New Horizons in Earth Reinforcement – Otani, Miyata & Mukunoki (eds)

Centrifuge model tests of static and dynamic behaviors of multi-anchored sea revetment

Y. Kikuchi & M. Kitazume
Port & Airport Research Institute, Yokosuka, Japan

ABSTRACT: In sea revetment construction, composite-type revetments in which huge concrete caissons are placed on a gravel mound to sustain the earth pressure induced by sea reclamation, have frequently been used in Japan. However, in several cases, serious disasters resulted from large displacement of the caisson in a giant earthquake. Therefore, research to find a new type of sea revetment with better static and dynamic performances was necessary. A type of tieback caisson, in which a concrete caisson of relatively small width is reinforced by multiple anchors, is one concept for satisfying this requirement. A series of centrifuge model tests of this new type of caisson in sea revetment construction was conducted to investigate its static and dynamic behaviors. This paper describes the test results and applicability of sea revetments with multi-anchors.

1 INTRODUCTION

Reinforced earth structures have been widely used in retaining structures such as Terre armee or anchored plates. On the other hand, few case records have been reported in connection with the construction of port facilities. In order to introduce this method in the construction of port facilities such as sea revetments, as shown schematically in Figure 1, the applicability of reinforced earth methods to sea revetment construction was examined in centrifuge model tests in a series of static and dynamic centrifuge model tests of this new type of caisson.

In the static tests, the effect of the stiffness of the foundation ground on the behavior of this kind of structure was examined. In the dynamic tests, the model ground was subjected to several earthquake motions in a 50 g centrifugal acceleration field until the ground failed. Based on these test series, this paper discusses the applicability of sea revetments with multiple anchors.

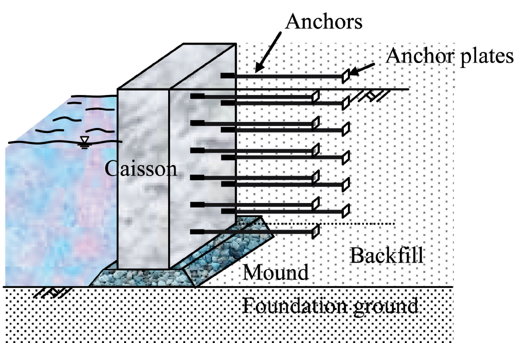

Figure 1. Schematic view of new type caisson.

Many types of retaining walls reinforced with anchors have been applied to various types of construction such as road and railroad embankments. Much research has investigated the static and dynamic behaviors of such walls, and a design manual was established for road and railroad embankments in Japan (Public Works Research Center, 1997). However, there has been little research on the behavior of sea revetments with multiple anchors for port facilities such as sea revetments. The authors therefore began to study the applicability of this new type of caisson reinforced by multiple anchors to sea revetment construction by conducting a series of centrifuge tests to investigate its static and dynamic behaviors. The model tests were conducted by changing the caisson width and number and length of anchors. This paper describes the model ground preparation, test results, and calculated results in detail.

2 CENTRIFUGE MODEL TESTS

2.1 *PARI centrifuge facilities*

The centrifuge used in this study is the PARI (Port & Airport Research Institute) Mark II geotechnical centrifuge. This centrifuge has a maximum acceleration of 113 g, maximum effective radius of 3.8 m, and maximum payload of 2,710 kg. For safe operation, the main part of the centrifuge is housed in an underground reinforced concrete pit. 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. As the centrifuge drive unit, a 450 kVA DC motor is mounted on the underground floor. The centrifuge and its peripheral equipment were described in detail by Kitazume and Miyajima (1996).

2.2 *Static loading tests*

To investigate the effect of the stiffness of the foundation on the behavior of a reinforced revetment, two extreme ground conditions were simulated, as shown schematically in Figures 2 and 3. In Figure 2, a thin clay layer underlaid by the revetment was modeled. The caisson was estimated to fail by sliding failure with negligible settlement (series S). In Figure 3, a relatively thick, low strength clay layer was modeled, and the caisson was estimated to fail with relatively large vertical and horizontal displacements (series B).

A rigid specimen box having inside dimensions of 50 cm in length, 35 cm in height, and 10 cm in width was used in both cases. The front side of the box has an acrylic window to allow direct observation of the model behavior during the test.

The sand used was Toyoura sand. The clay was a mixture of two types of Kaolin clay (ASP100:5M = 1:1, $w_L = 64\%$, $I_P = 37$). The dense sand layer for the base was compacted to Dr = 70% in a wet condition. Clay having an initial water content

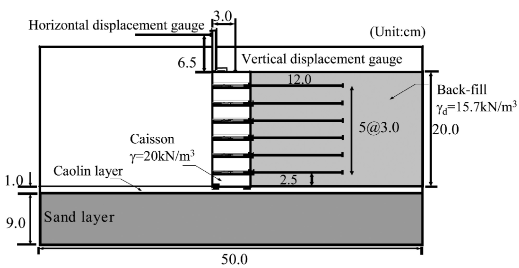

Figure 2. Schematic view of model (Series S).

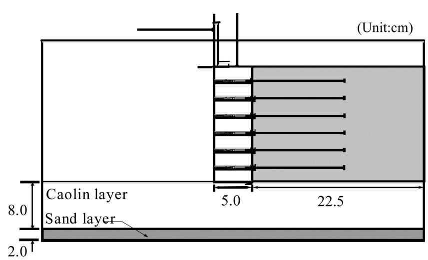

Figure 3. Schematic view of model (Series B).

of 120% was consolidated in the laboratory to the specified pressure. The conditions of the base ground are summarized in Table 1. Dry Toyoura sand, whose soil particle density and maximum and minimum void ratios were 2.652 g/cm^3, 0.992, and 0.624, respectively, was used for backfilling. Its unit weight was controlled to 15.4 kN/m^3 ($D_r = 80\%$, $\phi' = 40°$).

In the test series, two types of caisson were used with both ground conditions. One was a conventional type caisson (called C), the dimensions of which were 14.8 cm in width, 20 cm in height, and 9.6 cm in length. The other was a multi-anchored caisson (called R) with comparatively small width, in which several sets of anchor rods were installed on the rear side. The dimensions of the R caisson were 5 cm in width, 20 cm in height, and 9.6 cm in length. Each R type caisson was reinforced with either 0, 4, 8, or 12 steel anchor rods, which were inserted in 0, 2, 4, 6 levels in two rows from the bottom, respectively. Each anchor rod had a diameter of 0.45 mm and a length of 12 cm. Copper anchor plates, which were 1 cm square, were attached at the end of each rod. A strain gauge was installed on the copper plates, connecting each anchor rod at the caisson, to measure the tensile force induced in the test. The earth pressure acting on the caisson was measured by earth pressure gauges on the rear side of the caisson at five depths along its center.

The unit weight of both types of caisson was controlled to 20 kN/m^3 by filling the caissons with lead shot. Sandpaper was attached to the caisson bottom to simulate a rough condition.

In the static test series, centrifuge acceleration was increased continuously until the model ground failed. The height of the model caisson corresponded to 20 m in a prototype scale at a centrifugal acceleration of 100 g, which is within the previous case histories for larger sea revetments. Displacement of the caisson, earth pressure acting on the caisson, and the tensile force of each anchor rod were measured at 1 g increments. The ground behavior and displacement of the caisson during the test were also videotaped.

2.3 *Dynamic loading tests*

The shaking table used was specially designed for the centrifuge. Its main specifications are as follows; Maximum centrifugal acceleration is 50 g, Maximum mass to be shaken is 200 kg, Maximum frequency

Table 1. Base ground condition.

Layer	Mode of failure: Sliding (Series S)	Bearing (Series B)
Clay	1 cm (p = 196 kPa)	8 cm (p = 59 kPa)
Sand	9 cm (Dr = 70%)	2 cm (Dr = 70%)

is 250 Hz, Maximum acceleration is 18 g, Maximum stroke is 6 mm.

The specimen box was a 2-dimensional rigid box whose inside dimensions were 60 cm in length, 41 cm in depth, and 10 cm in width. In order to focus on the interaction of the ground and model caisson and avoid the complicated influence of seawater and liquefaction which might occur in the backfill under seismic loading, the model ground studied in this test series consisted of the caisson, base layer, and backfill with dry dense sand, as shown in Figure 4. Toyoura sand was used as the ground material.

The caissons were the same as those used in the static tests. Several anchors were installed in two rows on the rear plate of the caisson. The anchors were the same type as those used in the static tests. Several accelerometers were installed in the model ground and on the model caisson to measure their dynamic responses. Laser displacement transducers were installed to measure the displacement of the caisson.

The model ground was accelerated to a 50 g centrifugal field in order to simulate the prototype stress condition, and was then subjected to several seismic loadings of 50 sinusoid waves until the ground failed. During seismic loading, the accelerations in the model ground, earth pressure, tensile force along the anchors, and vertical and horizontal displacements of the caisson were measured. A total of five model tests were carried out using various caisson widths

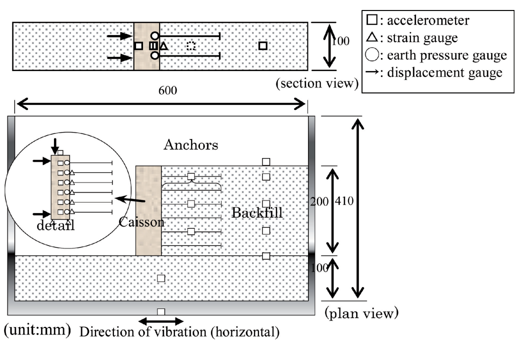

Figure 4. Schematic view of model ground for dynamic loading tests.

Table 2. Test cases for dynamic loading tests.

Test no.	Width of caisson	Number of anchors	Length of anchors
C0D-1	14.8 cm	0	–
C0D-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

and anchor conditions, as summarized in Table 2, and included non-anchored cases (C0D-1 and C0D-2).

3 TEST RESULT AND DISCUSSION

3.1 *Static loading tests*

3.1.1 *Acceleration field at failure*

Figure 5 shows the relationship between the number of anchor rods and centrifugal acceleration at failure for test series S. The upward arrows in the figure indicate that the model ground did not fail at the maximum centrifugal acceleration of 100 g. In the type R caisson, the acceleration at failure increased almost linearly as the number of rods increased. The measured acceleration in the conventional type caisson is also plotted as a full square in the figure. In this case, the model caisson was stable with very small displacement even at 70 g, at which centrifuge loading had to be terminated due to trouble in the displacement transducer. However, it can be concluded that the failure acceleration was higher than 70 g.

Figure 6 shows the relationship between the number of anchor rods and centrifugal acceleration at failure for series B. The failure acceleration increased with the number of rods, but became basically constant at

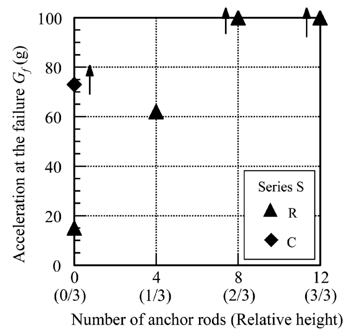

Figure 5. Acceleration at failure (Series S).

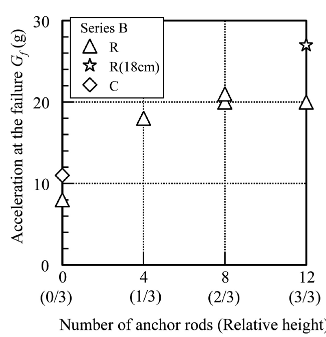

Figure 6. Acceleration at failure (Series B).

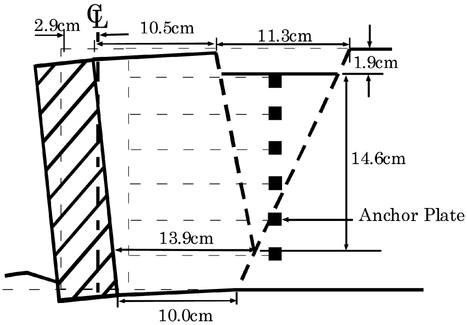

Figure 7. Slip in backfill (B-R-3/3).

8 rods. An additional experiment was carried out to investigate the effect of the anchor length, in which the length and number of anchor rods were 18 and 12 cm , respectively. The test result was plotted as a star mark in Figure 6. This result showed that the longer anchor rods gave higher resistance of this extent. The failure acceleration obtained in the conventional caisson test is also plotted as an open square in the figure. Even with 4 anchor rods, the failure acceleration of the R type caisson was higher than that of the C type.

Both figures show that the reinforced caisson has higher resistance than conventional caissons.

3.1.2 *Displacement of caisson and deformation of ground*

The displacement of the caisson and deformation of the ground were evaluated based on the video record. From this observation, only small deformation took place in the ground in series S until failure. In this series, the final failure mode of the caisson seemed to be rotational, and the slip deformation in the backfill was similar to the zone assumed in Coulomb's active earth pressure theory.

In series B, slip failure was clearly observed in the backfill layer. Figure 7 shows an example of the typical slip failure at the maximum centrifugal acceleration of 20 g. This kind of failure mode was observed only when the number of rods was 8 or 12. From this kind of deformation, the imaginary retaining wall width can be considered in the zone of anchor rods existing if the reinforced height is more than 2/3 of the caisson height.

3.1.3 *Change of earth pressure acting on caisson*

Figures 8 and 9 show the changes in the earth pressure acting on the caisson measured during increasing acceleration in series S and B, respectively. Several thin lines with various values of $K = \sigma_h/\sigma_v$ are also plotted in the figure, in which σ_h and σ_v are the horizontal and vertical earth pressures, respectively. It was found that the values of K obtained from the measured σ_h and estimated σ_v increased with the number of rods.

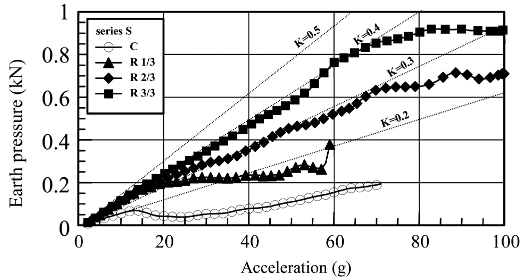

Figure 8. Relationship between acceleration and earth pressure (Series S).

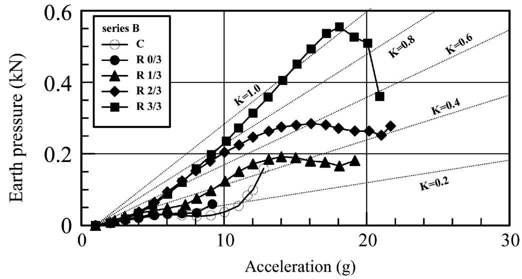

Figure 9. Relationship between acceleration and earth pressure (Series B).

It is considered that the sum of the measured tensile forces along the rods increased with increasing centrifugal acceleration in both series. A large value of K means that the backfill in the anchored zone was strengthened by the anchors. This phenomenon indicated that the group of anchor rods could also function to confine the backfill layer.

In series S, the values of K were substantially constant as long as acceleration remained low but decreased when acceleration increased. The decrease in K was dominant when the relative height of the anchored zone was small. In series B, the change in K was different from that in series S. The K estimated in the test was almost constant as long as the centrifugal acceleration remained relatively small but increased rapidly with increased acceleration for further acceleration.

In the non-anchored cases in both series, K values decreased temporarily and then increased or were constant as centrifugal acceleration increased. This kind of change in K was affected by the mode of caisson movement.

3.2 *Dynamic loading tests*

3.2.1 *Displacement of caisson*

Figure 10 shows the relationship between the base acceleration and horizontal displacements of the caisson at its bottom and top. The displacements in the figure were measured at the end of each seismic

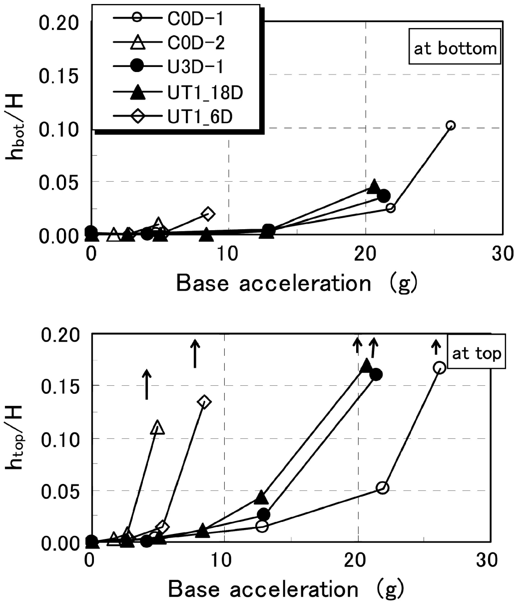

Figure 10. Displacement of caisson.

loading and normalized with respect to the caisson height. It was found that the displacements in all the test cases increased with base acceleration. The non-anchored caisson with a small caisson width, C0D-2, showed a relatively large increase in displacement with increasing base acceleration and failed at about 5 g acceleration. In the anchored caissons, on the other hand, the displacements of the caisson in U3D-1 and UT1_18D increased gradually and the ground failed with large displacement at about 20 g acceleration. However, in UT1_6D, with short anchors, relatively large displacement took place and failure occurred at smaller acceleration. It was found that the anchors function to increase the base acceleration at failure, provided that the number and/or length of the anchors are sufficient.

In the non-anchored caisson, C0D-1, the displacement at the top of the caisson is on virtually same order as that at the bottom of the caisson, which means that a caisson with a relatively large width moves almost horizontally under 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 means overturning displacement is dominant, rather than horizontal displacement. These phenomena indicate that the failure mode of the caisson becomes overturning failure rather than sliding failure when the caisson width is small.

3.2.2 *Interaction of caisson and backfill*

Several acceleration gauges were installed on the caisson and in the backfill in addition to the earth

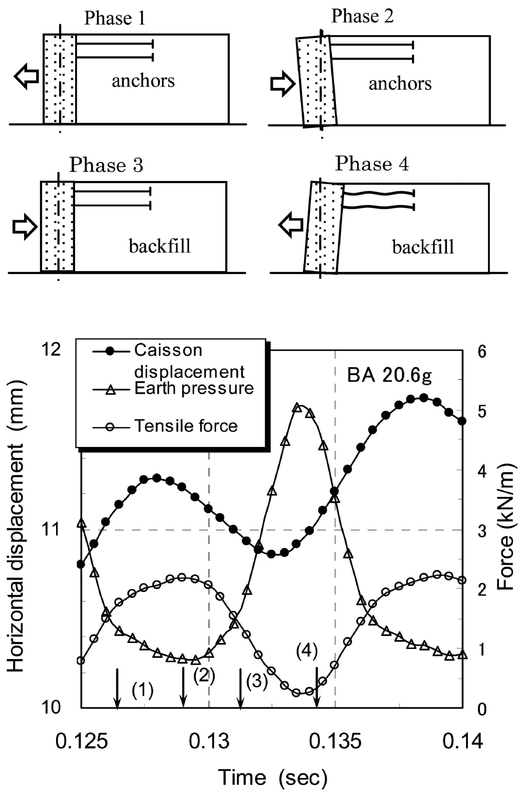

Figure 11. Interaction of caisson and backfill (UT1_18D; base acceleration is 20.6 g).

pressure gauges and tensile force gauges in order to investigate the interaction of the caisson and backfill. Figure 11 shows typical records measured in the test of UT1_18D, which include earth pressure, acceleration of the caisson, and the tensile force of the anchor. The figure also shows the horizontal displacement of the caisson at its center. Horizontal displacement of the caisson gradually increased with several rises and falls over the time duration. For ease in discussing the interaction of the caisson and backfill, it is convenient to divide the record into four phases.

In phase 1, in which the caisson and backfill move toward the sea side, the caisson moves faster than the backfill. The earth pressure acting on the rear side of the caisson decreases rapidly, whereas tensile force increases.

In phase 2, in which the caisson moves backward to the center, the earth pressure increases rapidly and the tensile force of the anchors decreases.

In phase 3, the caisson moves backward from the center, and the caisson movement is faster than the backfill movement, which causes an increase in earth pressure. Tensile force decreases continuously.

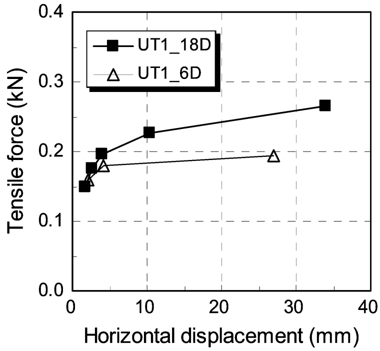

Figure 12. Tensile force.

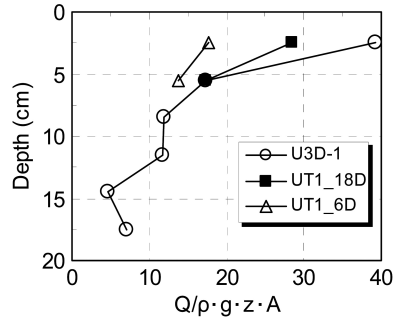

Figure 13. Tensile force distribution along the depth.

In phase 4, the caisson moves forward, and the earth pressure decreases because the caisson moves forward faster than the backfill. Tensile force also increases.

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

3.2.3 *Dynamic earth pressure*

In the case of a non-anchored caisson, the maximum earth pressure increases very rapidly as base acceleration increases. The minimum pressure at each shaking is almost zero throughout loading. This is because the caisson moves faster toward the sea side than the backfill, as described in the previous section.

In the case of the anchored caisson, the maximum earth pressure is smaller compared with the non-anchored case and also shows a small increase as base acceleration increases. The maximum earth pressure occurs when the caisson moves toward the backfill side. This indicates that the magnitude of the maximum earth pressure is influenced not by the dynamic backfill pressure but by the inertial force of the caisson.

3.2.4 *Tensile force of anchors*

Typical measured tensile forces induced along the anchor rods are plotted in Figure 12 against the horizontal displacement at the top of the caisson for UT1_18D and UT1_6D, plotting the sum of the tensile forces. The tensile force in UT_18D was slightly larger than that in UT_6D even when the number of anchors was same. The anchors in UT_18D extended beyond the slip surface and were large enough to mobilize large tensile resistance, while the anchors in UT_6D were short and did not extend beyond the slip surface. Therefore, it can be concluded that the anchor length should be large and the anchors should extend beyond the slip surface in order to mobilize tensile force.

In the current Japanese design procedure for earth reinforcements, the maximum tensile resistance of the anchor is derived in a similar manner to the bearing capacity formula and can be formulated in the following equations (Public Works Research Center, 1997). The equations mean that the ultimate capacity of the anchor increases linearly as horizontal stress increases.

$$Q_{pu} = q_p \cdot N_q \cdot A \qquad (1)$$

$$q_p = \rho \cdot g \cdot z \cdot K_a \qquad (2)$$

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 replotted in Figure 13 along the depth. Tensile force is normalized with respect to the calculated values. This figure shows that the mobilization ratio, Q/($\rho \cdot g \cdot z \cdot A$) at shallow depths is relatively large and then decreases rapidly in the depth direction. This is probably because the anchored caisson shows horizontal displacement in the deeper portion is not large enough to mobilize full resistance. This phenomenon indicates that only some anchors at relatively shallow depths mobilize their full resistance, and not all anchors achieve full capacity.

4 CONCLUSIONS

A series of static and dynamic centrifuge tests was performed to investigate the applicability of the anchored caisson to waterfront structures. The major conclusions derived from this study are summarized as follows:

1) A caisson reinforced with multiple anchor rods has higher resistance than conventional-type caissons.
2) From static loading tests, it was found that the earth pressure acting on the wall increases as the number of anchor rods increases. This increment is due to the increment of confining pressure in the

reinforced zone. An imaginary caisson width considering the safety of the structure can be estimated with a sufficient number of anchors.
3) The failure mode and resistance increment of the reinforced caisson are affected by the base ground condition.
4) Under dynamic loading conditions, the failure mode of an anchored caisson of relatively small width is overturning failure, whereas the failure mode of conventional-type caissons with large widths is sliding failure.
5) The tensile force on the anchors is influenced by the anchor depth and length at failure. A relatively large anchor length is required to mobilize large tensile force. The mobilization ratio of tensile resistance in the current design procedure decreases with increasing depth.

The authors wish to note that this research does not give sufficient consideration to actual construction problems. The conditions affecting construction of port facilities, such as the difficulty of backfill compaction in underwater construction and the effect of residual settlement of the base ground and backfill on anchor rods, should also be considered. Examination of problems of this type is important in the introduction of multi-anchored structures as sea revetments.

REFERENCES

Kikuchi, Y., Kitazume, M. and Kawada, Y. 1999. Applicability of Reinforced Earth Method to Sea Revetment. *Technical Note of the Port & Harbour Research Institute* (946): 36. (in Japanese).
Kitazume, M. and Miyajima, S. 1996. Development of PHRI Mark II Geotechnical Centrifuge. *Technical Note of the Port & Harbour Research Institute* (817): 33.
Public Works Research Center. 1997. *Design and execution manual for reinforced wall with multi-anchors*: 190. (in Japanese).