CHAPTER 150

STATISTICAL ANALYSIS OF DETACHED BREAKWATERS IN JAPAN

Takaaki UDA*

ABSTRACT

Construction of detached breakwaters is one of the main countermeasures against beach erosion in Japan. The number of breakwaters has been rapidly increasing, with about 2500 constructed as of the end of 1981. This study aims at the investigation of the effect and stability of detached breakwaters along Japan's coasts on the basis of survey of 1552 breakwaters constructed by the Ministry of Construction. The existing conditions of the dimensions of the detached breakwaters are statistically analyzed; the optimal dimensions for sand deposition behind a breakwater are proposed, and the critical conditions for advance of the shoreline facing an opening of breakwaters are investigated. Furthermore, the relations between the scattering rate of concrete blocks and various conditions such as bottom slope, the depth at the breakwater, the offshore distance of the breakwater and the weight of the blocks are studied. It is concluded that, in order to prevent scattering, the weight of the blocks should be at least 1.5 times heavier than that calculated from the Hudson formula.

1. INTRODUCTION

The coastal zone has been highly utilized in Japan because of the shortage of plains in the Japanese archipelago. Every effort has been made to protect the coastline from erosion due to sea waves. In 1950's, full-scale coastal protective measures were initiated in Japan. In this period, coastal dikes were mainly constructed to prevent coastal disasters brought by storm surges. In the late 1950's, coastal dikes and revetments of the vertical wall type were introduced against beach erosion. Thereafter, groins were constructed, but there were several cases with less effect. In the 1960's, the field test of detached breakwaters was conducted for the first time to confirm their effectiveness. Since then, detached breakwaters have been constructed extensively to preserve or revive the sandy foreshore, as the damage to coastal dikes and revetments, triggered indirectly by the disappearance of the foreshore, increased. At present, construction of detached breakwaters is one of the main countermeasures against beach erosion, and many of them have been constructed along Japan's coasts to dissipate wave energy and prevent beach erosion. The number of detached breakwaters has been rapidly increasing with about 2500 constructed as of 1981. However, there are still many problems to be solved for construction of detached breakwaters. The planning method to ensure the effect and

* Dr.Eng., Head, Coastal Eng. Div., Public Works Res. Inst., Ministry of Construction, Ibaraki 305, Japan.

stability of detached breakwaters has not yet been established. This study, based upon survey of 1552 breakwaters built by the Ministry of Construction, aims at the investigation of the effect and stability of detached breakwaters(Seiji et al., 1987).

II. METHOD OF INVESTIGATION

The survey was conducted in order to study the existing situations of detached breakwaters in Japan. Questionnaires were distributed to the prefectural government offices and to the work offices of the Ministry of Construction to collect the information on each of the 1552 detached breakwaters constructed by the Ministry or by the prefectural governments as subsidiary works of the Ministry by the end of 1982.

The contents of the questionnaire are summarized in Table 1, in which the principal items are general matters, natural conditions, dimensions of the breakwater, kinds of concrete blocks, information on the scattering of the blocks and the effect of the breakwater. Although the details of the items are summarized in Table 1 , there are some additional notes to be given. A serial number was attached to identify each breakwater. The difference between permeable and impermeable types was of interest, but all the breakwaters were of the permeable type. The water depth at the breakwater and the offshore distance to the breakwater

Table 1 Contents of the questionnaire.

Classification	Items
General Matters	name of the prefecture name of the coast number of the detached breakwater construction date
Design Conditions	design wave height design wave period tidal range bottom slope at the site water depth (reference: H.W.L.) offshore distance (reference: H.W.L.)
Dimensions of the Detached Breakwater	type (permeable or impermeable) placing (pellmell or uniform) crown height length elevation above the H.W.L. foundation
Kinds of Concrete Blocks	kind weight K_D value in the Hudson formula
Effect and Stability	subsidence of the blocks scattering of concrete blocks method of placing tombolo formation (yes or no) foundation (yes or no)

were measured above the H.W.L., whereas the crown height of the breakwater was measured above the standard mean sea level of Tokyo Bay.

In order to study the effect and stability of the detached breakwaters in general, the type of coasts was classified into five categories of A through E, as shown in Fig.1, based on the beach profile. The characteristic features of these coasts are as follows:

Type A: The coasts facing a bay or an inland sea, such as the Aomori Coast and the Toban Coast. The wave heights are low on these coasts compared with those on the coasts facing the open sea, and the critical depth for sand movement is small.

Type B: The coast with a fairly developed bar-trough topography, such as the Niigata Coast, the Ishikawa Coast and the Enshu Coast. The bottom slope in a region shallow enough for sand movement is mild, and the direction of mean incident waves is almost normal to the coastline.

Type C: The coast where the bottom slope in the shallow region is relatively steep without the formation of bar-trough topography, e.g., the Shimoniikawa Coast and the Suruga Coast.

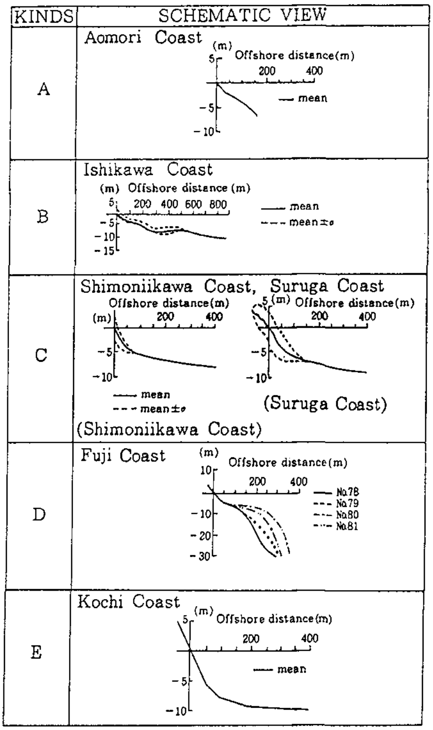

Fig.1 Type of the coasts classified into five categories of A through E.

Type D: The coast with an extremely steep slope of 1/3-1/10, e.g., the Fuji Coast in Suruga Bay.
Type E: The coast similar to Type C, but with a bar-trough topography sometimes observed in a far offshore zone, e.g., the Kochi Coast.

III. RESULTS OF SURVEY

3.1 Situations of detached breakwaters in Japan

The results of the survey about the dimensions of the detached breakwaters are shown in Figs.2 (a) to (h).

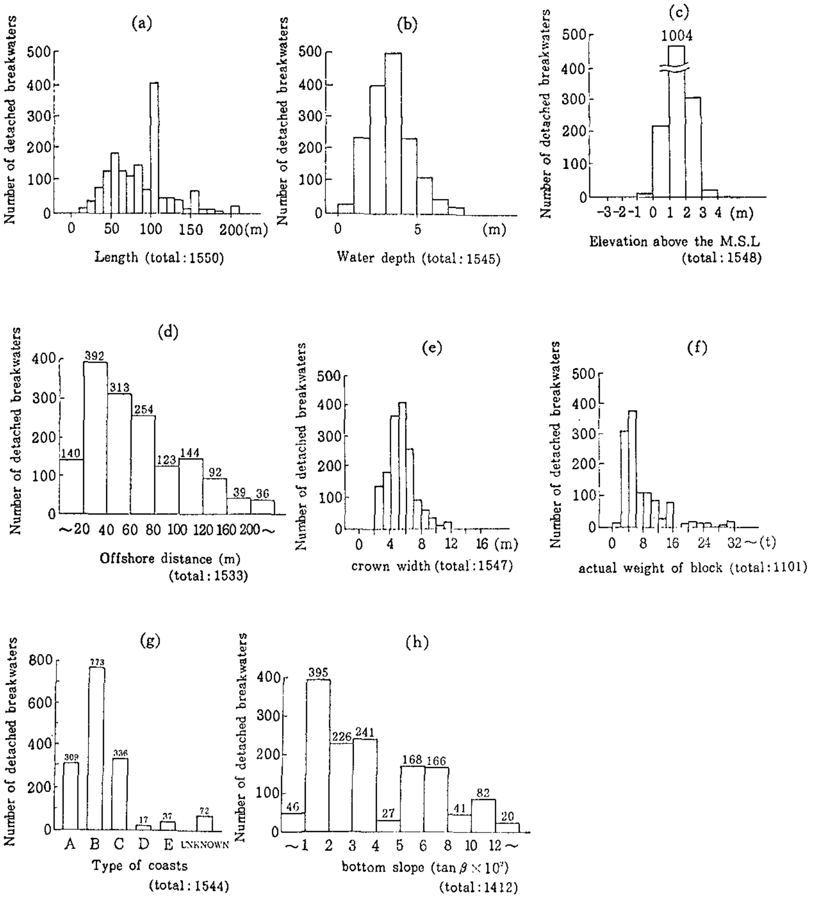

Fig.2 Frequency distribution of various dimensions of the detached breakwaters; (a) length, (b) water depth, (c) elevation above the M.S.L., (d) offshore distance, (e) crown height, (f) actual weight of block, (g) type of coasts and (h) bottom slope.

The maximum frequency of breakwater length, divided into 10m intervals, appears in the interval of 100-110m, amounting to 20%. The secondary peak is found in the interval of 50-60m. The maximum frequency of the water depths at the breakwaters is 3-4m, and it amounts to 30%. 90% of the breakwaters are located at a water depth less than 5m. The most frequent elevation of the breakwater above the M.S.L. is 1-2m and the frequency amounts to 65%. Regarding the distribution of the offshore distances, the number of breakwaters in each interval generally decreases with the increase in the offshore distance, except in the case less than 20m. The maximum number, 392, is included in the interval of 20-40m, amounting to almost 25%. The crown width varies between 2 and 12m, and the most frequent value is in the interval of 5-6m. The weight of the concrete blocks is mostly in the range from 2 to 6 tons, but there is an exceptional case of the Fuji Coast in Suruga Bay where 50-ton blocks were used (Kohno et al., 1986). Most breakwaters were built on the coasts of type B. All the data for type D, whose number is rather limited, belong to the Fuji Coast. The bottom slope ($\tan\beta$) at the breakwater was determined from the bottom topography before the construction of the breakwater, and its peak appears in the interval of 0.01-0.02. Few breakwaters were built on a coast with a slope milder than 0.01.

The sand deposition effect of the detached breakwaters was investigated statistically on the basis of tombolo formation. Figure 3 shows the percentage of tombolo formation. It is clearly seen that tombolos were formed in about 60% of all the cases. The frequency distribution of the maximum shoreline advance due to tombolo formation is shown in Fig.4. The shoreline advance ranges from 0 to 140m. The maximum frequency is found in the interval of 10-20m, and the cases with a shoreline advance of more than 100m is quite limited in number.

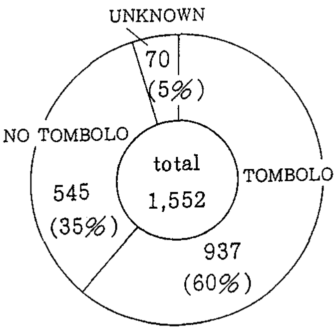

Fig.3 Percentage of tombolo formation.

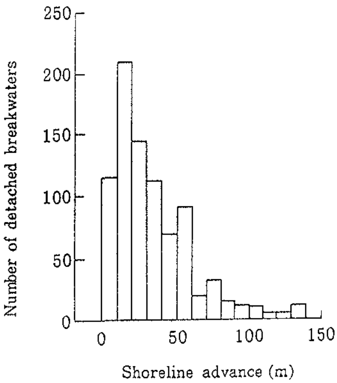

Fig.4 Frequency distribution of the maximum shoreline advance due to tombolo formation.

The number of the detached breakwaters with or without subsidence was investigated statistically as shown in Fig.5. It is found that the subsidence of the detached breakwater is observed in about half of the total number (1552). From this it is realized that the subsidence of the detached breakwater becomes an important problem regarding the stability of the breakwater. On the basis of 503 detached breakwaters whose subsided height is available, frequency distribution of the subsided height of detached breakwater is investigated as shown in Fig.6 . The subsided height ranges between 0 and 2.8m . The most frequent subsided height of the breakwater is 1.0-1.2m , and the number amounts to 158.

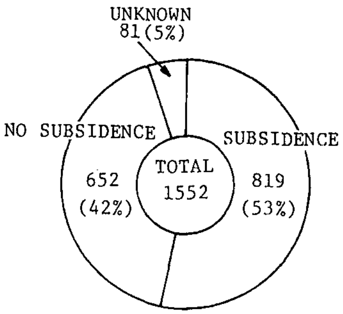

Fig.5 Percentage of the number of detached breakwater with or without subsidence of blocks.

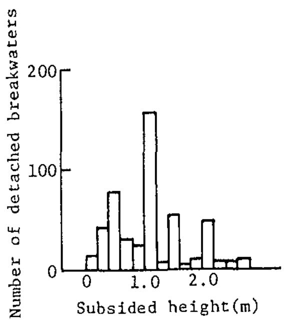

Fig.6 Frequency distribution of the subsided height of detached breakwater.

Table 2 shows the percentage of the number of the subsided detached breakwater corresponding to the kinds of the bed materials. The ratio of the number of the subsided breakwater relative to the total number accounts for 64% (sand), 43% (gravels) and 10% (rock), respectively. The reason of the subsidence of the breakwater for the rocky bottom materials may be due to the fact that the interlocking of the concrete blocks near the top of the

Table 2 Percentage of the number of the subsided detached breakwater corresponding to kinds of the bed materials.

Subsidence / Bottom materials	Exist	Nil	Unknown	Total
rock	(10%) 19	(73%) 141	(17%) 34	(100%) 194
gravel	(43%) 139	(56%) 183	(1%) 5	(100%) 327
sand	(64%) 678	(33%) 347	(3%) 42	(100%) 1067
silt	(100%) 1	(0%) 0	(0%) 0	(100%) 1
Total	(53%) 837	(42%) 671	(5%) 81	(100%) 1589

breakwater may be loosened by wave action. Comparing both foundations of sand and gravels, the ratio of the subsidence in the latter case is small. However, the ratio of the subsidence of the blocks is large enough in both cases, and it is necessary to take effective measures against subsidence if detached breakwater is constructed on the foundation of sand or gravels.

Percentage of the number of detached breakwater with or without scattering of blocks is shown in Fig.7 . Scattering of the blocks can be observed in 14% of the total. In addition, frequency distribution of the scattered distance of blocks is shown in Fig.8 in the case whose scattered distance is available. Scattered distance ranges between 0 and 13m, and the most frequent case of scattering distance is 4-5m .

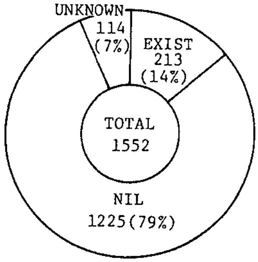

Fig.7 Percentage of the number of detached breakwater with or without scattering of blocks.

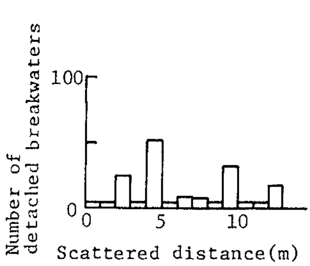

Fig.8 Frequency distribution of the scattered distance of the blocks.

3.2 Effect of detached breakwaters

The effects of detached breakwaters are mainly divided into two categories: the first is to cause the sand deposition behind the breakwater, and the second is to dissipate the incident wave. The former effect basically depends not only on the dimensions of the breakwater but on the rate of sand supply due to littoral drift. It is, however, difficult to study the influence of the littoral drift in general, because the conditions of sand supply differ to a large extent from place to place. Therefore, only the influence of the dimensions on sand deposition is discussed in this study.

The length l, the width of the opening l' , the offshore distance Y, and the water depth at the breakwater h' , are selected as the characteristic dimensions, as schematically shown in Fig.9. In order to indicate the effect of the detached breakwater on sand deposition behind the breakwater, an index T_a is introduced, which is defined by the ratio of the area of formed tombolo ($\approx 0.5 L_t B_t$) to the area of the original sea surface behind the breakwater (= $l \cdot Y$). Figure 10 shows the relations between the index T_a and the nondimensional parameters showing the breakwater

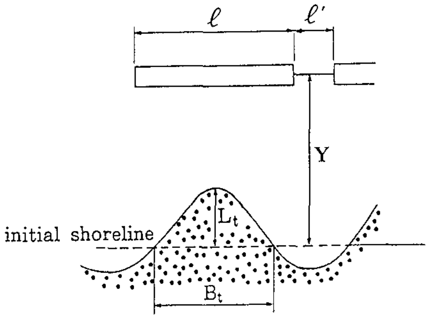

Fig.9 Characteristic dimensions of the detached breakwater (l: the breakwater length, l' : opening width, L_t : the tombolo length, B_t : the tombolo width, and Y: offshore distance.)

dimensions such as the ratios of the length to the offshore distance (l/Y) and of the relative water depth at the breakwater to the breaker depth (h'/h_b). The breaker depth was determined as follows. First, the data of the significant wave heights at each coast, measured in a typical year(1981), were ordered from the largest to the smallest. Secondly, the five largest data were selected and averaged to obtain a local reference wave height under relatively high wave conditions. This number of waves was selected since it seemed to be most significant in the discussion of stability and sand deposition under high wave conditions. Finally, the breaking depth was evaluated on the assumption that the ratio of the breaker height and the water depth at the breaking point is 0.78.

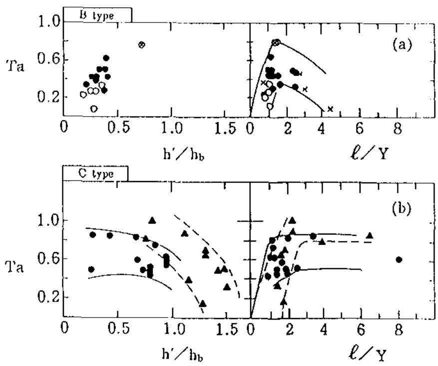

Fig.10 Relations among T_a, h'/h_b and l/Y. (The solid and open circles in (a) express the conditions of $l \fallingdotseq 100$m and $l \fallingdotseq 150$m, respectively. The 'x' sign shows the other cases. The solid circles and triangles in (b) express the cases of the beach materials composed of sand and gravels, respectively.)

Figure 10 shows the relations among T_a, h'/h_b and l/Y on the coasts of type B (e.g., the Ishikawa Coast and the Niigata Coast) and type C (e.g., the Shimoniikawa Coast and the Suruga Coast), with additional classifications on the length of breakwaters and the kind of the beach materials. The solid and broken lines in the figure show the upper and lower limits of the data. The coasts of these two types were selected as typical coasts in Japan. Although the data were limited to the case of $h'/h_b<1$ for the coasts of type B, T_a increase with h'/h_b under these conditions. The sand deposition effect due to the detached breakwaters improves with larger h'/h_b, and the relative scale of tombolo is larger when the location of the breakwater is closer to the breaking point. It was found that T_a takes the maximum value at $l/Y\approx1.6$; that is, the relative area of the tombolo is maximized when $l\approx1.6\,Y$.

In the case of type C, the data are scattered compared with the data for type B. The value of T_a tends to decrease if $h'/h_b<1$, which means that the relative area of tombolo decreases as the distance from the breaking point to the breakwater increases. As for the relation between T_a and l/Y, T_a appears to be maximum at $l/Y\approx2.0$, and thereafter it remains constant in contrast with the decrease in the case of type B.

As described above, a tombolo is formed due to the sand deposition effect of detached breakwaters, if various conditions are satisfied. The formation of a tombolo behind the breakwater is normally considered to be a favorable effect. On the contrary, the retreat of the shoreline facing openings can be caused by the construction of the detached breakwaters. This sometimes causes serious problems such as wave overtopping over the revetment behind a detached breakwater and/or the scouring at the foot of the revetment, when the original foreshore is narrow. Figure 11 shows the relations between the change in the shoreline facing the openings and the dimensions of detached breakwaters on the basis of the field data. Three dimensionless parameters l'/l, l'/Y and l/Y were selected to indicate the breakwater dimensions, where l', l and Y are the opening width, the breakwater length and the offshore distance, as illustrated in Fig.9 . For the detached breakwaters built on the Japan's coasts, the ratios of the opening width to the length concentrate to certain values, so that the data are plotted separately for different l'/l values. In Figs.11 (a) to (c), the effect of each parameter is shown without regard to the other parameters. Let us cosider the case of $l'/l\approx0.3$ for example. In Figs.11 (b) and (c), l'/Y and l/Y are respectively taken in abscissa. Between these variable, the following relations hold:

$$l'/Y=l/Y\cdot l'/l\approx0.3l/Y \qquad (1)$$

Consequently, Figs.11 (b) and (c) give the similar result. In the case of $l'/l\approx0.3$, shoreline facing the openings of detached breakwaters always advance regardless of l/Y. The tendency changes as l/Y approaches to 2; that is, if the offshore distance of the breakwater approaches to one half of the breakwater length.

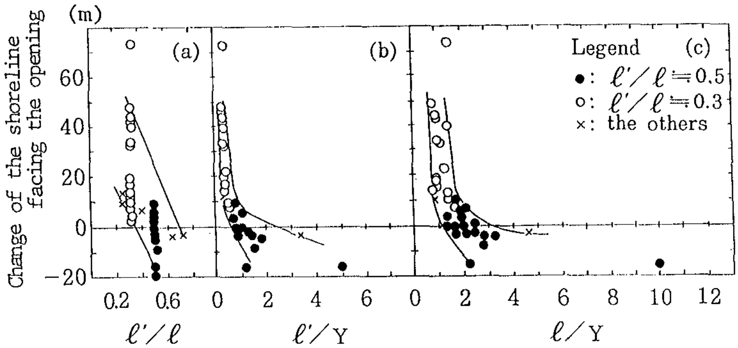

Fig.11 Relations between the change in the shoreline facing the openings and the nondimensional parameters indicating breakwater dimensions.

In the case of $l'/l \approx 0.5$, the possibility of the retreat of the shoreline facing the opening becomes high in contrast with the case of $l'/l \approx 0.3$. The critical condition for the shoreline advance may also be given by $l/Y \approx 2.0$. In other words, the shoreline retreats under the condition of breakwater length, if the offshore distance Y is less than $0.5l$. As described above, the shoreline facing the openings may retreat depending on the breakwater dimensions. This is due to the fact that the breakwater construction causes the increase in the wave height at a opening and, therefore, in the littoral drift from the opening toward the lee of the breakwater.

The second function of the detached breakwater is to dissipate the incident waves. This function can be discussed through the investigation of wave transmission coefficient. For the evaluation of the wave transmission coefficient K_T, the following formula has been proposed (Numata, 1975).

$$K_T = 1/\{1+1.135(B_h/D)^{0.66}\cdot(H_i/L_i)^{0.5}\}^2 \qquad (2)$$

where B_h is the mean width of the breakwater at the still water level, D is the height of a concrete block, H_i is the incident wave height and L_i is the incident wave length. Equation (2) holds only if the elevation of the crown of detached breakwater above the sea level is higher than the incident wave height.

The validity of the formula is examined by using the field data obtained through field investigations conducted on three coasts: namely, the Shimoniikawa Coast, the Niigata Coast and the Enshu Coast. As shown in Fig.12, the average of the field data can be predicted fairly well by use of Eq.(2) if $H_i/L_i > 0.02$, whereas K_T is underestimated if the wave steepness is smaller than 0.02.

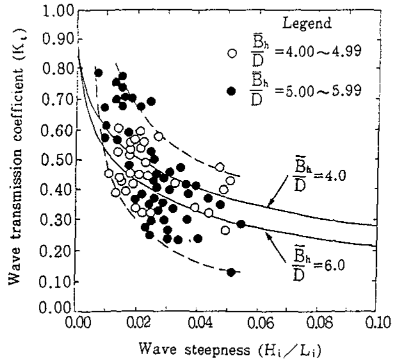

Fig.12 Comparison of the measured and predicted wave transmission coefficients.

3.3 Scattering of concrete blocks

Figure 13 shows the scattering rate, i.e., the ratio of the number of the breakwaters that suffered the scattering of concrete block to the total number of the breakwaters on the coasts of types A through E. The overall average scattering rates is 14.2%. The scattering rate of the coasts of type A is low compared with the others. This may be because the wave height is usually low in a bay and in an inland sea and consequently the wave forces acting on the concrete blocks and the changes in the beach topography caused by scouring around the blocks are small. On the other hand, the scattering rate for the coast of type D is as high as 52.9%. The scattering of concrete blocks on the coasts of this type was reported in the preceding paper (Kohno et al., 1986). Several reasons can be raised for this. First, on the Fuji Coast, incident waves tend to act on the concrete blocks without large attenuation, since the bottom slope is steep (1/3-1/10). The second reason is that strong wave actions cause the severe topographical changes around breakwaters.

The scattering rate of the concrete blocks is related to the various parameters characterizing breakwaters. Here,

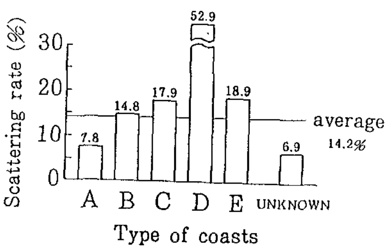

Fig.13 Scattering rate for the coasts of each type.

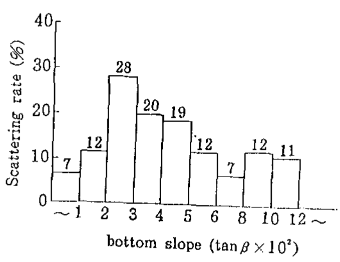

Fig.14 Scattering rate versus bottom slope.

three parameters are considered: the bottom slope, the water depth at the breakwater and the offshore distance. Figure 14 describes the relation between the scattering rate and bottom slope. The scattering rate has a maximum value of 28% for the bottom slope of 0.02-0.03, and it decreases for steeper beach slope, although it is expected that the steeper beach slope always causes the higher scatteing rate. On mildly sloping coasts, the beach material is usually fine sand, and the bar-trough topography is easily formed. The instability associated with the subsidence of the blocks and the scouring around the blocks can be the main reason of serious scattering.

The scattering rate depending on the water depth is shown in Fig.15. The scattering rate tends to increase with the water depth, fluctuating in the range from 6 to 27%. This is due to the fact that the concrete blocks are scattered by the action of breaking waves. The breaking point gets closer to the location of the breakwater under storm wave conditions. The high scattering rate at the depth of 6-7m is doubtful, because only 41 breakwaters fall in this range as shown in Fig.2 (b). In this view, there might be a tendency that the scattering rate decreases as the water depth exceeds 5m.

Similarly, the scattering rate depending on offshore distance is plotted in Fig.16. The offshore distance less than 120m are divided into 20m intervals, while those greater than 120m are divided into 40m intervals. The scattering rate increases with the offshore distance up to 100m, and then tends to decrease. High scattering rates were measured at offshore distance between 80 and 120m possibly because the locations of the detached breakwaters are close to the breaking points.

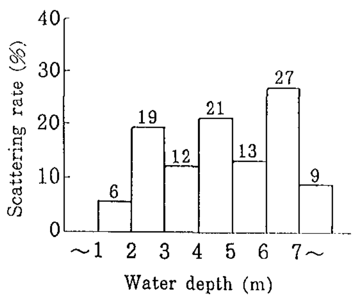

Fig.15 Scattering rate versus water depth.

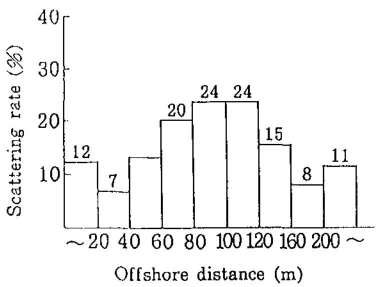

Fig.16 Scattering rate versus offshore distance.

The scattering rate was also investigated in relation with the weight of the concrete blocks. For this purpose, the ratio of the actual weight of the block to the weight calculated from the Hudson formula is introduced, where the design wave height is assumed to be equal to the water depth multiplied by 0.78, namely, the breaking wave height. The distribution of the number of the breakwaters that suffered the scattering and the distribution of the scattering rate are shown in Figs.17(a) and (b). The largest number of the detached breakwaters appears in the interval where actual weight-calculated weight ratio is 1.1-1.2. A high scattering rate is observed when the actual weight is smaller than the calculated weight multiplied by 1.1, and the scattering rate tends to decrease as the ratio of the actual to the calculated weight increases. The extent of scattering was relatively small for majority of the breakwaters with concrete blocks heavier than 1.5 times the calculated weight. If the scattering rate is re-investigated excluding the cases with small extent of scattering, the scattering rate reduces to 3.1% as shown in Fig.17(b). Effective preventive measures against scattering is the use of the concrete blocks whose weight is at least 1.5 times as large as that calculated from the Hudson formula. A firm foundation such as a rock mound is also effective.

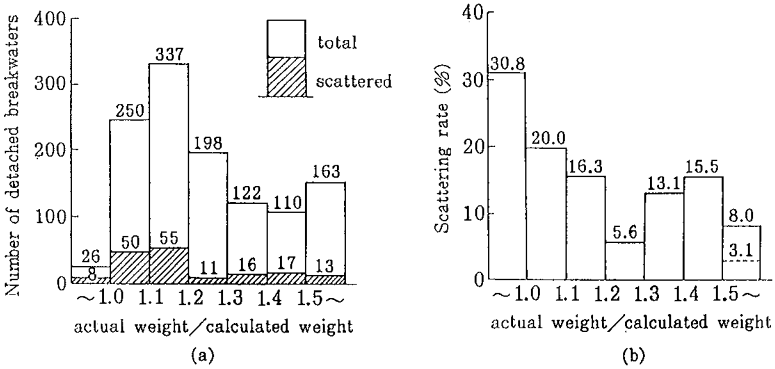

Fig.17 Number of scattered breakwaters and the scattering rate in relation with the weight of the concrete blocks.

Finally, the scattering rate of the concrete blocks is studied in relation with the kind of block placing, the foundation performance and the subsidence of the blocks. According to the preliminary investigation of the relation between the scattering rate and the kind of placing, the pellmell and uniform placings resulted in 19.5% and 11.0% scattering respectively. In studying the scattering of concrete blocks, it is important to consider the combined effects of the kind of placing and foundation performance as shown in Fig.18. The scattering rates in the cases of pellmell and uniform placings are almost the same if a foundation exists. Without foundations, however, the scattering rate in the case of pellmell placing becomes 18%, which is much larger than 8.5% in the case of uniform placing; the extent of scattering is greatly influenced by the kind of block placing. The influence of subsidence on the scattering of blocks is shown in Fig.19. The scattering rate for the breakwaters that subsided due to waves is 17.9%, which is nearly twice as large as the rate 9.4% for the breakwaters without subsidence.

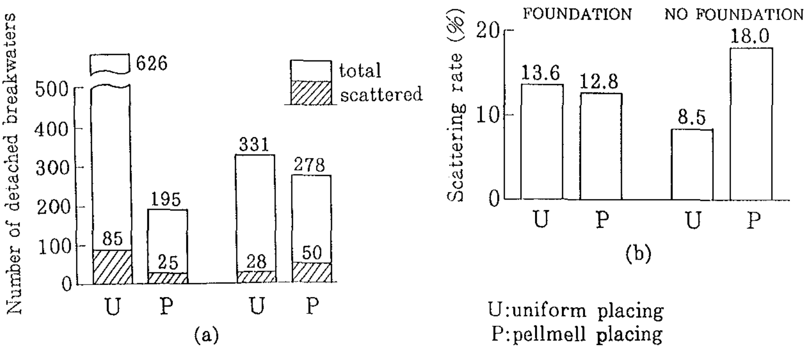

Fig.18 Combined effects of the kind of placing and the foundation performance on the scattering rate.

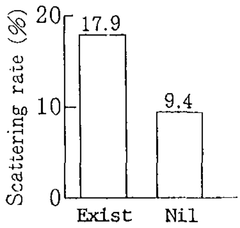

Fig.19 The scattering rate depending on the subsidence of concrete blocks.

IV. CONCLUSIONS

The dimensions of the detached breakwaters were satistically analyzed on the basis of the survey of 1552 breakwaters constructed by 1982. The main conclusions of this study are summarized as follows:

1) The optimal of a detached breakwater was evaluated for sand deposition behind the breakwater as well as the critical conditions for advance of the shoreline facing a breakwater opening.

2) The wave transmission coefficient to be used for prediction of the wave height distribution behind the breakwater can well be estimated by the formula given by Numata.

3) The scattering of concrete blocks was found in 13.7% of all the breakwaters surveyed.

4) The ratio of the number of the breakwaters that suffered scattering to the total number of the breakwaters on each coast takes the maximum value, when the bottom slope, the depth at the breakwater, and the offshore distance of the breakwater are equal to 0.02-0.03, 4-5m and 80-120m, respectively.

5) A high scattering rate appears when the actual weight of concrete blocks is smaller than 1.1 times the

weight calculated from the Hudson formula. The scattering rate reduces to 3.1% when concrete blocks heavier than 1.5 times the calculated weight are used.

6) The scattering rates of concrete blocks were 19.6% and 11.6% for the cases of pellmell and uniform placings. The scattering rate does not significantly depend on the kind of block placing, if a foundation is constructed. Otherwise, the scattering rate in the case of pellmell placing is more than twice as high as that in the case of the uniform placing. The extent of scattering is particularly influenced by the kinds of block placing in the case of detached breakwaters without foundation.

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