Centrifuge model tests examining stability of seawalls subjected to high waves

Essais sur modèle de centrifugeuse pour examiner la stabilité des digues qui sont soumises à de hautes vagues

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ABSTRACT: Some seawalls subjected to high waves would collapse because of the ground failure itself. However, the failure mechanism including ground behaviour has not been sufficiently verified yet. This study introduced the centrifuge technique in order to clarify it. The results of the model tests showed two patterns of failure: the blow-off of the covering panel, and the ground sliding. These were induced when the seawall became unstable during backwash after repeated surging and backwashing. Surge waves wet the ground behind the covering panel, and also increased the unit weight of the ground. In addition, the measured pore water pressure showed that a seepage force occurred in the ground, which is considered to contribute to the sliding failure.

RÉSUMÉ : Certaines digues qui sont soumises à de hautes vagues pourraient s'effondrer en raison de la rupture du sol lui-même. Cependant, le mécanisme de rupture, y compris le comportement du sol, n'a pas encore été suffisamment vérifié. Cette étude a introduit la technique de la centrifugeuse afin de le clarifier. Les résultats des essais sur modèle ont montré deux motifs de rupture : la couverture qui est soufflée et le glissement de terrain. Ceux-ci ont été induits quand la digue est devenue instable pendant le ressac après une houle et un ressac répétés. Les vagues humidifient le sol au-delà de la couverture et augmentent également le poids volumique du sol. De plus, la pression de l'eau interstitielle qui a été mesurée a montré qu'une force d'infiltration apparaît dans le sol et nous considérons qu'elle contribue à rupture de glissement de terrain.

KEYWORDS: centrifuge, seawalls, ocean wave, stability, sliding failure, seepage force.

1 INTRODUCTION

Most of the seawalls in Japan are constructed using the same type of structure, where the ground slope is covered and protected by concrete planes. These seawalls have been hit by high waves induced by typhoons and low pressures, and have collapsed, including the ground. Even today, seawalls suffer from the same type of failure. In the case where the seawalls failed at the ground, it has been generally considered that the covering plates were moved seaward by an uplift force induced by waves, or scouring around the toe, and subsequently the exposed ground was scoured. On the other hand, it is expected in some cases that seawalls would collapse because of the ground failure itself. Slopes in mountains and river embankments often lose stability due to rainfalls and the percolation of water, respectively. The same instability must occur in seawalls because waves allow the percolation of water into the ground and drastically change the boundary condition of water on the ground surface. Figure 1 shows the schematic view of seawalls subjected to high waves. The water level inside the ground and pore water pressure fluctuate in response to waves, and water percolates into the ground through the gap between panels and/or the ground surface as a result of overtopping waves. In particular, it is estimated that the seawall becomes most unstable at the backwash stage, where the water

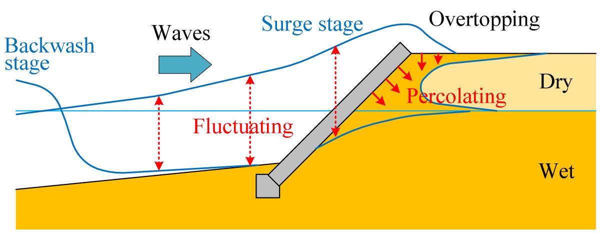


Figure 1. Schematic view of seawalls subjected to high waves.

level in front of the panel is the lowest. This is because the seaward seepage force in the ground is the largest at this time. However, the failure mechanism has not been sufficiently verified yet.

In this study, a series of model tests were conducted to investigate the failure mechanisms of seawalls, taking ground behaviour into account. The notable point of this study is that the model tests were performed in centrifugal acceleration by combining wave propagation and ground deformation. The Froude law has generally been used in hydraulic model testing on wave propagation in the gravitational field. It can be satisfied automatically in the centrifugal field because gravity can be increased to the model size. By using the modelling of models method, Takahashi et al. (2014a) has already demonstrated that the fundamental properties of waves can be reproduced in the centrifugal field, whereas the stability of the seawall ground can be assessed because the centrifugal acceleration causes prototype stress and pore water pressure, including suction. Satisfying the similitude laws on both wave propagation and ground deformation causes the centrifuge model test to simulate the prototype behaviour.

2 CONDITIONS OF CENTRIFUGE MODEL TESTS

2.1 *Law of similitude*

In this study, it was presumed that wave behaviour obeys the Froude law. The viscous force and surface tension of fluid could be considered negligible compared to the large inertia force because the scale ratio of the model was only 1/50. In the model tests using the centrifugal acceleration Ng, the gravity, g and length, L in the denominator of the Froude number are multiplied by N and $1/N$ times, respectively. In this case, the velocity in the numerator does not need to be multiplied by the scale ratio. This fact means that the model test has an advantage in that it can be conducted in a centrifuge, because most of the wave behaviour depends on the flow velocity of water, and it indicates that they can be reproduced in the model.

Table 1 summarises the similitude ratios for ground and pore water, and the ratios in the prototype and the model using water

Table 1. Similitude ratios in model tests.

Item		Prototype	Model	
			Water	Viscous fluid
Basic conditions	Centrifugal acceleration	1	N	N
	Model size	1	$1/N$	$1/N$
	Diameter of soil particle	1	1	1
	Density	1	1	1
	Dynamic viscosity	1	1	N
Ground properties	Stress	1	1	1
	Water pressure	1	1	1
	Hydraulic gradient	1	1	1
	Deformation	1	$1/N$	$1/N$
	Strain	1	1	1
Laminar flow	Mean flow velocity	1	N	1
	Time of seepage	1	$1/N^2$	$1/N$
Turbulent flow	Mean flow velocity	1	$N^{1/2}$	$N^{1/2}$
	Time of seepage	1	$1/N^{3/2}$	$1/N^{3/2}$

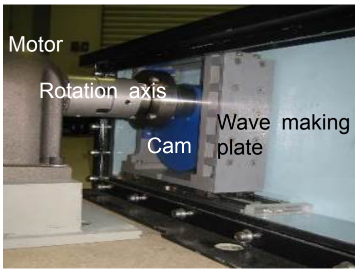
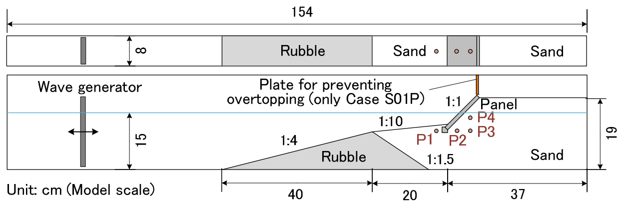


Figure 2. Wave generator used for tests.

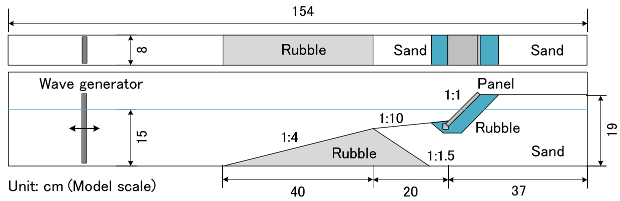
or viscous fluid are represented. Further detail, including the derivation process, can be seen in the paper by Takahashi et al. (2014b). Stress and pore water pressure in a prototype scale can be naturally reproduced in a model under centrifugal acceleration regardless of the viscosity of the fluid. As most of the soil behaviour depends on stress and pore water pressure, the similitude law of the ground behaviour, e.g. strain, can be satisfied. Regarding the flow of pore water, the similitude ratio of time to seepage flow is $1/N^2$ when using water as fluid, and seepage proceeds faster than the wave motion. Here, the flow in the void is presumed to be laminar. On the other hand, the similitude ratio is $1/N$ when using a viscous fluid with N times the viscosity of water. The times of seepage and wave motion agree in this case. In the present study, both water and viscous fluid were used to investigate the effect of seepage velocity on the stability of the seawall ground.

2.2 *Experimental apparatus and seawall model*

Figure 2 shows the wave generator used for the centrifuge tests. In this apparatus, a wave panel is moved using the cam mechanism, which is joined to a motor placed outside the specimen container, through a waterproof hole on the side wall. Although this wave generator cannot make complex irregular waves, it is quite simple and compact and also suitable for centrifuge model testing. The model grounds were prepared in the specimen container, and Figure 3 represents the schematic views of the models. The ground material was silica sand which was excavated in Yamagata Prefecture in Japan, and is called Iide sand cat. 7. The sand particles have a mean diameter, D_{50}, of 0.18 mm, and the fineness of the sand would make the flow of pore water laminar. The ground was created using a sand raining technique in dry conditions. The target for relative density was 90%, which corresponds to dense ground. The acrylic plates affixed with lead beads were put on the slope of the formed ground to model the covering panel, which is usually used to protect the inner ground. The ground pressure from the panel was 7.9 kN/m^2 perpendicular to the slope. A test



(a) S01, S01P, S50, S02



(b) S01R

Figure 3. Plan and elevation views of models.

Table 2. List of centrifuge model tests.

Case	Viscosity of fluid against water	Overtopping	Backfill
S01	1	Allow	Sand
S01P	1	Prevent	Sand
S01R	1	Allow	Rubble
S50	50	Allow	Sand
S02	2	Allow	Sand

case had rubble with a size of 3 ~ 7 mm behind the panel. After preparing the dry ground model, water or viscous fluid was percolated into the ground slowly so as not to demolish the ground.

All test cases are listed in Table 2. Five tests were performed to examine the effects of the viscosity of the fluid, overtopping wave, and rubble behind the panel. Three kinds of viscosity were applied to the fluid: water, and a viscous fluid with twice and 50 times the viscosity of water, respectively. Figure 3 (b) shows the location of the rubble in case S01R, where rubble was put under the covering panel. In cases S50 and S02, miniature pore water pressure gauges were embedded in order to measure pore water pressure in the ground.

2.3 *Experimental methods*

The prepared model was put on the platform of a centrifuge machine. The machine used in the study is PARI Mark II, owned by Port and Airport Research Institute (Kitazume & Miyajima, 1995). This machine has a large platform, which can accommodate a specimen container with a maximum length of 1600 mm. Under a centrifugal acceleration of 50g, waves were generated, and pore water pressure and seawall failure were observed. Both amplitudes of the displacement of a wave making plate were set to 100 mm, and the frequency was 5 Hz. The waves broke completely, and the wave height and period in front of the seawall were approximately 60 mm and 0.2 seconds, respectively, which correspond to approximately 3 m and 10 seconds in the prototype scale. The breaking waves ran up the seawall and overtopped it. A high speed camera, which was able to work in a centrifugal field, was used to observe the fluid and ground behaviours. The capture speed of the camera was set to 500 frames per second.

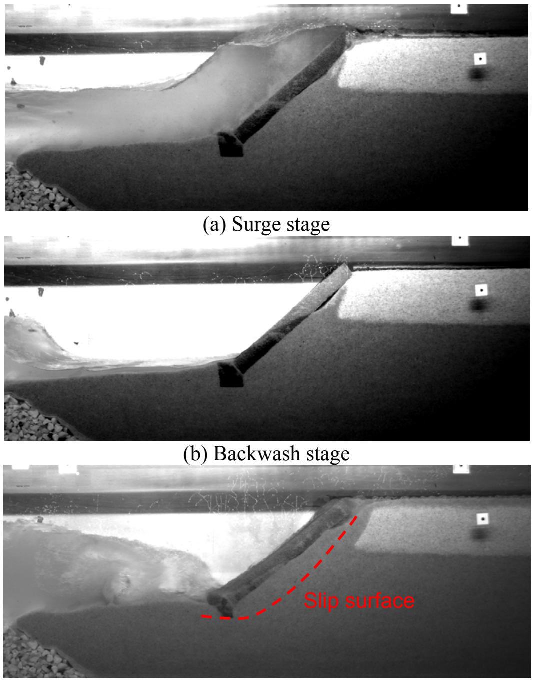
3 RESULTS OF CENTRIFUGE MODEL TESTS

3.1 *Ground failure behaviour*

Table 3 summarises the test results of five cases, and shows the failure patterns and the time periods from wave generation

Table 3. List of test results.

Case	Result	Time to failure
S01	Ground was failed with sliding.	3.0 sec
S01P	Ground was failed with sliding.	4.7 sec
S01R	No failure	-
S50	Cover panel was blown off.	45.8 sec
S02	Ground was failed with sliding.	10.1 sec



(a) Surge stage

(b) Backwash stage

(c) Failure stage during backwash

Figure 4. Seawalls subjected to high waves (case S01).

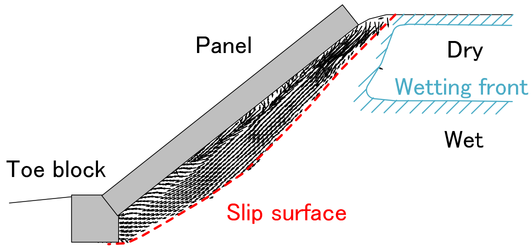
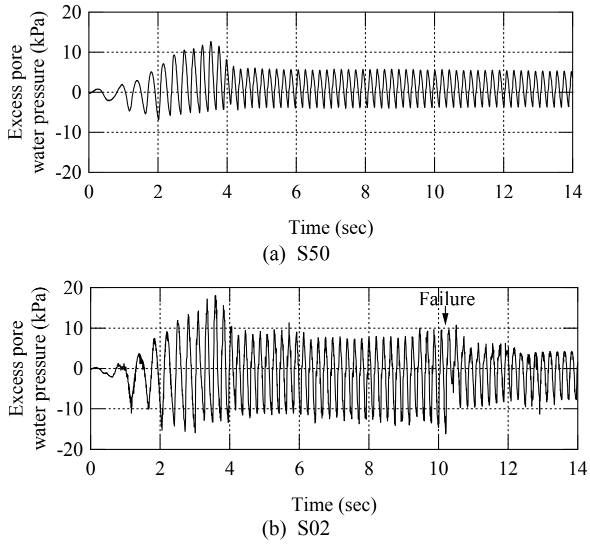


Figure 5. Displacement vectors at failure stage (S01).



(a) S50

(b) S02

Figure 6. Time histories of excess pore water pressure at P1.

initiation to the failure of the seawall in a prototype scale. As shown in the table, failure occurred in most of the test cases, while in only case failure was not observed. There are two patterns of failure: the blow-off of the covering panel, and the ground sliding under the covering panel. Only S50 failed by the former pattern during backwash. This case had a high fluid viscosity. This condition is considered to prevent the dissipation of pore water pressure behind the covering panel, which would blow the panel off. The measured pore water pressure data are discussed in a later section.

In the remaining test cases, the ground failed during backwash by sliding under the covering panel. The appearances of the surge, backwash, and ground failure stages of S01 are shown in Figure 4 as a representative. These images were captured by a high speed camera. During the surge stage, the water level of the ground increased under the influence of the rising water level in front of the covering panel. In contrast, the water level decreased during the backwash stage. However, some water remained above the water level, and caused an unsaturated area in the ground. As the alternating surge and backwash stages were repetitive, the unsaturation area developed, and in addition overtopping occurred. This induced the wet condition and sliding failure during backwash. The displacement of the ground at failure was calculated by the PIV method. Figure 5 shows the displacement vectors by using a series of captured pictures. It is clear in the figure for the ground to fail by means of sliding. In case S01P using a plate for preventing overtopping, the time period to the failure was longer than that of S01. This indicated that backfill wetting caused by overtopping advanced the sliding failure.

Several factors were considered to induce the sliding failure. The first factor was the wet condition of the ground, which increased the unit weight of the ground. The seepage force in the ground was the second factor. It was induced by the low water level in front of the covering panel during backwash. The measured water pressure data to prove the generation of seepage force are shown in the latter section. The third factor was an uplifting force against the covering panel. This reduced the load from the panel to the ground, and also decreased the confining pressure of the ground. The fact that these factors caused the sliding failure can be certified by observing that there was no failure in case S01R, in which rubble was put under the covering panel to reduce the above factors.

3 .2 *Excess pore water pressure*

Figure 6 shows the time histories of excess pore water pressure in a prototype scale, which was measured by the embedded gauges in S50 and S02 and initialized by the pore water pressure before the wave generation. The position of measurement can be seen at point P1 in Figure 3(a). In each history, approximately ten waves, which were larger than the subsequent ones, were disturbed at an early stage and the following waves became stable with a constant amplitude. The amplitudes of the waves in the stable stage were 9.6 and 20.2 kN/m^2 in cases S50 and S02, respectively. The variation in pore water pressure in S02 was significantly larger (greater than double) than that of S50. The difference in these cases was limited to the viscosity of fluid, and it indicated that decreasing viscosity and increasing permeability affected the pore water pressure.

Both amplitudes of pore water pressure at each point in cases S50 and S02 are shown in Figure 7. There was no large phase difference in data at each point. As shown in the figure, the variation in front of the toe block was larger than that behind the covering panel in both cases, and the variation in S02 is larger than that in S50 at all points. Considering the backwash

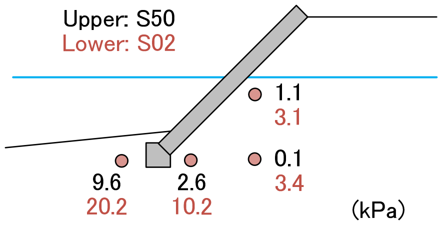


Figure 7. Fluctuation of pore water pressure.

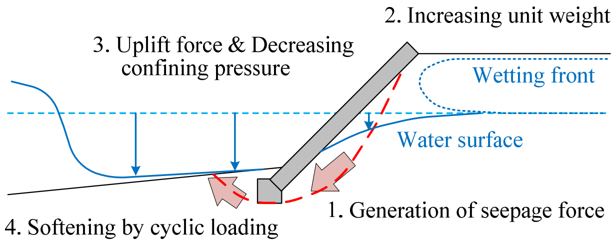


Figure 8. Failure mechanism of seawall.

stage, the boundary condition of the pore water pressure was fixed as zero on the ground surface in front of the covering panel, because the water level corresponded to the surface. The surface also allowed drainage from the ground. In contrast, the water level was free to move inside the ground and water was not supplied there. These boundary conditions provided lower pore water pressure around the toe block, and they gradually reduce pore water pressure inside the ground. In addition, low pore water pressure around the toe block induced seaward seepage inside the ground. The high permeability of S02 decreased pore water pressure faster, and the seepage force was larger than that of S50. This explains why S02 failed with sliding and S50 did not.

4 SUMMARY OF THE FAILURE MECHANISMS

As mentioned in the previous chapter, two patterns of failure were observed in the model tests: the blow-off of the covering panel, and the ground sliding under the covering panel. The former can be easily understood to be caused by an uplift force against the covering panel. The mechanism of the latter failure has several factors to induce the sliding failure of the seawall during backwash. Figure 8 shows the five factors: (1) Generation of a seepage force behind the panel and around the toe block, (2) Increasing unit weight due to the wetting of the ground behind the panel, (3) Decreasing confining pressure due to the uplift force against the panel, (4) Softening of the ground due to cyclic loading of the waves. Factors (1) ~ (3) have been already described above, and only factor (4) is mentioned here. It is known that the seabed is repeatedly loaded by waves, and in some cases the generated excess pore water pressure softens the ground (e.g. Sekiguchi et al., 1995). In the case of the present tests, the pore water pressure was not residually increased, as shown in Fig. 6, and this indicates that the ground was not softened under the influence of factor (4). Thus, the seawall ground in this study loses stability due to factors (1) ~ (3).

5 CONCLUSIONS

This study investigated the failure mechanism of seawalls, including the ground, by using centrifuge model tests. Centrifugal acceleration in the model enabled the production of prototype waves, stress, and pore water pressure including suction, and facilitated the simulation of the stability of the seawalls in a prototype scale. The results of the model tests showed two patterns of failure: the blow-off of the covering panel, and the ground sliding under the covering panel. These were induced when the seawall became unstable during backwash after repeated surging and backwashing. Surge waves wet the ground behind the covering panel, and also increased the unit weight of the ground. In addition, the measured pore water pressure showed that a seepage force occurred in the ground, which is considered to contribute to the sliding failure. A more detailed investigation using numerical analyses is required to understand the failure mechanism because it is difficult to clarify the states of stress and seepage force by a model test only.

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