CHAPTER 129

FIELD INVESTIGATIONS ON WAVE-DISSIPATING CONCRETE BLOCKS COVERING VERTICAL WALL BREAKWATER

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Abstract

The failures experienced in Japan by wave-dissipating concrete blocks (WDCB) covering vertical wall breakwaters are investigated, and the deformation characteristics such as failure features and factors are examined.

Typical examples for failures are illustrated, and two main types for failures are suggested: (a) scattering of WDCB due to shortage of their weight, (b) settlement of WDCB following deformation of the toe area. These types are analyzed and then the latter is discussed with some preliminary experiments. The results suggested that both stability of WDCB and applicability of the Hudson formula depend on the location and their cross-sectional shape, and that a weakening of sand bed due to wave action, especially wave-induced liquefaction, is an important factor of settlement deformation as well as scouring.

From these results and additional field surveys, finally, two parameters are suggested which can explain the effect of stability of WDCB and toe area on both scattering and settlement behavior, and a classification of resultant failure characteristics and a conceptualized diagram of failure behavior of WDCB are presented.

1. Introduction

Throughout the world, and especially in Japan, the Hudson formula has

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been applied in the design process used to evaluate the stability of WDCB which cover the front of large-scale vertical wall breakwaters. However, based on the fact that this design tool was not for WDCB, but originally formulated for evaluating the armor layers of rubble mound breakwaters, WDCB may show different stability properties in the applied fields.

Therefore, firstly, we performed field stability investigations to determine the deformation characteristics and resultant suitability of the Hudson formula in designing Japan's recently built vertical breakwaters covered with such blocks. Secondly, we also carried out some preliminary experiments and field surveys to understand a unique failure characteristics of settlement deformation observed at Miyazaki Port. Finally, in discussion, we classified these complicated failure features and explained them quantitatively, so that the results will be helpful to develop an improved design method.

2. Investigation method

Field investigations were conducted in Japan on major breakwaters located at 16 ports among more than a hundred as shown in Figure 1. Failure

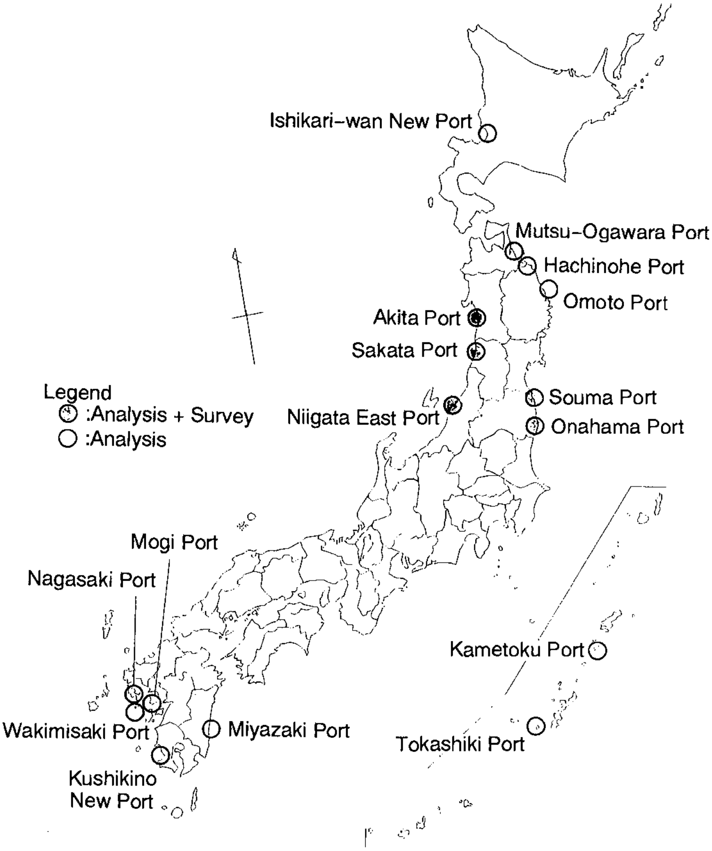

Figure 1. Map of ports investigated in this study

Table 1. Summary of failures of WDCB

No.	Disturbance	Port: Breakwater	Location	Sectional Shape	Design: $H_{1/3}$,T,i
1	'91, Feb.	Mutsu-Ogawara:East	trunk	sectional end	7.1m/ 13.0s/ 1:50
2				fully covered	
3				sectional end	
4		Hachinohe: No.1	head	sectional end	6.3m/ 13.0s/ 1:100
5				fully covered	
6		Hachinohe: No.2	head	sectional end	6.6m/ 13.0s/ 1:100
7				fully covered	
8		Omoto: Offshore	head	fully covered	7.9m/ 12.0s/ 1:30
9	'91, Sep. Typhoon 19	Nagasaki(Oe): Offshore	head	sectional end(berm)	5.5m/ 10.7s00/ 1:30
10				sectional end	
11				fully covered	
12		Wakimisaki: South	trunk	sectional end	3.9m/ 10.0s
13				fully covered	
14		Kusikino New: West	trunk	fully covered	6.0m/ 13.0s
15				fully covered	7.7m/ 13.8s
16		Mogi: Offshore	head	fully covered	4.5m/ 12.5s
17			trunk	fully covered	
18	'87, Aug.	Kametoku: South	head, on a reef	fully covered	10.2m/ 16s/ 1:50
19		Tokashiki: South	head	fully covered	-
20	'88 - '90	Miyazaki: South	trunk	fully covered	8.9m/ 14.0s/ 1:200
21	'85, Nov.	Ishikari-wan New	trunk	fully covered	5.6m/ 11.0s
22	'93, Aug. Typhoon 11	Onahama: No.1, West	trunk	fully covered	6.2m/ 14.0s/ 1:100
23		Onahama: No.2, West12	trunk	fully covered	8.1m/ 14.0s/ 1:100
24		Souma: South2	trunk	fully covered	4.5m/ 15.0s
25	'80 - '90	Sakata: North	trunk	temporaly low crest	7.5m/ 11.0s
26	'93 - '94	Akita: South(E)	trunk	fully covered	7.5m/ 13.5s
27	'95, Nov.	Niigata East: West	trunk	sectional end, fully covered	8.3m/ 12.9s

cases investigated in this study are limited to those which recently occurred remarkably and whose data have been accumulated enough to analyze their features and factors. As the result, 27 cases including both damage and no damage were analyzed using pertinent data including wave conditions, damage features (area, type, and weight of blocks), and design conditions. After these analyses some preliminary experiments were done to study a unique failure at Miyazaki port. Furthermore, in order to see not only failure results but also its process going on in site, 6 cases (Case 22 to 27 in Table 1) were surveyed noting the physical conditions before and/or after deformation. All cases are summarized in Table 1.

3. Investigation results

From all the cases in Table. 1, the following specific features of WDCB failures are obtained:

1) Few failure cases of WDCB are reported in spite of the fact that they are used in many sites.

Table 1 (continued)

No.	Block*	Wave conditions**:$H_{1/3}$, T, θ	Failure features of WDCB	Other failure features
1	T:50t, S:50t (1:4/3)	9.6m/ 13.4s/ -7.1°	scattering, settlement	caisson sliding, breakage
2	T:50t (1:4/3)		a little settlement (0-1.5m)	
3	S:50t (1:4/3)		scattering, settlement	
4	T:50t (1:4/3)	7.5m/ 11.4s/ 8.9°	scattering, settlement	caisson sliding
5			a little settlement	
6	T:50t (1:4/3)	5.9m/ 11.4s/ 23.8°	scattering, settlement	caisson sliding
7			a little settlement	
8	T:64t (1:4/3)	9.3m/ 13.7s/ 31.8°	scattering, breakage	caisson sliding, breakage
9	T:20t (1:4/3)	7.2m/ 15.6s/ 36°	scattering, breakage	caisson sliding
10	T:20, 40t (1:4/3)		scattering, settlement	
11	T:20, 40t (1:4/3)		no damage	
12	T:32t (1:4/3)	4.8m/ 15.1s	scattering, settlement	
13			no damage	
14	T:50t (1:4/3)	-	scattering, settlement, breakage	
15	T:64t (1:4/3)			
16	T:16t (1:4/3)	-	scattering	caisson sliding
17			no damage	
18	D:50t (1:1.3)	5.9m/ 12.2s/ 39°	scattering	caisson sliding
19	T:5, 32t (1:4/3)	7.0m/ 14.4s/ 51°	settlement	caisson sliding, breakage
20	T:64t (1:4/3)	-	settlement	scouring at the toe area
21	T:4, 20t	-	settlement	scouring at the toe area
22	T:25t (1:4/3)	6.6m/ 12.0s	scattering, settlement	scouring at the toe area
23	T:50t (1:4/3)	9.1m/ 12.0s	scattering, settlement	scouring at the toe area
24	H:25t (1:1.5)	5.0m/ 10.8sec	scattering, settlement	scouring at the toe area
25	T:32, 50t (1:1.5)	-	settlement	
26	T:40t (1:1.5)	-	settlement	
27	T:50t (1:1.5)	-	settlement	

* T: Tetrapods, S: Sealock, D: Dolos, H: Hexa-leg-block

** Incident wave conditions calculated by wave hindcasting when the failures occurred

2) Though the predominant disturbances are typhoons in summer and depressions in winter, gradually advancing deformations during about one year are also observed.

3) Tetrapods and its normal slope gradient of 1:4/3 are used for more breakwaters, however, gentler slope of 1:1.5 is locally adopted at the ports facing to the Sea of Japan where scouring at the toe area of composite type breakwater is remarkable.

4) Occurrence of the breakage of blocks is less than that of scattering and settlement which seem to be typical failure features.

5) Other two failure features , caisson sliding and breakage, and scouring at the toe area, are observed at the breakwater head/sectional end and breakwater trunk, respectively.

In the following paragraphs, the investigation results on scattering and settlement of WDCB will be indicated.

3.1 Scattering failures of WDCB

Typical examples

Figure 2 shows the scattering of WDCB, 40 t Tetrapods, and the damage of caissons of No.2 breakwater at Hachinohe Port (Case 6,7). The important point to note in these cases is that the scattering of WDCB was found to be severe at the breakwater head/sectional end, A-A line, and that it was very mild at the trunk section, B-B line, in spite of neighboring the damaged area. The predominant reason responsible for the former is the action of severe wave force at the sectional end as pointed out by Takahashi et. al.(1993). A nesting process of the scattering of WDCB and the caisson sliding due to increase of wave force acting on the caisson wall lead to the larger scattering. Similar failure features like this are observed at east breakwater in Mutu-Ogawara Port (Case1,2,3), No.1 breakwater in Hachinohe Port (Case 4,5), Nagasaki Port (Case9,10,11), and Wakimisaki Port (Case12,13).

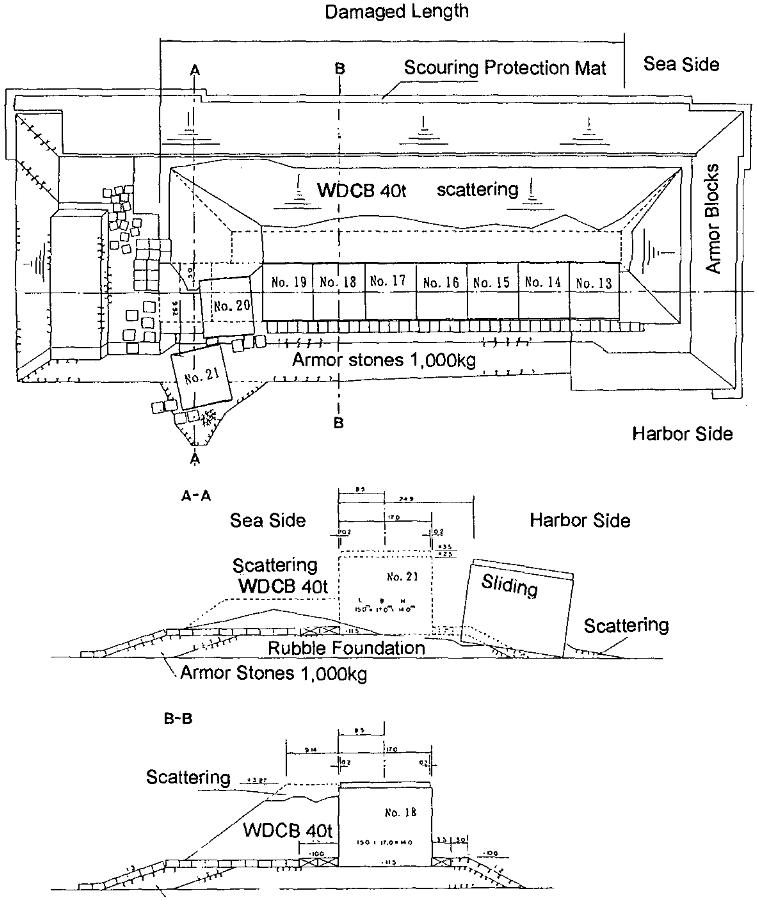

Figure 2. Scattering of WDCB at breakwater trunk section and head sectional end (Hachinohe Port)

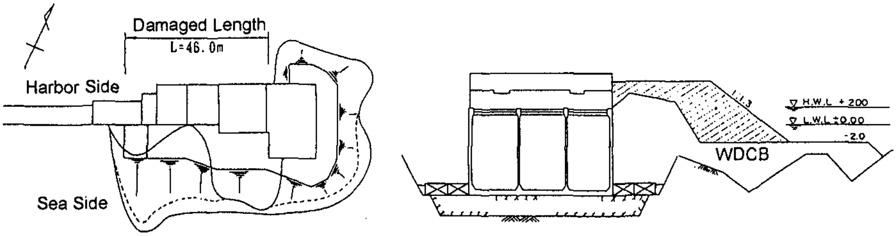

Figure 3. Scattering of WDCB covering a reef (Kametoku Port)

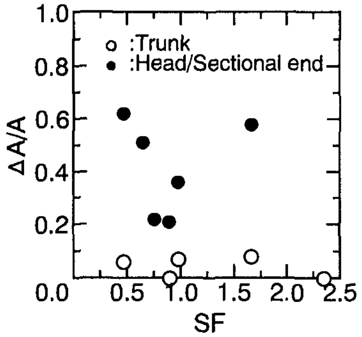

Figure 4. Relationship between degree of scattering and safety factor

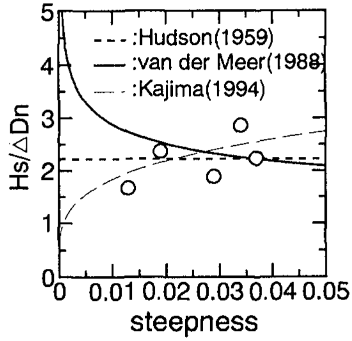

Figure 5. Effect of steepness on stability number as determined by three formulas and observed failure cases

Figure 3 shows the scattering of WDCB, 50t Dolos, covering the reef at Kametoku Port (Case18). Here, the south breakwater is located on the natural reef around the Tokunosima island, and its head on the edge of reef whose bottom slope is steep. This scattering occurred due to both waves breaking there suddenly and resultant severe currents.

Relationship between degree of scattering and safety factor

Judging from the above, the degree of scattering of WDCB seems to depend on its location and cross-sectional shape. Figure 4 shows the relationship between the degree of scattering of WDCB and the safety factor, where ΔA/A is the ratio of the cross-sectional damaged area to design area, and SF shows the ratio of the actual weight to the calculated weight when failure occurred. It is clear that WDCB at the trunk section remains stable at a safety factor as low as 0.5, and in contrast, the scattering of WDCB at the breakwater head/sectional end occurs severely even though the safety factor is as high as 1.7. Consequently, it is indicated that the applicability of the Hudson formula is adequate at the breakwater trunk section and marginal at the head/sectional end.

Applicability of stability formulas for WDCB

Corresponding analyses are also performed using the design formulas by van der Meer(1988) and Kajima(1994) as well as the Hudson formula. Figure 5 shows the effect of steepness on the stability number by comparing the no damaged cases at trunk section to the results calculated by three formulas in such conditions that relative damage level in van der Meer(1988),No=0.2; deformation level in Kajima(1994);S=1.2, and wave number; N=1000. It is found that they show similar applicability when considering limited amount of field data though the effects of steepness varies among them. In other words, there is almost no difference among them in a practical wave steepness ranging from 0.01 to 0.05.

3.2 Settlement failure of WDCB

Typical examples

Of particular interest, the failure at Miyazaki Port is a typical one caused by long-term, gradual settlement of blocks, being a sometimes hard-to-recognize type of damage that frequently occurs in areas where sand transport is significant. Figure 6 shows that the cross-sectional change such as settlement of WDCB, 64t Tetrapods and armor blocks. Although the nesting process of blocks and/or scouring at the toe area have generally been considered to be the main cause, block settlement may instead be due to various wave actions weakening the sand bed to such an extent that the blocks literally sink into it. Figure 7 shows a photograph supporting this possibility, i.e., the entire body of blocks appears to have moved toward and down during settling. This characteristic feature is also observed at Kushikino Port.

Reproduction of settlement behavior at Miyazaki Port

In order to discuss this type of settlement behavior in detail, wave flume experiments designed to reproduce the breakwater deformation at Miyazaki Port were conducted with reduced scale of 1:55. It was found that block scattering did not occur, even when attacked by waves exceeding the design wave height , and scouring was produced at the toe area, though the use of gravel mats prevented subsequent deformation of the block section.

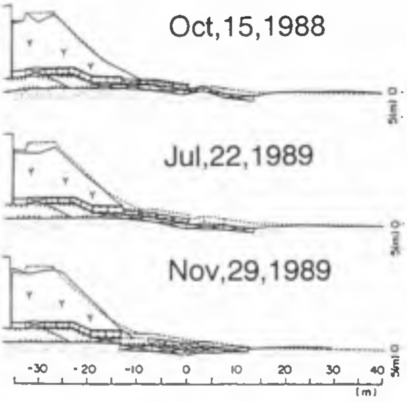

Figure 6. Cross-sectional change of south breakwater at Miyazaki port

Figure 7. Settlement deformation of WDCB at Miyazaki Port

Then, to clarify whether weakened strength of the sand bed is responsible for settlement of blocks, we liquefied it by supplying pore water from bottom of the bed. Figure 8 shows a photograph of the results. The important point to note is that the settlement of the block section is quite definitive, i.e., the blocks at the toe area have sunk into the sand bed and the entire body of blocks has moved forward and down (Figure 8(b), (c)), being a similar behavior to that actually observed (Figure 7) and quite different from the not-liquefied case(Figure 8(a)). These results indicate that weakening of the bed caused such settlement deformation, and that as wave loadings most likely lead to bed weakening, the phenomenon of wave-induced liquefaction may play a key role.

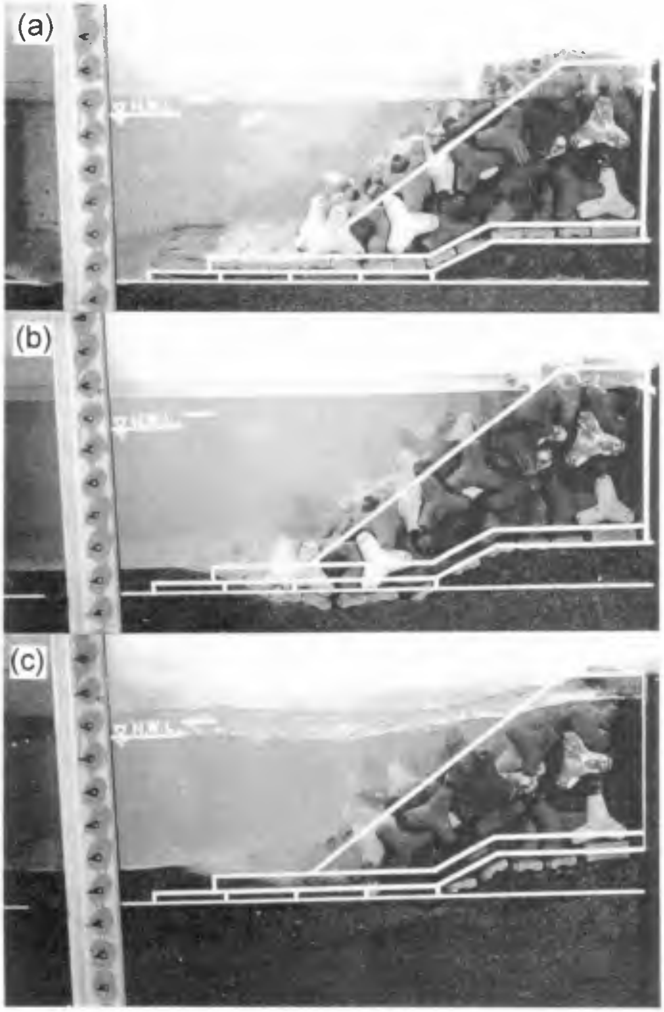

Figure 8. Block settlement deformation due to weakening the sand bed by liquefaction

3.3 Surveys of settlement deformation

During Dec. 1995 to Mar. 1996, field surveys were carried out at 5 ports as shown in Table 1, to examine whether a similar settlement deformation like Miyazaki Port is observed or not. The results indicate that there are two patterns of settlement, excluding the initial settlement due to compaction by wave attack after construction. These are 1) settlement of the top of WDCB due to scattering, a pattern which looks like true settlement, and 2) settlement of an entire body of WDCB following the deformation of a toe area. Furthermore, it is reasonable to think that these features are possible to occur either alone or together.

4. Discussions

The discussions were made below towards a better understanding of the scattering and settlement behavior of WDCB.

Classification of predominant failure characteristics of WDCB

The following classification and identification of failures can be obtained from the investigated failure cases:

1) Failure features
    - Direct and independent:
        - · Scattering
        - · Breakage
        - · Others
    - Indirect and complex:
        - · Scattering with caisson sliding
        - · Settlement following deformation of toe area
        - · Others
2) Failure factors except for waves exceeding the design condition
    - Major factors for scattering
        - · Sea bottom topography: reef and steep slope
        - · Location: breakwater head
        - · Cross-sectional shape: sectional end
    - Major factors for settlement
        - · Soil condition: sand
        - · Toe structure

In the following discussions, the scattering and settlement at the breakwater trunk will be discussed in particular.

Structural Parameterization

Considering the settlement feature and its process, it seems reasonable to suppose that both material and dimension of the toe area are important factors to prevent settlement deformation of blocks. Therefore, the structures including WDCB in front of a vertical wall are represented with dimensionless parameters as shown in Figure 9. In this figure, x and z indicate the distance measured from the vertical wall and sea bottom, and h and L show the water depth and wave length in design, respectively. Furthermore, the following abbreviations are used: AB (armor block), AS (armor stone), FPB (foot protection block), FPS (foot protection stone), G (gabion), GM (gravel mat), M (asphalt mat or scour protection mat), RF (rubble foundation).

As illustrated in this figure, the structures for toe area have a certain range from the thick and wide to the thin and narrow. Consequently, we parameterized the structure for toe area by its thickness;t and width;s as shown in the top right, where st shows an index of cross-sectional area of toe structure.

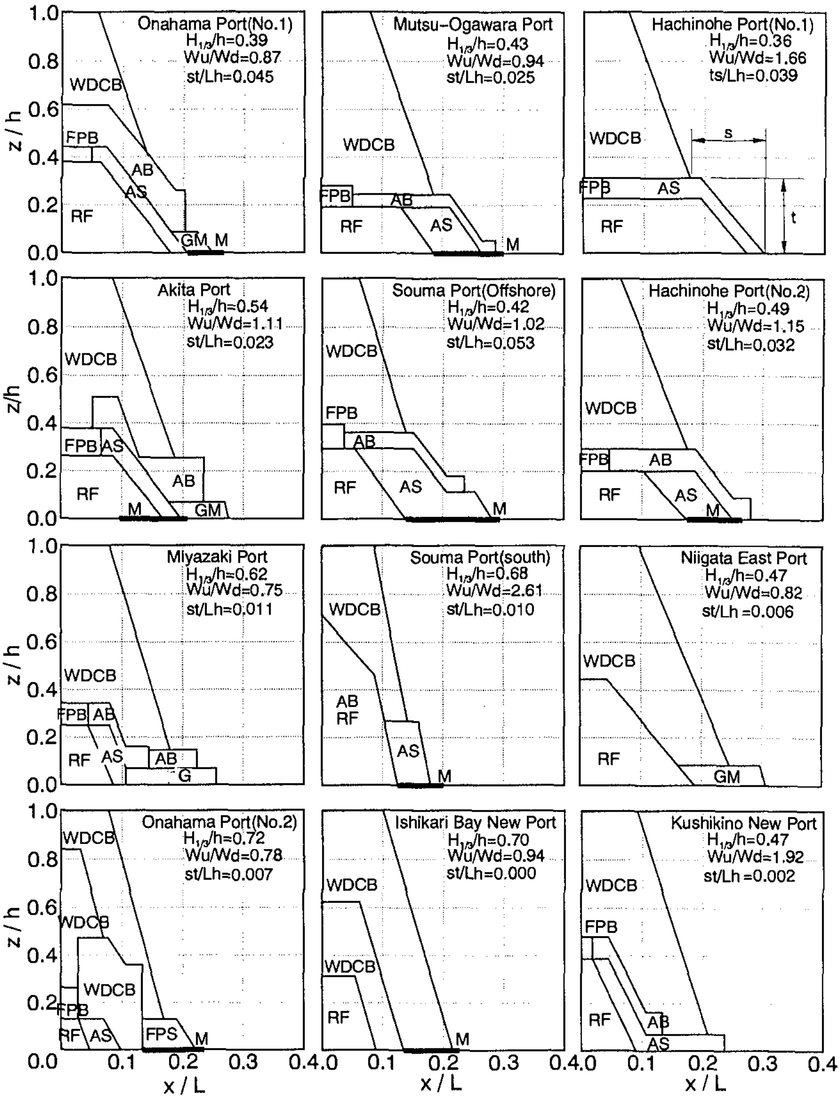

Figure 9. Structure parameterization

Effects of stability of WDCB and toe area on scattering and settlement behavior

To discuss both effect of stability of WDCB and toe area on scattering and settlement behavior, two parameters are suggested: $st/LH_{1/3}$ which indicates the stability of toe area being non-dimensional parameter with st, design significant wave height; $H_{1/3}$ and wave length; L, and Wu/Wd which indicates the stability of WDCB by using actual weight; Wu and design weight; Wd. Figure 10 shows the relationship between two parameters and the degree of deformation at trunk section. As shown in this figure, deformation becomes larger when $st/LH_{1/3}$ is smaller than 0.04 and the failures can be divided into four regions in this figure: no failure, settlement, settlement and scattering, and scattering.

Furthermore, each failure case can be explained reasonably and estimated. For example, the following consideration is possible:

1) Both Miyazaki Port and Kushikino Port are unstable for settlement and indicate similar failure feature, however, if severe waves exceeding the design wave condition attack, they will show different failure features, with scattering or no scattering, because of the difference in the stability of WDCB.

2) The failure case observed at Souma Port (south) shows the severe deformation against the wave attack slightly exceeding the design wave condition although the weight of WDCB is enough to keep itself stable under such a wave condition. This case can be explained as typical one caused by settlement deformation.

3) The case at Onahama Port (No.2), where the blocks less than design weight were used, the value of $st/LH_{1/3}$ is 0.01, and the exceedance of wave design condition was experienced, seems to indicate a complex failure feature which both settlement and scattering occurred at the same time.

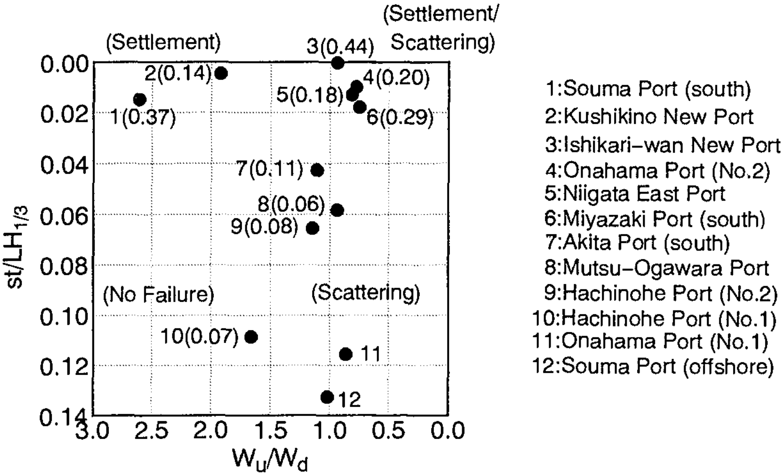

Figure 10. Influence of stability of toe area and WDCB on scattering and settlement behavior (values in parentheses indicate $\Delta A/A$)

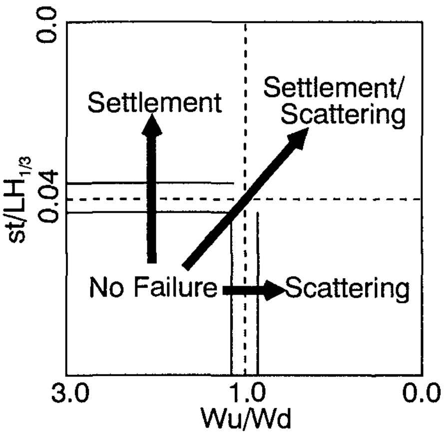

Figure 11. A diagrammatic representation of Figure 10

Conceptualization of failure behavior of WDCB

Based on the above discussion and Figure 10, the failure behavior can be conceptualized as shown in Figure 11. This diagram shows a summary representation of the effects of stability of toe area and WDCB on failure behavior of WDCB.

5. Conclusion

The following main conclusions can be drawn from these investigations:

1) Few failure cases of WDCB covering vertical breakwaters are reported in spite of the fact that they have been used in many sites.

2) WDCB designed by using the Hudson formula are very stable at the breakwater trunk. On the other hand, those at the breakwater head/sectional end are less stable and have experienced the typical scattering failures consequently.

3) Of the failures which have been considered as scattering failures, not a few failures due to settlement are observed like Miyazaki Port and Kushikino Port.

4) Not only scouring at the toe area but also liquefaction due to waves may play a key role on the settlement failure, and to clarify its cause, further research is necessary.

5) However, a suggestion is possible as a countermeasure for the settlement failure that one adopts a large value of the parameter st, that is, makes a toe structure wider and thicker.

Acknowledgements

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