CHAPTER 198

FUNCTION OF DETACHED BREAKWATER TO CONTROL LONGSHORE SEDIMENT TRANSPORT

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ABSTRACT

The function of offshore detached breakwater of controlling longshore current and resulting sediment transport under oblique wave incidence is examined mainly through experiments. Although the offshore detached breakwater can effectively reduce incident wave energy, it has little influence on longshore current. More than 50% of the volume of sediment transported in the longshore direction on the natural beach is trapped behind the breakwater. The total longshore sediment transport rate around the breakwater can be predicted more precisely by integrating the local longshore sediment transport rate estimated from the flux model than by the empirical formula of Savage type.

INTRODUCTION

Various coastal structures have been used to construct protective works against beach erosion. Among them, offshore detached breakwaters are the most popular structures in Japan. This is because they can effectively reduce and absorb incident wave energy. A crown height of the offshore detached breakwater in Japan is usually determined to be one half of the design wave height higher than the high water level. So, the offshore detached breakwater often detracts from natural coastal views and prevents effective utilization of coastal regions. Strongly diffracted waves by the offshore detached breakwater also creates concavoconvex shoreline.

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Recently, there is increased concern with preservation of coastal environments and easy access to the shoreline. To cope with these requirements, another coastal protection works such as sea dikes of gentle slope, artificial reef with a submerged breakwater, head-land defence works and so on have been newly planned and constructed in Japan. However, all offshore detached breakwaters cannot be replaced by these new structures. The applicability of these engineering works depends on the causes and local situations of potential disasters together with the ability of these structures to control sediment movement.

As regards the offshore detached breakwater, it became possible to predict wave deformation behind it by some numerical procedures(for examples, Ohnaka, et al., 1988) and the authors have already developed numerical model for predicting wave-induced current behind it (Sawaragi et al.,1981). Formations of salient or tombolo behind the offshore detached breakwater have also been investigated by many researchers. However, until now, only a few studies have been carried out about the wave-induced current and sediment movement around the offshore detached breakwater under the condition of oblique wave incidence.

On the other hand, a suitable plane-arrangement of coastal protective works against beach erosion caused by longshore sediment transport can be effectively determined by predicting the shoreline deformation based on the so-called one-line theory. In such cases, it is very important to know how the offshore detached breakwater affects the longshore sediment movement on a natural beach.

The aim of this study is to investigate the function of the offshore detached breakwater of controlling obliquely incident waves, longshore current and resulting longshore sediment transport by conducting 3-D experiments.

EXPERIMENT

Method of experiment:

Experiments were carried out in a wave basin of 20m long, 10m wide and 0.6m deep. A model beach of the slope of 1/10 whose contour lines made an angle of 30^0 to the wave generator was constructed in the basin as shown in Fig.1. The experimental wave height and period were 6.5cm and 1sec. In this study, effects of the offshore detached breakwaters on waves, wave-induced current and longshore sediment transport caused by this wave are investigated. The dimensions of the model offshore detached breakwater are summarized in Table 1. The wave height, water depth and direction at the breaking point on the natural beach were 7.7cm, 7.5cm and 18°.

In this paper, the following notations and coordinate system are used: x axis is taken offshore from the initial shoreline and y axis is in the direction of longshore. Xb is the width of the breaker zone and Xoff is the distance between the initial shoreline and the breakwater, l is the length of the breakwater, B is the opening between breakwaters when they are constructed as a pair, and Lo is the wave length in deep water.

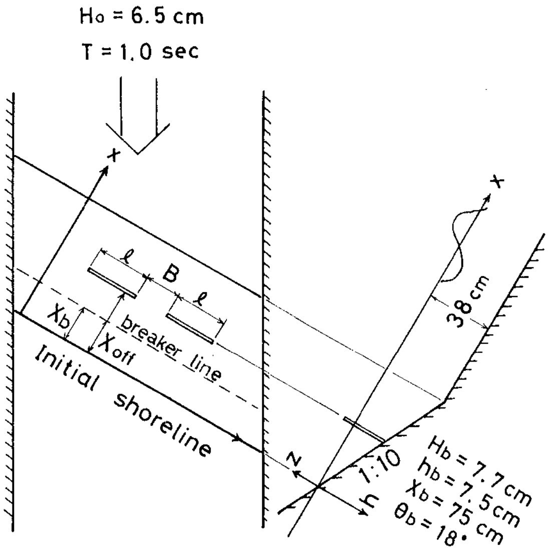

Fig.1 Wave basin and coordinate system

Table 1 Experimrntal conditions

[Fixed bed experiment]

Xoff/Xb	0.57,0.86,1.7
l/Lo	0.5,0.75,1.0,1.5
B/l	0.25,0.5,1.0

[Mobable bed experiment]

Xoff/Xb	l/Lo	B/l
0.86	0.5	---
0.86	1.0	---
1.70	0.5	---
1.70	1.0	---
0.86	1.0	1.0
0.86	1.0	0.5
1.70	1.0	1.0
1.70	1.0	0.5

Through the whole movable bed experiments, sand of median grain size of 0.05cm was used to make a movable bottom. Distributions of wave heights and directions, velocity of wave-induced current and topographic change around the breakwater were measured at time intervals determined in advance.

Data analysis:

Based on the measured change in the water depth, $\Delta h(x,y,t_k)$, longshore distributions of total longshore sediment transport rate, $Qye(y)$, was evaluated to investigate the effeet of offshore detached breakwater on the longshore sediment transport. The water depth was measured at grid points set at the distance Δx=12.5cm and Δy=25cm in the wave basin. The change in the watcr depth, $\Delta h(x,y,t_k)$, is defined as a difference of water depths mcasured at time $t=t_{k+1}$ and $t=t_k$

$$\Delta h(x,y,t_{k+1})=h(x,y,t_{k+1})-h(x,y,t_k). \qquad (1)$$

A eontinuity equation of the total longshore sediment transport, $Qy(y,t)$, is expressed as follows:

$$\frac{\partial A(y,t)}{\partial t}=\frac{1}{(1-\lambda)}\frac{\partial Qy(y,t)}{\partial y}. \qquad (2)$$

where $A(y,t)$ is the seetional area shown in Fig.2 and is defined as

$$A(y,t)=\int h(x,y,t)dx. \qquad (3)$$

The total longshore sediment transport rate in the experiment is ealeulated by transforming Eq.(2) into the following differenee form and is represented by $Qye(y,t)$.

$$Qye(j,t_{k+1})=\frac{\Delta y}{\Delta t}(1-\lambda)\sum_{\ell}[A(j,t_k)-A(j,t_{k+1})]$$
$$+Qye(j-1,t_{k+1}) \qquad (4)$$

where j indicates the j-th grid point along the shoreline and $y=j*\Delta y$.

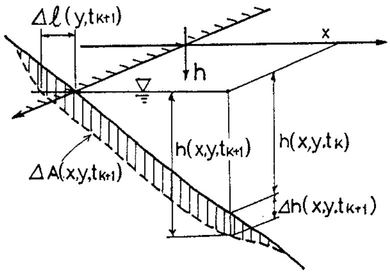

Fig.2 Definition sketeh of $\Delta h, \Delta A$ and Δl

An eigenfunetion analysis beeomes a great help to understand the mode and eharaeteristies of sediment movement around the breakwater(for example, Deguehi et al.,1986). In this study, measured ehanges in water depth $\Delta h(x,y,t_k)$ are expanded into the produets of longshore and eross-shore eigenfunetions $Ci(y)\cdot Ei(x)$.

$$\Delta h(x,y,t_k) = \sum_{i=1}^{\infty} Ci(y)*Ei(x) \qquad (5)$$

WAVE HEIGHT AROUND BREAKWATER

Figure 3 illustrates eomparisons of measured wave heights along the line of x/Xb=0.28,ie, near the shoreline behind the offshore detaehed breakwaters of different lengths (Xoff/Xb=0.57,0.86 and 1.7). A verti-eal axis is the ratio of measured wave height,H, around the breakwater and that measured on the natural beaeh, Hn, at the same point.

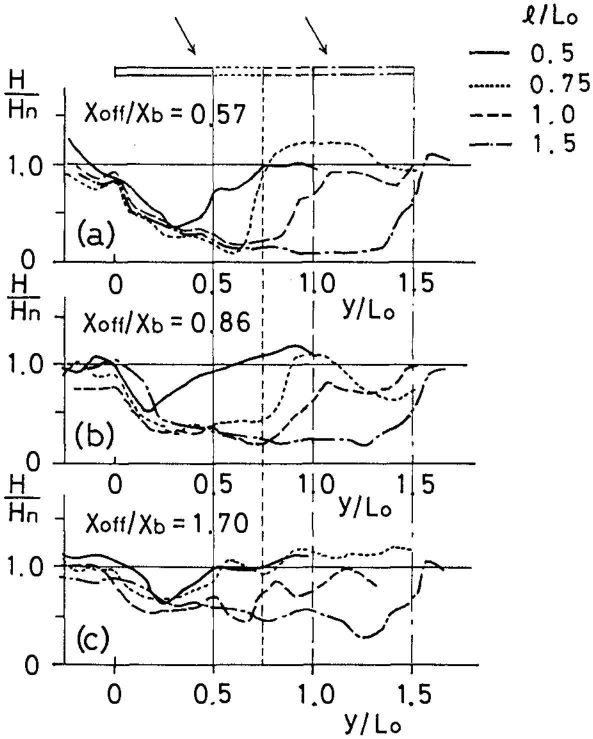

Fig.3 Wave height distribution behind breakwater ((a):Xoff/Xb=0.57,(b):Xoff/Xb=0.86,(e):Xoff/xb=1.7)

Solid, dotted, broken and chainlines in these figures are the wave height around the breakwaters whose lengths l correspond to l/Lo=0.5,0.75, 1.0 and 1.5, respectively.

As the distance between the line of x/Xb=0.28 and the breakwater increased, that is in the case where the breakwater was constructed outside the breaker zone, the longshore distribution of wave height approaches uniform due to the interaction of two diffracted waves from both sides of the breakwater.

An attenuation of wave height behind the breakwater also becomes less significant because the wave height at the depth along x/Xb=0.28 is depth-limited. Naturally, the longer the breakwater, the larger attenuation of wave height took place. However, when the length of the breakwater is larger than the incident wave length, the maximum attenuation behind the breakwater is almost the same.

WAVE-INDUCED CURRENT AROUND BREAKWATER

It is well known that wave-induced current behind the breakwater caused by the normally incident waves is featured by the formation of a pair of circulation cells. However, under conditions of oblique wave incidence, as were the cases of our experiments, longshore current flowed behind the breakwater smoothly as can be seen from Fig.4.

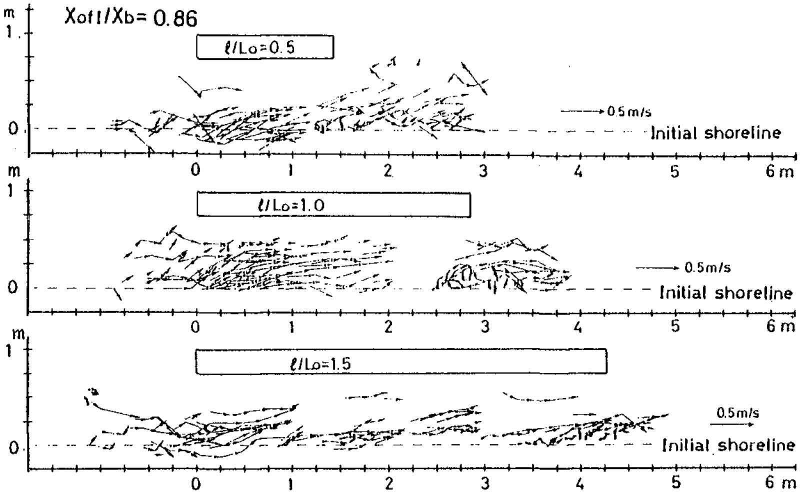

Fig.4 Flow pattern of wave-induced current(Xoff/Xb=0.86) ((a):l/Lo=0.5,(b):l/Lo=1.0,(c):l/Lo=1.5)

Figure 4 is the flow patterns of wave-induced current around the breakwater of various length. Arrows in the figures are the velocity vectors obtained by tracing floats in the experiments.

Although wave heights decrease to a great extent behindthe breakwater, these wave field have little influence on the longshore current behind the breakwater.

TOPOGRAPHIC CHANGE AROUND BREAKWATER

Figure 5 shows three examples of the topographic changes took place around the breakwaters during 1hr after wave generation. Figures (a) and (b) are the cases of the single breakwater constructed within and outside of the breaker zone. Figure (c) is the case of a pair of breakwaters constructed outside the breaker zone.

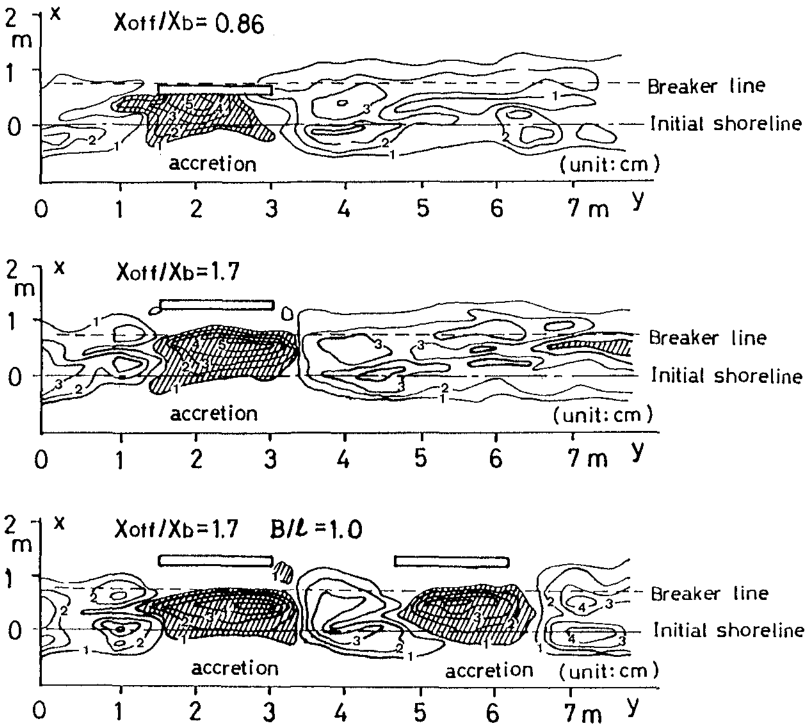

Fig.5 Topographic change around breakwater(l/Lo=1.0) ((a):Xoff/Xb=0.86,(b):Xoff/Xb=1.7 and (c):Xoff/Xb=1.7,B/l=1.0)

In the figure accreted regions are shown by the hatched area. A significant deposition took place behind the breakwater in every cases.

To discuss the function of the offshore detached breakwater of controlling sediment transport, it is necessary to examine where did these depositted sand come from, ie, from the upstream side, downstream side or from the offshore. The authors investigated this point by analyzing the topographic change, $\Delta h(x,y)$, at a measuring grid point (x,y) in two different ways. One is to examine the distribution of the total longshore sediment transport rate, $Qye(y)$, and the other is the empirical eigenfunction analysis.

EFFECT OF BREAKWATER ON CONTROLLING LONGSHORE SEDIMENT TRANSPORT

Total longshore sediment transport rate:

Solid line in Fig.6 shows some examples of estimated longshore distribution of the total longshore sediment transport rate, $Qye(y)$, calculated from Eq.(4).

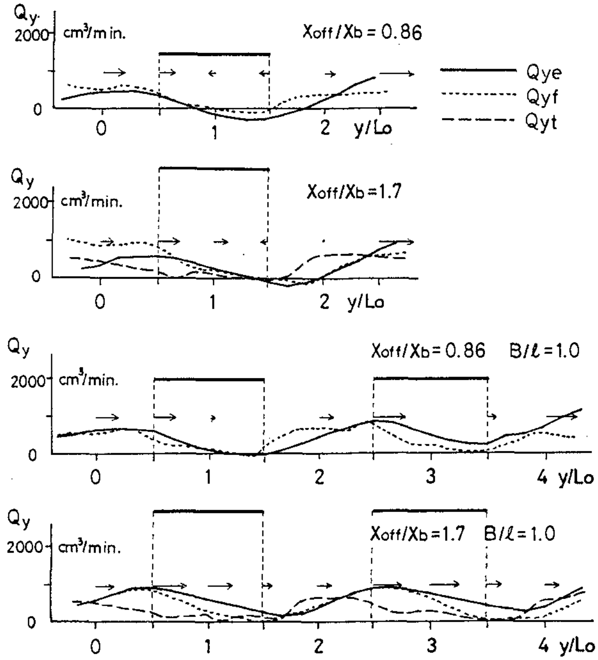

Fig.6 Total longshore sediment transport rate around breakwater ((a):Xoff/Xb=0.86,(b):Xoff/Xb=1.7, (c):Xoff/Xb=0.86,B/l=1.0,Xoff/Xb=1.7,B/l=1.0)

When the single breakwater was constructed within the breaker zone, the value of Qye becomes negative in the lee-side of the breakwater which means that sediment was transported in the opposite direction of the longshore current in this region. On the other hand, when a pair of breakwaters was constructed, no significant negative value of Qye appears regardless of its position.

Cross-shore and longshore eigenfunction:

Figures 7 illustrates examples of the longshore and cross-shore eigenfunctions with the maximum eigenvalue. The ratio of these maximum eigenvalues to the traces are more than 60%.

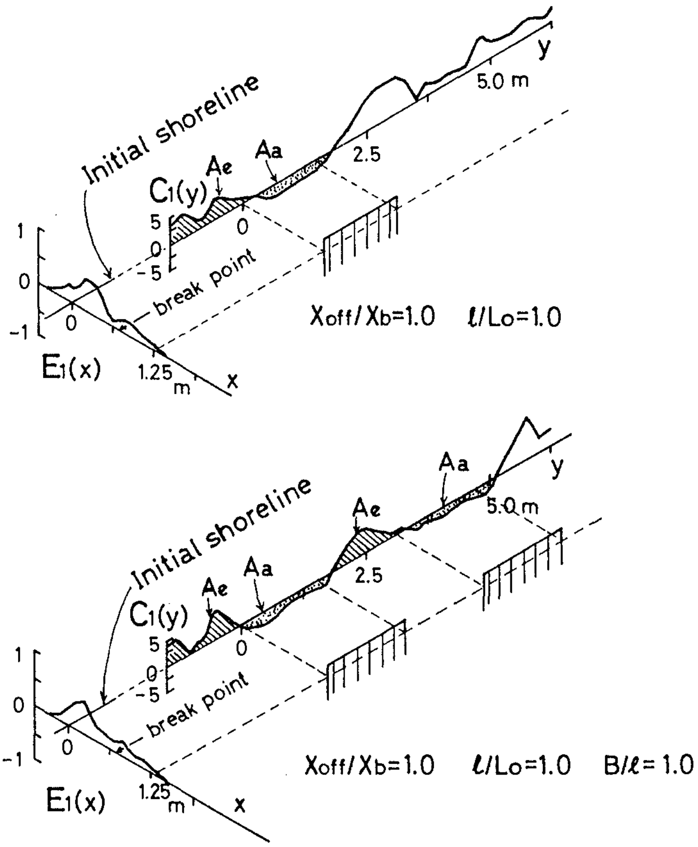

Fig.7 Cross-shore and long-shore eigenfunctions correspond to the largest eigenvalue(Xoff/Xb=1.0) ((a): l/Lo=1.0, (b): l/Lo=1.0, B/l=1.0)

Figurc(a) is the case where the single breakwater was set at x/Xb=1.7. Figure(b) is the result of the case where a pair of breakwaters was constructed at the same location. As can be seen from these figures, E1(i) is positive throughout the whole region and C1(y) indicates both positive and negative values along the longshore direction. Especially, behind the breakwater, the value of C1(y) is negative. Therefore, it can be judged that the pattern of the topographic change represcnted by the product C1(y)*E1(x) was caused by the longshore sediment transport.

Ability of breakwater to trap sediment:

The ratio of the volume of depositted sedimcnt behind the breakwater and the volume of eroded sediment in the upstream side of the breakwater is also estimated by the ratio of the arca of hatched region Ae and the area of dotted region Aa. If Aa is greater than Ae, more sediment transported from thc upstream side of the breakwater was depositted behind the breakwater. This means that thc sediment in the downsream side of the breakwater was transportcd in the opposite direction of longshore current by the diffracted wavcs. If Aa is smaller than Ae, a part of sediment transported from the upstream side of the breakwatcr in the longshore direction was transported to the lee-side through behind the breakwater.

Figure 8 shows the ratio of Aa/Ae of the whole cases carried out in the experiments. Open circles are the cases of single breakwater and the breakwater of upstream side. Closed circles are the results of the leeward breakwater.

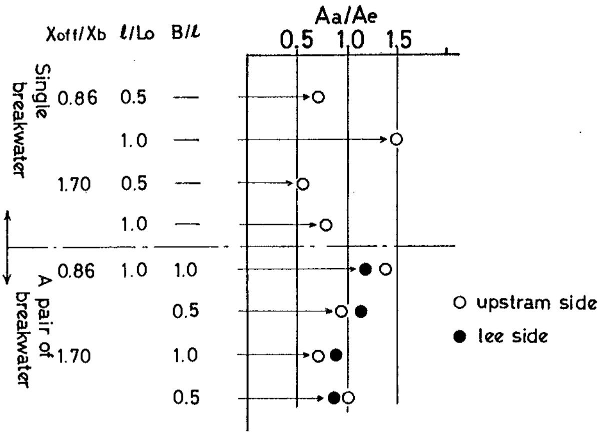

Fig.8 Ratio of Aa/Ae

In the case of Xoff/Xb=0.86 and l/Lo=1.0, the ratio of Aa/Ac becomes almost 1.5. In this case, the sediment in both upstream-side and lee-side of the breakwater was transported behind the breakwater and settled down there. The same conclusion has already been derived from the analysis of the distribution of Qye.

When the length of the breakwater is 1/2 of the incident wave length, 60 to 70% of the amount of the sediment transported in the longshore direction is trapped behind the breakwater and the rest is flow through behind the breakwater to the leeward. Furthermore, the each breakwater constructed as a pair has a high efficiency to trap sediment behind them when compared to the single breakwater of the same dimension.

Relation between ΔA and Δl:

Figure 9 shows the relationbetween the change in sectional area ΔA and the shoreline displacements Δl. It is found that relatively high correlation exists between ΔA and Δl regardless of the location and dimension of the breakwater.

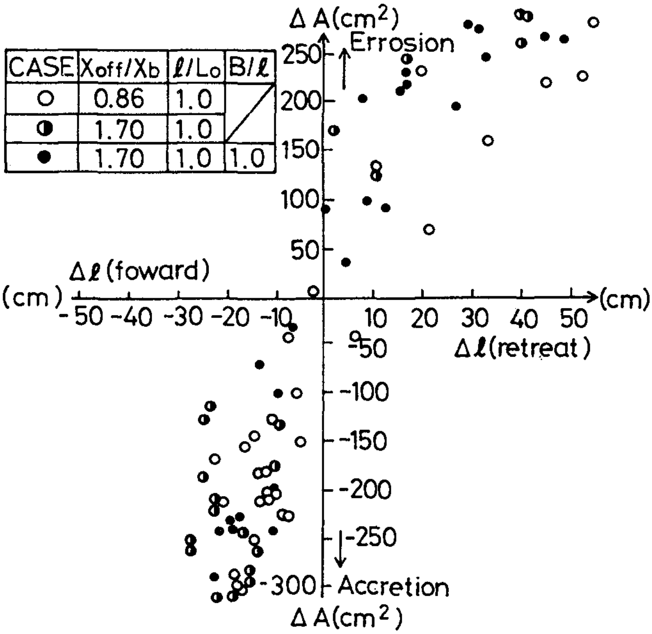

Fig.9 Relation between ΔA and Δl around breakwater

From these results, a so-called one-line theory can be applied for the prediction of shoreline change which will take plaee around the offshore dctached breakwaters provided that the longshore distribution of total longshore sediment transport rate ean be given.

ESTIMATION OF TOTAL LONGSHORE SEDIMENT TRASNPORT RATE AROUND THE BREAKWATER

The total longshore sediment transport rate is generally estimated by the following empirieal formula of Savege type.

$$Qy=\alpha(ECg)_b\,sin(2\theta_b) \qquad (5)$$

where $(ECg)_b=(\rho gH^2Cg)_b/8$ is the incident energy flux at wave breaking point, θ_b is the wave breaking angle and α is the empirieal eoefficient. According to Eq.(5), Qy is direetly related to the wave eonditions at breaking point. Therefore, the total longshore sediment transport rate around the structures eonstrueted in the breaker zone ean not be predicted by this kind of formula.

There also remains another problems in the expression of Qy beeause the direetion of the longshore sediment transport is uniquely determined by the wave breaking angle. It seems reasonable to assume that the longshore eurrent play a more important role in the longshore sediment transport than the wave breaking angle does.

We can also estimate the total longshore sediment transport rate by integrating local longshore sediment transport rate,qy. Some formulas for predicting the local longshore sediment transport rate have already been proposed. In this study, the value of qy is estimated from the flux model(Sawaragi et al.,1985). The wave field and the veloeity of wave-indueed current were obtained by the numerieal simulation based on the unsteady linear mild slope equations(Ohnaka et al.,1988) and depth and time averaged basie equations of wave-induced eurrent(Sawaragi et al.,1981).

In Fig.6, the total longshore sediment transport rate,Qyf, calculated by integrating the loeal longshore seidment transport rate are shown by the dotted line. Broken lines in the figure are the total longshore sediment transport rate,Qyt, caleulated from the empirical formula of the form of Eq.(5). The value of Qyt can be estimated only in the eases where the breakwater were eonstrueted outside the breaker zone. In the ealculation of Qyt, simulated results of wave height, water depth and direction at the wave breaking point were used and the value of α was tentatively determined to be 1.

As ean be seen from Fig.6, there is a large diserepaney between Qye and Qyt. On the other hand, Qyf ealeulated by integrating loeal longshore sediment transport rate gives more accurate estimation of the total longshore sediment transport rate,Qye, estimated from the topographie ehange.

CONCLUSIONS

1. Waves behind the offshore detaehed breakwater under the obliquely ineident waves attenuate signifieantly as is the ease of normal wave ineidenee. However, these wave fields have little influenee on the longshore current behind the breakwater. Longshore eurrent flowed smoothly behind the breakwater. No eireulation eell of wave-indueed eurrent appeared.

2. In spite of the flow pattern of longshore eurrent, a large amount of sediment transported in the longshore direetion is trapped behind the offshore detaehed breakwater. The pair of offshore detaehed breakwaters has higher effieieney to trap sediment transported in the longshore direetion than the single breakwater does.

3. The total longshore sediment transport rate behind the offshore detaehed breakwater ean be predieted more preeisely by integrating the loeal longshore sediment transport rate estimated from the flux model than by the so ealled Savege type formula.

Referenee

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