EFFECTIVENESS OF TOP-SHAPED BLOCKS FOR PREVENTING SETTLEMENT OF WAVE-DISSIPATING BLOCKS UNDER WAVE ACTION

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Installing a foundation of top-shaped concrete blocks under wave-dissipating blocks is a well-established method for preventing wave-induced scouring and settlement of wave-dissipating blocks in front of a seawall along beaches that are exposed to high waves. The top-shaped blocks used in this paper have 2m in diameter, 2m in total height, and leg of 1m long. This paper describes the effectiveness of such foundations in an *in situ* test of breakwaters with and without top-shaped block foundations performed mainly in Hokkaido. An experiment to examine the mechanisms of the top-shaped block foundations was conducted in a large wave tank with waves to model both the relatively short-period, high waves typical to the Japan Sea coast and the relatively long-period waves typical of typhoons striking the Pacific Ocean coast. The results of our experiment showed that whether the top-shaped block foundations were used for on-shore breakwaters in the swash zone and for offshore breakwaters in the surf zone, both installations were effective for reducing the settlement of the wave-dissipating blocks compared to breakwaters of wave-dissipating blocks placed on unimproved ground. Froude's law was employed to extend the experimental results to full-sized blocks under real wave conditions. This estimation indicated that even if the top-shaped blocks were exposed to scour processes, the wave-dissipating blocks would not settle if no more than 80 cm was scoured away. This indicates that the top-shaped blocks provide stable support for load of the wave-dissipating blocks.

Keywords: Top-shaped blocks (TSB), wave-dissipating blocks (WDB), scouring, settlement, off-shore breakwater.

1. INTRODUCTION

Japan is surrounded by ocean, with a coastline measuring some 34,000 km. About half, 16,000 km, of the coastline is classified as requiring some kind of reinforcement against erosion, and many shore-connected and offshore breakwaters have been constructed, using a vast number of wave-dissipating blocks (WDB). At present, many of these blocks are due for replacement, as they have been subjected to scouring and displacement by waves, and eventually become buried. From one inventor's observation that teacups would not be sunken by oncoming waves when placed at the edge of the water, "top-shaped" concrete blocks used for these breakwaters were constructed and shown to be extremely stable under wave action. These blocks are receiving more attention for their ability to prevent coastal erosion and scouring when buried in the sand, and this property allows them to function as stable foundations for preventing wave-dissipating blocks from settling into the sand. Construction of these foundations is expected to save on maintenance costs over the long term. This construction method was first implemented in Hokkaido, where wave-dissipating blocks are especially prone to settling. It was verified that foundations of these top-shaped blocks showed almost no settlement.

This paper provides a simple explanation of the construction procedures for these foundations and describes the results of these installations in Hokkaido. In conjunction, a tank experiment was performed to validate the mechanisms affecting these blocks determined in a previous *in situ* test. The experiment employed a large wave-making tank to create both short-period waves with large amplitudes relative to waves on the Japan Sea coast and the long-period waves that are typical during typhoons on the Pacific Coast. The investigation assumed two uses of the top-shaped blocks: under an onshore breakwater in the swash zone and under an offshore breakwater in the surf zone. The results of the tank experiment were extrapolated to blocks of actual size by Froude's law in order to estimate the limits of loads supportable by the top-shaped blocks against scouring and of loads for stability of the top-shaped blocks. Fig. 1 shows a top-shaped block. It measured 2 m in diameter and 2 m high, with an axial leg 1 m in length. Use of similar, but smaller blocks (33-cm and 50-cm diameters), has already been well established as a method for improving soft ground layers. Over the last 20 years, 8.03 million of these blocks have been installed on land, covering an area of about 153 hectares. In contrast, the use on coasts has been rare.

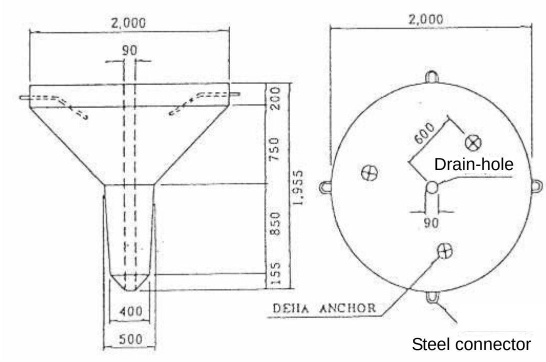

Fig.1. Dimension of Top-shaped 1 block

2. CONSTRUCTION METHOD

The steps of installing the top-shaped blocks are shown in Fig 2(a-d). Water is forced down through a pipe built into the axial leg of the block, washing away the sand underneath with a water jet to clear space in the sand for the block. Adjacent blocks are linked together with a chain to create a unified structure. The wave-dissipating blocks or other structures are then installed on top of the top-shaped

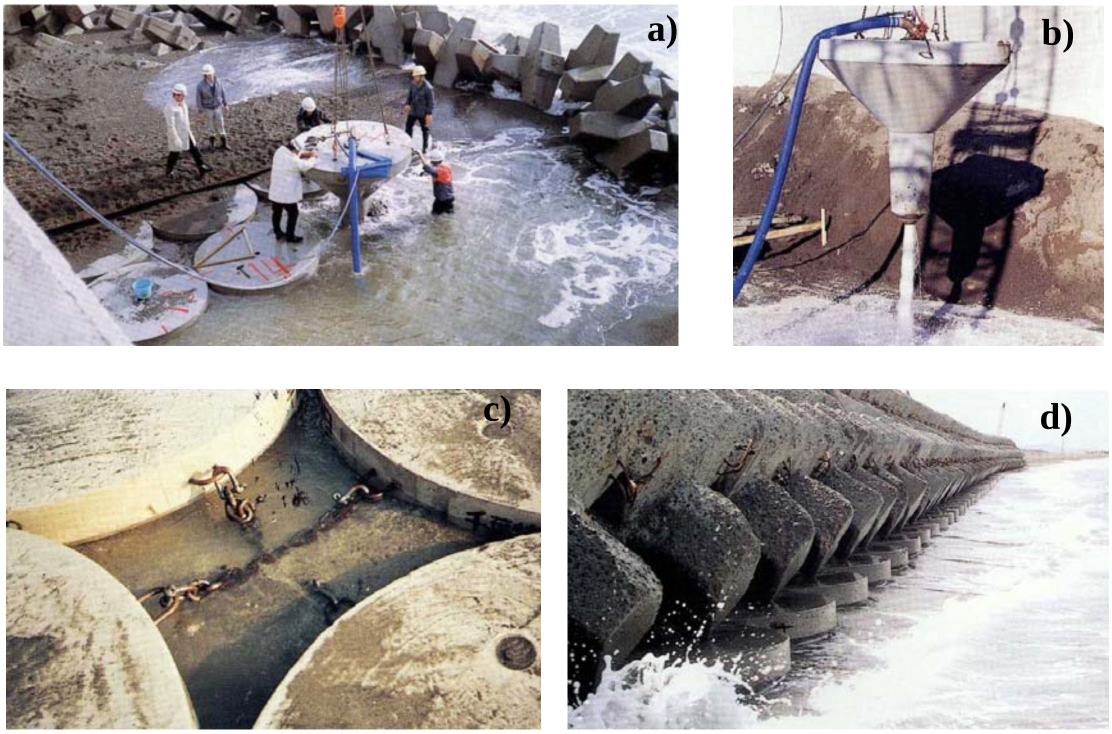

Fig.2. Construction method for top-shaped block foundation

blocks to complete the installation.

In order to protect the national highway that runs along the Pacific coast of Hokkaido from coastal erosion and wave actions, wave-dissipating blocks are installed on the seaward edge of the breakwaters. However, these blocks have been settling underwater and they are being repeatedly replaced every year. The results of one survey of this settlement are shown in Fig. 3. In the survey shown in Fig. 3, the elevation was recorded in March 1986 before installation of the wave-dissipating blocks, in July of the same year after the wave-dissipating blocks had been installed, and a year later. A year after installation, the shore had settled 3 m, to nearly the same level as before the installation. Wave-dissipating blocks were installed in two locations on the Shiraoi coast, without and with top-shaped blocks in locations where there had been three previous cycles of installations without the top-shaped blocks. Photographs of these two locations taken 2 years after installation are shown in Fig. 4; the wave-dissipating blocks had sunk just 3 cm in the location where the top-shaped blocks had been installed. Fig. 4 shows the comparison between locations without and with foundations of top-shaped blocks, 2 years after installation. Similar test installations were also carried out in four locations on the Horobetsu coast in Hokkaido; one location had top-shaped blocks, one employed steel basket to link the wave-dissipating blocks together, and the other two locations had no reinforcements at

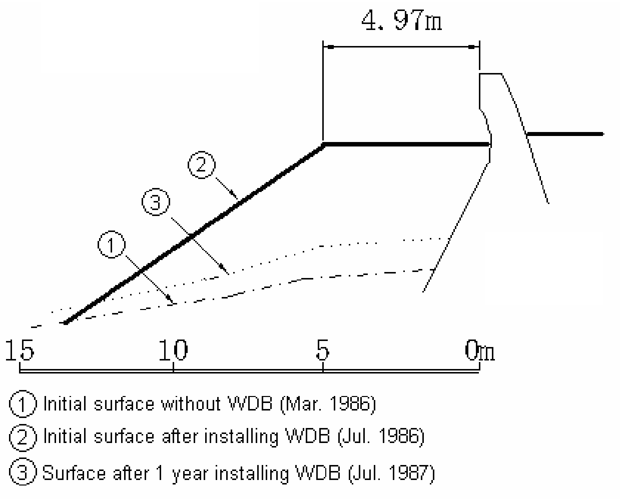

Fig.3. Observed settlement of wave-dissipating blocks at an actual site

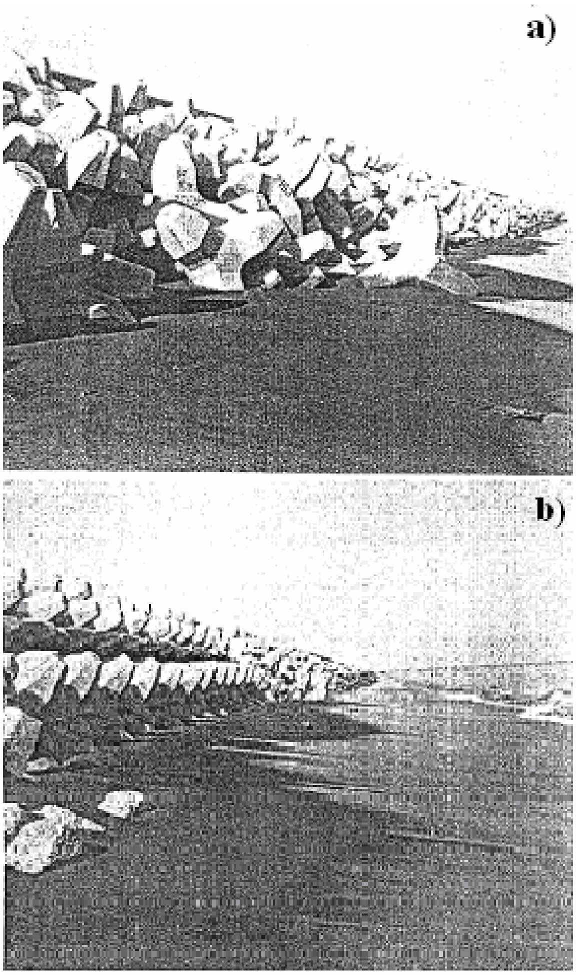

Fig.4. Appearances of wave-dissipating blocks 2 years after construction: a) When top-shaped blocks had not been installed under wave-dissipating blocks, disruption of armor units was observed. b) When top-shaped blocks had been installed, little disruption was visible.

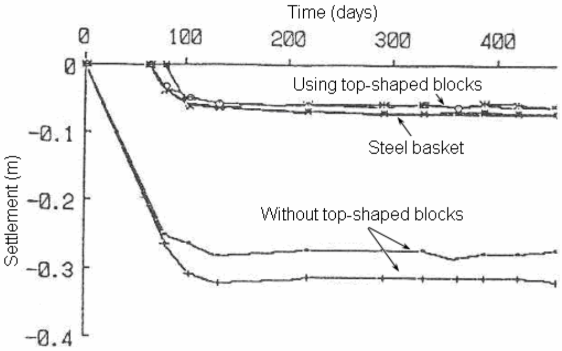

Fig.5. Effect of top-shaped blocks on the settlement of wave-dissipating blocks at an actual site.

all. Settlement data of the wave-dissipating blocks over several months are shown in Fig. 5. The top-shaped blocks were effective for preventing settlement.

3. VALIDATING EFFECTIVENESS OF TOP-SHAPED BLOCKS IN TANK EXPERIMENT

The top-shaped blocks were effective for protection against both scouring and settlement processes in *in-situ* tests. A tank experiment incorporating a wave-maker was performed in order to elucidate the conditions under which these blocks may be effective.

(1) Outline of tank experiment

A wave tank was constructed with the following dimensions: 50 m long; 1 m wide; and a shore slope of 1/20. The wave-maker was of the pendulum type and shore slope was set by adjustments to an 18-m section of the tank bottom. The adjustable bottom was split longitudinally; each 50 cm wide half-section could be set independently, allowing simultaneous observation of the behavior of an identical wave on the two different slopes. A total of 5 sets of experiments were conducted. Soma silica sand with a median diameter of 0.15 mm was shaped into a 1/20 slope with wooden trowels. Wave action was applied for 20 hours in a preliminary experiment to ensure that the initial shore topography was stable. It was found that stable wave conditions were obtained with a deepwater wave height of H_0 = 7 cm at a period T_0 = 2.24 s. Before each experiment, the slope was set to 1/20 and the wave-maker was set to deliver the described waves for a period of 10 hours in order to obtain an initial topography. Miniature top-shaped blocks and wave-dissipating blocks at a scale of 1/20 were employed in the experiments. However, as the dimensions of the test blocks were not identical to those of actual blocks, there was incomplete compliance to the similarity rule. Since gravity most affects the water surface behavior, the effects of viscosity, surface tension and elastic compressibility

Table.1 Settlement of wave-dissipating blocks (WDB) at swash-zone and surf-zone (Experiment②)

Analysis condition / Loading condition		Swash-zone (Including coastal dike)		Surf-zone (Including detached breakwater)	
		WDB without TSB	WDB with TSB	WDB without TSB	WDB With TSB
Condition of WDB	2-layers	(-3.8～-13.8) 9.2	(-0.1～-7.6) 3.3	—	—
	3-layers	(-5.2～-11.1) 8.0	(-2.1～-5.7) 3.9	(-0.1～-5.8) 2.5	(-0.0～-1.3) 0.7
	4-layers	(-8.1～-15.2) 11.2	(-3.1～-5.1) 4.8	(+0.2～-10.0) 3.8	(+1.0～-1.9) 0.7
	5-layers	—	—	(+0.1～-11.0) 3.7	(+0.4～-4.6) 0.4

Note: Values in bracket indicate the minimum and maximum of settlements (min～max), while the ones outside mean average settlement of WDB.

can be neglected; the experiment was carried out assuming Froude's law held with respect to gravity.

This experiment was broken into 4 major targets of investigation. A portion of the experiment focused on the effectiveness of the top-shaped blocks for preventing scouring and erosion of coastal embankments by the waves in the swash zone. Another portion focused on preventing scouring and erosion of offshore breakwaters in the surf zone.

1) Experiment ①: Verification of basic effectiveness of top-shaped blocks: This examined whether top-shaped blocks are actually effective for their stated purposes. The effects were observed in 5 cases: top-shaped blocks without linked structures; top-shaped blocks with linked structures; installation of only top-shaped blocks; placement of wave-dissipating blocks on top of top-shaped blocks; and placement of wave-dissipating blocks on unimproved sand. It was also examined whether top-shaped blocks prevented settlement of wave-dissipating blocks. It was found that top-shaped blocks are more effective when they are linked; therefore, they were always linked in Experiments ②-③, and the difference in performance between wave-dissipating block-only breakwaters and wave-dissipating block on the top-shaped block breakwaters was examined.

2) Experiment ②: Elucidation of supporting characteristics by blocks: wave-dissipating block breakwater models were created with and without top-shaped blocks. Breakwaters had 2, 3, 4 and 5 layers of wave-dissipating blocks.

3) Experiment ③: Investigation of effects of wave type: 26 wave conditions were considered, including wind-driven waves of the Japan Sea coast, long-wavelength swells typical of the Pacific coast, and the typhoon swell.

4) Experiment ④: Investigation of sand displacement: scouring and the re-burial of top-shaped blocks under fair-weather waves were investigated. The effects of lengthening the axial leg and of changing the block shape were tested under storm wave conditions to

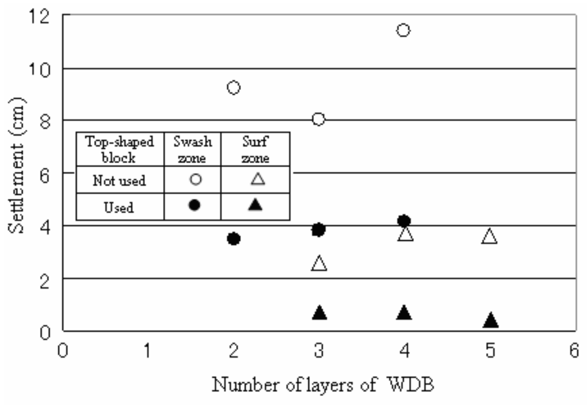

Fig.6. Monitored settlement of wave-dissipating block (WDB) at surf-zone and swash-zone (Experiment ②). Top-shaped blocks reduce the settlement of WDB (graphical expression of Table 1).

evaluate the benefits in terms of reducing settlement. This paper mainly focuses on the results of Experiments ② and ③.

(2) Elucidation of supporting characteristics by top-shaped blocks (Experiment ②)

As explained in 3.1, the settlement results of placing wave-dissipating blocks on unimproved sand were compared with the results of placing wave-dissipating blocks on top-shaped blocks. Both the swash zone adjacent to coastal reinforcements and the surf zone adjacent to offshore breakwaters were observed. Table 1 provides an overview of the experiments. The waves were applied to the model conditions for 10 hours and had the conditions described previously: deepwater height, H_0 = 7 cm, and period, T_0 = 2.24 s. The settlement data for the various conditions given in Table 1 are shown in Fig. 6. Settlement was minor in the tank experiment when the wave-dissipating blocks were placed on the top-shaped blocks. In the simulated swash zone, the settlement was reduced to less than 50% of that occurring when there was no blocks, indicating greater stability for the wave-dissipating blocks. In the surf zone, there was almost no settlement of the wave-dissipating blocks on the top-shaped blocks; thus, the offshore breakwater was still effective. Settlement of the sand due to scouring was notable, but the provided support of the axial legs of the top-shaped blocks sustained the weight of the wave-dissipating blocks.

Table.2 Settlement of wave-dissipating blocks (WDB) at swash-zone and surf-zone under wind wave (Experiment③)

Incident wave conditions			Swash-zone （Including coastal dike）		Surf-zone （Including detached breakwater）		Wave conditions
Wave height	Wave period T_0 (sec)	Wave steepness	WDB without TSB	WDB with TSB	WDB without TSB	WDB With TSB	
H_0 = 10cm (practical wave: 2 m)	1.3	0.038	(5.8～12.3) 7.9	(1.1～2.0) 1.6	(0.41～15.1) 5.4	(0.0～0.7) 0.2	Wind wave of Japan sea
	2.2	0.013	(4.5～11.7) 8.1	(0.0～5.9) 2.2	(0.11～13.3) 4.4	(0.1～2.1) 0.8	Swell wave of Pacific Ocean
	3.1	0.007	(4.9～16.5) 10.5	(3.2～6.0) 4.0	(0.1～5.1) 0.6	(0.0～1.1) 0.3	
			（3 layers of WDB）		（4 layers of WDB）		

Note: Values in bracket indicate the minimum and maximum of settlements (min～max), while the ones outside mean average settlement of WDB.

(3) Effect of wave types (Experiment ③)

The Japan Sea coast reinforcements are prone to damage from wave impact and overtopping, due to the relatively short periods and great heights of the waves. In contrast, the Pacific coast reinforcements are most often damaged under wind-driven waves with long periods, such as those typically caused by typhoons. Therefore, expected conditions of both the Japan Sea and Pacific coasts and during passage of a typhoon were examined by subjecting the top-shaped blocks to 26 wave conditions formulated using 2 different heights and 3 different periods. The measured settlements in Table 2 were arranged by wind conditions in the same manner as in Table 1. In the swash zone, sand was considerably scoured under the long wave conditions, but settlement was extremely small, due to the support provided by the axial legs. From the mean settlement data in Table 2 and Fig. 7, the top-shaped blocks appear to be very effective. To model typhoon swelling, waves were created for 8 hours with T_0 = 2.2seconds and H_0 of 10, 20, and 7 cm. These tests were performed continuously. These test conditions represent *in situ* waves lasting for 1.5 days. The first condition (H_0 = 10 cm) represented somewhat high ordinary 2m waves, the second condition (H_0 = 20 cm) represented a storm with 4m waves, and the final condition (H_0 = 7 cm) represented 1.4m compound waves. The settlements from the storm condition shown in Fig. 8 exposed the axial legs of the top-shaped blocks. During the final condition with compound waves, scouring caused some settlement; but as the stacked arrangement of the wave-dissipating blocks was preserved, the energy of incident waves continued to be dissipated. In contrast, the stacks of wave-dissipating blocks that had been placed on unimproved sand completely collapsed.

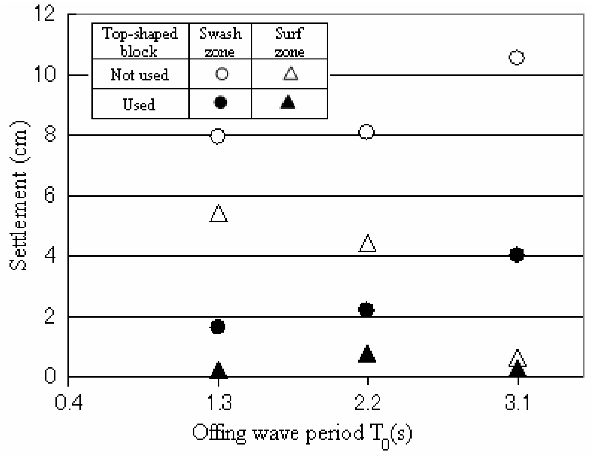

Fig.7. Monitored settlement of wave-dissipating blocks (WDB) at surf-zone and swash-zone under wind wave (Experiment ③). Top-shaped blocks reduce the settlement of WDB (graphical expression of Table 2).

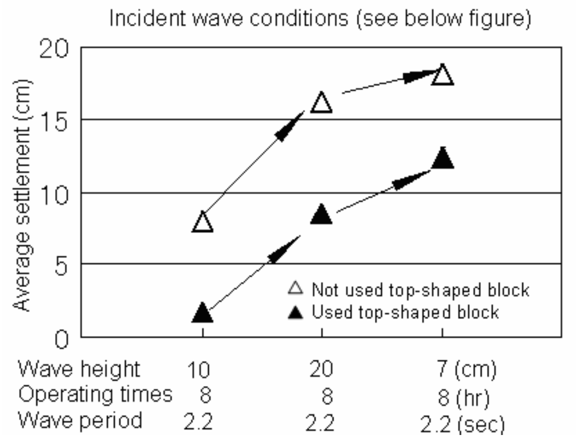

Fig.8. Monitored average settlement of WDB under several typhoon wave conditions (Experiment③). Top-shaped blocks reduce the settlement of WDB.

(4) Stability condition associated with scouring (Experiment ④)

Experiment ④ examined the influence of the shape of the top-shaped block with various lengths of axial leg, on scouring and load limit. The maximum height for incident waves was assumed to be 4 m, and the time period of exposure was set at about 9 hours. Only the data for the 1-m axial leg blocks, which are currently in use, are shown in Fig. 9. Among 9 different loads examined, top-shaped blocks with loads less than 690 kN were stable, even with settlement, but blocks with higher loads were overturned. This result indicates that a single block can support a load of approximately 700 kN.

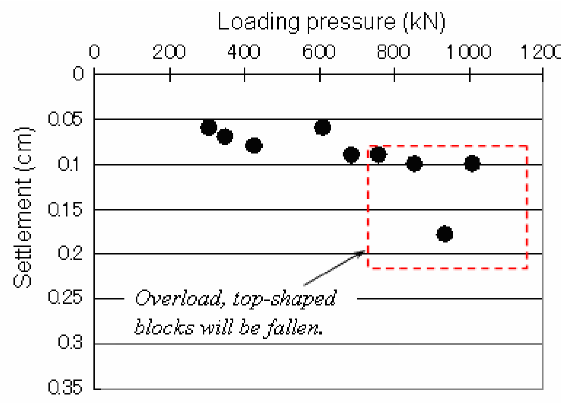

Fig.9. Monitored load-settlement relationship of top-shaped blocks footing (1m length) under stormy wave condition (Experiment④).

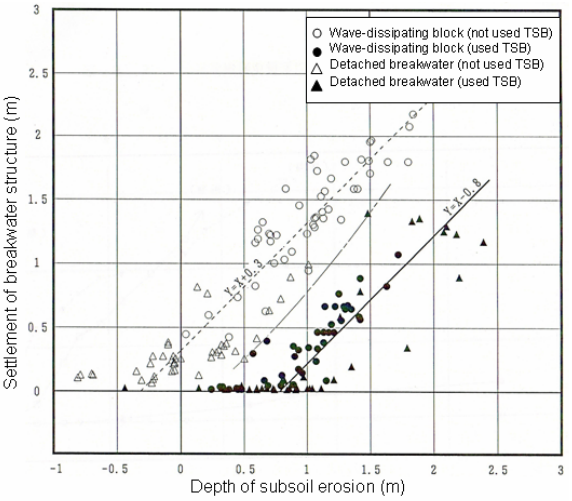

Fig.10. Relationship between settlement of breakwater structure and depth of subsoil erosion under the effect of TSB. TSB reduces the settlement.

4. REMARKS AND FUTURE STUDY

The effectiveness of the top-shaped blocks was observed by comparing settlement for wave-dissipating blocks on the blocks and on unimproved sand under different load and incident wave conditions. The wave-dissipating blocks on unimproved sand settled due to wave action, even when the sand level itself did not change. When top-shaped blocks were present the wave-dissipating blocks did not settle without settlement of sand layer. In addition, scouring affected the sand adjacent to the breakwaters, which caused some settling of wave-dissipating blocks. Scouring is a key phenomenon in disturbances to wave-dissipating blocks. However, when top-shaped blocks are installed, even if there is some decrease in sand level due to scouring, the blocks prevent settling by stabilizing the wave-dissipating block structure. The sand level difference was calculated from the experimental results using Froude's law. Fig. 10 shows how the settling of the breakwater structure and the sand level was affected by the presence of the top-shaped blocks. As long as the sand level fell less than 80 cm below the tops of the top-shaped blocks, the wave-dissipating blocks did not settle. Even under a variety of wave conditions, including storms, as long as the sand level changed less than 80 cm due to scouring, the top-shaped blocks stabilized and supported the breakwater structure, and when wave conditions were calm, the scoured areas were replenished with sand. Thus, the ability of top-shaped blocks to stabilize the breakwater structure under 80 cm of scouring is very beneficial. Top-shaped blocks do not always settle in sand under non-scouring conditions that cause settling for wave-dissipating blocks. These observations may be attributed to the liquefaction property of sand, and explaining the mechanism of this property will be an important subject for future research on breakwater foundations.

In situ tests showed that foundations of top-shaped blocks prevented wave-dissipating blocks on coasts from settling into the sand. The effectiveness of the top-shaped blocks was verified in a tank experiment that exposed the wave-dissipating blocks to various wave conditions; however, scouring conditions have not yet been sufficiently understood. Since the scale of the tank experiment was 1/20, further *in situ* research is also necessary. Currently, there is insufficient information about the performance of top-shaped blocks *in situ*, despite the importance of extending the life of these breakwater structures.