CHAPTER 148

Experimental Analysis of the Settlement Failure Mechanism Shown by Caisson-Type Seawalls

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ABSTRACT

We conducted a series of model in a wave flume measuring pore pressures in the reclaimed soil (sand) to investigate the settlement failure mechanisms of caisson type seawalls. Settlement of reclaimed soil was reporduced by considering that the geotextile sheet, which separates the backfill and reclaimed soil regions, had an opening ripped in it such that soil rapidly leaks out. Also reproduced were the phenomenon of sand boiling (liquefaction), the presence of saturated reclaimed soil above the backfill stones, seawall construction with no backfill stones, and impulsive pressures acting on the joint plate connecting two caissons. Experiment results further clarified the fundamental mechanisms of the settlement failures.

INTRODUCTION

The recent utilization of reclaimed land to provide large-area, man-made islands, e.g., those used for airports, has necessitated their construction in relatively deep seas, which naturally requires them to be surrounded by seawalls that are directly exposed to strong waves since no protective breakwaters are present. Consequently, failures frequently occur during and after construction. The settlement of reclaimed soil behind the seawalls is considered to be responsible for most, and while this type of failure *does not* result in complete failure of the seawall, it *does* lead to land-usage problems and expensive long-term maintenance requirements.

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Photo 1(a) shows a typical seawall failure by settlement, occurring at S Port located along the Pacific Coast in Japan, where a large hole is formed behind the seawall. This type settlement failure occurred during construction, being the end result of wave actions from a strong storm. Figure 1 shows the cross section of the seawall, a relatively deepwater seawall protecting a large, man-made island; being particularly chosen due to a water depth of more than 10 m and a design significant wave height of about 8 m. The caisson is 12 m wide and covered by wave-dissipating concrete blocks. Backfill stones placed behind the caisson reduce the soil pressure acting on it. The large holes were formed in the reclaimed soil located above the backfill stones. A permeable geotextile sheet laid on the top of the backfill stones should prevent such soil leakage; thus, we surmise that it was damaged by waves either during and/or after placement of reclaimed soil.

The seawall failure in S Port is unique in that it also provided evidence of air blow, which can be seen in Photo 1(b), i.e., air is being blown out a gap between the caisson and reclaimed soil. Air blow occurs when wave motion inside the

Photo 1(a) A large hole formed behind a seawall.

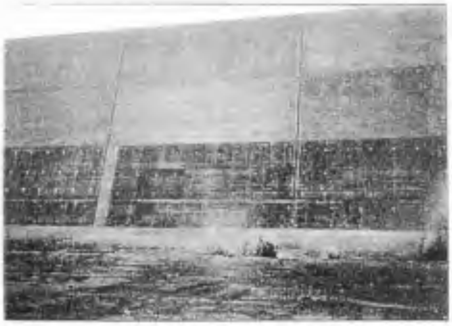

Photo 1(b) Air blow occurring from a gap between the caisson and backfill stones.

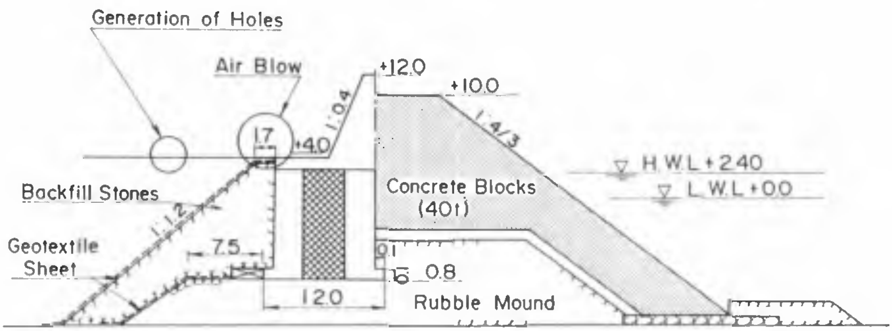

Fig. 1 Cross section of a caisson type deepwater seawall.

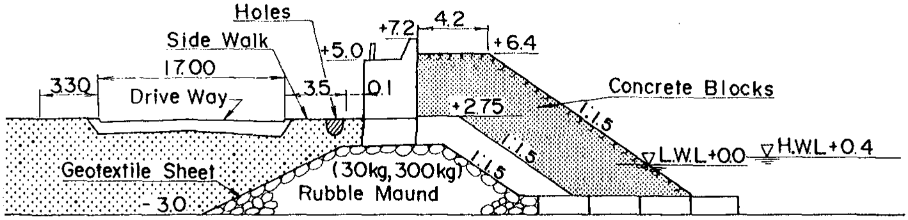

Fig. 2 Cross section of a rubble mound type shallow water seawall.

backfill stones compresses the air within the stones such that it blows out through the gap; a phenomenon that occurs even at not-so-large wave heights.

Figure 2 shows another settlement failure, in this case for a rubble mound type seawall located in relatively shallow water. The apparent damage was caused by a winter storm, leaving numerous holes in the sidewalk. Note that the interlocking blocks in the sidewalk have been upturned/knocked out of place; a phenomenon thought to occur when the pore pressure in the backfill stones exceeds the overburden soil pressure in the overlying reclaimed soil.

Three years ago, a comprehensive study on the mechanisms of settlement failures was initiated at the Port and Harbour Research Institute (PHRI), Japan. The study is considered comprehensive due to the inclusion of hydraulic, geotechnical, and material aspects in conjunction with determining practical construction methods. Here, we report the results of hydraulic model experiments which further elucidate the mechanisms leading to settlement failures of seawalls.

EXPERIMENTAL PROCEDURES

Experiment series

Four series of model experiments were conducted. In series 1, the settlement failures of reclaimed soil were reproduced, and in series 2, pore pressures in the backfill stones and reclaimed soil were measured. Standard and special cross sections were tested along with a cross section in which the boiling type of failure can easily occur.

In the series 3 experiments, we measured the impulsive pressure acting on the joint plate connecting two caissons, as destruction of the plate is known to result in damage to the geotextile sheet and subsequent settlement of the reclaimed soil; while in series 4, a cross section with no backfill stones was tested to show the effect of the stones in preventing settlement failure. In this case, no reduction occurs in the ground pressure acting on the caisson, nor in the direct wave actions affecting the reclaimed soil. Pore pressures were also measured for this cross section.

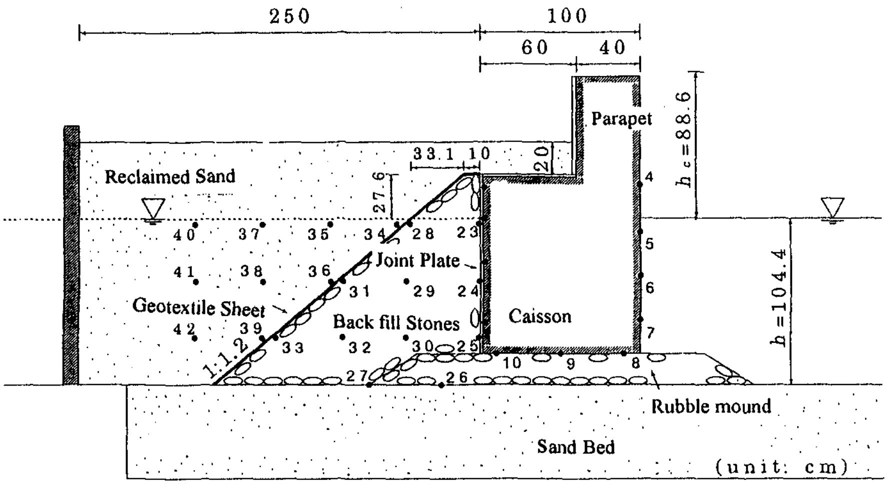

Fig. 3 Cross section of the standard seawall model.

Seawall Model

Figure 3 shows a cross section of the standard seawall model in which the geotextile sheet is placed between the backfill stones and reclaimed sand (soil) in order to stop sand from leaking through the backfill. Although the surface of the reclaimed soil is usually paved, this was not simulated in the model.

Models at 1/16-scale were installed in a wave flume on top of a sand bed. The water depth and caisson width were both about 1 m, and crest elevation of the seawall was 88.9 cm, which is relatively high compared to the water depth. Equivalent water depth is about 16 m and crest elevation about 14 m. The locations of more than 40 wave pressure and pore pressure transducers are indicated.

We also tested a model cross section similar to one occurring during the construction period, where the reclaimed sand is filled just up to the top of the backfill stones. In this case, which was mainly considered in series 1 experiments, the crest height of the caisson is relatively low at 58.1 cm.

Waves

Regular and irregular waves were generated in the experiments, with wave height being varied from 25 to 61 cm and wave period from 2.1 to 3.5 s. The standard case uses a wave height of 52.4 cm and wave period of 3.04 s, i.e., equivalent to 8.4 m and 12.2 s for actual waves.

EXPERIMENTS REPRODUCING SETTLEMENT FAILURE

Soil leakage due to geotextile sheet damage

In series 1 experiments, under the assumption that the settlement of reclaimed soil was caused by an opening being ripped in the geotextile sheet either during or after construction, we cut a relatively large, 10-cm diameter hole in the sheet, laying it between the backfill stones and reclaimed sand such that the hole was situated below the still water level.

Photo 2 shows the effect of sand leakage before applying wave action. After adding the overlying reclaimed sand, while slowly filling the wave flume with water, sand started leaking through the hole right after the water reached its level, with the end result being the formation of the large tunnel (cave) shown in the photo.

Upon commencing wave action after crushing the tunnel and refilling in the sand lost by leakage, the water surface in the backfill stones began moving up and down and gradually sand began leaking through the hole, in turn forming another tunnel. Some sand is trapped in the backfill stones, but most passes through them and piles up on the seabed.

Although larger waves led to a larger tunnel, when wave overtopping occurred, the water motion in the backfill region increased, leading to a higher leakage rate and rapid growth of the tunnel until the weight of the overlying sand suddenly collapsed it. Photo 2 also shows the resultant settlement of the reclaimed sand which is greatest just above the location of the hole.

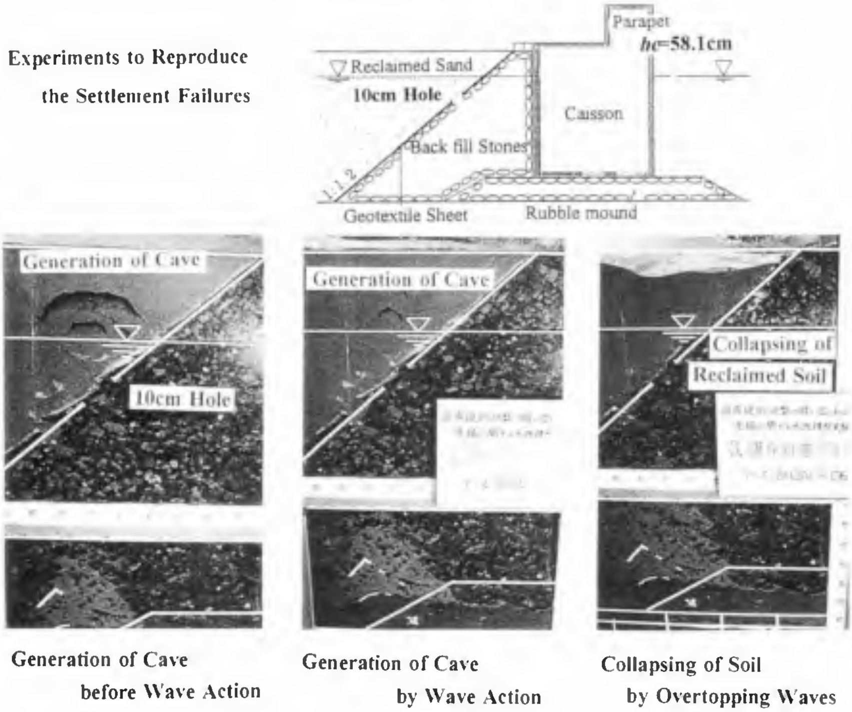

Photo 2 Soil leakage through a 10-cm hole in the geotextile sheet at a location below the still water level.

Effect of hole size and location

To further investigate this behavior, we varied the size and location of the hole. Although the rate of sand leakage naturally increased with the size of the hole, for very small holes with a diameter of 1 cm, the leakage stopped due to the hole being blocked by sand that is trapped nearby between backfill stones. In addition, the rate of leakage is highest for holes located just below the still water level, being substantially increased by overtopping waves, or by rainfall which was also simulated.

Behavior of reclaimed sand without a geotextile sheet

Because some seawalls have been constructed in Japan without a geotextile sheet, under the premise that adding reclaimed soil to the backfill section during construction will prevent subsequent leakage upon completion, this case was also examined in the experiments.

As expected under this situation, the sand literally flowed into the backfill stone section during the filling process. Also, small wave actions promoted infiltration into the backfill section. In fact, even if reclaimed sand is added to fill all the void spaces in the backfill stones, the sand in the backfill stones located just behind the caisson is still carried away through the rubble mound. Such behavior indicates a good possibility that leakage will continue after construction, especially if large waves attack the seawall.

MEASUREMENT OF PORE PRESSURES

Pore pressure distribution

Figure 4 shows typical analogue data for the standard cross section measured at four channels, i.e., the front and bottom of the caisson (7, 10), in the backfill stones (23), and in the reclaimed sand (38). Channels 7 and 10 indicate ordinary standing wave pressure that is simultaneously transmitted to the backfill stones, where slight damping is apparent and negative pressures indicate higher damping than positive ones. Also, pore pressure in the reclaimed sand is highly damped and shows a very smooth pressure curve. Pore pressures in the backfill stones and reclaimed sand provide important data as settlement failure is more likely to occur at high positive and/or negative values.

Peak pore pressure for standard cross section

Figure 5 shows the corresponding pressure distribution for the standard cross section, where the size of the arrows indicates the relative magnitude of nondimentionalized positive peak pressure, while its inclination indicates the phase difference at peak pressure. Note that the pore pressure in the backfill stones is almost constant, being quite high at about 80% of the wave pressure at the front of the caisson. Pressure is not substantially reduced because the water and air in the backfill stones are enclosed relatively tightly by the reclaimed sand, i.e., the movement of pore water in the rubble mound and backfill stones is very limited by the reclaimed sand and the dissipation of pore pressure is low. This pore pressure, however, rapidly damps out as shown by the pore pressure in the reclaimed sand.

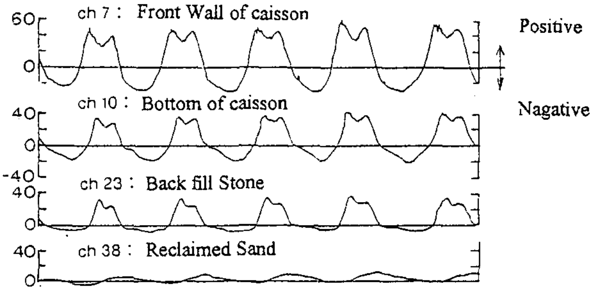

Fig. 4 Analogue data for the standard cross section indicating pore pressures measured at indicated channels.

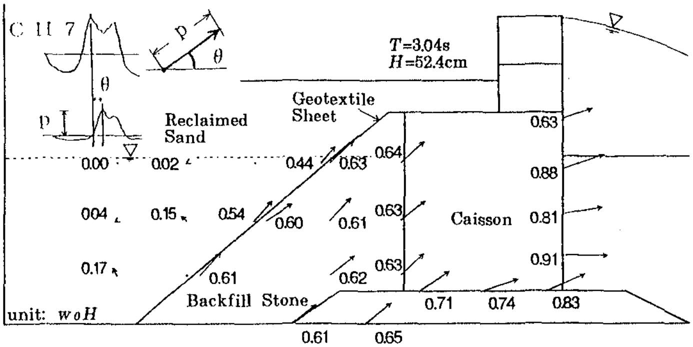

Fig. 5 Distribution of positive peak pressures in the standard cross section in which reclaimed sand above the backfill region is not in a saturated condition.

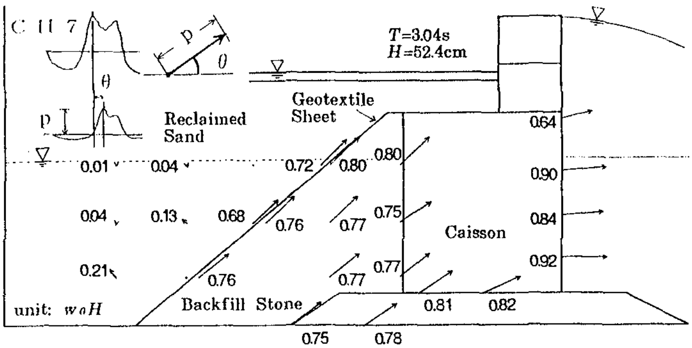

Fig. 6 Distribution of positive peak pressures for a cross section in which the reclaimed sand above the backfill region is maintained in a saturated condition.

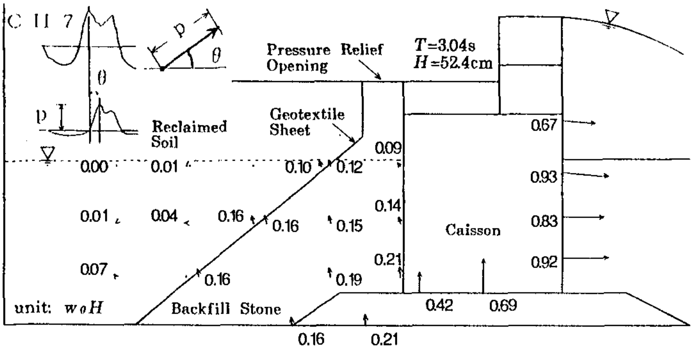

Fig. 7 Distribution of positive peak pressure using pressure relief opening.

Pressure increase due to saturation of reclaimed soil

Due to wave overtopping and rain, the reclaimed soil will normally be water saturated; thus, to simulate the strong effect of this condition on pore pressure in the backfill region, we added water as necessary to ensure the reclaimed sand stayed saturated during the experiments.

By comparing Figs. 5 and 6, which show the resultant pressure distribution of peak pressures with and without saturation, it is clear that much higher pore pressures are present when the reclaimed sand is saturated, being nearly equal to the wave pressure in front of the caisson. This phenomenon is a result of the backfill region being tightly enclosed by the saturated reclaimed sand above the still water level, i.e., pore pressure is transmitted without damping in the backfill stones.

Pressure relief measures

The transmission of pore pressure in the backfill region without damping can be prevented, however, by providing a vent path or opening in the backfill stones, which can be established if a portion of the upper surface of the stones is situated at or above the level of reclaimed soil. Figure 7 shows the resultant pressure distribution if such an opening is established, where the peak values are significantly reduced to about 10% of the wave pressure acting on the front of the caisson; and accordingly, the pressure in the reclaimed sand is reduced as well.

As another method for reducing pore pressure in the backfill stones, a pressure relief opening was made in the rear chamber of the caisson, with results indicating a substantial reduction in pressure, (although the data are not shown here).

Water level oscillation in backfill stones

Movement of pore water, especially that of the water level in the backfill stones, is another important factor affecting sand leakage. For the standard cross section, the level of water fluctuated between 10 and 20% of incident wave height as shown in Fig. 8. Note that the magnitude of fluctuations decreases as wave height increases. Naturally the fluctuations in water level are smaller when the reclaimed sand is in a saturated condition, being less than 10% of the incident wave height. If, however, a pressure relief opening is established in the backfill region, the size of the fluctuations increases, ranging from 23 to 32% of the incident wave height.

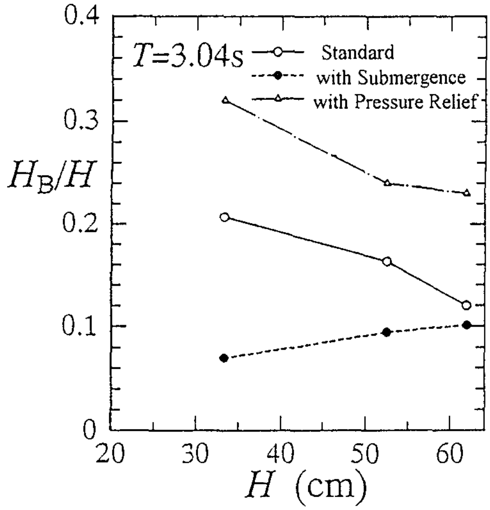

Fig. 8 Water level oscillations in backfill region.

BOILING OF RECLAIMED SOIL

As boiling or liquefaction of sand is considered a major factor causing settlement failures of seawalls, we modified the cross section of the standard seawall to experimentally reproduce this behavior. That is, a 20-cm-thick layer of reclaimed sand was used to cover the backfill stones, and the level of water was maintained at the surface of the reclaimed sand in order to limit the overburden soil pressure acting on the stones.

Although no unusual behavior was observed at small wave heights, at a wave height of 42.8 cm, the entire layer of sand appears to lift up as shown in Fig. 9. This is the first indication of sand boiling (liquefaction), with increases in the wave height forcing the sand further upward until boiling occurs. The effect of boiling is disastrous as can destroy both the layer of reclaimed soil and any type of pavement covering this region. As another consequence, the geotextile sheet can be ripped such that an opening occurs.

Figure 10 shows the pore pressure distribution when boiling occurs, where the pore pressure in the backfill stones reaches about 17.8 gf/cm^2(14.5kN/m^2), approaching close to the overburden soil pressure. Note that the pore pressure stays at this level even though wave height is increased.

These experiments confirm that boiling of reclaimed soil occurs when the pore pressure in the backfill region increases close to the overburden soil pressure acting on the backfill region. Consequently, to withstand large wave heights, the layer of the reclaimed soil should be sufficiently thick such that the force produced by the weight of the soil counteracts that produced by the increase in pore pressure in the backfill region;

or alternatively, the backfill pore pressure should be reduced by establishing a pressure relief path.

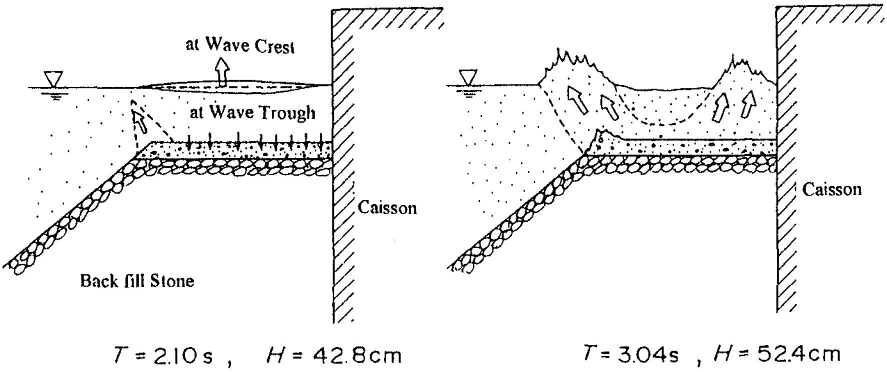

Fig. 9 Boiling of reclaimed sand.

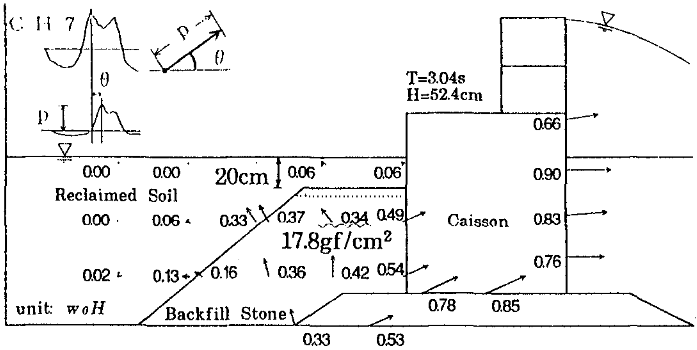

Fig. 10 Distribution of peak pore pressure in the case of sand boiling.

IMPULSIVE PRESSURE ON A JOINT PLATE

Caisson joint model

In series 3 experiments, the impulsive pressures acting on the joint plate connecting two caissons were measured, being done in response to learning that destruction of the joint plate leads to the damaging the geotextile sheet and settlement failure due to soil leakage.

Figure 11 shows the cross section and front view of the seawall model, where a 1.5-cm joint plate has been installed between the caisson and a glass observation window. Several pressure transducers were placed to measure impulsive pressures on the joint plate.

Wave action and impulsive pressure on the joint plate

Figure 12 shows typical analogue measurements indicating wave pressure on the caisson's front wall and joint plate respectively. Channel 11 provides pressure on the joint plate at the still water level, while channel 4 provides the pressure on the caisson at the same level, and channel 14 on the plate near the caisson bottom. As shown, an impulsive pressure appeared near the water surface, having an intensity of more than 3 woH. Also shown is the movement of the wave front which contains a layer of air such that it generates an impulsive pressure upon impact against the plate.

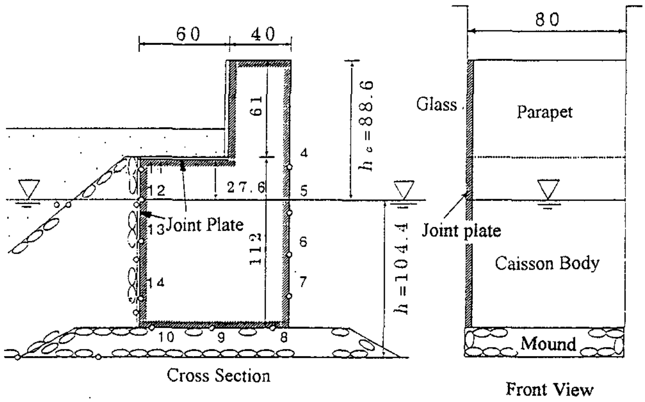

Fig. 11 Seawall model with a caisson joint plate.

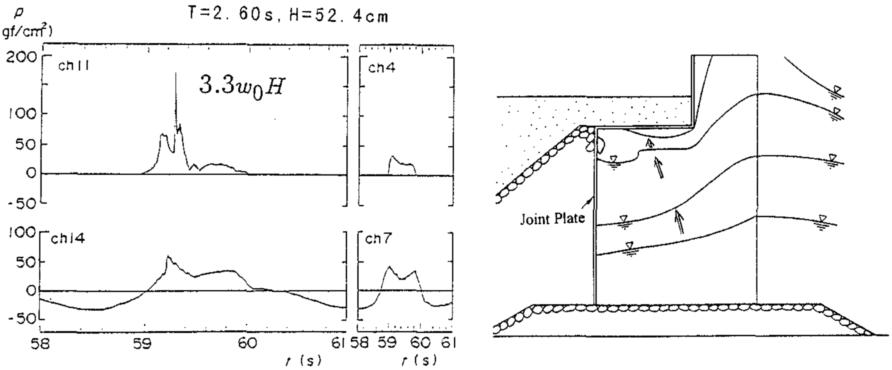

Fig. 12 Generation of impulsive pressure on joint plates.

Peak impulsive pressure on the joint plate

Figure 13 shows nondimensionalized peak pressure acting on the joint plate near the still water level, where experimental values are plotted for four different wave periods as a function of wave height. Due to data scatter, the ranges and mean values are indicated, with pressure ranging from 1 to 4 woH and having an average value of about 2 woH.

The impulsive pressure acting on the joint plate above the still water level is very similar to the uplift pressure on the horizontal plate, e.g., the superstructure of a pillar quay or that acting on the ceiling slab of a wave chamber in a perforated wall caisson. Based on this similarity, the methods used to determine these pressures can be applied here for determining the impulsive pressure.

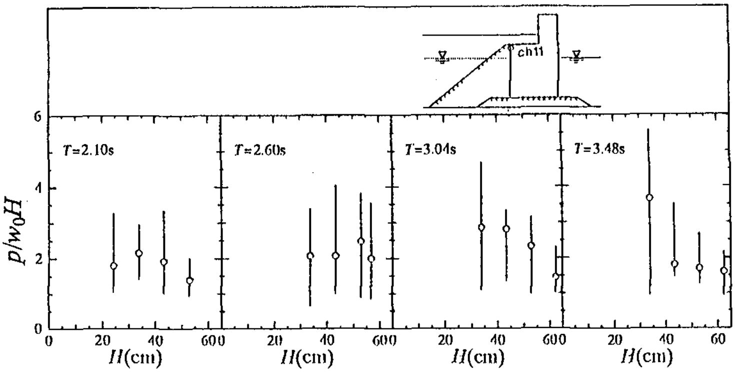

Fig. 13 Impulsive pressure intensity on a joint plate.

Reduction of impulsive pressure by spacer plates

The impulsive pressure on the joint plate can be reduced by narrowing the gap (space) between two caissons using spacer plates. Figure 14 shows that two spacer plates installed in the gap between the caisson and observation window can substantially reduce impulsive pressure, although one spacer plate works almost as well.

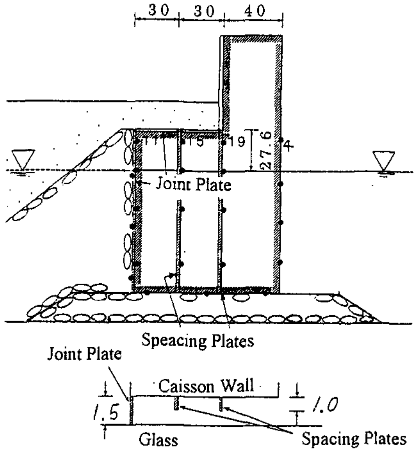

Fig. 14 Spacer plates to reduce the impulsive pressure.

SEAWALLS WITHOUT BACKFILL STONES

Loss of reclaimed soil due to joint plate damage

The main purpose of using backfill stones is to reduce ground pressure acting on the caisson. If, however, the wave pressure is large compared to ground pressure, then backfill stones need not be used. This is commonly the case in Japan where the design wave height is large and the design acceleration produced by an earthquake is small. In addition, if backfill stones are not used construction costs will be lower.

Using backfill stones along with a geotextile sheet reduces the risk of the leakage of reclaimed soil through the joint plate should it be damaged. In fact, the stones function as a filter medium which reduces direct wave pressure acting on the reclaimed soil. When a small hole was made in the joint plate, wave actions led to a continuous leakage of sand from the back region of seawall.

Pore pressure in the reclaimed sand

Figure 15 shows the pressure distribution for a cross section without backfill stones, where the high pressure in the reclaimed sand near the rubble mound should be noted, being almost 90% of the frontal wave pressure. Consequently, the pressure gradient in the sand near the rubble foundation will be large, which might easily lead to the adverse consequence of damaging the geotextile sheet placed between the sand and rubble mound.

The pore pressure in the reclaimed sand can be reduced using an opening in the caisson. Figure 16 shows the pressure distribution with an opening in the rear chamber of the caisson, which reduces the pressure near the sand and rubble mound to 10% of the frontal wave pressure. If the backfill stones are not used, then obviously measures such as this one must be taken in order reduce pore pressure in reclaimed soil.

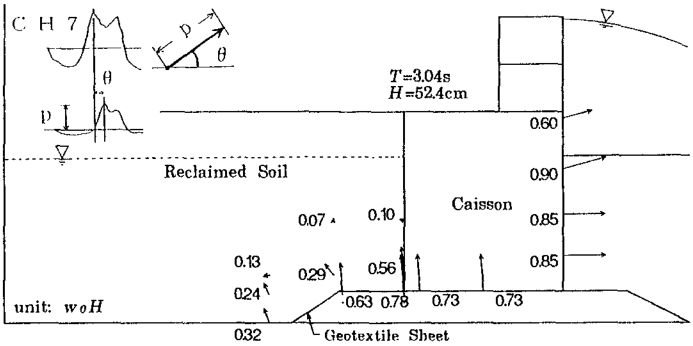

Fig. 15 Distribution of peak pore pressure without backfill stones.

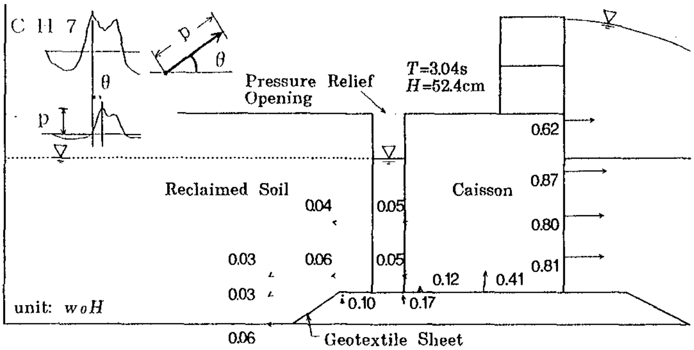

Fig. 16 Distribution of peak pore pressure with a pressure relief opening.

CONCLUDING REMARKS

By combining the present experimental results with those from field surveys various mechanisms were found to cause leakage of reclaimed soil, with the loss of this soil subsequently leading to seawall failure by settlement. Figure 17 shows the resultant settlement failure mechanisms using a failure path diagram. For example, failure occurs if the wave actions during and/or after construction breech the integrity of the geotextile sheet, where the soil can then leak into the backfill stone region due to wave actions. The occurrence of sand boiling and damage to the joint plate were also implicated as being important settlement failure mechanisms.

Although we have obtained a relatively sound qualitative understanding of settlement failure mechanisms, being an essential aspect towards realizing practical seawall designs, only with a sound quantitative understanding of the mechanisms can a full understanding be obtained.

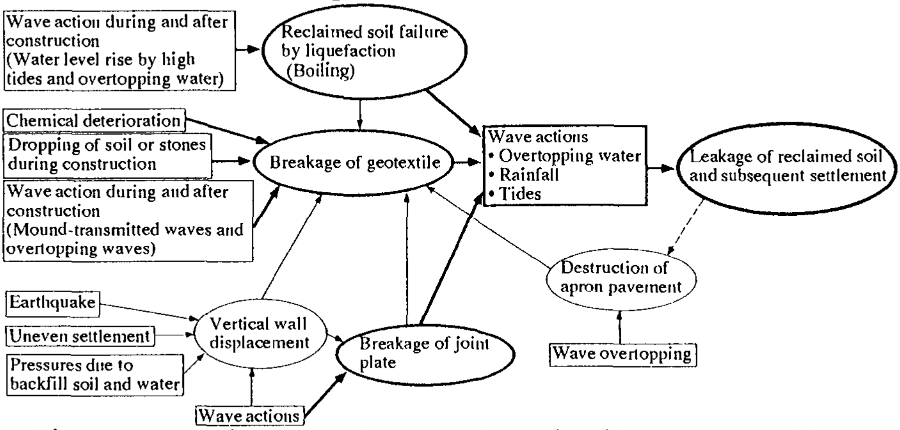

Figure 17 Diagram of mechanisms leading to seawall failure by settlement.

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REFERENCES

Takahashi, S., Tanimoto, K., and Miyanaga, S. (1985) "Uplift force due to compression of enclosed air layer and their similitude law," Coastal Eng. in Japan, JSCE, Vol. 28, pp.191-206.

Williams, A.F., Burcharth, H.F., den Adel, H. (1992) " The permeability of rubble mound breakwaters, New measurements and new ideas, Proc. of 23rd International Conference on Coastal Engineering, ASCE, pp. 1720-1733.