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EFFECTS OF GROUND IMPROVEMENT AND ARMORED EMBANKMENT TO THE DISPLACEMENTS OF THE SEAWALLS AND BACKFILL DURING EARTHQUAKE

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ABSTRACT

Large shaking table tests of the caisson type seawalls under various conditions were conducted in order to investigate the effects of the armored embankment and the improvement of sandy seabed and backfill by densification to the deformation of the seawalls during earthquake. Main results obtained from the shaking table tests were as follows : (1) Seaward horizontal displacement and tilting of the caisson were drastically reduced by the existence of the armored embankment in front of the caisson. (2) Improvement of the sandy seabed by densification method just under the rubble mound was much effective to reduction of the displacements of the caisson. (3) It was possible that the lateral movement of the liquefied backfill was reduced by the improvement of a part of the backfill just behind the caisson even though without the armored embankment in front of the caisson.

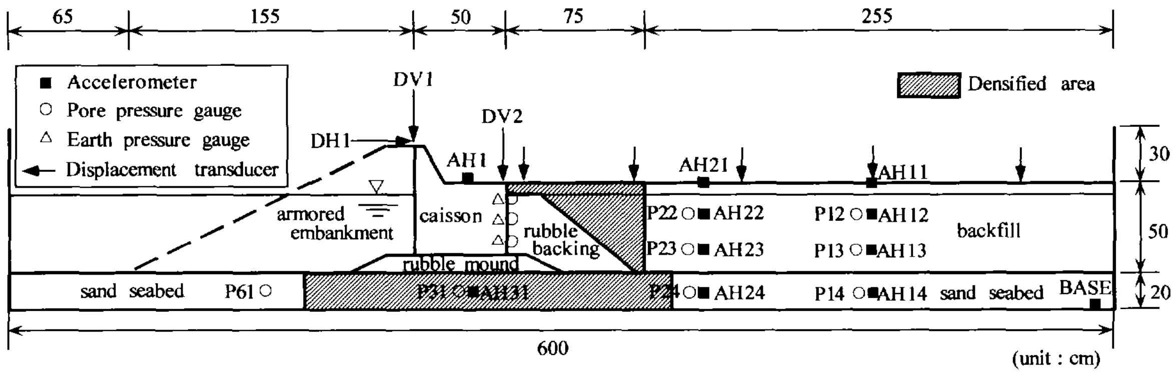
INTRODUCTION

Many caisson type quay walls near the waterfront in Hanshin area moved seaward and large ground deformation occurred behind the caisson due to soil liquefaction during the 1995 Hyogoken-nambu Earthquake. The average lateral and vertical displacements of the caisson, for example, reached 2.7 m and 1.3 m, respectively, in Port Island, a man made island in the Kobe City. The ground behind the caisson laterally flew, which brought severe damage to various structures such as bridges, buildings and lifelines. Affected area reached from 100 m to 200 m into the inland. Since the earthquake, various model tests and numerical investigations have been conducted in order to investigate the mechanism of the movement of quay walls and its effect to the backfill ground and structures. Most of these investigations pointed out the importance of not only the inertia force but also the accumulation of the shear deformation in the foundation soil beneath the caisson [Inagaki et al.,1996 ; Ghalandarzadeh et al.,1998 ; Iai et al.,1998 ; Kanatani and Yoshida,1998 ; Kanatani et al.,2000]. On the other hand, the authors have experimentally and analytically investigated the seismic performance of the caisson type seawalls covered with the armored embankment [Tochigi et al.,1993 ; Tochigi et al., 1997 ; Kawai et al., 1998 ; Kanatani et al., 1998 ; Kanatani et al., 1998 ; Kanatani et al.,1999]. The biggest difference in the structural form of the above seawalls is the existence of the armored embankment in front of the caisson. In present study, parametric model tests were conducted in order to make clear the effects of the armored embankment and the improvement of the foundation ground and backfill against the deformation of the seawalls and backfill ground during earthquake and distinguish between seawalls which were the research target of the authors and the quay walls as damaged at the time of the Hyogoken-nambu Earthquake.

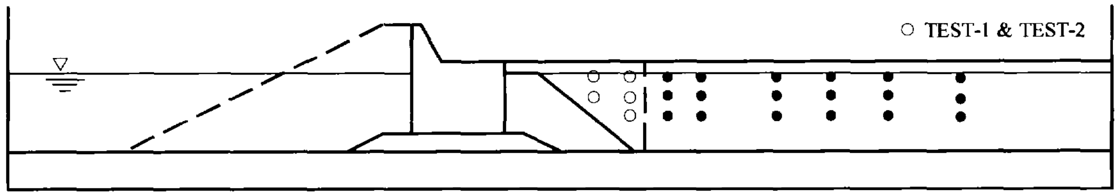
METHOD OF SHAKING TABLE TESTS

Model preparation

The configuration of models employed in the present study is illustrated in Fig.1. Whole model was placed in a soil container which had 600cm in length, 100cm in width and 100cm in height. Both end of the container were made of rigid steel walls, while the side walls were transparent in order to facilitate the direct observation of the movements of the caisson, armor units and backfill. Locations of the measurement devices and of the red-colored markers, set up in the side surface of the backfill to display the movements of the soils at the several points in the backfill before and after the excitation, are shown in Fig.1 (a) and (b), respectively. The model of the caisson was made of a concrete which had the parapet at the seaside top of the caisson. Gifu sand which had the physical properties as shown in Table 1



(a) Seawall model and locations of measurement devices



(b) Locations of red-colored markers in backfill

Fig. 1. Seawall model and locations of measurement devices and markers

was used for the sand stratums such as the sand seabed and backfill. Loose sand portions, whose relative density Dr was about 40%, in the sand seabed and backfill were prepared by the air pluviation method. Improved portion in the sand seabed was prepared by the tamping method intended to be its relative density of 80%. On the other hand, on the preparation of the improved portion just behind the caisson in the backfill, three-pieces of frozen sand blocks, whose relative density was about 90%, were made and put them on the expected locations while they didn't melt. And shaking tests were performed waiting for the frozen blocks to completely melt after making the whole model. Crushed stone which had the physical properties as shown in Table 1 was used for the materials of the rubble mound and rubble backing. Owing to expect the high saturation of the ground, de-aired water was supplied from the bottom of the model. Configuration and representative dimensions of an armor unit model, which was made of mortar, was illustrated in Fig.2. The weight of the armor unit model was about 6N and each block was randomly piled up on the seabed. Slope of the embankment piled up the blocks was 1:2. Nominal porosity of the armored embankment was about 0.5 and its value was almost coincident with that of prototype one.

Table 1. Physical properties of ground materials

		Gifu sand	Crushed stone
D_{max}	mm	0.84	25.4
D_{60}	mm	0.35	13.79
D_{10}	mm	0.22	8.3
D_{min}	mm	—	4.76
Uc	—	1.59	1.67
Gs	—	2.643	2.687
e_{min}	—	0.717	0.667
e_{max}	—	1.126	0.961

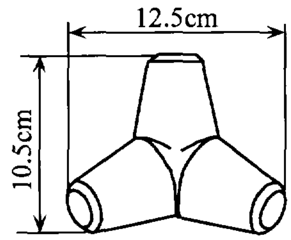


Fig. 2. Configuration and dimensions of armor unit model

Test cases and model parameters

The entire cases of test and model parameters of each case are presented in Table 2. Five types of tests were conducted in the this study. TEST-1 is a standard model imitating the quay walls damaged at the time of the 1999 Hyogoken-numbu Earthquake. In the standard of this model, conditions of each model were determined to compare the effect of the armored embankment and the improvement of the sand seabed and backfill against the displacements of the caisson and deformations of the backfill. Horizontal shaking took place in the longitudinal direction of the model. The profile of the input motion was the sinusoidal wave and its frequency and number of the waves were 5Hz and

Table 2. Test cases and conditions

	Armored embankment	Improvement of seabed	Improvement of backfill	Amplitude of input acc. (gal)
TEST-1	not exist	not improv.	not improv.	172, 290
TEST-2	not exist	improv.	improv.	169, 295, 390, 476
TEST-3	exist	not improv.	not improv.	220, 470
TEST-4	exist	improv.	not improv.	166, 290, 388, 469, 522
TEST-5	exist	improv.	improv.	170, 291, 396, 477, 540

10, respectively. Shaking tests were performed gradually increasing an amplitude of the input acceleration for one model. Amplitudes of the input acceleration in each tests are also shown in Table 2.

TEST RESULTS AND DISCUSSIONS

Displacements of caisson

There were three kinds of freedom on the movement in the center of gravity of the caisson, i.e. horizontal, vertical and rotation. These residual displacements obtained from each test were compared to make clear the effects of the armored embankment and ground improvement. The sign convention for displacement and rotation of the caisson is defined positive for seaward and downward direction.

Residual horizontal displacement. Fig.3 shows comparisons of the relationship between residual horizontal displacement of the caisson and input acceleration. In the case of TEST-1 imitating the quay wall damaged at the time of the 1995 Hyogoken-nambu Earthquake, in which there were no armored embankment and improved area of the ground, the largest residual horizontal displacement takes place compared with other cases. Because the displacement became too large at the end of shaking event of the input acceleration of 290gal and it overreached the capacity of the displacement transducer, next shaking could not be performed in TEST-1. In the tests of TEST-3, TEST-4 and TEST5, in which there was the armored embankment in front of the caisson, the horizontal displacement is stopping at the small value such as under 1cm. It is of particular remarkable that the residual horizontal displacement in TEST-3 is as small as that in TEST-4 and TEST-5, even though the sand seabed under the rubble mound was not improved as is in the case of TEST-4 and TEST-5. These results demonstrate that the armored embankment provides considerable support against the horizontal movement of the caisson. On the other hand, the horizontal displacement in TEST-2 is larger than that in TEST-3, TEST-4 and TEST-5, because there was no armored embankment in front of the caisson. But comparing TEST-1 with TEST-2, the horizontal displacement is fairly suppressed and it manifests that the improvement of foundation ground beneath the caisson by densification method is effective to reduce the horizontal displacement.

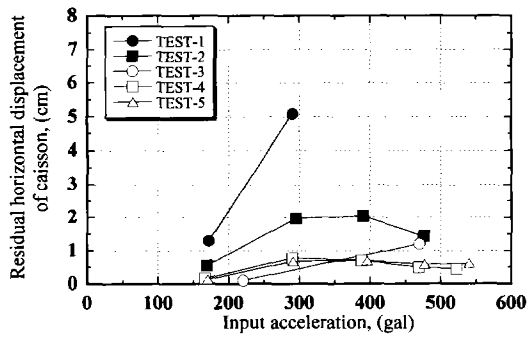


Fig. 3. Comparisons of residual horizontal displacement of caisson

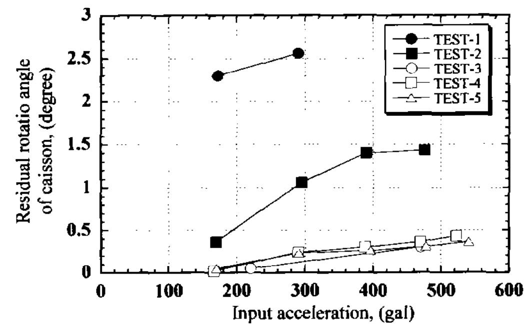


Fig. 4. Comparisons of residual rotation angle of caisson

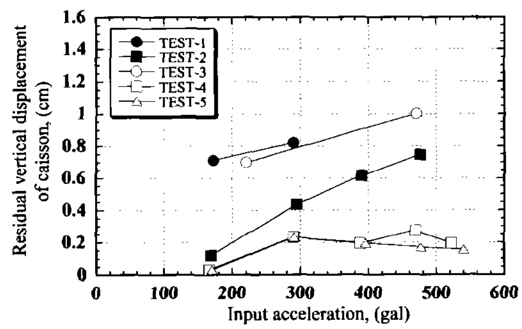


Fig. 5. Comparisons of residual vertical displacement of caisson

Residual rotation angle. Comparisons of the residual rotation angle of the caisson versus input acceleration are shown in Fig.4. The tendency on the rotation is very similar to the residual horizontal displacement. Over 2.5 degree of rotation is induced even in the shaking event of the input acceleration of 290gal in

TEST-1 and seaward rotation of the caisson is suppressed by the existence of the armored embankment.

Residual vertical displacement. Fig.5 shows the relationship between residual vertical displacement and input acceleration. Also in this relationship, displacement in TEST-1 is largest as well as other displacements mentioned above. But very interesting characteristic seems to appear in the vertical displacement. First of all, the vertical displacement in TEST-3 is large as much as that in TEST-1. In the case of TEST-3, there existed the armored embankment but the sand seabed beneath the caisson was as loose condition of Dr = 40%. This result suggests that the large vertical displacement is possible to take place in the condition that the foundation ground is loose, nevertheless the armored embankment exists in front of the caisson. The condition of the improved area in the sand seabed and backfill was the same in TEST-2 and TEST-5 and the difference between both cases was only whether the armored embankment existed or not. The vertical displacement in TEST-2 is larger than that in TEST-5. This suggests that the armored embankment is more effective to reduction of the vertical displacement of the caisson, if the foundation ground beneath the caisson is hard to deform during shaking. On the other hand, the difference of model condition between TEST-4 and TEST-5 was only the improvement of small area in the backfill just behind the caisson. In both cases, even if the excess pore water pressures in the loose stratum area of the backfill built up to almost the liquefaction condition in the case of the large shaking events, the vertical displacement of the caisson is as very small as a difference is not recognized. It seems that the liquefaction induced in the backfill does not affect to the vertical displacement of the caisson, if at least the armored embankment exists and the foundation ground beneath the caisson is enough densified.

Excess pore water pressure

Residual excess pore water pressure ratios at the end of each shaking event in TEST-1 are shown in Fig.6. The values of the excess pore fluid pressure ratio were normalized by the initial effective vertical stress at the locations of the transducers. Excess pore water pressure ratios in the backfill and sand seabed under the backfill achieved almost the 1.0 level. It proves that the liquefaction took place in these areas. However the excess pore water pressure ratio in the sand seabed just beneath the caisson, i.e. P31, dose not achieved 1.0 but was within about 0.5, even though the seabed was loose condition as its relative density was 40% and the large movement of the caisson was induced in this case. This tendency is consistent with that from the another model tests of the quay walls [Inagaki et al.,1996 ; Ghalandarzadeh et al.,1998 ; Kanatani et al.,2000]. It seems that the large accumulation of seaward shear deformation took place in the sand seabed beneath the caisson where the comparatively large initial shear stress was loaded before excitation as demonstrated by Ghalandarzadeh et al. (1998).

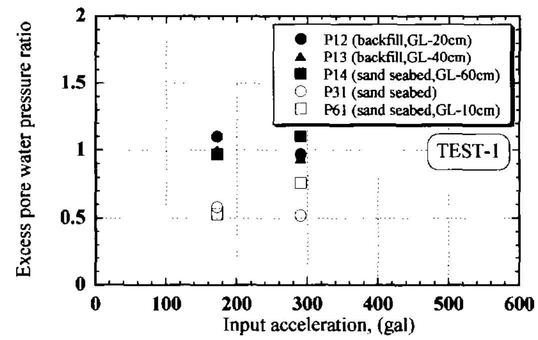


Fig. 6 Excess pore water pressure ratio in TEST-1

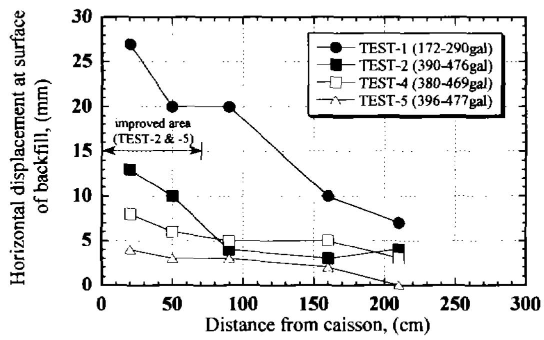


Fig. 7 Comparison of horizontal displacement at the surface of backfill

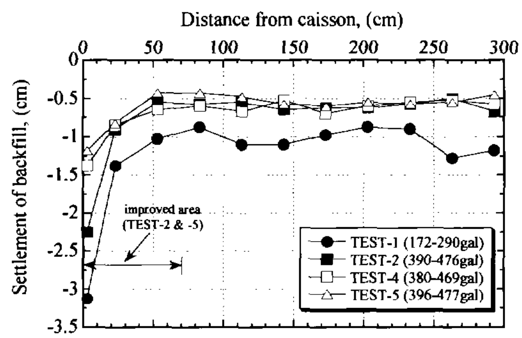


Fig. 8 Comparison of subsidence of backfill

Deformation of backfill

Lateral displacement at the surface of the backfill are plotted versus the distance from the caisson in Fig.7. The lateral displacements in the figure are the incremental ones induced by the shaking event of the large input acceleration in each test case showing in the figure. The lateral displacements in TEST-1 are largest compared with other cases, even though the input acceleration of 290gal was the smallest value among all tests. It seems that the large lateral displacement of the backfill is due to the large lateral movement of the caisson. Nevertheless its effect decreases with increasing distance from the caisson, it propagates as far back as over 200cm from the caisson. On the other hand, it may be seen that the large lateral displacement in TEST-2, in which there was not the armored embankment but a part of the backfill behind the caisson was improved, was concentrated almost in the improved area and the displacements behind its area are reduced as much as in TEST-4 and TEST-5. This demonstrates that the improved area absorbs the effect of the large lateral movement of the caisson and it plays the role of the suppressing the lateral deformation of the backfill behind it. In TEST-4, the lateral displacements are very small, regardless of the backfill being improved. This is because the lateral displacement of the caisson is fairly small as indicated in Fig.3. The distribution of the settlements of the backfill in the direction perpendicular to the caisson line is shown in Fig.8. The settlements in TEST-1 are largest, even though the input acceleration was smallest, and it is also seen that the ground subsidence tends to drastically decrease with increasing distance from the caisson. In TEST-2, the area where the large settlement took place is concentrated just behind the caisson. These tendencies are apparently associated with the lateral displacement of the backfill stated above.

Next pay attention to the distributions of the lateral displacements in the backfill. In the all test cases, excess pore water pressures in a loose sand stratum of the backfill built up to almost the liquefaction condition when the input acceleration was large. Therefore depending on the condition, it was expected that the liquefaction-induced lateral flow should be taken place in the backfill. Standing in such view point, the distributions of the lateral displacements in the backfill obtained from each test were compared. Fig.9 shows the comparison of the lateral displacements in the backfill versus distance from the caisson between TEST-1 and TEST-2. In TEST-1, due to the combination of the large lateral movement of the caisson and the occurrence of the liquefaction in the backfill, very large lateral displacements are induced in the backfill and its effect expands as far away as over 200cm from the caisson. Such performance of the backfill seems to bring the damages of the structures and pile foundations behind the caisson as found at the time of the 1995 Hyogoken-nambu Earthquake. On the other hand, in TEST-2, the lateral displacements are fairly reduced compared with TEST-1, because of the improvement of a part of the backfill in addition to the reduction of the lateral movement of the caisson due to the improvement of the sand seabed beneath the caisson. Comparisons of TEST-2 with TEST-4 and TEST-2 with TEST-5 are displayed in Fig.10 and Fig.11, respectively. The distributions of the lateral displacements in both figures are very similar and in any case displacements are very small. These results exhibits two main characteristics on the lateral spreading of the liquefied backfill as follows. In the case that the lateral movement of the caisson is originally suppressed due to the armored embankment and improvement of the sand seabed such as in TEST-4 and TEST-5, liquefaction-induced lateral flow of the backfill is restricted, because the caisson can not largely move and there is little room which the liquefied backfill laterally spreads. And, even though the larger lateral movement of the caisson is occurred due to without the armored embankment in front of the caisson, it is possible that the lateral spreading of the liquefied backfill is considerably reduced by the improvement of a part of the backfill just behind the caisson.

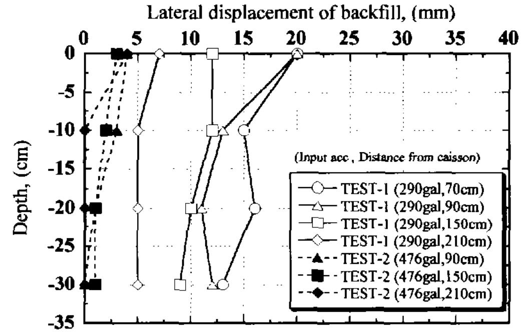


Fig. 9 Comparison of lateral displacements in backfill (TEST-1 and TEST-2)

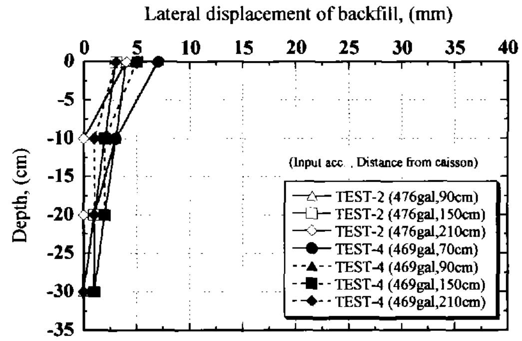


Fig. 10 Comparison of lateral displacements in backfill (TEST-2 and TEST-4)

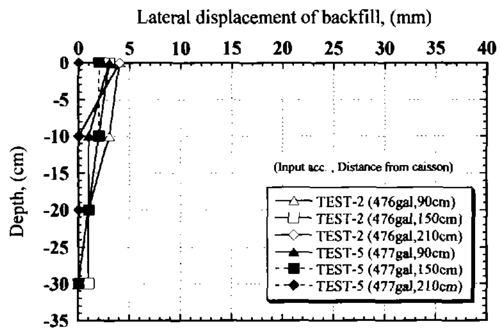


Fig. 11 Comparison of lateral displacement in backfill (TEST-2 and TEST-5)

CONCLUDING REMARKS

In present study, large shaking table tests of the caisson type seawalls under the various conditions were conducted in order to investigate the effects of the armored embankment and the improvement of sandy seabed and backfill by densification to the deformation of the seawalls. The major conclusions drawn from this study can be summarized as follows:

(1) The existence of the armored embankment in front of the caisson and the improvement of the sand seabed beneath the caisson leads to the reduction of the horizontal displacement and tilting of the caisson to the direction of the sea.
(2) The large vertical displacement of the caisson is possible to take place in the condition that the foundation ground is loose, nevertheless the armored embankment exists in front of the caisson.
(3) The lateral displacement and settlement of the backfill are closely associated with the lateral movement of the caisson during shaking. And, when the large lateral movement of the caisson takes place, large lateral spreading of the liquefied backfill is induced. Such performance of the backfill seems to bring the damages of the structures and foundations behind the caisson as found at the time of the 1995 Hyogoken-nambu Earthquake.
(4) In the case that the lateral movement of the caisson is originally suppressed due to the armored embankment and improvement of the sand seabed, the liquefaction-induced lateral flow of the backfill is fairly restricted.
(5) Even though the larger lateral movement of the caisson is occurred due to without the armored embankment in front of the caisson, it is possible that the lateral spreading of the liquefied backfill is considerably reduced by the improvement of a part of the backfill just behind the caisson.

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