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# Study on Mechanism of Caisson Type Sea Wall Movement During Earthquakes

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## ABSTRACT

Model vibration tests under gravity and centrifuge model vibration tests in 50G were performed to investigate the behavior of caisson type sea wall with reclaimed ground below and behind the caisson. In the tests, sliding of caisson occurred only during excitation, which indicates that it is impossible to predict the displacement of caisson and the deformation of back-fill ground without taking account of both inertia force of caisson and dynamic earth pressure. As for the dynamic earth pressure acts on the caisson, it was found that when input acceleration is small, the dynamic earth pressure seems to restrain the movement of caisson and the excess pore water pressure hardly occurs. On the other hand, when input acceleration is large enough to cause liquefaction, the dynamic earth pressure seems to promotes the movement of caisson.

## KEYWORDS

caisson type sea wall, reclaimed ground, liquefaction, excess pore water pressure, dynamic earth pressure, large ground deformation

## INTRODUCTION

From the past damage of harbor structures, many cases of large ground deformation such as lateral flow and settlement due to liquefaction accompanying a large displacement of caisson toward sea side were found. In recent earthquakes, particularly in Kushiro-oki earthquake (1993), Hokkaido Nansei-oki earthquake (1994) and Hyogo-ken Nambu earthquake (1995), such kinds of damages were observed in various seaside places. In their neighborhoods large accelerations of 400gal to 500gal were observed. However, in the design of such structures as caisson type sea walls, only the evaluation weather the sliding of caisson occurs or not is performed by applying around 0.1 to 0.2 of seismic coefficient, and the evaluation on the amount of caisson's sliding is scarcely performed.

From now on, in the aseismic design for airport facilities, power station facilities on reclaimed islands as well as general harbor structures, the evaluation on the amount of both sliding and settlement of caisson should be implemented. Through such evaluation, we can assess whether these structures can maintain the fundamental function to be safe against earthquakes.

In this study, model vibration tests, which are fundamental research for the above purpose, are performed in order to examine the mechanism of movement of caisson type sea wall with reclaimed ground behind it. Besides, centrifuge model vibration tests in 50G were performed to investigate the behavior of caisson and reclaimed ground just below and behind the caisson under the same confining pressure as actual structure.

## MATERIAL FOR MODEL

Generally, in shaking table tests, liquefaction does not last long because the model is so small that the excess pore water pressure disperses too early. Besides, the behavior of ground model during excitation becomes different from that of real ground because of extreme low confining pressure (Towhata et al. 1995). Taking account of the above facts, the ground model made of extreme lose sand, for example relativity density less than 0 %, is occasionally prepared so that it can shows negative dilatancy even in the low confining pressure. Moreover, the experiments with viscosity fluid which makes the permeability of soil very small are performed frequently.

Based on the past studies by authors (Sato et al. 1997), however, it is found that the specimen made of Toyoura sand

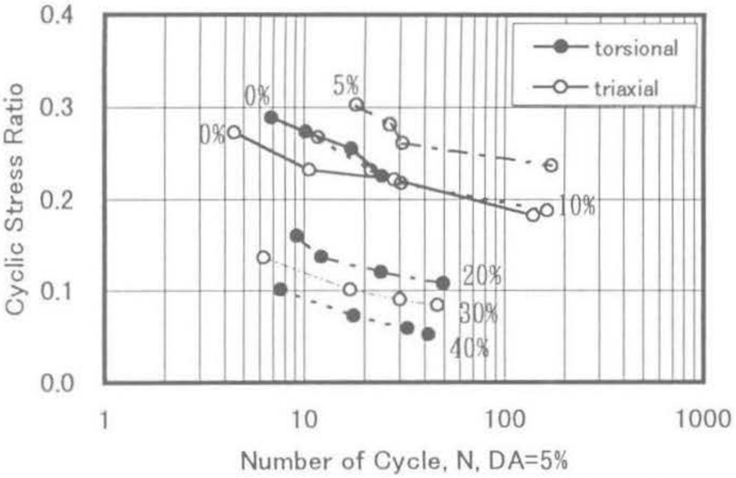


*Fig.-1 Liquefaction Strength of DL-clay Mixture Sand*

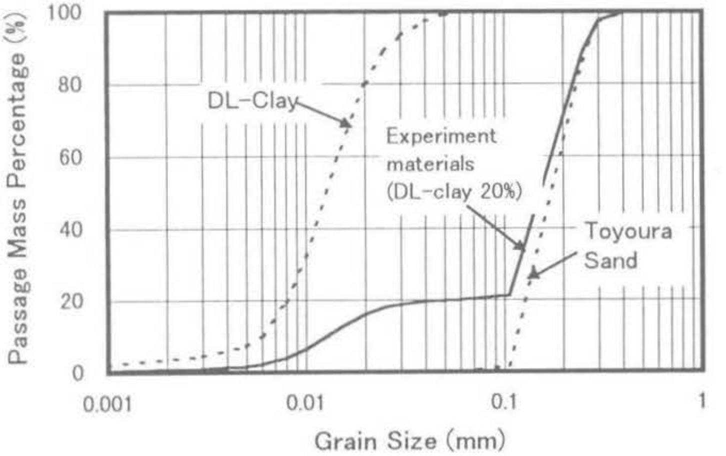


*Fig.-3 Grain Size Distribution of Toyoura Sand, DL-clay and DL-clay ( 20%) Mixture Sand*

mixed with DL-clay indicates extremely lower liquefaction strength (Fig.-1) and shows more remarkable tendency of negative dilatancy than those of the specimen made of 100% Toyoura sand with the same relative density as that of DL-clay mixed sand specimen. Besides, the specimen made of the DL-clay mixture sand indicates low permeability too (Fig.-2).

DL clay is non-plastic silt which has the grain size distribution shown in fig.–3. The grain size distributions of Toyoura sand and the mixture of 80% Toyoura sand and 20% DL clay are also shown in Fig.-3. The microstructure of the same mixed by means of microscope is shown in photo-1.

In this study, the models of not only Toyoura sand but also 20% DL-clay mixed Toyoura sand are prepared for the experiments. It is one of the purposes for us to confirm that the experiments on the model made of DL-clay mixed sand can improve the problems mentioned above.

## MODEL VIBRATION TESTS

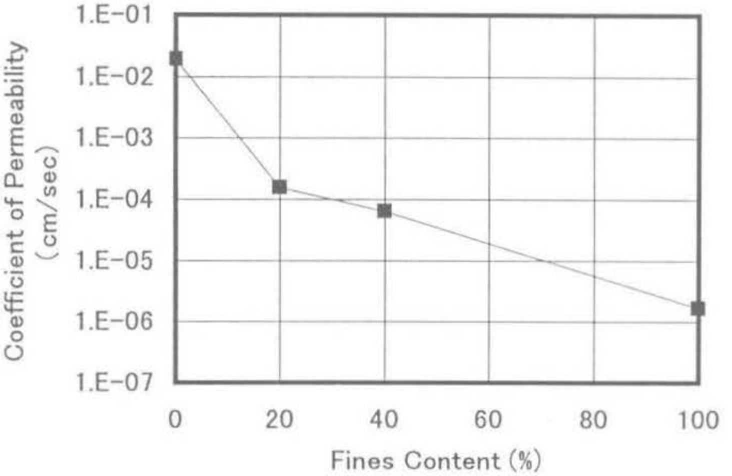


*Fig.-2 Coefficient of Permeability of DL-clay Mixture Sand*

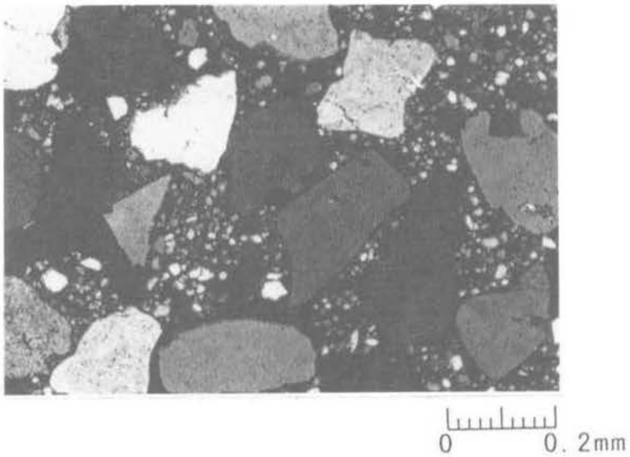


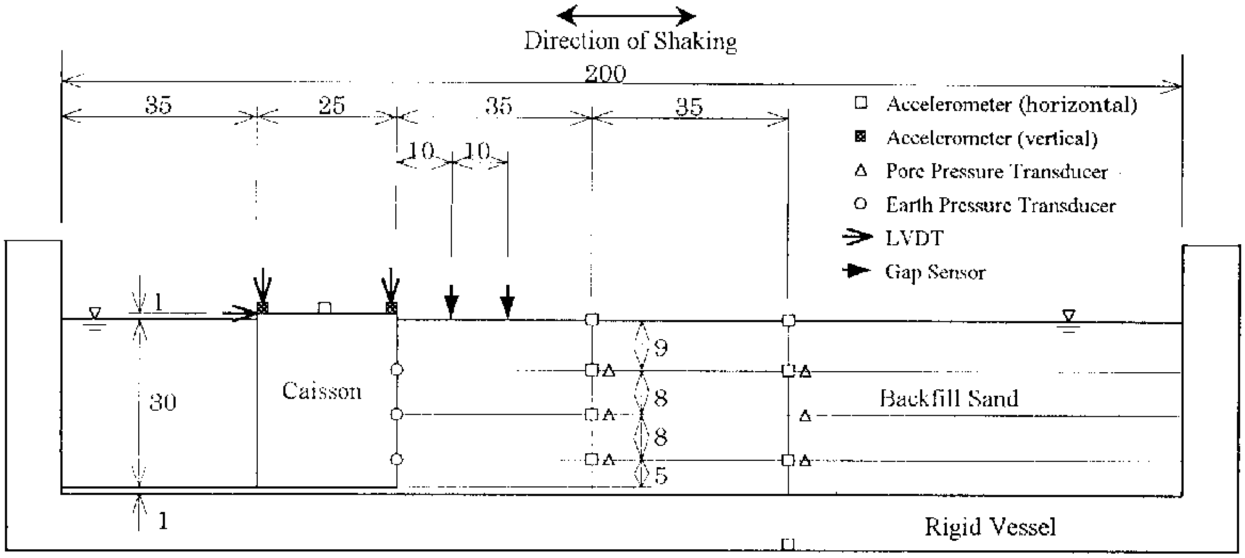
*Photo-1 Microstructure of DL-clay (20%) Mixture Sand*

### Model Description

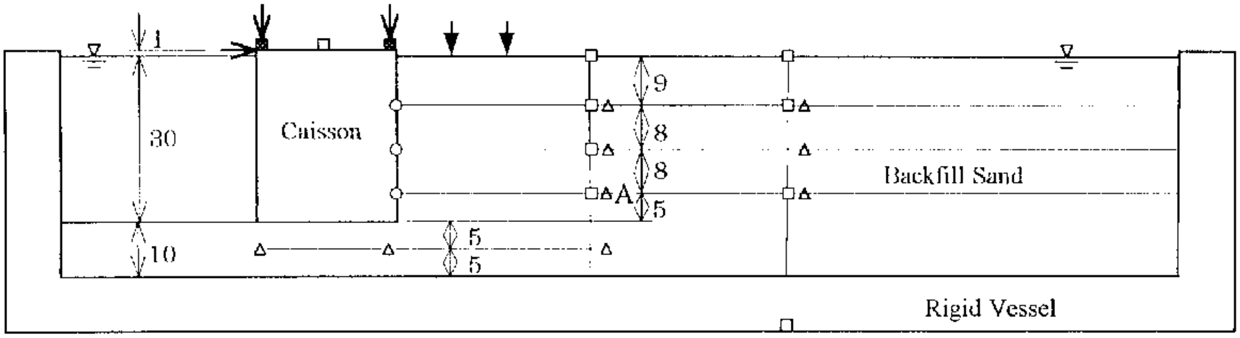
A rigid vessel made of steel plates having its inner dimension, 200 cm long, 65 cm wide, and 45 cm high, was fixed on the shaking table. Inside the vessel, the model consisting of a mortar block, front water, water saturated base and backfill soil was installed as shown in Fig.-4. For simplicity, rubble mound and rubble back-filling of actual structure were not considered, and the water level was set at ground surface.

Two types of models, the thickness of the sand layer below caisson being 1cm and 10cm, were prepared for the tests. The model which has 1cm thickness of sand layer below the caisson (Model-A) is for the case that the caisson stands on the dense subsoil or on the rock. On the other hand, the case of 10cm thickness of sand layer below the caisson (Model-B) simulate the case that the liquefiable layer exists below the caisson as observed in Hyogo-ken Nambu earthquake (1995).

The sand or DL-clay mixed sand was poured into the rigid box, in which the caisson model had been set, by dry pluviation. Then water was introduced to the soil through the inlet tube at the base of the rigid vessel. Sensors and measurement positions of the model are shown in fig.-4.



*(a) Model-A* Unit : cm



*(b) Model-B* Unit : cm

*Fig-4 Model Configration*

*Table-1 Experimental Cases*

| Model | Material of Recraimed Ground | Experimental Case | | |
|---|---|---|---|---|
| | | Expected Level of Input Motion | | |
| | | 50gal | 150gal | 400gal |
| Model-A | DL-clay Mixture Sand | AF-50 | AF-150 | AF-400 |
| Model-B | DL-clay Mixture Sand | — | — | BF-400 |
| | Sand | — | — | BS-400 |

## Model Testing and Test Cases

Sinusoidal acceleration of 20Hz for about 2 seconds was input to the base of the model. Experimental cases are shown in Table-1. The experiments were performed for both models of the sand and DL-clay mixed sand as shown in the table. Maximum acceleration of input motion was adjusted to about 50gal, 150gal, or 400gal.

For model-A in which the ground was made of sand, 50gal, 150gal and 400gal of input acceleration were applied to the identical model (AF-50,AF-150 and AF-400). Excitation was done sequentially from smaller input acceleration to large one, after confirming the dispersion of excess pore water pressure due to previous excitation.

Model-B is for the investigation of influence of the liquefiable layer below the caisson on the behavior of caisson. Two types of models, one was made of sand and another was made of DL-clay mixture sand were prepared, and only large input motion such as about 400gal was input (BF400 and BS-400).

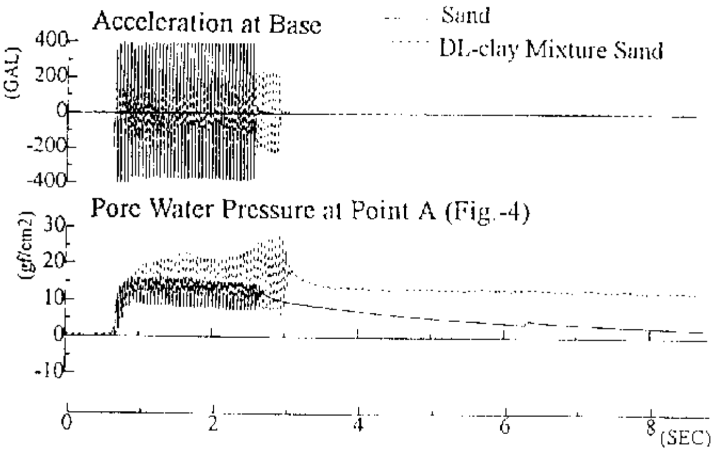


*Fig.-5 Input Acceleration and Pore Water Pressure*

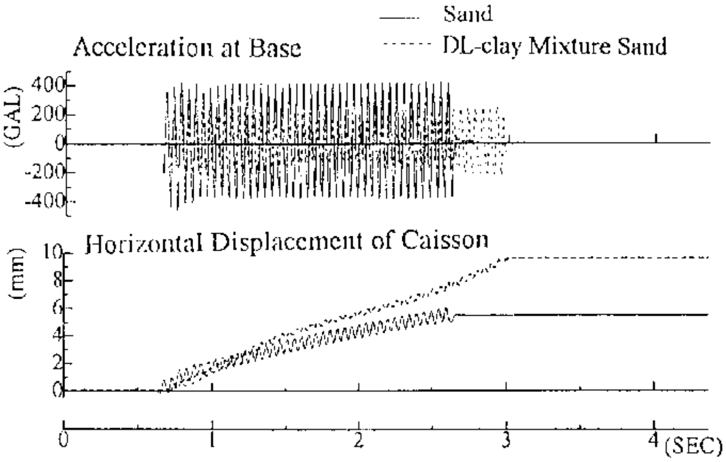


*Fig.-6 Input Acceleration and Horizontal Displacement of Caisson*

## Test Results

Fig.-5 shows the horizontal input acceleration recorded at the base of the vessel and excess pore water pressure recorded at point A indicated in Fig.-4 during the tests of Model-B. Fig.-6 shows the horizontal input acceleration and the horizontal displacement at the top of the caisson in the same case as Fig.5. In these figures, the test results of BS-400 in which sand was used for the model and BF-400 in which DL-clay mixed sand was used for the model are compared.

Recorded input acceleration of BF-400 was considerably smaller than that of BS-400 as found in Fig.-5, because the control of shaking table was not so proper in BF-400. In spite of such a low input motion, excess pore water pressure of BF-400 indicates almost similar initial buildup and reaches the level as that of BS-400, and the horizontal displacement of caisson in BF-400 grows larger than that of BS-400. Moreover, excess pore water pressure in BS-400 almost disperses out by about 8 seconds, while excess pore water pressure of BF-400 hardly disperses in the same period. Thus, it can be state that the ground model which is easier to liquefy and hard to disperse pore water pressure than the model made of sand only, can be made by using the mixture of sand and non-plastic silt.

As for the behavior of caisson in the tests of BF-400 and BS-400, in spite of the ground just below caisson was thick and large input motion was applied, sliding of caisson occurred only within excitation, as shown in Fig.-6.

Fig.-7 shows the relationships between the response accelerations of caisson and the dynamic earth pressures acting on caisson in Model-A (AF-50 , AF-150 and AF-400). EP-1, EP-2 and EP-3 indicate shallow, middle and deep depth of pressure meters attached to the caisson model, respectively; to measure the dynamic earth pressure at different depth. In the figure, though the axial scales are different in test cases, the ratio of vertical axis to lateral axis is adjusted constant so that the inclination of each loop in the figure can explain the ratio of earth pressure versus unit response acceleration of caisson.

According to this figure, as the excess pore water pressure of AF-50 hardly generates due to low input motion, so that, the loop traces around the starting point, and its inclination indicates distinct right correlation,. This explains that the dynamic earth pressure acts in opposite direction of caisson's inertia force, in other words, the backfill soil restrains the motion of caisson.

On the other hand, in AF-150 and AF-400, because of high input motion, the loops gradually shift upward due to initial buildup of excess pore water pressure, particularly at the deeper points (EP-2 and EP-3). Then finally, the loops trace around the higher point than initial point, and the inclination of the loops are apparently smaller than that of AF-50. Moreover, the loop having negative inclination can be recognized at EP-3 of AF-150. This phenomenon indicates that the effect of backfill soil, restraining caisson's movement, becomes minor, or on the contrary, as the case of EP-3 of AF-150, the behavior of backfill soil promotes the motion of caisson.

## CENTRIFUGE MODEL VIBRATION TESTS

### Model Description

A rigid vessel made of aluminum plates having its inner dimension, 110 cm long, 40 cm wide, and 30 cm high, was fixed on the shaking table which was connected to a steel basket supported by a hinge at the end of rotating arm of about 6.5m in length. Inside the vessel, the model consisting of a mortar block, front water, water saturated base and backward soil was installed as shown in Fig.-8. The condition of the model, such as rubble mound and rubble back-filling of actual structure were not considered and the water level was set at

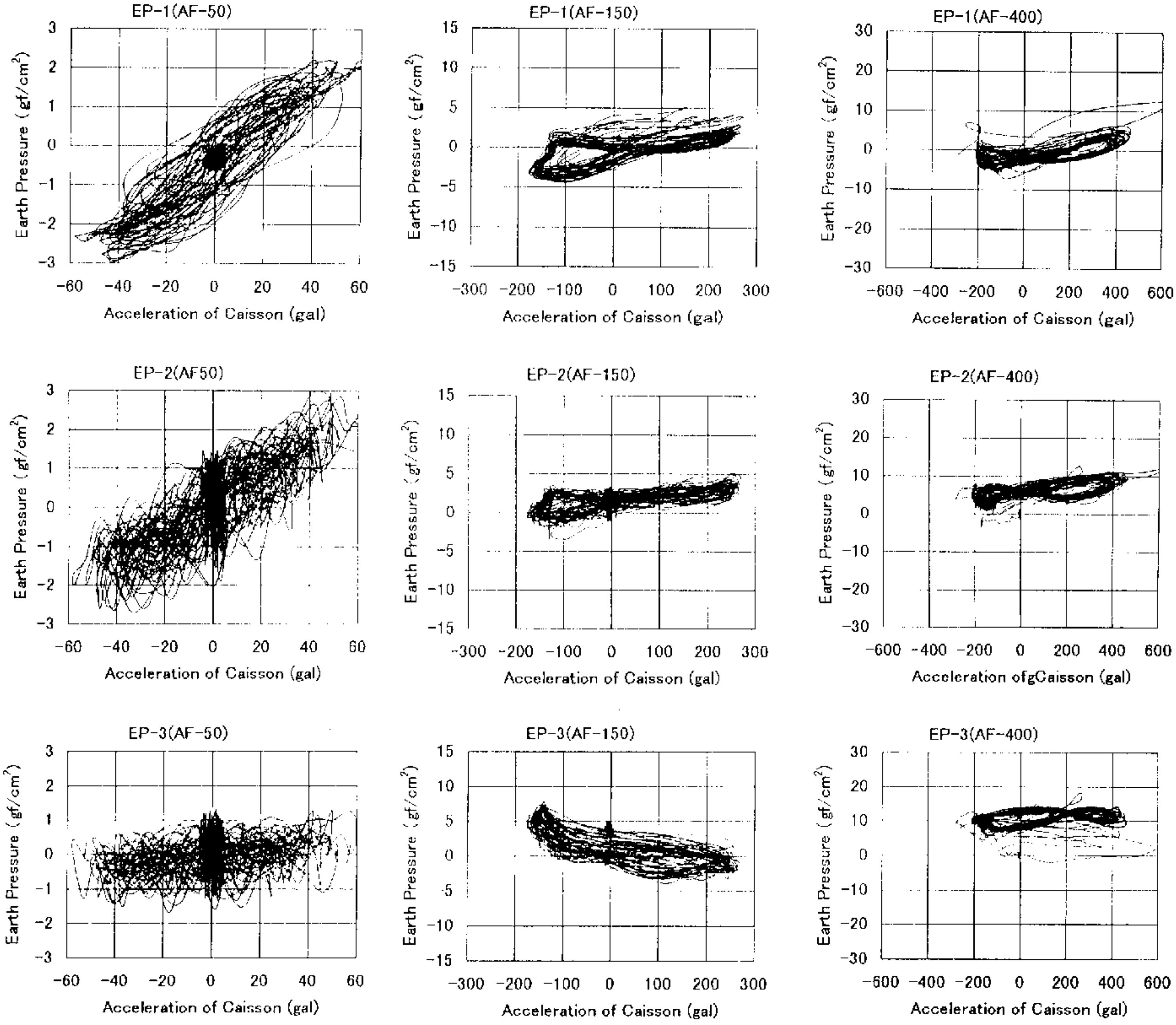


*Fig.-7 Relationship Between Accelerations of Caisson and Earth pressures Act on Caisson (Model-A)*

ground surface, which were similar to above-mentioned model of vibration test under gravity. One type of model (Model-C) in which the thickness of the sand layer below caisson was 10cm were considered, and two models were prepared for the tests. One was made of sand and the other was made of DL-clay mixed sand.

The sand or DL-clay (20%) mixed sand was poured into the rigid box, in which the caisson model had been set, by dry pluviation. Then water or silicon-oil was introduced to the soil through the inlet tube at the base of the rigid vessel which was put in the evacuated container. In the tests, from the law of similarity, silicon-oil at 50 cSt dynamic coefficient of viscosity was used as the pore fluid for the model made of sand. For the model made of DL-clay mixed sand, water was used as pore water, since its permeability is about 1/100 of sand as shown in Fig.-3. Sensors and measurement positions of the model are shown in Fig.-9.

## Model Testing and Test Cases

The models were subjected to maximum about 20G (G= 980cm/sec$^2$) sinusoidal input acceleration of 150Hz for 0.2 seconds under the initial confining pressure of 50G given by the centrifuge test facility.

Two cases of experiment were performed for Model-C as shown in Table-2. CF-20G is a model made of DL-clay mixture sand, and CS-20G is a model made of sand only.

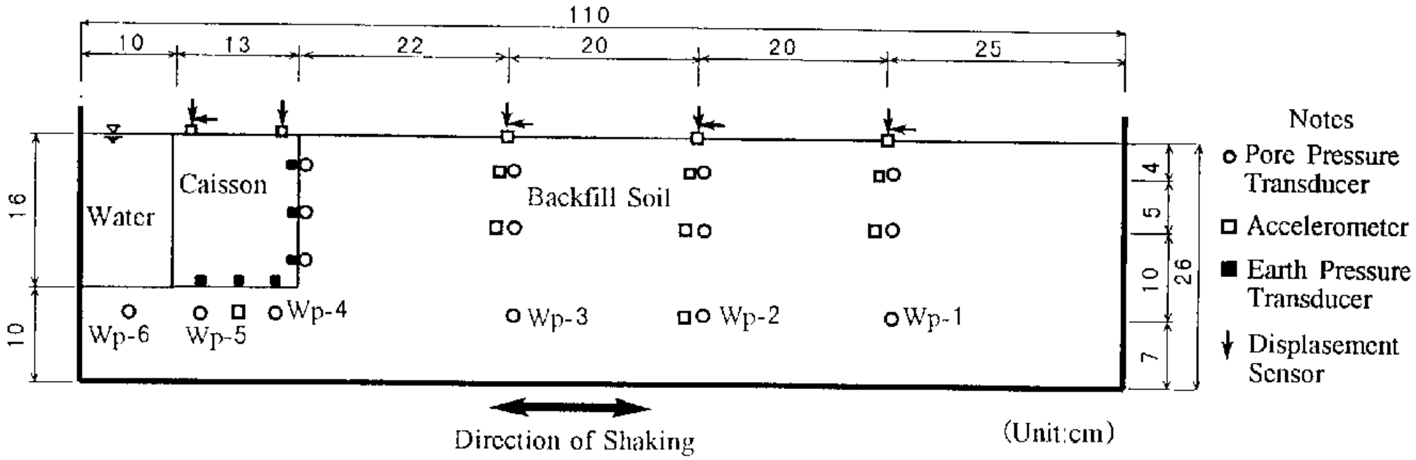


*Fig.-8 Model Configuration (Model-C)*

*Table-2 Experimental Cases of Centrifuge Tests*

| Model | Material of Recraimed Ground | Experimental Case |
|---|---|---|
| | | Expected Level of Input Motion ; 20G |
| Model-C | DL-clay Mixture Sand | CF-20G |
| | Sand | CS-20G |

## Test Results

Fig.-9 shows the acceleration and relative displacement measured at the top of caisson model, comparing CF-20G and CS-20G. In the tests, confining pressure and permeability of the ground models were approximately similar to actual ground, and liquefaction continued for a while after the excitation apparently because the excess pore water pressure in the backfill ground didn't reduce as described below. Besides, the ground just below the caisson was thick, and the larger level of excitation was applied. It is noted that, in spite of such conditions of model, the sliding of caissons occurred only during excitation in both cases.

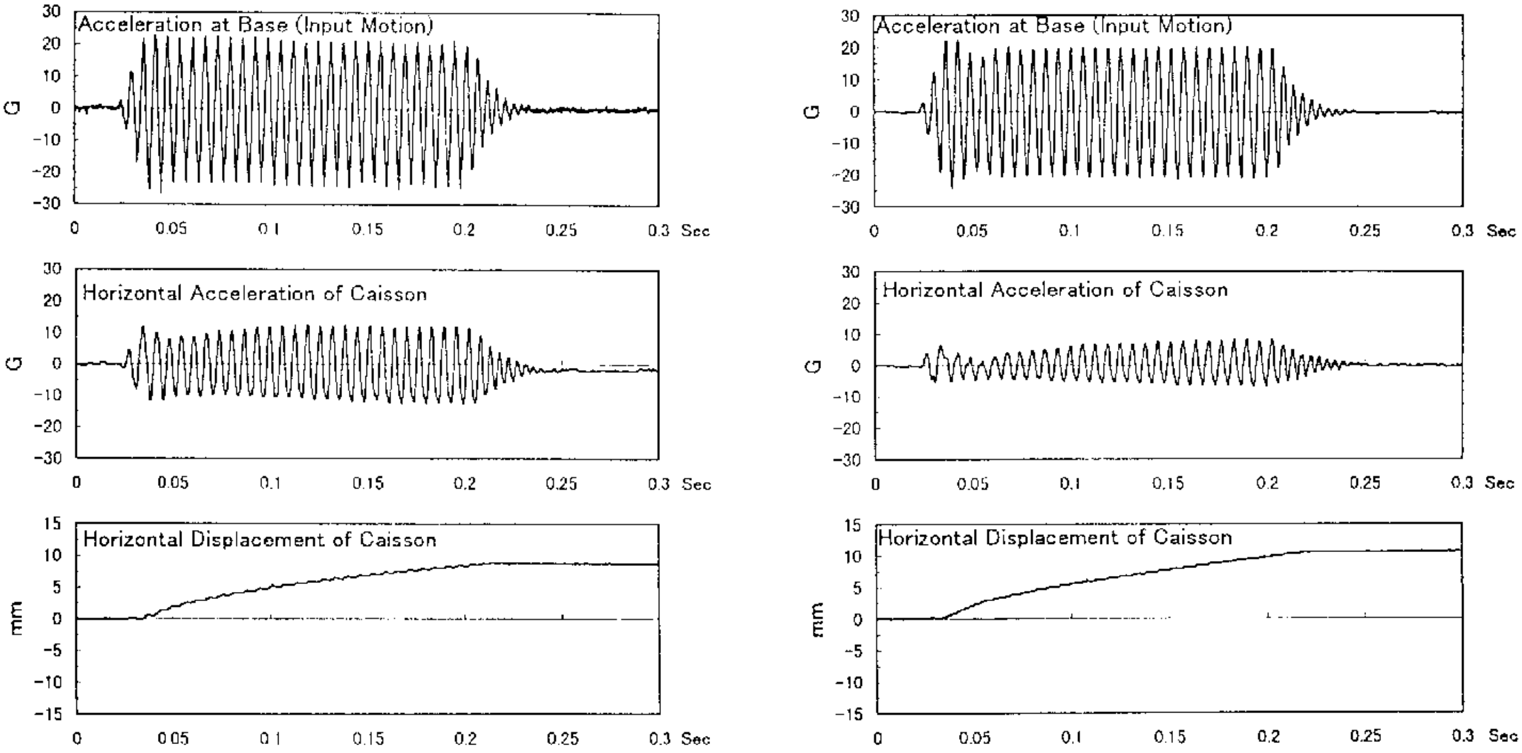
Fig.-10 shows excess pore water pressure of CF-20G, measured in deep positions plotted in Fig.-8 as WP-1, WP-2, WP-3, WP-4, WP-5 and Wp-6. Looking at the records of WP-1, WP-2 and WP-3, which were not much subjected to the influence of caisson's behavior because of the distance from caisson, prompt dispersion of excess pore water pressure during or just after excitation cannot be found, while this kind of phenomenon was commonly shown in previous centrifuge experiments using sand and water. This means the ground model of DL-clay mixed sand and water can maintain liquefied condition as the model of sand and silicon-oil made in the same way can.

Looking at wp-4, wp-5 and wp-6 right under or near the caisson, it seems that the sublayer right under the caisson didn't completely liquefy simultaneously, because the excess pore water pressures apparently changes intensely. So that, it is supposed that the strength of the soil right under the caisson repeated loss and recovery with the oscillation of caisson.

Fig.-11 shows the relationships between the response accelerations of caisson and the dynamic earth pressures of both models plotted in the same manner as in Fig.-7. Slight differences are recognized in each case, though, almost all loops indicate negative inclination, and as described before, it seems that the behavior of backfill soil promoted the motion of caisson

## CONCLUSION

As for the applicability of DL-clay mixed sand to shaking table tests on liquefaction, it is clarified that the model made of DL-clay mixture sand liquefies more easily and the excess pore water pressure disperses more hardly than the model made of sand only.



*(a) Case of CF-20G (DL-clay Mixture Model)*

*(b) Case of CS-20G (Sand Model)*

*Fig.-9 Input Motion and Response of Caisson Model*

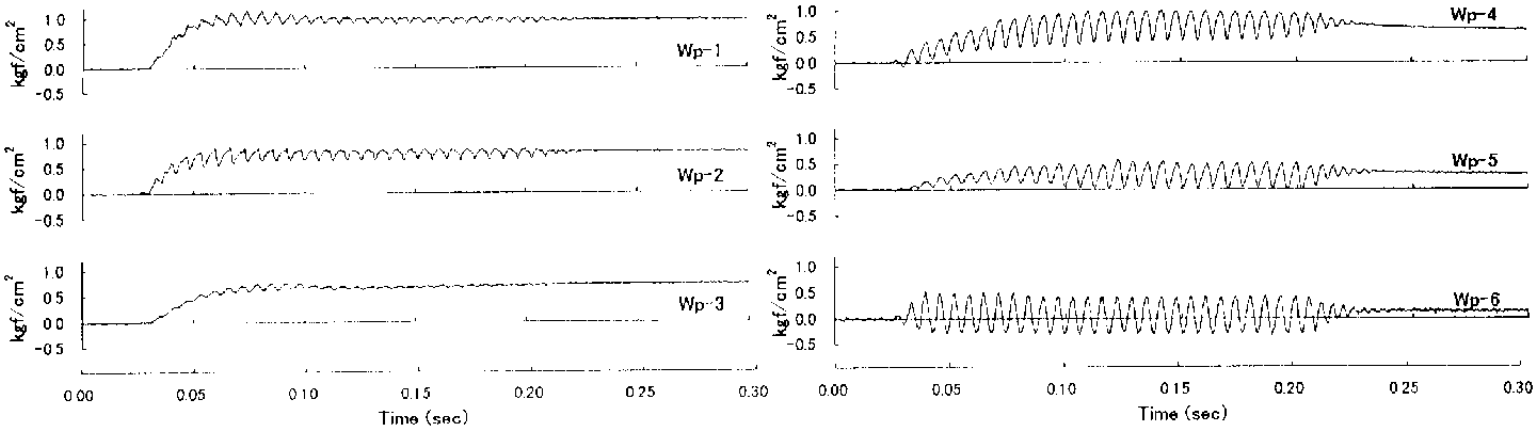


*Fig.-10 Excess Pore Water Pressure in Case of CF-20G (DL-clay Mixture Mode)l*

As for the behavior of caisson, sliding of caissons occur only during excitation. In the case where the ground just below the caisson is more thick, or in the case when the high level of excitation is applied, the possibility of post-excitation displacements of caisson might not be denied. However, it must be impossible to predict the displacements of caisson and the deformation of back-fill ground unless both inertia force of caisson and dynamic earth pressure are taken account.

From the analysis on dynamic earth pressure observed in experiments, it is found that when input acceleration is small, the dynamic earth pressure acts so as to restrain the movement of caisson and the excess pore water pressure hardly occurs. On the other hand, when the input acceleration is large enough to cause liquefaction, dynamic earth pressure acts rather so as to promote the movement of caisson. Consequently, even if in the same ground, it may be concluded that a tendency of the influence of the back-fill on the caisson changes depending upon the level of input acceleration and the degree of excess pore water pressure.

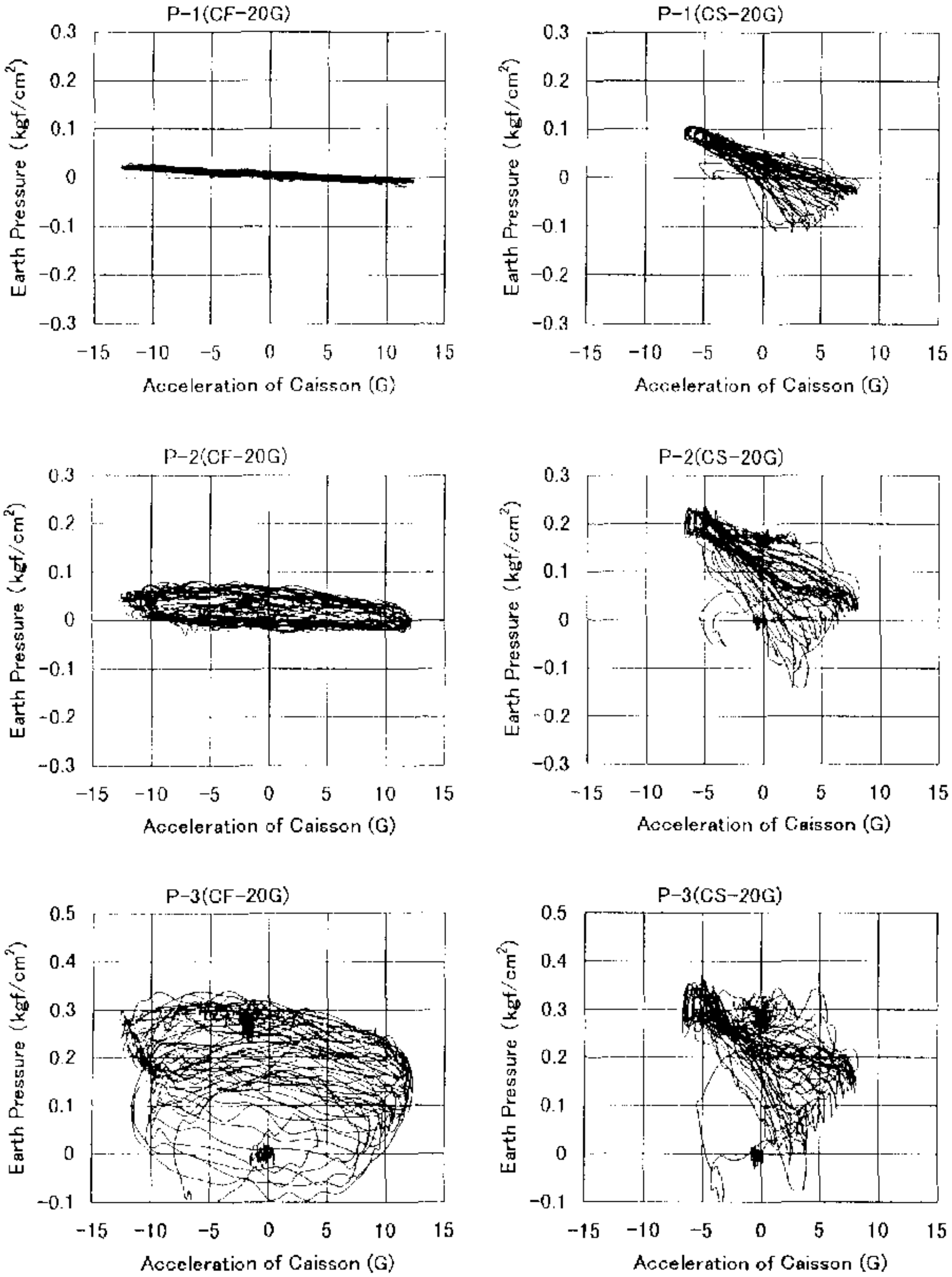


*Fig.-11 Relationship Between Accelerations of Caisson and Earth pressures Act on Caisson (Model-C)*

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