the seismic performance of a quay wall, the subsoil ground and the backfill soils were made dense to exclude the effect of liquefaction in the backfill and excessive deformation in subsoil ground for all models. The subsoil ground was compacted to have the relative density about 85% by using a sinusoidal wave lasting 60 seconds at a frequency 20Hz and maximum acceleration 0.4g. The backfill soils were made to have the relative density about 70%, which was achieved by pouring the saturated sand from a constant height.

The dynamic responses of the quay wall and backfill were measured with 9 accelerometers, 3 displacement transducers, 3 load cells and 8 piezometers. The dimensions of the shaking table were 2m by 2m square. The maximum specific weight and maximum acceleration of the table were 5 ton and 1g, respectively. A rigid soil container was made of plexi-glass, whose dimensions were 195cm long, 44cm wide and 60cm high. The soil container was shaken horizontally by using a sinusoidal wave at a frequency of 5Hz for 5 seconds. The amplitude of the maximum base acceleration was increased step by step from the initial value of 0.1g to the final value of 0.3g at an increment of 0.1g.



Case 1 : Conventional wall (with gravel mound)

Case 2 : Hybrid caisson wall 1

Case 3 : Hybrid caisson wall 2

Case 4 : Hybrid caisson wall 1 with light backfill material

Case 5 : Conventional wall (without gravel mound)

Case 6 : Piled caisson wall 1

Case 7 : Piled caisson wall 2

Case 8 : Piled caisson wall 2 with light backfill material

Fig. 1 Cross-sections of test models

Table 1. Sliding safety factors of Hybrid caisson quay wall with various width of wall (B) and length of extended footing base (L) (by pseudo static analysis (k_h=0.1g))

Type	B (cm)	L (cm)	FS of sliding
Case 1	18.0	0	1.07
Case 2	12.0	10.0	1.06
Case 3	12.0	20.0	1.21

TEST RESULTS AND DISCUSSION

Case 1 to 4 (Hybrid caisson quay wall)

Response of excess pore pressure in backfill soils

Fig. 2 shows the contours of the excess pore pressure ratios (=peak excess pore pressure / initial vertical effective stress) when the excess pore pressures in the backfill soils reach the maximum value. As shown in Fig. 2, the excess pore pressure ratios tend to decrease as the backfill soils approaches the wall and as it goes deeper toward the bottom, when the excess pore pressures near the walls is released faster due to the outward rotation of the top of the walls and when those near the bottom dissipate rapidly due to the high permeability of the gravel mound at the bottom of the wall. The maximum value of the excess pore pressure in the case of a conventional wall (Case 1) reached 0.70 on the surface near the wall at 0.2g, which was the maximum value among those of the other cases.

In Case 4, the maximum excess pore pressure ratio, which was generated in the gravel backfill near the wall, was 0.12 at 0.2g. The result showed that if a part of the backfill soil is replaced with light materials and gravel, the excess pore pressure dissipates rapidly. In all tests, the maximum excess pore pressure ratio did not reach 1.0 and liquefaction did not occur.

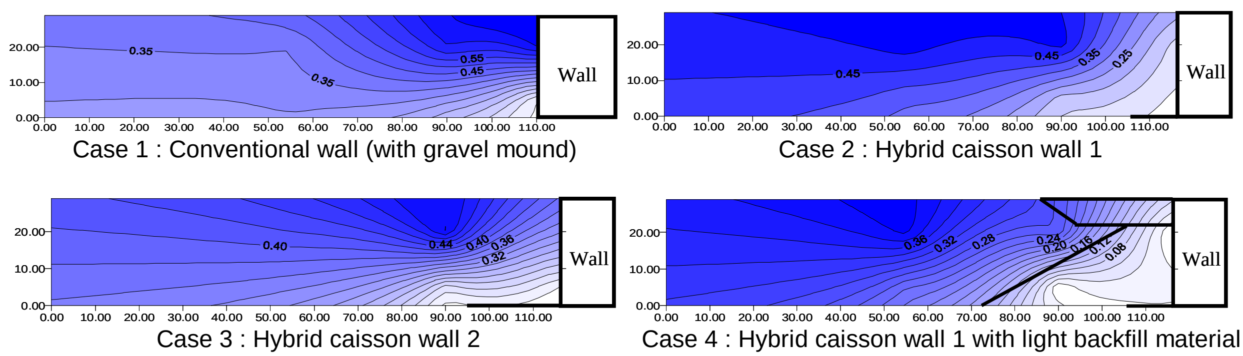
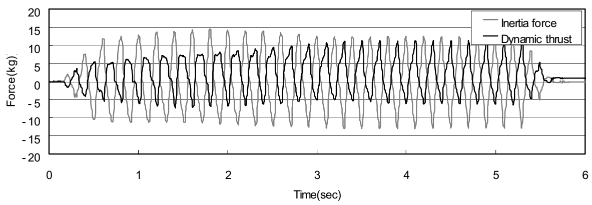


Fig. 2 Contours of the excess pore pressure ratio (Hybrid caisson, 0.2g)

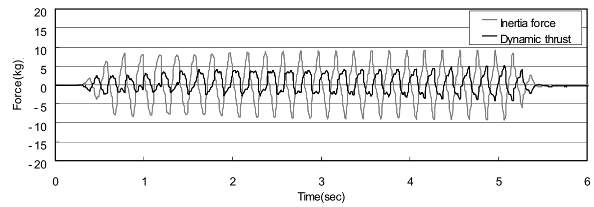
Dynamic thrust acting on wall

Fig 3 shows the time history of the dynamic thrust acting on the wall and the inertia force of the wall at 0.2g. The dynamic thrust is the force which is generated from the interaction among the wall, the soil in the backfill and the pore water during vibration. The dynamic thrust was calculated from the sum total of 3 load cells located in the backfill of the quay wall. In our tests, the dynamic thrust was measured after setting up to the initial stage (i.e., the point indicated "0" before shaking), so this value did not contain the static force. A positive dynamic thrust means that the value of force acting to the wall increases more than that in the initial static state.

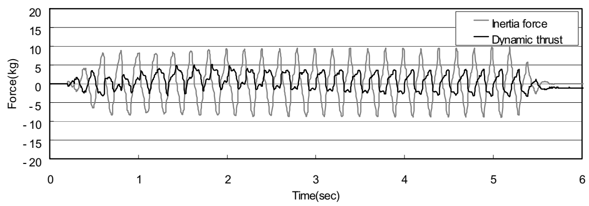
As shown in Fig 3, the dynamic thrust was 180˚ out of phase with the inertia force at 0.2g (before failure). In other words, when the inertia force increased, the dynamic thrust decreased and vice versa. This phenomenon is contrary to the design assumption that inertia force and dynamic thrust act always in the same direction. In the case of the Hybrid caisson quay walls (Cases 2 ~ 4), the dynamic thrust has a much smaller value than that in the case of the conventional wall (Case 1). These results may imply that the backfill soils above the extended footing base move together with the Hybrid caisson quay wall as if it is attached to the wall.



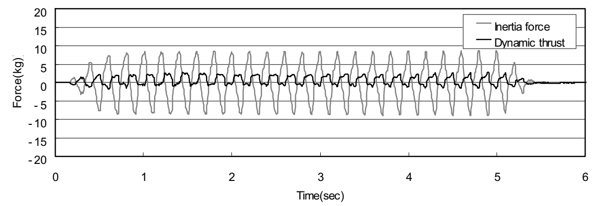
Case 1 : Conventional wall (with gravel mound)



Case 2 : Hybrid caisson wall 1



Case 3 : Hybrid caisson wall 2



Case 4 : Hybrid caisson wall 1 with light backfill material

Fig. 3 Time history of inertia force of wall and dynamic thrust acting on the wall (Hybrid caisson, at 0.2g)

Behavior of Hybrid caisson quay wall

Table 2 shows the test results of the Hybrid caisson quay wall. As mentioned earlier, the conventional wall (Case 1) and the Hybrid caisson quay wall with a 10cm-long extended footing base and with a 6cm shorter wall body (Case 2) were designed to have an identical static sliding safety factor(refer. to Table 1). Nevertheless the horizontal displacement in Case 2 decreased by about 64% at 0.2g and 49% at 0.3g, compared with those in Case 1, decreases which prove that the Hybrid caisson quay wall is a good earthquake resistant structure.

However, when the length of the extended footing base was doubled (Case 3), the horizontal displacement of the wall was slightly increased contrary to our expectation as shown in Table 2. These results indicate that as the length of the footing base increases, the seismic stability of a quay wall does not always improve.

The comparison of the test results of Cases 2 and 4 showed that the horizontal displacement in Case 2 was smaller than that in Case 4 and the settlement in Case 4 was smaller than that in Case 2. Thus, using gravel and light materials is not very effective in improving the seismic stability of the quay wall if liquefaction is not a concern.

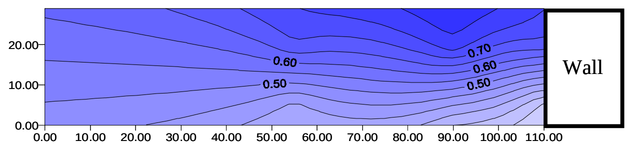
Table 2. The test results of the Hybrid caisson quay wall

Type	Horizontal disp. (mm)		Settlement (mm)		Rotation (°)	
	0.2g	0.3g	0.2g	0.3g	0.2g	0.3g
Case 1	5.09	21.61	1.70	4.15	0.37	0.63
Case 2	1.82	10.98	0.61	3.52	0.15	0.36
Case 3	2.80	11.94	0.80	3.05	0.05	0.41
Case 4	2.98	14.12	0.43	2.22	0.07	0.43

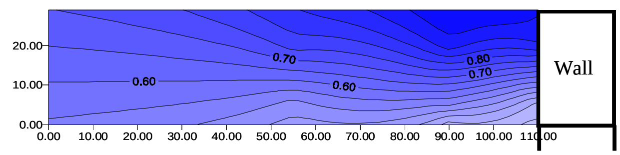
Case 5 to 8 (Piled caisson quay wall)

Response of excess pore pressure in backfill soils

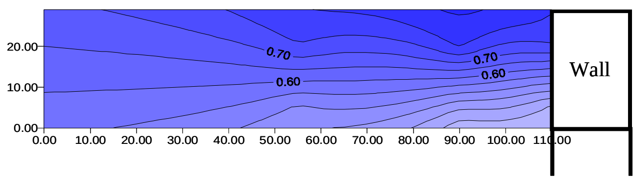
Fig 4 shows the contours of the excess pore pressure ratio at the backfill at 0.2g. For the cases of the conventional wall (Case 5) and the Piled caisson walls 1 and 2 (Case 6 and 7), the range of maximum excess pore pressure ratio was 0.80 ~ 0.95. And the total shape of the contours of the excess pore pressure ratio in Cases 5, 6 and 7 was similar. However, the maximum excess pore pressure ratio that was generated in the backfill was only 0.06 in Case 8 due to the high permeability of the gravel and light materials used in the backfill.



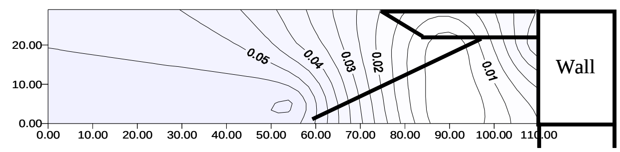
Case 5 : Conventional wall (without gravel mound)



Case 6 : Piled caisson wall 1



Case 7 : Piled caisson wall 2

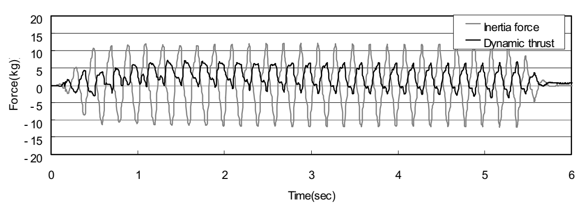


Case 8 : Piled caisson wall 2 with light backfill material

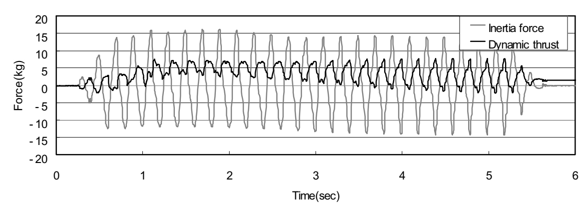
Fig. 4 Contours of the excess pore pressure ratio (Piled caisson, 0.2g)

Dynamic thrust acting on wall

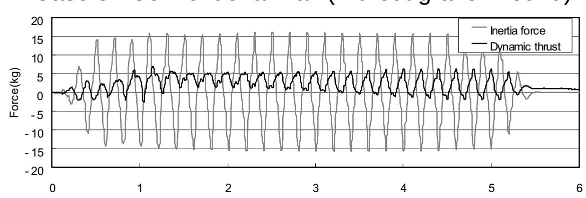
Fig. 5 shows the time history of the dynamic thrust acting on the wall and the inertia force of the wall at 0.2g. In the figure, the dynamic thrust in Case 8, where light material was used in the backfill, was reduced for the entire test time period, while the dynamic thrusts in Cases 6 and 7 were reduced only during the initial part of the test period and, later, become about the same with that of the conventional wall (Case 5).



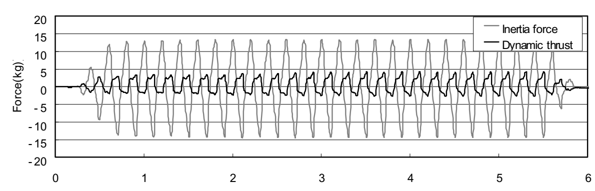
Case 5 : Conventional wall (without gravel mound)



Case 6 : Piled caisson wall 1



Case 7 : Piled caisson wall 2



Case 8 : Piled caisson wall 2 with light backfill material

Fig. 5 Time history of inertia force of wall and dynamic thrust acting on the wall (Piled caisson, at 0.2g)

Behavior of Piled caisson quay wall

Table 3 shows the test results in terms of the horizontal displacement, the settlement and the rotation of walls. In the table, the horizontal displacement in Case 7 decreased about 54% at 0.2g and 51% at 0.3g compared with those in Case 5. However, the seismic stability was not improved at all in Case 6 when the vertical displacements were compared with those of Case 5. Thus, for the Piled caisson wall to be seismically effective, the foundation pile should penetrate the ground to an adequate depth, for example, one-half of the wall height in this study.

Horizontal displacement in Case 8, in which a part of backfill ground was replaced with gravel and light materials, decreased by about 29% at 0.2g and by about 68% at 0.3g compared with those in the conventional quay wall (Case 5). This decrease is due to the fact that the generation of excess pore pressure in the backfill ground adjacent to the quay wall was restrained due to the high permeability of the gravel and light materials and that total acting force to the wall was decreased due to the light materials.

Table 3. The test results of the Piled caisson quay wall

Type	Horizontal disp. (mm)		Settlement (mm)		Rotation (°)	
	0.2g	0.3g	0.2g	0.3g	0.2g	0.3g
Case 5	3.80.	32.26	1.48	5.42	0.25	0.82
Case 6	5.45	19.64	2.45	8.38	0.45	3.19
Case 7	1.76	15.81	0.45	5.34	0.16	2.26
Case 8	2.70	10.47	1.11	4.96	0.32	2.37

CONCLUSIONS

Shaking table tests and pseudo static analysis on newly-designed quay walls were carried out, and the following conclusions were obtained.

1) The dynamic thrust acting on the back was dramatically reduced in the Hybrid caisson quay wall compared to that of the conventional wall, a reduction which occurred due to the in-phase motion of the backfill soil with the wall as is assumed in pseudo static analysis.

2) When the conventional quay wall and the Hybrid caisson quay wall were designed to have an identical factor of safety for the sliding by pseudo static analysis, the horizontal displacement of the Hybrid caisson quay wall decreased by 64% at 0.2g and 49% at 0.3g compared with those of conventional wall, which prove the seismic efficiency of the Hybrid caisson quay wall.

3) Compared with horizontal displacement of the conventional quay wall, that of Piled caisson quay wall with the pile penetration depth of one half of the wall height was reduced by 54% at 0.2g and by 51% at 0.3g, which also prove the seismic efficiency of the Piled caisson quay wall.

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