Dynamic Centrifuge Tests on Sea Revetment with Multi-Anchors

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ABSTRACT

In the construction of sea revetment, composite type of revetment has been frequently used in Japan, in which huge sized concrete caissons are placed on gravel mound to sustain earth pressure induced by sea reclamation. There are several case records of serious disaster with large displacement of the caisson in huge earthquake. This requires research efforts to find a new type of sea revetment having better static and dynamic performances. A sort of tieback caisson is an idea for the requirement, in which a concrete caisson with relatively small width is reinforced by many anchors. Authors started to study the applicability of this new type of caisson to sea revetment construction, in which a series of centrifuge tests has been conducted to investigate its static and dynamic behaviors. In the dynamic tests, the model ground was subjected to several earthquake motions at a 50 g centrifugal acceleration field until the ground failed. The model tests were conducted changing the caisson width and the number and length of anchors. Simple calculations incorporating with the anchor force were also conducted to evaluate stability of the caisson. This paper describes the model ground preparation, test results and calculated results in detail.

INTRODUCTION

In the construction of sea revetment, composite type of revetment has been frequently used in Japan, in which huge sized concrete caissons are placed on gravel mound to sustain earth pressure induced by sea reclamation. There are several case records of serious disaster with large displacement of the caisson in huge earthquake such as Hanshin-Awaji Earthquake in 1995, probably because of huge inertia force of the caisson induced by earthquake. This requires research efforts to find a new type of sea revetment having better static and dynamic performances. A sort of tieback caisson is an idea for the requirement, in which the concrete caisson with small width is reinforced by many anchors, as schematically shown in Fig. 1. It is expected to reduce the inertia force by downsizing the caisson and to increase stability by the anchors. These can contribute to improve dynamic performance of the caisson.

Retaining walls reinforced by anchors have been applied to various constructions such as road and railroad embankments. Many research efforts have been done to investigate static and dynamic behaviors of the wall, and design manual is established for road and railroad embankments in Japan (Public Work Research Center, 1997). However, there is few research on behavior of sea revetment with multi-anchors for port facilities such as sea revetment. Authors started to study the applicability of this new type of caisson reinforced by many anchors to sea revetment construction, in which a series of centrifuge tests was conducted to investigate its static and dynamic behaviors. A part of research activities on the static behavior has already been presented elsewhere (Kikuchi, et. al., 1999). In the dynamic tests, a model ground composed of a model caisson reinforced with several anchors and dry dense sandy ground were constructed in a two-dimensional

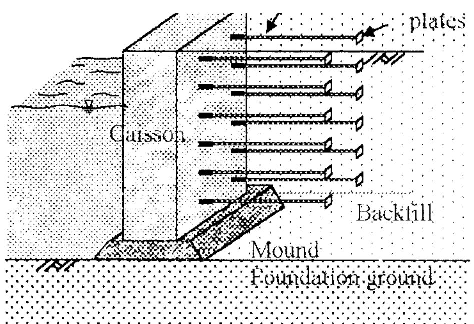

Fig. 1. Schematic view of new type caisson.

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specimen box. The model ground was subjected to several earthquake motions at a 50 g centrifugal acceleration field until the ground failed. The model tests were conducted changing the caisson width and the number and length of anchors. Simple calculations incorporating with the anchor force were also conducted to evaluate stability of the caisson. This paper describes the model ground preparation, test results and calculated results in detail.

CENTRIFUGE MODEL TEST

PHRI Centrifuge Facilities

The centrifuge used in this study is the PHRI (Port and Harbour Research Institute) Mark II geotechnical centrifuge. The centrifuge has a maximum acceleration of 113 g, a maximum effective radius of 3.8 m and a maximum payload of 2710 kg. The main part of the centrifuge is housed in an underground reinforced concrete pit for safety operation. Two swinging platforms are hinged to a rotating arm via torsion bar systems to safely deliver the radial force at high acceleration to end plates at both ends of the arm. A drive unit for the centrifuge of 450 kVA direct current motor is mounted on the underground floor. Figure 2 shows general view of the centrifuge apparatus. A shaking table is specially designed for centrifuge tests whose major capacity is summarized in Table 1. The centrifuge and surrounding equipment are described in detail by Kitazume and Miyajima (1996).

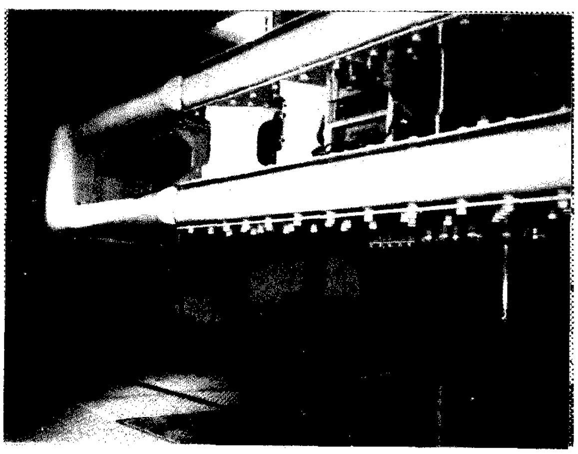


Fig. 2. PHRI Mark II Geotechnical Centrifuge.

Table 1. Major property of shaking table.

property	capacity
maximum centrifugal acceleration	50 g
maximum mass to be shaken	200 kg
maximum frequency	250 Hz
maximum acceleration	18 g
maximum stroke	6 mm

Model Ground Preparation

A specimen box used in the study was two dimensional rigid box whose inside dimensions were 60 cm in length, 41 cm in depth and 10 cm in breadth. Model ground selected in this study was very simple and was dry dense sandy ground as shown in Fig. 3, to focus upon the interaction of ground and model caisson and to avoid the influence of seawater and liquefaction which might happen in the backfill during the seismic loading. Toyoura sand was used as a ground material, whose soil particle density, maximum and minimum void ratios were 2.652 g/cm^3, 0.992 and 0.624, respectively.

The sandy ground was made by multi-sieved falling techniques in order to control the ground density with high repeatability. The caisson was manufactured of acrylic plates, having 20 cm in height, 5 cm in length and 10 cm in breadth. Several anchors were installed at two rows on the rear plate of the caisson. Each anchor had small end plate of 1 cm in square. A small strain gauge was also installed at the connection of the anchor and the caisson in order to measure the tensile force mobilizing along the anchor. Several accelerometers were also installed in the model ground and on the model caisson to measure their dynamic response. The laser displacement transducers were also installed to measure the displacement of the caisson.

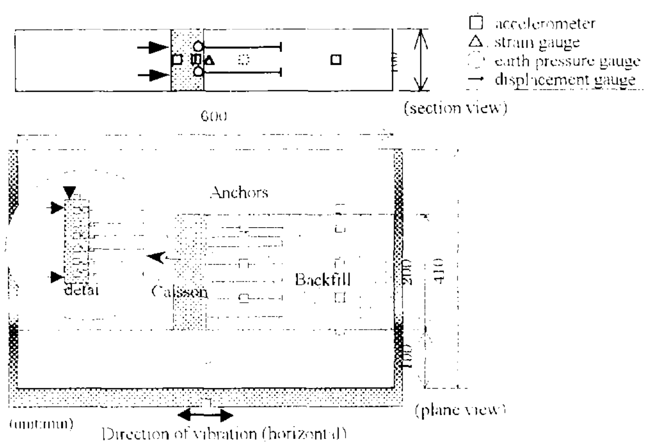


Fig. 3. Schematic view of model ground.

Dynamic loading tests

Model ground was brought up to a 50 g centrifugal field to simulate the prototype stress condition and then was subjected to several seismic loadings of 50 sinusoid waves until the ground failed. During the seismic loading, the accelerations in the model ground, the earth pressure, the tensile force along the anchors and the vertical and horizontal displacements of the caisson were measured. A total of 5 model tests was performed changing the caisson width and the anchor condition as summarized in Table 2, which included the test cases of non-anchored caisson (COD-1 and COD-2).

Table 2. Test cases.

test no.	width of caisson	number of anchors	length of anchors
COD-1	14.8 cm	0	-
COD-2	5.0 cm	0	-
U3D-1	5.0 cm	12 (6 rows)	12 cm
UT1_18D	5.0 cm	4 (2 rows)	18 cm
UT1_6D	5.0 cm	4 (2 rows)	6 cm

TEST RESULTS AND DISCUSSIONS

Displacement of Caisson

Figure 4 shows the relationship between the base acceleration and the horizontal displacements of the caisson at its top and bottom. The displacements in the figure are measured at the end of each seismic loading. It is found that the displacements of all the test cases increase with the increase of base acceleration. The non-anchored caisson with small caisson width, COD-2, shows relatively large increase in displacement with increasing the base acceleration, and fails at about 5 g acceleration. In the anchored caisson, on the other hand, the displacements of the caisson in U3D-1 and UT1_18D increase slowly and fail with large displacement at about 20 g acceleration. However in the case of UT1_6D, with short anchors, relatively large displacement takes place and fails at smaller acceleration. It can be found that the anchors function to increase the base acceleration at failure, if the number of anchors and/or the length of anchor are sufficient.

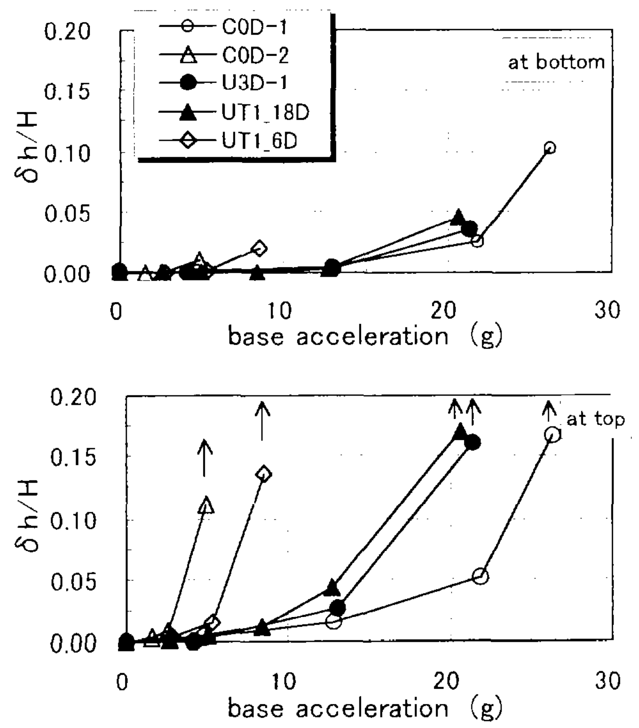
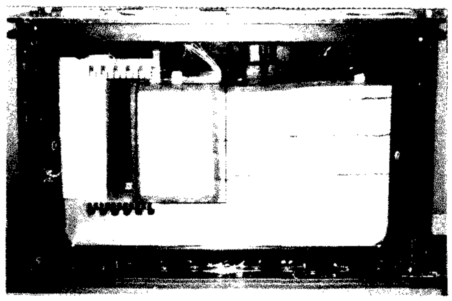


Fig. 4. Displacement of caisson.

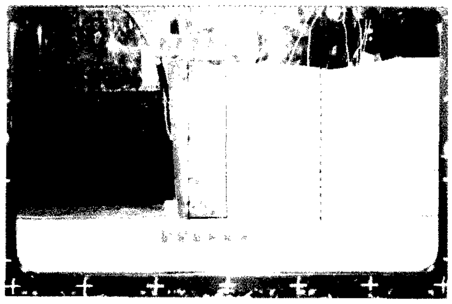
The displacement at the top end of the caisson is almost same order as that at the bottom of the caisson in the non-anchored caisson, COD-1, which means that the caisson with relatively large width moves almost horizontally by the seismic loading. In the anchored caisson, on the other hand, the displacement at the top of the caisson is larger than that at the bottom, which shows that the overturning displacement is prominent rather than the horizontal displacement. These phenomenon indicate that the failure mode of the caisson becomes the overturning failure rather than the sliding failure when the caisson width becomes small.

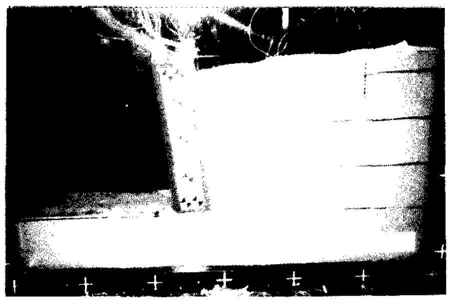
Failure Pattern of the Ground

Typical failure pattern of the ground is shown in Fig. 5. In the non-anchored caisson, COD-1, a clear straight slip line can be seen from the rear bottom of caisson toward the ground surface (Fig. 5(a)). Its gradient is about 61 degree to horizontal. In the case of anchored caisson as shown in Fig. 5(b), the caisson rotates about its front bottom due to the large horizontal inertia force together with the dynamic earth pressure of the backfill. It can be seen that relatively small



(a

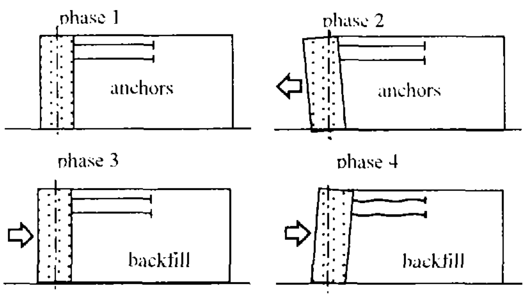




straight slip line develops not from the caisson but from the end plate of the middle depth anchor. In another anchored caisson as shown in Fig. 5(c), the caisson anchored with two rows, relatively small straight slip line takes place at the end of the anchors and develops toward the ground surface. This phenomenon means the sandy ground where the anchors are installed is confined by the anchors, and behaves as a whole together with the caisson.

Interaction of the Caisson and Backfill

Several acceleration gauges are installed on the caisson and in the backfill as well as the earth pressure gauges and the tensile force gauges in order to investigate the interaction of the caisson and backfill. Figure 6 shows typical records measured in the test case of UT1_18D, which includes the earth pressure, the acceleration of caisson and the tensile force of anchor. The figure also shows the horizontal displacement of the caisson at its center. It is found that the horizontal displacement of the caisson gradually increases together with several ups and downs with the time duration. It is convenient to divide the records into 4 phases for ease of discussing the interaction of the caisson and the backfill.



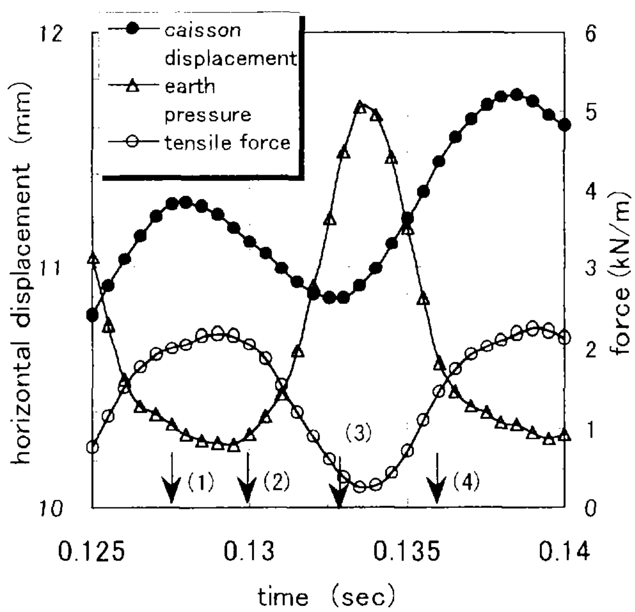


Fig. 6. Interaction of the caisson and the backfill.

At phase 1, in which the caisson and the backfill move toward the sea, the caisson moves faster than the backfill. It is found that the earth pressure acting on the rear side of the caisson decreases rapidly and the tensile force, on the other hand, increases.

At phase 2, in which the caisson moves backward to the center, the earth pressure increases rapidly and the tensile force of the anchor decrease.

At phase 3, the caisson moves backward from the center, the caisson movement is faster than the backfill movement, which provide the increase of the earth pressure. The tensile force continuously decrease.

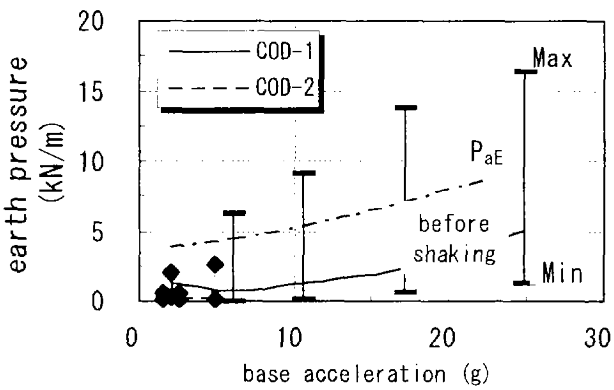
At phase 4, the caisson moves forward, the earth pressure decreases because the caisson moves forward faster than the backfill. The tensile force also increases.

These phenomena show that the earth pressure changes due to the interaction of the caisson and the backfill, and the maximum earth pressure takes place when the caisson moves toward the backfill.

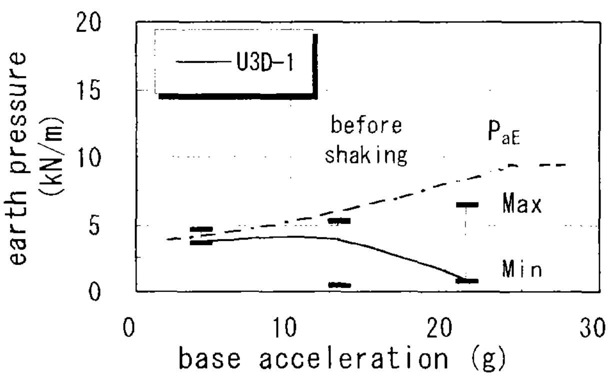
Dynamic Earth Pressure

Figure 7 shows the relationship between the measured dynamic earth pressure and the base acceleration. The sum of earth pressures before the shaking and the maximum and the minimum pressures during the shaking are plotted in the figure. In the case of non-anchored caisson (Fig. 7(a)), the earth pressure before the shaking is very small, which is probably because an arch effect within the backfill functions to reduce the earth pressure. The earth pressure before each shaking gradually increases to almost active earth pressure by the loading steps. This phenomenon is because the arch effect disappears due to transferring the active condition of the backfill. It is also found the maximum earth pressure increases very rapidly with increasing the base acceleration. The minimum pressure at each shaking is almost zero throughout the loading. This is due to the fact the caisson moves toward the sea direction faster than the backfill as described in the previous section. In the case of anchored caisson, on the other hand, the maximum pressure shows smaller value compared with those in the non-anchored case, and also shows small increase with the increase of base acceleration. The maximum earth pressure generates when the caisson moves toward the backfill. This indicates the magnitude of the maximum earth pressure is influenced not by the dynamic backfill pressure but by the inertia force of the caisson.

Mononobe and Okabe Equation has been frequently used to calculate the dynamic active earth pressure. The calculated earth pressure is also plotted in the figure. The calculated in the non-anchored case falls within the measured ranges. The calculated earth pressure in the case of the anchored caisson, however, overestimates the measured pressures. There is a sort of contradict in the comparison of the earth pressure, that the maximum earth pressure takes place when the caisson moves toward the backfill, in other ward at the passive condition, while earth pressure theory indicates the maximum pressure takes place in the active condition. Further research efforts are required to investigate the interaction of the caisson and the backfill, and the dynamic earth pressure.



(a) non-anchored caisson



(b) anchored caisson

Fig. 7. Dynamic earth pressure.

Tensile Force of Anchor

Strain gauge is installed at the joint of each anchor on the caisson in order to measure the tensile force along the anchor. Typical measured tensile forces in UT1_18D and UT1_6D are plotted in Fig. 8 against the horizontal displacement at the top of the caisson, in which the sum of the tensile forces is plotted. It is found that the tensile force in UT_18D is slightly larger than that of UT_6D even if the number of anchors is same each other. The anchors in UT_18D exceed beyond the slip surface and large enough to mobilize the large tensile resistance, while the anchors in UT_6D is short and does not exceed the slip surface. It can be concluded that the anchor length should be large and exceed beyond the slip surface in order to mobilize the tensile force.

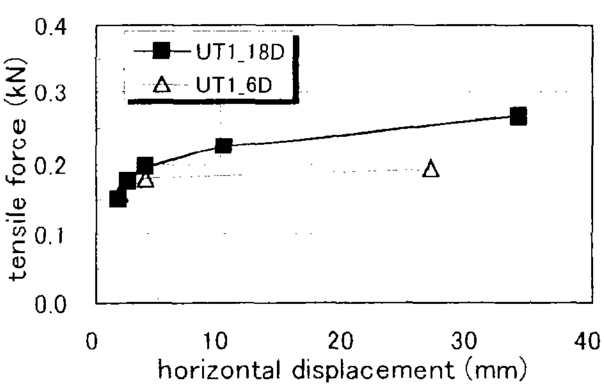


Fig. 8. Tensile force.

In the current design for earth reinforcement in Japan, the maximum tensile resistance of the anchor is derived as same manner as the bearing capacity formula, and can be expressed as following equation (Public Work Research Center, 1997). The equation means that the ultimate capacity of the anchor increase linearly with increase of the horizontal stress.

$$Q_{pu} = q_p \cdot N_q \cdot A \tag{1}$$

$$q_p = \rho \cdot g \cdot z \cdot K_a \tag{2}$$

where

- A : sectional area of anchor plate
- g : centrifugal acceleration
- K_a : coefficient of active earth pressure
- Q_{pu} : ultimate tensile resistance of anchor
- N_q : bearing capacity factor
- z : depth of each anchor
- q_p : horizontal stress
- ρ : density of backfill

The measured tensile forces of each anchor are re-plotted in Fig. 9 along the depth in which the tensile force is normalized to respect with the design value. It shows that the mobilization ratio, Q/A ρ g z at shallow depth is relatively large and then decreases rapidly toward the depth. The is probably because the anchored caisson shows the horizontal displacement at the deeper location is not sufficient to mobilize the full resistance. This phenomenon indicates that all of the anchors does not mobilize their full capacity but only some anchors at relatively shallow depth does.

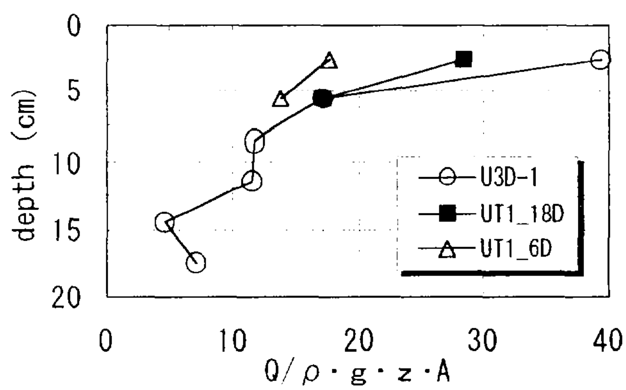
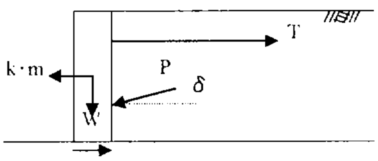


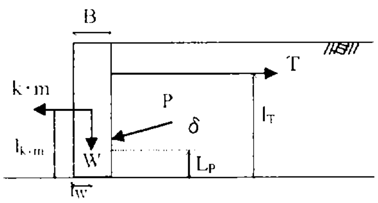
Fig. 9. Tensile force distribution along the depth.

Evaluation of Stability of Caisson

In order to evaluate the stability of the caisson with anchors, a simple calculation is conducted, in which the sliding failure and over-turning failure are simulated. The safety factors for two failure patterns are derived by the horizontal force and the moment equilibrium of the caisson as shown in Fig. 10, and can be expressed as following equations.



(a) sliding failure



(b) overturning failure

Fig. 10. Evaluation of safety factors for sliding and overturning failures.

$$Fs(sliding) = \frac{T + F}{P \cdot \cos\delta + k \cdot m} \quad (1)$$

$$Fs(overturning) = \frac{T \cdot l_t + W \cdot l_w + P \cdot \sin\delta \cdot B}{P \cdot \cos\delta \cdot l_p + k \cdot m \cdot l_{km}} \quad (2)$$

where

Fs(sliding): safety factor for sliding failure
Fs(overturning): safety factor for over turning failure
k: inertia coefficient
l_t: length of the moment for tensile force
m: self mass
P: earth pressure
T: total of tensile force mobilized along the anchors
δ: friction angle on the caisson surface

The safety factors are calculated by substituting the measured earth pressure and tensile forces into the equations (1) and (2). The calculated safety factors for two failure patterns are shown against the base acceleration in Fig. 11. It is found that the safety factors decrease with increase of the base acceleration. The safety factor for overturning failure is smaller than that for the sliding failure in the case of the anchored caisson, which confirms that the failure pattern of the anchored caisson. In the case of UT1_6D and C0D-2, the safety factors decrease rapidly compared with other test cases, which shows the caisson with relatively small reinforcement by the anchors becomes unstable in the seismic condition even if it is stable in the static condition.

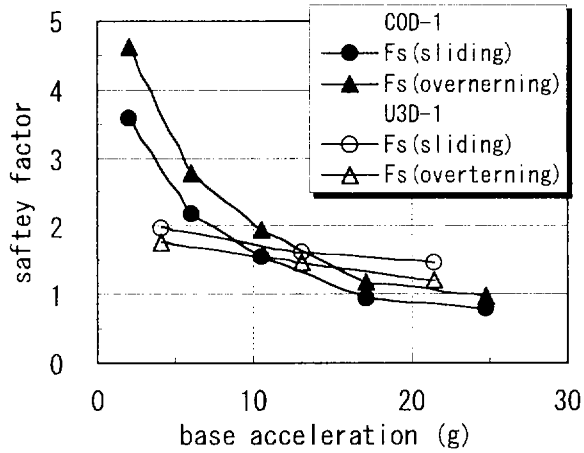


Fig. 11. Safety factor.

CONCLUSIONS

A series of centrifuge dynamic tests was performed to investigate the interaction of the anchored caisson and backfill, and the applicability of the anchored caisson. The specific conclusions derived from this study are as following:

1. The anchored caisson with relatively small width shows overturning failure while the conventional caisson with large width shows sliding failure.
2. The tensile anchor force is influenced by its depth and length. The relatively large anchor length should be required to mobilize the large tensile force. The mobilization ratio of the tensile resistance against the current design procedure decreases with the increase of depth.
3. The simple calculations assuming the sliding and the overturning failure of the caisson shows fairly good estimation of the base acceleration at failure.
4. The anchored caisson shows large dynamic resistance, and the relatively high applicability of such an anchored caisson is confirmed.

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