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MODEL SHAKE TABLE TEST ON THE SEISMIC PERFORMANCE OF GRAVITY TYPE QUAY WALL WITH DIFFERENT FOUNDATION GROUND PROPERTIES

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SUMMARY

Many gravity type quay walls have been damaged in large earthquakes as typified by the 1995 Hyogo-ken Nambu earthquake. Study of performance-based seismic design procedures has been frequently carried out in the design field for port structure recently in Japan. The seismic performance of gravity type quay walls is significantly affected by the interaction between the wall itself and the soils adjacent to and beneath the structure. However, the detail of the influence is not well known in general. The focus of this study was the influence of foundation ground properties on the dynamic behavior of quay walls.

The model tests on caisson type quays were conducted, in order to qualitatively evaluate the following: (1) the relation between the residual quay deformation and the strain distribution of foundation soils, (2) the relation between the dynamic quay behavior and the frequency characteristics of the foundation soils. Two cases were carried out with an underwater shaking table under a 1G field (model scale of 1 / 12.5). For one case the foundation sand was dense and for the other case it was loose. From the model tests observation, it was clarified that the quay deformation significantly depends on the properties of the foundation soil. The deformation of caisson type quays did not originate in the sliding at the boundary between the caisson bottom and the rubble-mound but was due to shearing strain generated in the foundation ground. The amount of caisson type quay deformation was almost equal to the summation of shearing deformation in the foundation ground and rubble-mound. The vibration properties of caisson type quays were influenced by seismic characteristics of the foundation ground and sinusoidal wave shaking.

INTRODUCTION

Studies on the dynamic behavior of gravity type quay walls have been frequently carried out in Japan since many port structures have been damaged in large earthquakes as typified by the 1995 Hyogo-ken Nambu earthquake[1)]. In these studies, it was focus that dynamic interaction between structures and the surrounding ground plays an important role in the stability of quay walls. It is generally recognized that

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the residual deformation of quay wall is affected by the vibration characteristics of structures and adjacent soils together[2,3].

Frequency characteristics of earthquake motion have a large influence on dynamic behavior of quay walls and change in the course of propagation through soils beneath structures. Amplification of earthquake motion through the ground is considered in the actual design as a coefficient based on ground classification is commonly used in the seismic coefficient method. Foundation ground deformation directly connecting the damage of structures is significantly important in performance-based seismic design procedures as well.
In this study, the influence of foundation ground properties on the dynamic behavior of quay walls is examined through a series of model shake table tests. Two model cases of gravity type quay walls were prepared on an underwater shake table; a primary difference between two cases was the use of either dense or loose foundation sand. By comparing the behavior of these models, the influences of dynamic properties of the foundation ground are investigated with regard to the frequency characteristics and the deformation distribution.

TEST METHOD AND CONDITIONS

Experimental Model

A large underwater shaking table was used in this study. A caisson type quay wall was modeled at a scale of 1/12.5 of the prototype and is equivalent to a quay wall of prototype caisson height of 10m. Figure 1 illustrates the cross section and transducer layout of the model which has a depth of 1.5m. The model consisted of a caisson, backfill rubble, backfill ground, rubble mound, and foundation ground. The caisson was 800mm in height and 478mm in width and was constructed from a hollow box made of aluminum. Its total density was controlled by filling the caisson with sand. Three caissons were prepared and lined up in a row on the foundation ground. Only the center caisson had transducers for measurement of acceleration and the earth pressure acting on it.

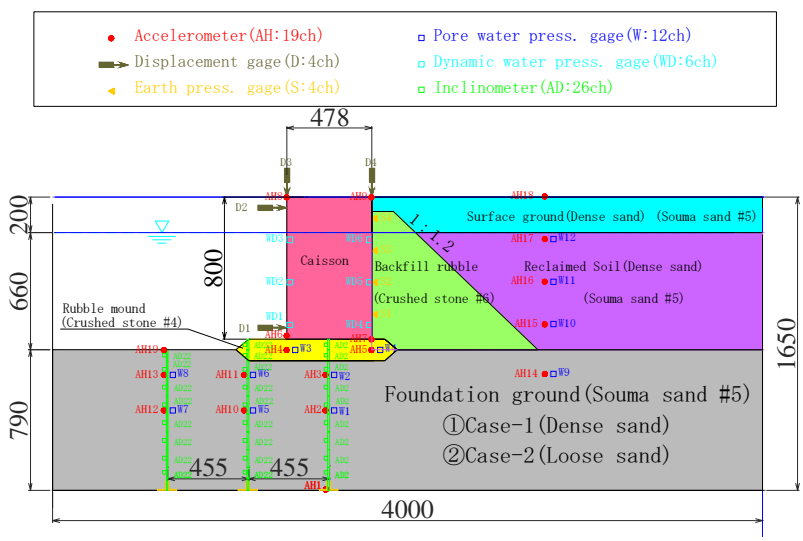


Figure 1 Model quay wall and transducer layout

Acrylic plates connected to each other with hinges were installed in the foundation ground to measure the displacement distribution. The plates had accelerometers for sensing inclination. Displacement distribution can be obtained by integration of this data from the bottom to the surface of the model[4]. About 100 markers accurately following ground displacement were installed to observe deformation of the foundation on the acrylic sidewall windows of the soil container.

Figure 2 shows grain size distribution of the siliceous sand and stones used in this experiment. The rubble mound and backfill rubble was made of crushed stone while the foundation and backfill ground was made of the sand. The backfill ground was compacted with foot stepping not to liquefy during the excitation. Density of the foundation ground was controlled to be dense or loose so as to investigate influence of

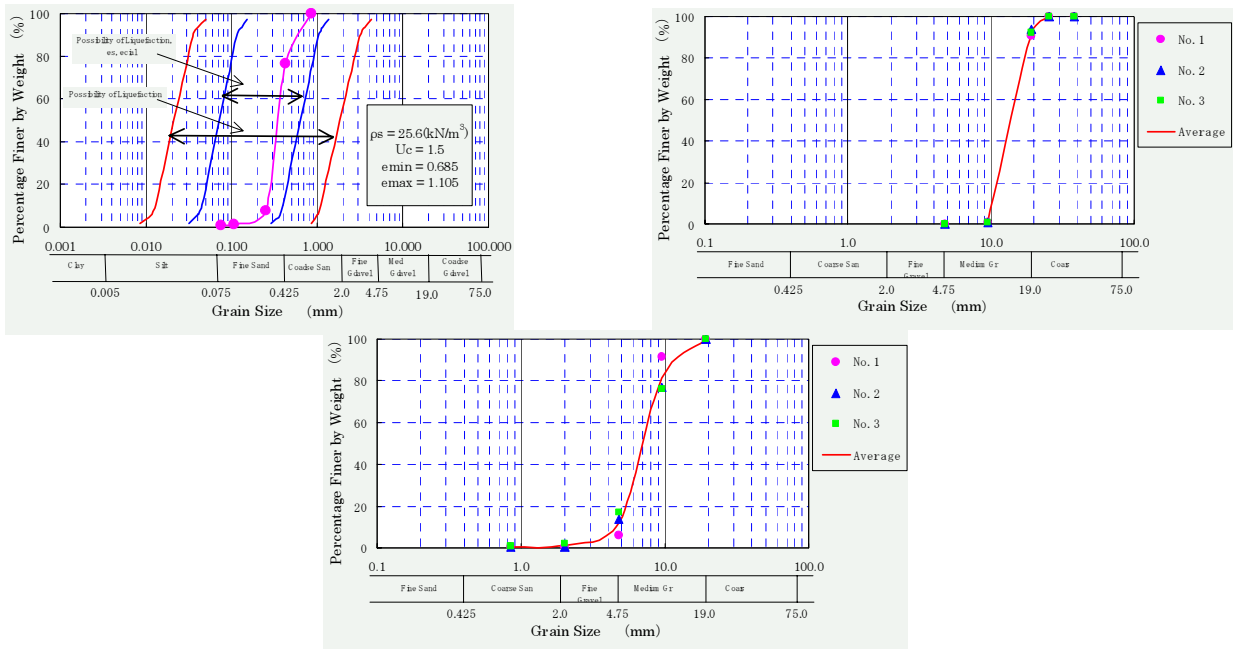


Figure 2 Grain size distribution of sand and stone

foundation soils: this was performed by stepping compaction for the dense ground and underwater sand sedimentation without adjustment for the loose condition. Test cases are shown in Table 1.

Experimental Condition

Sinusoidal waves having 10 – 40 Hz in frequency and 10 times in cycle were used as input motions for the model to clarify the frequency characteristics of gravity type quay walls. In each case the model quay was subjected to 6 sinusoidal waves from 40 to 10 Hz in sequence; see Table 1. These waves correspond to about 1.5 – 6 Hz in the prototype scale, based on the similitude law[5]. The input motion had only one horizontal component and a target magnitude of 200Gal. However, the target magnitudes for some frequencies of shaking were magnified; the specifics of this situation are discussed more in this paper.

TEST RESULTS AND DISCUSSION

The time histories of case-2 of 15Hz in frequency are shown in Fig. 3 as an example of the test results. The caisson sinks and displaces toward sea during the shaking. The residual horizontal and vertical displacements are about 1.8cm and 0.8cm respectively. Excess pore water pressure is generated in the model ground but its amount is not large. Amplitudes of acceleration are different depending on accelerometer location. In the following section, the relationships of acceleration amplification ratio, residual displacement and excess pore water pressure to the shaking frequency are discussed.

Dynamic Response Properties of Model Quay Wall

Acceleration

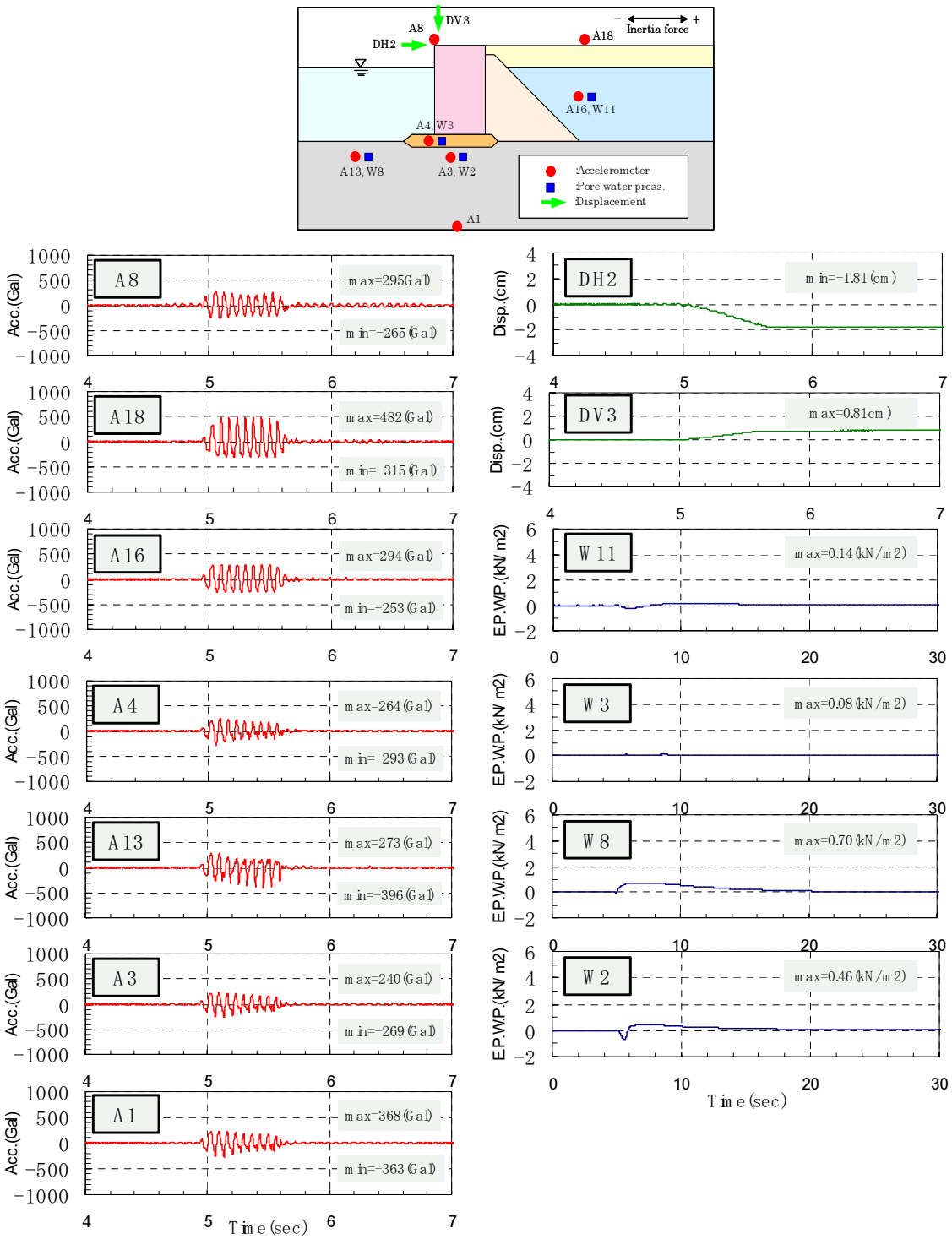
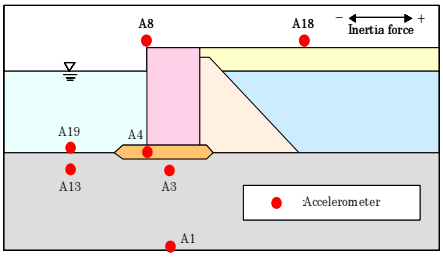


Figure 3 The time histories of 15Hz in frequency in the case of loose ground (case-2)

Figures 4(a, b) show the relationship between the shaking frequency and amplification factor of acceleration in case-1 and case-2, respectively. From the graph of amplification in the foundation ground (A19/A1)



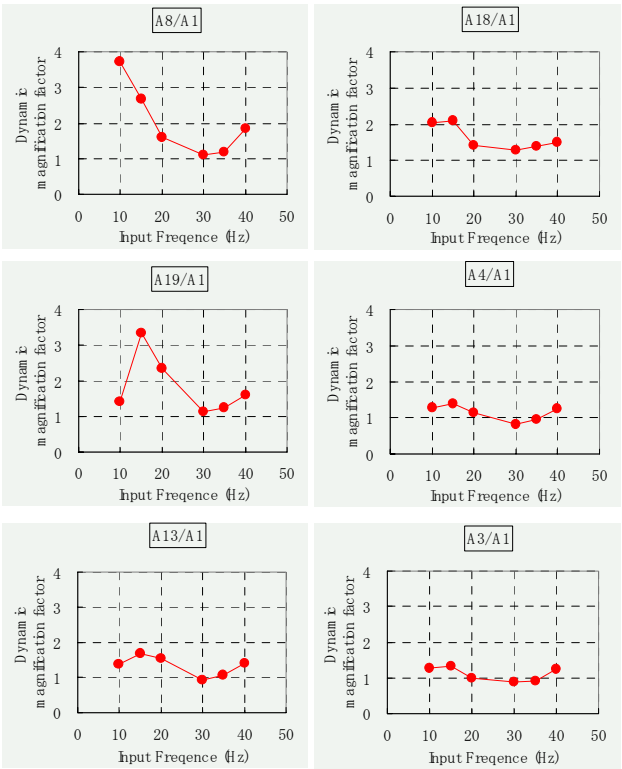


Figure 4(a) Relationship between acceleration amplification and frequency for the case of dense foundation soils (case-1)

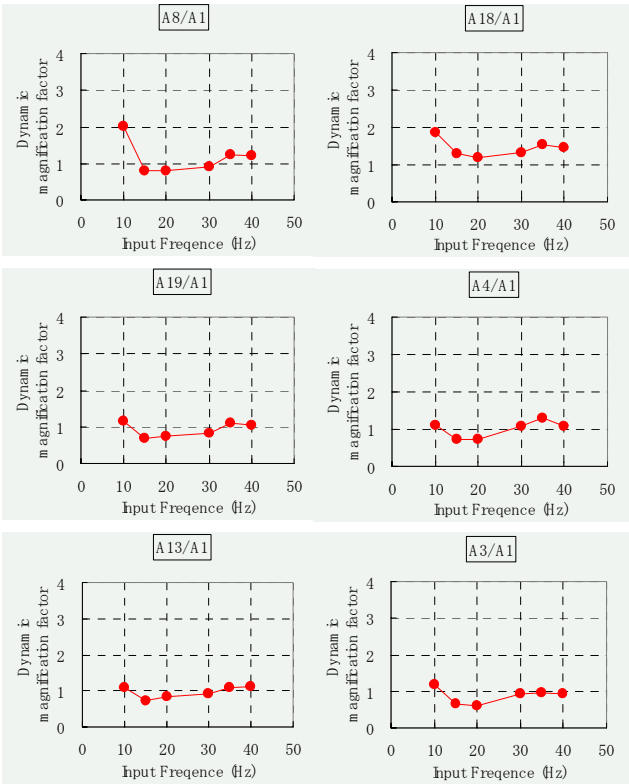


Figure 4(b) Relationship between acceleration amplification and frequency for the case of loose foundation soils (case-2)

in Fig. 4(a), it is clarified that the dominant frequency of the dense foundation in case-1 is about 15Hz. For the caisson and backfill ground, it seems that their natural frequency are lower than 10Hz, on the basis of the graphs (A8/A1, A18/A1). Large amplification of acceleration is not observed in the other portions of the model. In the case of loose foundation ground for case-2, there is no predominant frequency in acceleration amplification as shown in the graph (A19/A1) in Figure

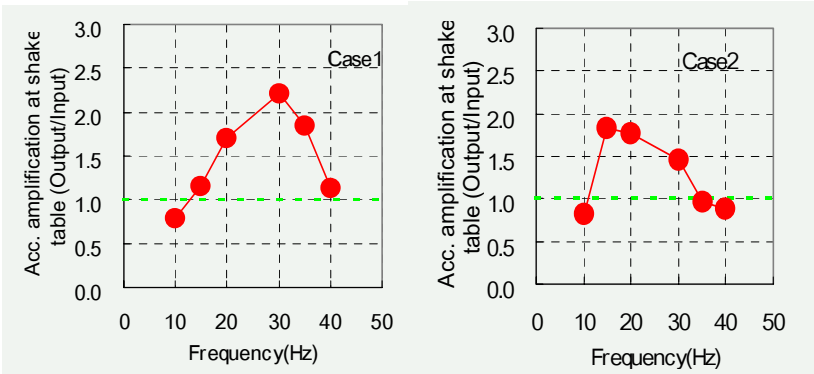


Figure 5 Relationship between shaking frequency and acceleration amplification factor at the shake table

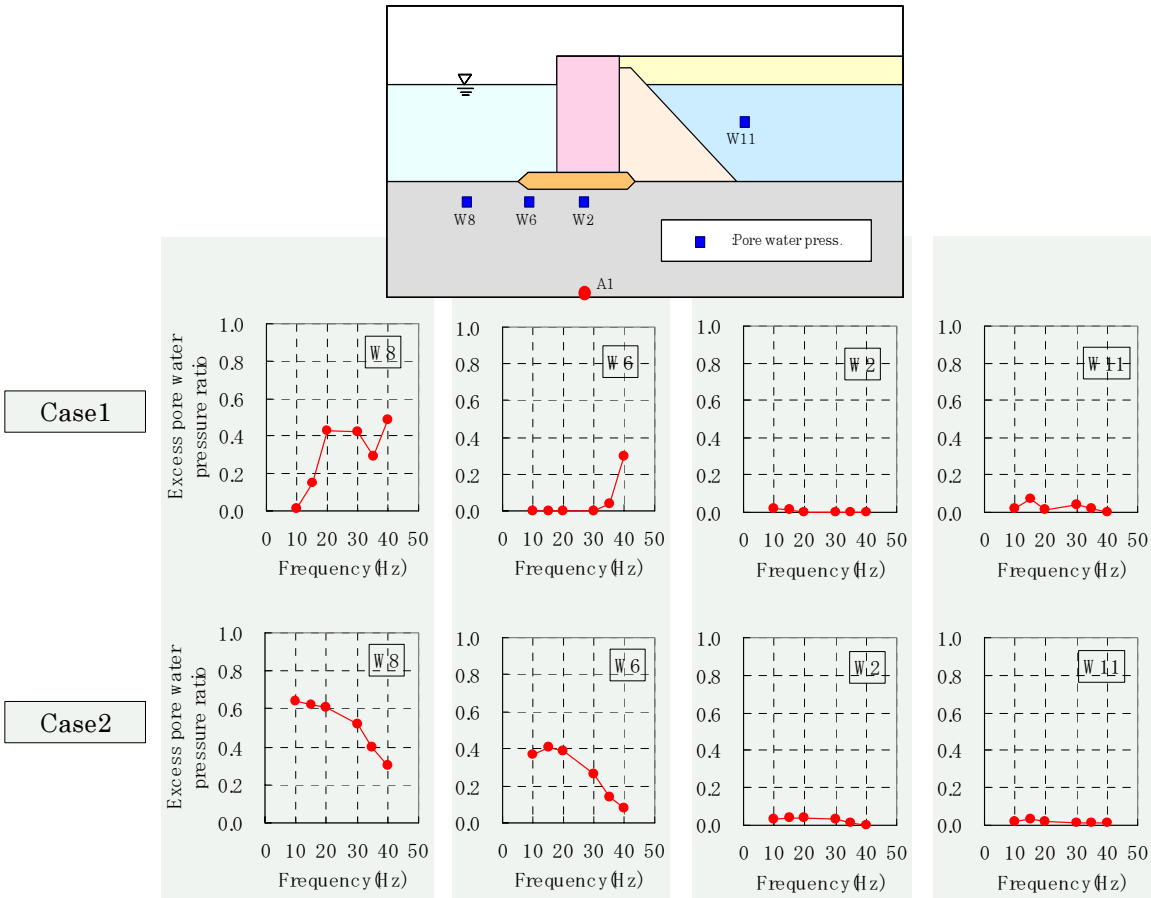


Figure 6 Relationship between shaking frequency and excess pore water pressure ratio

4(b). It seems that the natural frequency of the foundation is lower than 10Hz. The natural frequencies of the caisson and backfill ground are lower than 10Hz in the case of loose foundation of case-2 as well. The amplification factor at the caisson (A8/A1) for a frequency of 10Hz in case-2 is smaller than that in case-1. The natural frequency for a caisson on loose foundation appears to be lower than that on a dense foundation.

The target amplitude of the input acceleration in the tests was 200Gal but the actual amplitudes varied in dependence of shaking frequency; see Fig. 5. Because of the heavy mass of the model quay wall and non-linearity of soil deformation behavior, control of the shake table did not work well for a shaking frequency of 15 – 35Hz. Acceleration amplitude at the shake table reached around 450Gal for the case-1 frequency of 30Hz. Taking account of this occurrence, excess pore water pressure and residual displacement are examined in the next paragraph with regard to shaking frequency.

Pore water pressure generation and caisson displacement

Maximum excess pore water pressure generated in the ground is plotted against the shaking frequency in Figure 6. There is scarcely any excess pore pressure generation in the foundation just under the caisson and in the backfill in both case-1 and case-2. The density of backfill was increased by compaction and, therefore, excess pore water pressure didn't generate at all. The foundation just beneath the caisson seems to be influenced by caisson mass and initial shear stress in relation to the absence pore pressure rise.

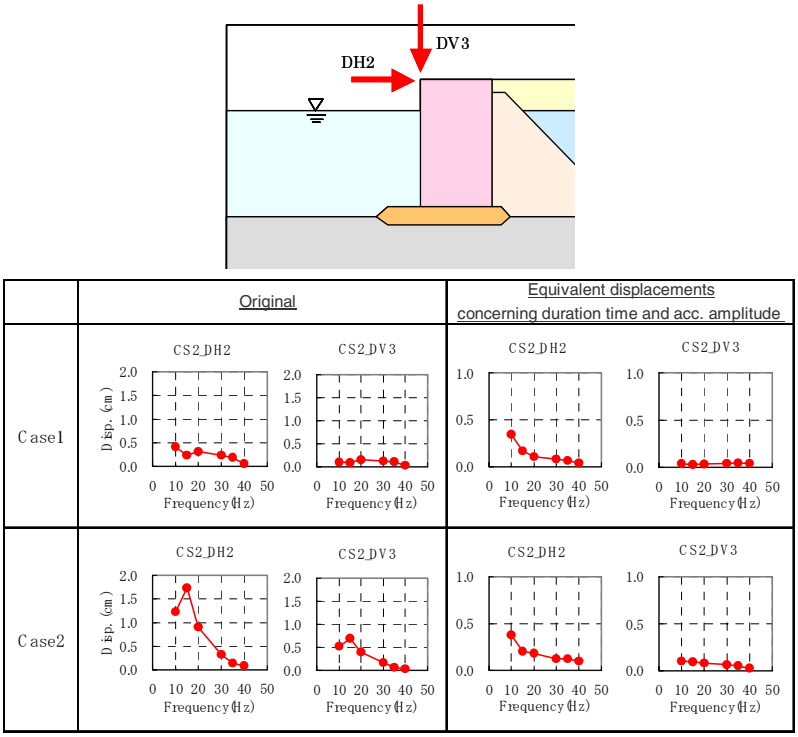


Figure 7 Relationship between shaking frequency and residual displacement of the caisson

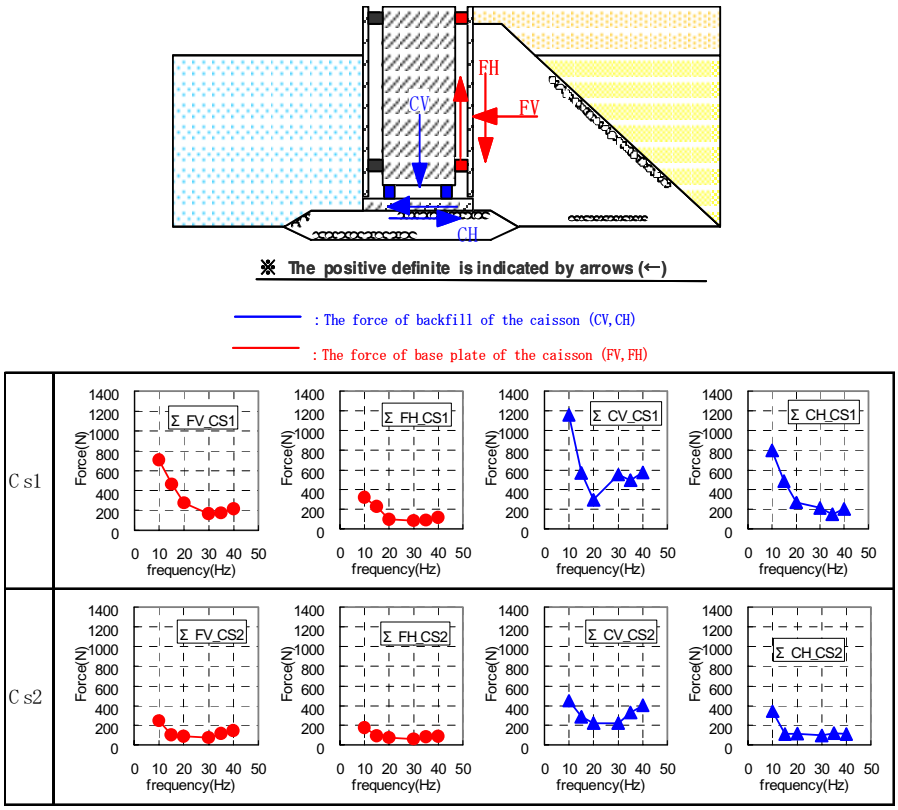


Figure 8 Relationship between shaking frequency and maximum amplitude of the force acting on the caisson

Excess pore water pressure in the foundation in front of the caisson generates for a higher and lower frequency range in the case of dense (case-1) and loose (case-2) foundation ground, respectively. However, the excess pore water pressure ratio doesn't reach 1.0 in either case. When excess pore water pressure is generated in the ground, the stiffness of ground could decrease depending on a drop in confining pressure; the natural frequency of the ground could decrease in the process of excess pore pressure. Accordingly, excess pore pressure has to be taken into account by examining the model vibration properties as mentioned in Fig. 4.

Residual displacements of the caisson for a lower frequency range in case-2 are much larger than that in case-1, as shown in Fig. 7. The duration time of shaking for a lower frequency range is longer than that for a higher frequency range as the input sinusoidal wave in each frequency was fixed at 10 cycles. In addition, acceleration amplitude at the shake table changes in dependence on the input frequency as shown in Fig. 5. Figure 7 also shows the equivalent displacements concerning duration time and amplitude. The measured displacement is linearly scaled to be equivalent to that of 0.25 sec in duration and 200 Gal in amplitude. The equivalent displacement of 10 Hz is largest among those of various shaking frequency in both case-1 and case-2. Consequently, it is obvious that low frequency has

low frequency has more of an effect on quay deformation. This tendency is due to the dynamic vibration properties of the quay wall as shown in Fig. 4.

Figure 8 shows the relationship between the shaking frequency and maximum forces acting on the caisson during shaking. Similarly to Fig.7, the value of the forces is adjusted to be equivalent to that of shake table acceleration of 200Gal. The lower the frequency of shaking is, the larger the forces are that act on the caisson. It is thought that dynamic vibration properties of model quay, as shown in Fig. 4, influences the relationship between the frequency and acting forces.

The influence of the foundation's vibration properties isn't large in this test; the predominant frequency of the foundation in case-1 is 15 Hz as shown in Fig. 4(a) but maximum residual displacement occurred for a shaking frequency of 10Hz. It is conceivable that the dependence of displacement on frequency corresponds to the trend in the forces acting on the caisson. The force pushing out the caisson toward sea (FV) is largest in the case of 10 Hz as shown in Fig. 8.

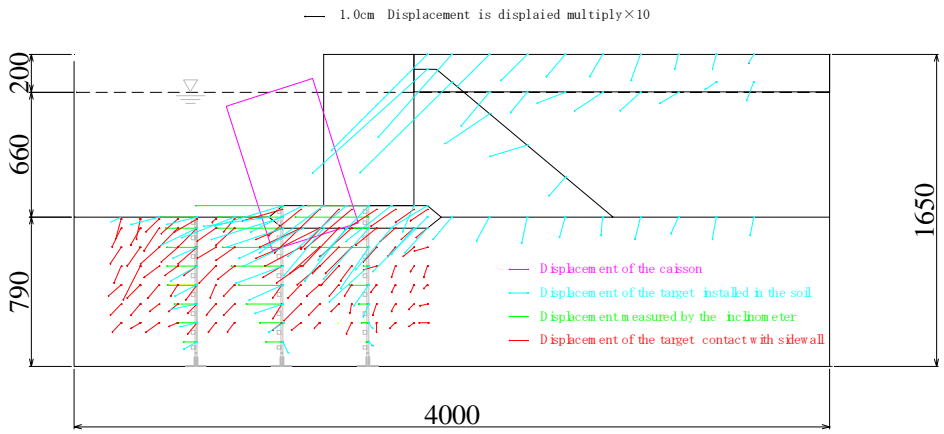


Figure 9 Residual deformation of the model quay (CASE2) (displacement is multiplied by 10)

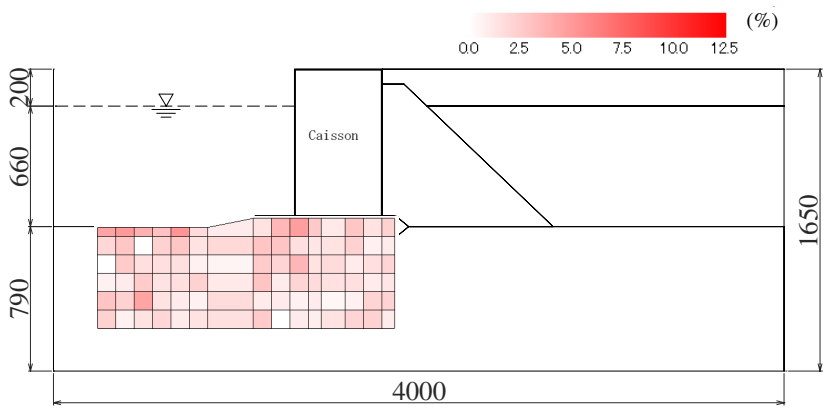


Figure 10(a) Distribution of maximum shear strain γ_{max} (case-1)

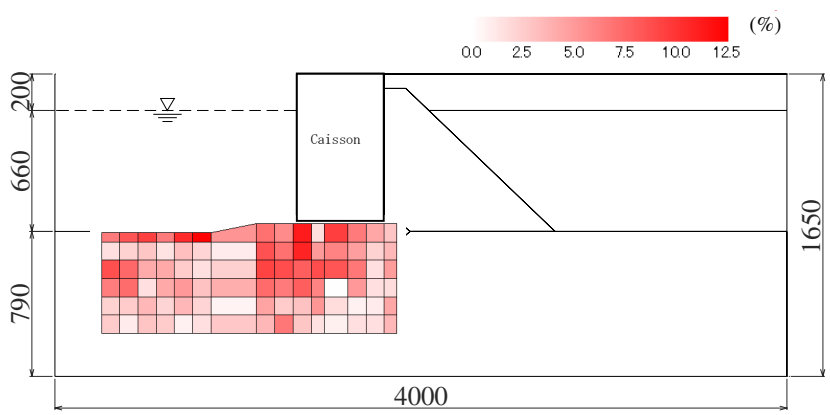


Figure 10(b) Distribution of maximum shear strain γ_{max} (case-2)

Deformation of the Ground below the Caisson

Figure 9 shows the residual displacement distribution at the end of case-2 after the shaking from 40Hz to 10Hz. The markers contacting the sidewall and in the center part of the soil profile were measured after draining water from the under water shake table and during dismantling of the model quay, respectively. Large displacement of ground was concentrated on the section under and behind the caisson. The foundation ground is loose in case-2 and sinks during the excitation. As shown by the inclinometer displacement, the bottom of the foundation ground did not displace significantly and there is no obvious boundary. The displacement of the model quay wall is almost equal to the summation of shearing deformation in the foundation ground and the rubble-mound. It was then found as a result of the model test that deformation of the caisson type quay wall originated not in sliding at the boundary between the caisson bottom and rubble-mound but in shearing strain generated in the foundation ground.

Figure 10 shows the shear strain distribution in the foundation grounds of case-1 and case-2. This figure was drawn from calculations similar to FEM, based on displacement distribution of the markers contacting with the sidewall window of the soil container. An obvious shear band is not seen in this figure. However, there is a tendency of shear deformation to concentrate in the foundation under the former heel part of the caisson. Shear deformation of the loose foundation in case-2 is larger than that of the dense foundation in case-1.

CONCLUDING REMARKS

Dynamic behavior of gravity type quay walls during earthquakes was investigated experimentally. The mechanism of the damage to the quay walls due to the liquefaction of backfill was clarified. The following conclusions were obtained from the examination of a series of model shake table tests.

- Vibration characteristics of a gravity type quay walls were clarified as a result of the model tests. Natural frequencies of the caisson and the foundation ground in the case of a loose foundation are smaller than those in the case of a dense foundation.
- The residual displacement of 10 Hz in shaking frequency is largest among those of various frequencies and it is obvious that low frequency was more of an effect on deformation of a gravity type quay. This frequency dependence of quay deformation is due to the relationship between the frequency and acting forces; the lower the frequency of shaking is, the larger the forces acting on the caisson will be. Vibration properties of the whole quay wall influence deformation properties as opposed to independent effects from the wall or foundation.

of gravity type quay wall.

- Large displacement of ground concentrates on the section under and behind the caisson but there is no obvious boundary such as a sliding line or a shear band. The displacement of the model quay wall is almost equal to the summation of shearing deformation in the foundation ground and the rubble-mound; the caisson doesn't slide at the boundary between the caisson bottom and the rubble-mound.

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