

## METHODOLOGY OF BEACH EROSION CONTROL AND ITS APPLICATION

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### **Abstract**

The objective of this study is to present the various methodologies available for beach erosion control in the hope that they may be better applied. Countermeasures for beach erosion control function depending on the local conditions of wave characteristics and littoral sediment transport. In this paper, coastal structures in the control works are classified in terms of their locations; that is, the offshore zone and nearshore zone. In the former case, quantitative descriptions of the rate of longshore sediment transport and the predominant direction of cross-shore sediment transport can be obtained by considering both the decrease of the depth of wave breaking and the incident angle of the waves. In the latter case, an analogy is drawn between the sediment transport dynamics of rivers and those of coasts. The concept of a stable river channel shows itself to be useful in the attainment of a stable beach through consideration of (1) decreased flow rate of longshore current, (2) increased sediment size and (3) decrease of surf zone width. Moreover, it is pointed out that selection of any beach erosion control work and the philosophy behind its operation depend on the availability of local materials (land rule) in the process of developing methods of the control. Finally, improvements to beach erosion control works are proposed on the basis of the above discussion.

### **I. INTRODUCTION**

In Japan, beach erosion has become more serious of late years. In particular, beaches adjoining the mouths of big rivers with their wide watersheds have been significantly eroded due to the rapid decrease of river sediment supply. To add to this, several large typhoons accompanied by heavy rainfall struck Japan on almost a yearly basis after World War II, causing severe flooding at the flood plain in downstream areas. In order to combat this, construction of flood control dams as well as debris control dams were encouraged by the government. Unfortunately such structures considerably decreased the sediment discharge and sediment size in the lower river reaches. Consequently, a gradual recession of the river delta resulted along with increase in the water depth in the shallow water area adjacent to the coast. After around 20 to 30 years had passed, a sudden and remarkable retreat of the shoreline occurring under certain storm wave conditions was noticed. The time for this beach erosion to become apparent chiefly depended on how fast the rate of longshore sediment transport decreased from the upcoast area. Many industrial, commercial and

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Supplementary countermeasure	Seawalls	Submerged breakwaters	Beach nourishment
	Groins	Groins	Groins
Main countermeasure	Submerged breakwaters	Offshore breakwaters	Artificial reef works
	1951	1966	1988
	Year		

Fig. 2 Historical changes of beach erosion control works in Niigata coast.

Niigata harbor, and land subsidence which resulted from overmining of natural gas. In 1946, a committee was organized to survey the erosion and produced countermeasures. The construction of the system of groins, continuous submerged breakwaters and seawalls, shown in Fig. 2 was the result. However, the area of beach erosion started to spread further westward and offshore breakwaters had to be constructed to replace the submerged breakwaters previous used. Recently, the control system has been modified to include beach nourishment and an artificial reef of a large submerged breakwater type like the coral reefs around islands in the tropics. In most projects, hydraulic model experiments are performed before the construction of any beach erosion control, but the results have sometimes proved ineffective in the field. In the case of offshore breakwaters, subsidence of armor units is generally more serious in the field than that predicted from experimental data. On the Niigata coast, the concrete blocks in the offshore breakwaters subsided as much as 10 m below the sea bottom, so it became necessary to pile up new blocks on the old ones after winter seasons. Other control works have also been tried, but the beach erosion has not yet been stopped.

The history of the struggle with beach erosion has taught us a lot and it is well recognized that the time is right to clear up the methodology of beach erosion control. The results of such a clarification could form the basis for the production of more desirable applications of countermeasures from the viewpoint of the long term future. Furthermore, improvements in our understanding of nearshore dynamics would support the appropriateness of any methodology adopted.

The objectives of this paper are to propose the methodology of beach erosion control and to improve the applicability of both the traditional and newly developed control works.

## II. SERIOUS BEACH EROSION IN JAPAN

The construction of dams and the dredging river sediment for construction materials have remarkably decreased the amount of sediment available to supply the coasts. The mining was regulated by the Ministry of Construction after about 1965, and the annual amount of the licensed sediment mining held at about  $6$  to  $7 \times 10^7$  m<sup>3</sup> (Ashida *et al.*, 1983). However, dams now present a problem by disturbing the continuity of sediment discharge to the lower reaches of rivers. A recent report said

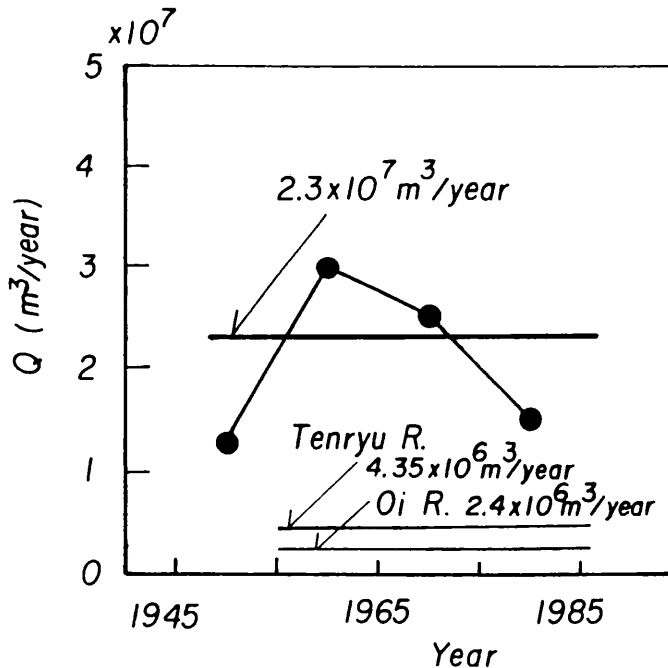


Fig. 3 Annual rate of accumulated sediment in high dams (dam height is more than 15 m and capacity is more than one million tons) and those at the Tenryu and Oi rivers.

that the mean amount of sediment accumulated by dams of height more than 15 m and capacity more than one million tons is  $8.6 \times 10^9 \text{ m}^3$ . This value is about 6.6 times the annual amount of sediment yielded from the mountain areas. The number of dams fitting into this category is 332 and this can be added to the number of small ones now estimated to be more than 4000 in 1987. Therefore, the actual amount of sediment accumulated by dams has been estimated to be at least twice as much as the reported value.

Figure 3 shows the annual amount of sediment accumulated by high dams after 1945. The data are averaged over each decade. Between 1945 and 1955, not many dams existed and the accumulated sediment was rather little. If the rate of sediment yield from the mountains remained constant, the accumulated amount would not have decreased. However, it actually decreased year by year after 1955. This was chiefly attributable to the construction of debris control dams in the mountain areas.

The amount of sediment accumulated by dams on the Tenryu and Oi Rivers was found to be more than 30 percent of the total annual yield. The resulting beach erosion adjacent to the mouths of the both rivers is very serious. Figure 4 shows a prediction for when the sandy beaches will finally disappear if erosion continues. In the prediction, the maximum annual rate of shoreline recession has been used because recession usually accelerates at the final stage of a beach erosion process. From the figure, the beach at the river mouth of the Oi River will disappear first in early 90's

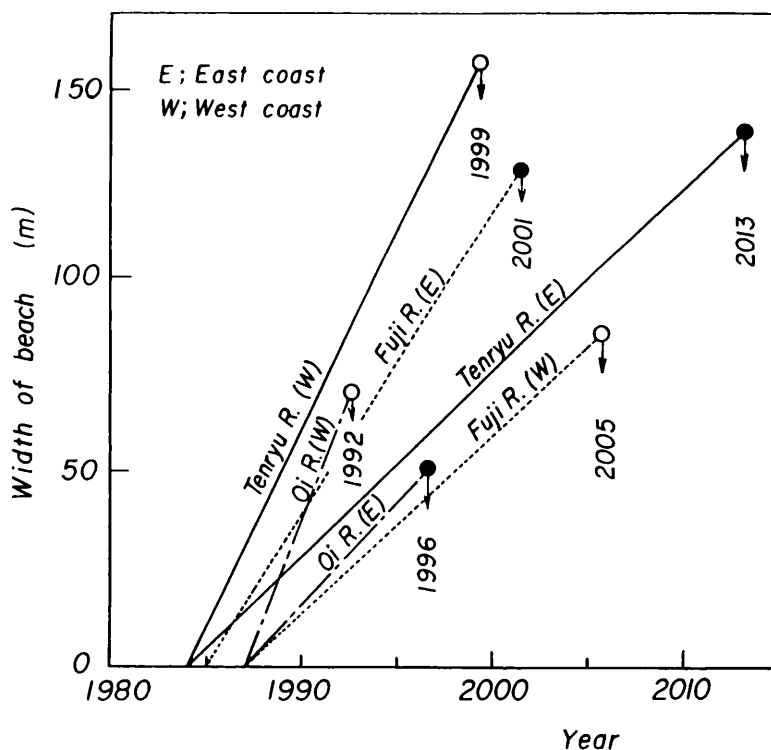


Fig. 4 Predicted year of disappearance of sandy beaches due to continuous beach erosion.

and the beaches at the mouths of the Tenryu and Fuji Rivers will vanish from sight by the early 21st century. Urgent erosion control is now under way at both sites, but significant changes in the erosion trend are not expected for a while.

Changes in the Japanese coastline and countermeasures undertaken in 1965 and 1985 are summarized in Table 1. For the past 20 years, the lengths of beaches eroded and those protected with some form of control works have increased 25 and 50 percent, respectively. It is also clear that the difference between the protected and eroded shorelines has gradually increased. At some severely eroded beach sites two or more combinations of control works, such as a double line of offshore breakwaters and systems with a combination of jetty and offshore breakwater have been constructed. This illustrates the sense of urgency the problem has, in our country. It is necessary to map out a better strategy to ensure longer term stability of Japanese beaches.

### III. PRINCIPLES OF BEACH EROSION CONTROL

In order to control beach erosion at any coast, it is first necessary to find the most suitable means of control. There are several construction manuals in which effectiveness of control measures is discussed. Every beach erosion control technique,

Table 1 Changes of Japanese coasts and beach erosion control works between 1965 and 1985.

year	length of beach eroded (km)	sea dike (km)	seawall (km)	the number of groin	the number of offshore breakwater	total beach length protedted by control work (km)
1965	10701	2086	3743	6781	347	6100
1985	15958	2836	5806	9630	3732	9008

however, originates from a different physical background. Coastal engineers therefore must understand the principles in order to render the control work effective.

In this paper, I describe the process of beach erosion resulting from discontinuity of longshore sediment transport in a situation following sediment supply decrease or stoppage in an upcoast area from where beach erosion is advancing. As the erosion proceeds, the mean water depth in the nearshore zone gradually becomes deeper and the slope of the foreshore becomes steeper. In the process, the wave breaking point approaches the shoreline and the reflection coefficient at the foreshore increases. Such changes in the characteristics of the wave conditions in the nearshore zone then lead to an increase in the offshore sediment transport. Consequently, the loss of beach sediment accelerates in the final stages of the beach erosion process, and a sandy or gravel beach quickly disappears. What was just described is a typical process of beach erosion resulting from the discontinuity of longshore sediment transport.

Every beach erosion control project has at least two hydraulic functions, *i.e.*, control of waves and control of littoral sediment transport. In the offshore zone where the littoral sediment transport is not so active the construction of control work can be considered as the wave control factor. This is contrary to the case of the surf zone where waves are already broken and so do not have as much energy as those before breaking. In the surf zone, littoral sediment transport is very active and direct control of sediment transport is applicable. The construction of control works, however, is not practical in the breaker zone from the viewpoint of maintenance.

### 3.1 Control of waves in the offshore zone

The rate of littoral sediment transport in the nearshore zone is predominantly controlled by shallow water waves and nearshore currents closely associated with waves before breaking. Therefore, any artificial change in wave conditions in the offshore zone tends to reduce the rate of longshore sediment transport and increase the rate of onshore sediment transport.

#### (1) Expression of rate of littoral sediment transport

There are many formulae to find the rate of longshore transport. Tsuchiya(1982) roughly estimated the rate  $Q_x$  using the water depth  $h_b$  and the incident angle of waves  $\theta_b$  at the breaking point as follows:

$$Q_x = c_1 \sqrt{g} h_b^{5/2} \sin 2\theta_b \quad (1)$$

in which  $g$  is the acceleration of gravity and  $c_1$  a constant.

No reliable formula for the rate of cross-shore sediment transport on a sloping sea bottom has thus far been established. The direction, however, of cross-shore sediment transport might be obtained by the parameter  $K_*$  from the viewpoint of the coastal geomorphology as mentioned by Short (1979) and Sunamura (1988).

$$K_* = (\bar{H}_b/\bar{T})^2/gd \quad (2)$$

in which  $d$  is the mean sediment diameter,  $H_b$  the breaking wave height,  $T$  the wave period. The variables in Eq.(2) are daily averages. Equation(2) corresponds to the case of a wave approach normal to the shoreline. To apply this parameter to the obliquely incident waves, the wave energy flux in the onshore direction can be introduced into Eq.(2). This flux at the breaker point is approximately proportional to  $H_b^2 T \cos^2 \theta_b$ , so that Eq.(2) can be modified as follows:

$$K'_* = c_2(h_b/\bar{T})^2(\cos^2 \theta_b/gd) \quad (3)$$

in which  $c_2$  is a constant and  $K'_*$  the modified  $K_*$ . Kato *et al.*, (1987) found that the increment of the daily averaged wave energy flux in the onshore direction leads to a recession of the shoreline on the Naka coast facing the Pacific Ocean. Therefore,  $K'_*$  is applicable to the characteristic change in cross-shore sediment transport.

Before discussing the control of littoral sediment transport, the relationships between longshore bar formation and berm migration should be investigated because their mechanisms are closely related to cross-shore sediment transport. It is well known that cross-shore sediment transport is associated with beach profile changes resulting from storm to swell conditions and is generally correlated to the wave steepness  $H_o/L_o$  and the ratio of the wave height to the mean sediment diameter including the effect of relative density [Iwagaki and Noda (1963), Nayak (1971)]. Figure 5 shows this relationship, where  $\sigma$  and  $\rho$  are the sediment and water densities respectively and suffix  $o$  denotes the deep water condition. The figure, however, only gives the criterion for longshore bar formation as the experimental data do not fit that well with the curve, and the characteristics of formation of longshore bar and berm and the effect of the beach slope can not be included. In order to introduce these factors into the traditional criterion, the Sunamura's (1982) empirical relationship between wave characteristics and beach slope is employed.

$$H_b/H_o = (\tan \beta)^{0.2}(H_o/L_o)^{-0.25} \quad (4)$$

in which  $\tan \beta$  is the beach slope. By application of Eqs. (2) and (4), the parameter  $K_{0*}$  is given by,

$$K_{0*} = \sqrt{\frac{H_o}{L_o}}(\tan \beta)^{0.4} \frac{1}{\sigma/\rho - 1} \left(\frac{H_o}{d}\right) \quad (5)$$

in which  $K_{0*} = 2\pi K_*/(\sigma/\rho - 1)$ . In Fig. 5, typical examples of beach stages as predicted by Eq.(5) are shown with straight, solid and dashed lines. As already pointed out by Short (1979), Wright (1979) and Sunamura(1985), six commonly observed morphodynamic states of beaches and surf zones are recognized. The two extreme states are (1)fully dissipative (large  $K_*$ ) and (2)fully reflective (small  $K_*$ ). In the case

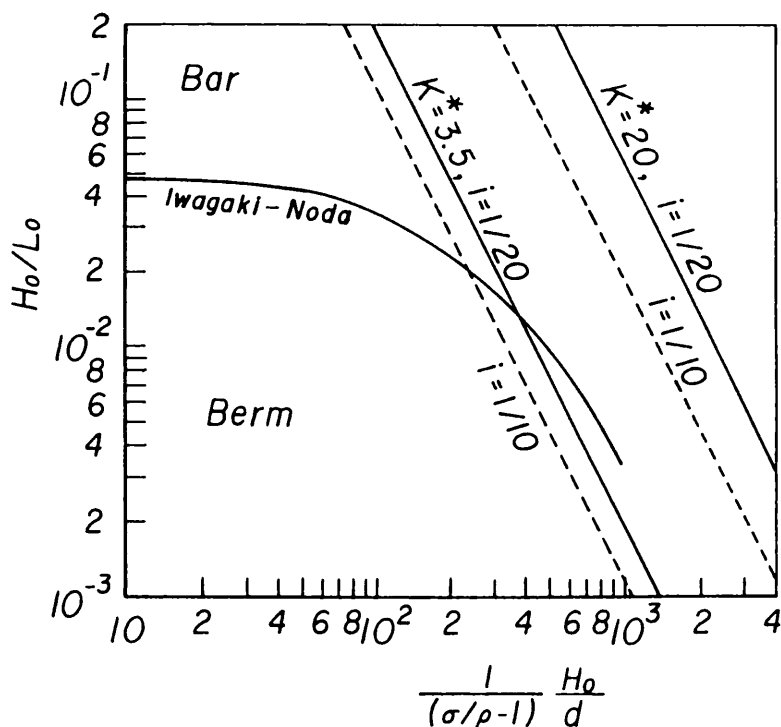


Fig. 5 Relationships between traditional criterion of longshore bar formation and expression of beach stages with  $K^*$  and beach slope.

of decrease from  $K_* = 20$  to 5 or less, the longshore bar moves in the onshore direction and forms a berm on the foreshore through a welded bar; the shoreline advances. On the contrary, in the case of the increment  $K_*$  up to around 20, the longshore bar clearly forms at the breaker zone. Consequently, it is recognized that Eq.(2) and Eq.(3) as well can predict the macro-scopic movement of nearshore sediment in the cross-shore direction.

#### (2) Control of littoral transport

By using Eq.(1), Tsuchiya(1982) proposed methods to control longshore sediment transport. In this paper, the control of cross-shore sediment transport is also mentioned. Equations (1) and (3) show that the control of littoral sediment transport can be attained by two methods, i.e., an artificial reduction of both the breaking depth and incident angle of waves. In the former case, the decrease in wave height is equivalent to that in breaking depth.

##### a) Change of breaking depth (change of wave height)

With Eq.(1), the rate of longshore sediment transport is proportional to the 2.5th power of the breaking depth. Equation(3) shows that  $K'_*$  also decreases with the square of the breaking depth. For example, if the breaking depth dropped to 80 percent of the original depth, the decrease in the longshore sediment transport and  $K'_*$

would be about 40 percent, so that bars would naturally advance in the onshore direction. This would be due to decrease in wave height in the nearshore zone. A practical measures for reducing the breaking depth would be to construct shoals such as submerged breakwaters and artificial reefs. The construction of offshore breakwaters and floating breakwaters is also very effective to reduce the wave height.

#### b) Change of incident angle of waves

Usually, it is somewhat difficult to change the incident angle of waves in the offshore zone. To reduce the rate of longshore sediment transport, it is possible to change the overall direction of a shoreline as pointed out by Tsuchiya (1982). As previously discussed, reduction of the wave energy flux in the onshore direction leads to a decrease in  $K'_s$ , and therefore, the most effective method would be to make the shoreline longer. The construction of a curved beach is recommended over a straight beach, because the wave energy flux per unit shoreline length notably decreases. In a natural pocket beach with a concave shoreline, wave rays diverge in a fan shape. When the longshore sediment supply from the upcoast area is completely cut off, the method becomes more applicable than a method involving changes in breaking depth because it is possible to create an incident angle of waves perpendicular to the beach so that longshore sediment transport does not occur. On the contrary, as a breaking depth is finite, longshore sediment transport could be expected to occur.

### 3.2 Control of littoral transport in the nearshore zone

#### (1) Diffusion process

In the field, storm waves significantly agitate the bottom sediment in the breaker zone and suspended sediment is transported in the offshore and onshore directions owing to the diffusion effect. The sediment which is carried into the offshore zone usually can not return to the nearshore zone; i.e., from the viewpoint of sediment budget, a beach process is essentially non-reversible. This is mainly due to the diffusion process of suspended fine sediment being in the offshore direction. In order to make a beach stable for as long a term as possible, it is necessary to compensate this loss by supplying some sediment to the beach. The smaller breaking depth would lead to the slower beach change.

#### (2) Stable beach on the analogy of stable channel in rivers

Tsuchiya (1980) first brought up the similarity between countermeasures of sediment transport problems in rivers and coasts. If a longshore sediment transport is reduced, the beach slope begins to steepen and the sediment gradually becomes coarser in the downcoast. This is a natural phenomenon, balancing the characteristics of the beach and beach reaction to external forces such as waves and nearshore currents. To discuss a methodology for creating a stable beach, the concept of a stable channel in a river was introduced as an analogy for sediment transport.

Fujita (1980) investigated stable channels in rivers and proposed the schematic diagram shown in Fig. 6. From the figures, it can be seen that a stable channel is formed when the water depth or coarseness of sediment increases and the width of the river decreases under the condition of a constant river discharge.

The driving force of longshore sediment transport comes from the longshore current in a unidirectional flow such as a river flow. A method to control longshore sediment transport would be equivalent to that to control a longshore current.

Fujita explained that a stable channel can be achieved from the following four con-



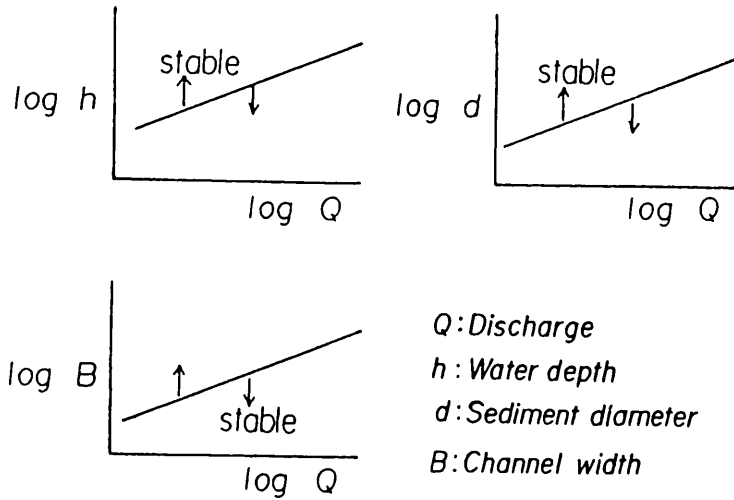


Fig. 6 Schematic diagram of condition of stable channel in rivers.

ditions: (1) controlling river discharge with constructions of dams or weirs, (2) changing river bed slope with shortcuts or consolidation work, (3) reducing side bank erosion with revetments, and (4) controlling river width with streamline-parallel groins. The conditions for stabilization of rivers can be obtained with no generation of any kind of bar.

The concept of a stable channel might be applicable to beach stabilization because several parameters used to describe the criteria for the formation of meso-scale bed configurations, such as alternating bars and double row bars, can be extended to coastal sediment problems.

Miwa(1983) analyzed a number of data on meso-scale bed configurations in both the laboratory and field and found the following dimensionless parameter.

$$K_i = (U/\sqrt{gh})(B/h) \quad (6)$$

in which  $U$  is the mean flow velocity and  $B$  the channel width. In order to apply Eq.(6) to the coastal sediment problems, the width of the surf zone is taken as  $B$ . It can be assumed that the breaking wave height is controlled only by the water depth. Komar and Inman(1970) showed that the mean velocity of the longshore current  $u_m$  can be given by,

$$u_m = (2E_b/\rho h_b)^{1/2} \quad (7)$$

in which  $E_b$  is the wave energy. Based on the above-mentioned assumption, Eq.(7) can be written by,

$$u_m \approx c_3 h_b^{1/2} \quad (8)$$

in which  $c_3$  is a constant.

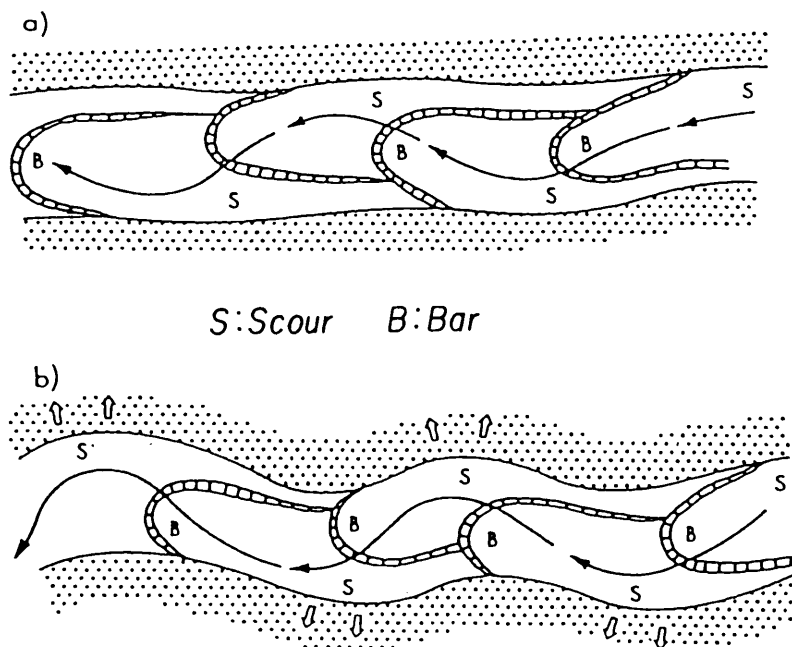


Fig. 7 Meandering of river channel and formation of alternating bars (Ashmore, 1982).

Komar(1976) showed that the rate of longshore sediment transport could be obtained from the wave energy flux in the longshore direction. Taken with Eq.(1), the rate of the longshore sediment transport can then be roughly estimated by,

$$Q_x \approx c_4 E_b h_b^{1/2} \quad (9)$$

in which  $c_4$  is a constant. It is widely accepted that the rate of longshore sediment transport correlates with the longshore component of the wave energy flux. With Eq.(9) and this empirical relationship, it is found that the wave group velocity at the breaking point is roughly proportional to the half power of the breaking depth. Substitution of Eq.(8) into Eq.(6) yields the following expression:

$$K_i = a_1 / (\tan \beta / \sqrt{H_b / L_o}) \quad (10)$$

in which  $a_1$  is a constant. Equation(10) is the reciprocal of the surf similarity parameter defined by Battjes(1974). Moreover, Yamaguchi *et al.*(1981) showed another dimensionless parameter which is useful in estimating the generation of meso-scale river bed configurations as

$$(I_e / F_r)(B/h) = (g/C_i^2) K_i \quad (11)$$

in which  $C_i$  is the Chezy's coefficient,  $F_r$  the Froude number and  $I_e$  the slope of the energy grade line. The left hand side of Eq.(11) is also equivalent to the surf

similarity parameter. It has been acknowledged that the surf similarity parameter is quite useful in explaining some physical phenomena in nearshore dynamics, such as the classification of rip currents and breaking waves.

Furthermore, similar morphodynamical features of rivers and coasts appear in relation to sediment transport. Figure 7 gives a schematic diagram of the development of alternating bars under a meandering flow. Meandering flow selectively erodes a river bank and forms bars in the channel. Meso-scale bottom topography corresponds to the meandering of a river channel.

Similar topography can be observed on the Ogata coast facing the Japan Sea, as shown in Fig. 1. This sandy beach is very straight for about 30km in length. The shoreline changes during two periods, 1947 to 1971, and 1947 to 1979, respectively, are shown in Fig. 8(a). Recently, notable shoreline recession to the east in the downcoast area has been observed due to the construction and extension of the west breakwater at Naoetsu harbor (about 2.5 km long and 20 m deep at the offshore end). Figure 8(b) shows the bottom topography of the bar-trough stage located 4km east of the breakwater, as shown with an arrow in Fig. 8(a). It was found that the predominant spacings of shoreline recession and locations of shoals and dips in the nearshore zone are about 500 m. The locations of these geographical features are almost stable annually in the longshore direction. A wavy shoreline can also be found in the formation process of a giant cusps which usually appear in a beach erosion process. However, since they move in the longshore direction, the shoreline changes on the Ogata coast differ from those normally attributed to giant cusps. If the longshore currents meandered along the nearshore zone, alternating shoals and dips would appear, possibly resulting in wavy changes in the shoreline similar to those in rivers. Therefore, the analogy between the stable channel and the stable beach turns out to be close to the true situation.

(3) Application of analogy between stable channel and stable beach to beach erosion control

The continuity equation of littoral sediment transport is expressed by

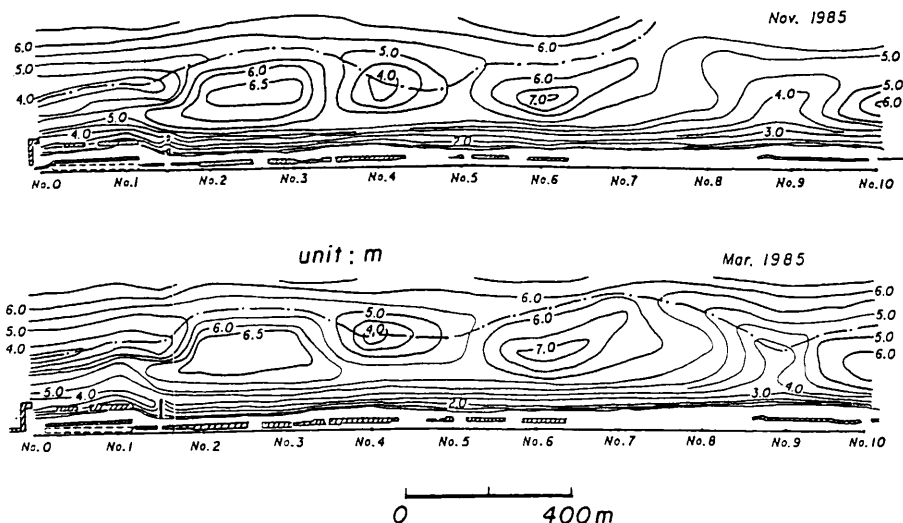
$$\frac{\partial h}{\partial t} = \frac{1}{1-\lambda} \left( \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \right) \quad (12)$$

in which  $\lambda$  is the porosity and  $q_y$  the offshore sediment transport rate. Here, applying Eq.(12) to the above discussion, some methods by which stable beaches could be obtained are proposed.

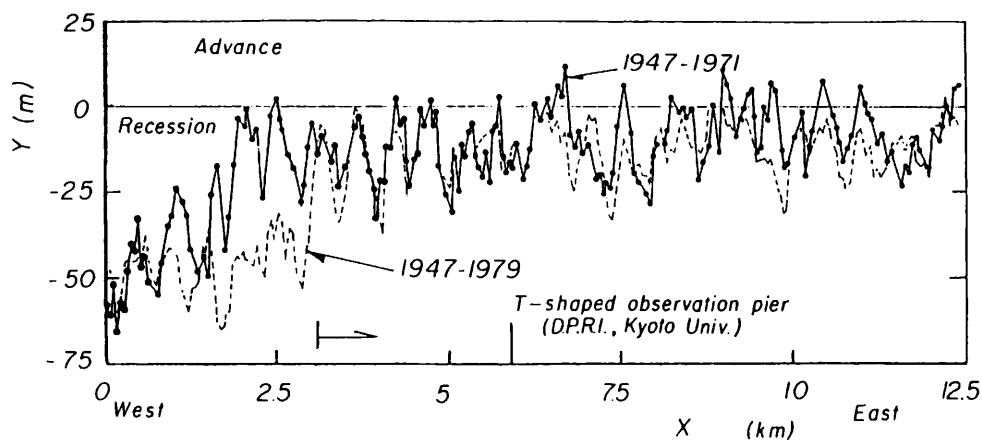
#### a) Decrease of discharge of longshore currents

If the sign on the spatial gradient of rate of longshore sediment transport is made negative, the longshore accretion of sediment can be predicted by Eq.(12). This condition is reached by a gradual reduction of discharge of longshore currents. To meet this condition, the coefficient of roughness along a coast must be increased artificially. An example is the construction of a series of permeable groins with low crown and mild slope. If a massive structure with a large coefficient of reflection is constructed, it will cause a large spatial gradient in the radiation stress due to local changes of wave height and therefore, increase the nearshore current velocity.

The right hand side of Eq.(12) represents the sum of the spatial gradients of rates of longshore and offshore sediment transport. Therefore, even if the ratio of these two sediment



(a) Shoreline changes of Ogata coast during two periods, 1946 to 1971, and 1946 to 1979, respectively.



(b) Bottom topography of the eroded area (an arrow in this figure shows location at 4 km eastward from the breakwater).

Fig. 8 Beach changes at Ogata coast

sediment transport rates changed, the left hand side of the equation would remain constant, that is, the changes of water depth with time would be independent of this ratio. These characteristics might be applied to beach erosion control. Shoreline recession due to offshore sediment transport under storm conditions should be considered as a containment in a temporary sediment reservoir in the offshore zone rather than actual beach erosion, because the sediment could return to the shoreline under

Table 2 Observed and estimated value of velocity of erosion waves.

California, U.S.A. (Inman(1987))	
Santa Cruz	2.2-2.8 km/year
Santa Barbara	2.5-2.8
Ocean side	2.2-4
Japan	
Shizuoka coast	0.26 km/year
Kaike coast	0.14
Kochi coast	0.24
Fuji coast	0.28

swell conditions. In the equation, this is equivalent to a small  $K_*$ , and consequently the velocity of longshore sediment transport would be retarded.

Recently, Inman(1987) revealed some field test results on propagating speeds of erosion waves after the sudden placement of a groin in an upcoast area. Table 2 shows his results for the California coast and an estimation of the propagating speed of the waves on some coasts in Japan. Because the rate of longshore sediment transport in Japan is usually lower than that in California, the propagating speed is also lower. In conclusion, if seasonal variations in cross-shore sediment transport can be increased, the occurrence of beach erosion in the downcoast area will be retarded. Of course, decrease of the breaking depth (equivalent to a decrease of incident wave height) and the incident angle of incoming waves could also lead to reduction of discharge of longshore currents.

#### b) Increment of coarseness of sediment

When sediment becomes coarser, the water depth in the nearshore zone increases and the width of the surf zone decreases, so that a stable beach could be achieved. Practically, if sediment for beach nourishment were selected with sediment a little coarser than the original, early stabilization after some erosion is expected. When the rate of longshore sediment transport is reduced a certain amount by the presence of man-made obstacles such as jetties or breakwaters, the average size of the transported sediment automatically decreases in the downcoast area, leading to acceleration of beach erosion. The supply of sediment slightly coarser than the original would therefore be a good method to promote a more stable beach formation.

#### c) Decrease of surf zone width

To reduce the surf zone width, it is necessary to decrease the incoming wave height or to increase the water depth in the surf zone. In the latter case, waves would be more liable to break close to the foreshore, causing an adverse effect on the stabilization of the beach as the sediment would be easily carried in the offshore direction due to wave breaking and diffusion. The wave height decreases notably after breaking. Therefore, forced wave breaking in relatively deep water is very effective in reducing the discharge of longshore currents. This could be accomplished by the construction of shore-parallel beach erosion control of permeable or submerged type. However, if construction in the nearshore zone, two problems will occur. One is that the structures

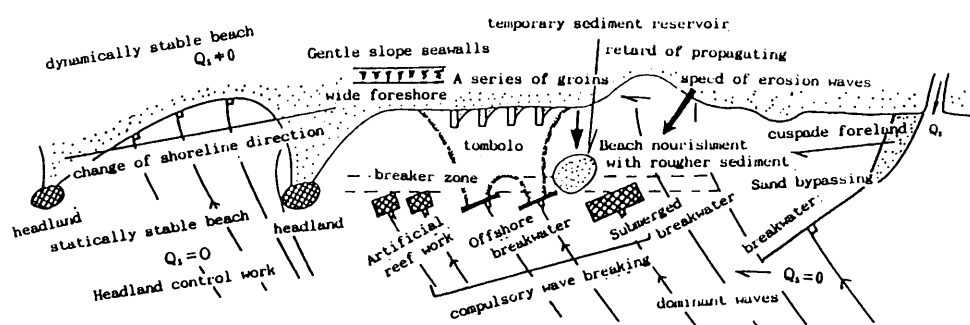


Fig. 9 Recommended location of beach erosion control works on the basis of the function of countermeasures.

will significantly agitate the bottom sediment and will therefore be likely to increase the rate of longshore sediment transport. The other is that they will disturb the cross-shore sediment transport which moves to the offshore under storm conditions to form a longshore bar.

To summarize the above discussions, recommended usage of particular beach erosion control works is schematically shown in Fig. 9.

#### IV. THE "LAND RULE" AND A VARIETY OF EROSION CONTROL

As is well known, there are many principles for beach erosion control. Moreover, each technique can be conducted in many ways. This is obvious and yet there are many examples in the past where beach erosion control projects were not carried out in accordance with the established principles. Studies of the successes and failures have been repeatedly performed and semi-empirical relationships have been obtained. In the process of developing methods of the control in the past, their applicability to beach erosion control was not investigated, and only a few were developed under restricted conditions in most countries.

Blache (1940) pointed out the "land rule", stating that the original construction materials were very important to determine styles of buildings and structures. For example, in the Netherlands around 1850, it was very difficult to use masonry due to lack of stones, so techniques using fascine and polder clay developed. Around the same time, construction of beach erosion control works as well as breakwaters developed under the influence of the Industrial Revolution. Table 3 shows the construction materials available in Europe in the 19th century. In France and Italy, it was common to use limestone as a material. Around the Mediterranean Sea, countries such as Algeria and Egypt were in a similar situation. In contrast, the U.S.A. had almost every kind of material available, but the construction styles were influenced by immigrant engineers and designers who had been trained in their own countries. Nowadays, however, the choice of the material is secondary to design, but in traditional control works the land rule is reflected. In Japan, composite breakwaters have been used

Table 3 Materials for breakwater constructions in the 19th century.

Country	Materials for breakwater construction
England	Limestone, Sandstone and imported Timbers
France	Limestone, Sandstone
Italy	Limestone
Netherlands	Clay, Fascine, Stone and Timbers imported from Belgium, Germany and Russia
U.S.A.	Stone, Timber

exclusively, while in other countries rubble mound breakwater are more popular. This is a typical example of a bias resulting from the modernization process in a country (Kawata, 1988).

## V. IMPROVEMENT OF BEACH EROSION CONTROL WORKS

### 5.1 Characteristics of beach erosion control

Characteristics of beach erosion control works are summarized in Table 4. Brief descriptions of some types are as follows:

#### (1) Groins

A coastal structure jutting out from the shore into the sea to trap longshore sediment transport or control longshore currents in an effort to stop or retard beach erosion. Usually, series are constructed.

#### (2) Seawalls

A wall structure sheltering the shore from wave action. If it is constructed at the foreshore, it tends to promote offshore sediment transport due to wave reflection. Recently, mild slope seawalls (1/3 to 1/6 in Japan) have proved popular.

#### (3) Offshore breakwaters

Traditionally, a shore-parallel structure located in the nearshore zone to act as both a wave absorber and barrier to littoral sediment transport by forming a tombolo behind.

#### (4) Beach nourishment (sand bypassing included)

Sediment is artificially supplied to eroded areas. The main function is to diminish wave power on a sloping sandy beach. To mitigate the loss of newly supplied sediment, additional works such as groins and offshore breakwaters are usually involved.

#### (5) Artificial reefs (wide submerged breakwaters)

Coral reefs in the tropics prevent beach erosion by storm waves. They function by forcing waves to break prematurely.

#### (6) Headland defense works

Pocket beaches tend to be very stable and have a high efficiency in absorbing wave energy. The creation of artificial headlands copying nature (Silvester, 1979) leads to stable beaches.

Table 4 Characteristics of beach erosion control works.

kind of control work	object of control	function for control	advantages	weak points	budget (in Japan)*
groin	wave, longshore current	velocity of longshore current, longshore sediment transport	simple structure	single groin is not effective	ordinary
offshore breakwater	wave	defraction, pattern of nearshore current, cross-shore sediment transport	large control of waves	longshore sediment transport is disturbed. usual maintenance, sightseeing	expensive
sand bypassing,	—	—	keep continuity of sediment	cost performance,	expensive
beach nourishment	—	—	transport, wave absorber	another control work need	
artificial reef work	wave	pattern of nearshore current, cross-shore sediment transport	wave absorber	questionable applicability to control of longshore sediment transport	very expensive
headland defense work	wave, longshore current	longshore sediment transport	clear principle	stability against huge waves	cheap
mild slope seawall	wave run-up	cross-shore sediment transport	low reflection	weak structure, questionable applicability to control of longshore sediment transport	ordinary

\* per unit longshore length



(7) Sub-sand filter systems

By pumping water from the sand layer close to beach, and hence lowering the water table, some of the beach sediment carried landward during the up-rush does not return to the offshore during the down-rush. Accretion may be expected to result.

## 5.2 Improvement of beach erosion control work

On the basis of the above discussion on the methods used in beach erosion control, some improvements can be proposed.

(1) Groins

The main function of groins is to provide roughness against longshore currents. Therefore, it is difficult to control beach erosion with a single groin. A series is recommended, because a gradual retardation of the longshore current velocity can be accomplished with low, permeable and mild-sloped groins. If massive structure is constructed on a sandy beach, it will disturb the wave field and fail to stop beach erosion. Since the efficiency of a longshore sediment trap by groins is not clear, the criterion for groin length and spacing can not be generalized.

(2) Seawalls

It is impossible to stop or mitigate beach erosion with seawalls. If waves collide directly with a seawall, erosion will quickly occur. Toyoshima(1972) pointed out many examples. Seawalls, including those with mild slopes, are applicable only if a wide foreshore exists in front. The purpose of a seawall is to keep a residential district and other important areas safe from the effects of extremely huge waves with a long return period.

(3) Offshore breakwaters

Offshore breakwaters have some shortcomings such as difficulty in maintenance and excessive trapping of longshore sediment. On coasts where longshore sediment transport is predominant, offshore breakwaters cause severe beach erosion in the downcoast areas of the structure. They are only effective in controlling the cross-shore sediment transport. If beach erosion occurs owing to increases in offshore sediment transport in accordance with the construction of seawalls or other coastal structures with large wave reflection coefficients, offshore breakwaters may be recommended, because they reduce the wave energy and diffracted waves carry some sediment into the sheltered area to form cusped forelands or tombolos behind. The main function of offshore breakwaters is to control waves, so that their location is an important factor in the design.

(4) Artificial reefs

Basically, these should be in the offshore zone. When incident waves approach obliquely and break on a reef, currents are inevitably generated leading to renewed beach erosion. In natural coral reefs, open sections can be found to facilitate flow in the offshore direction. It is necessary to study the mechanism of a circulation system resulting from construction of this type.

(5) Headland defense work

This can control the rate of longshore sediment transport. Under conditions of no sediment supply from the upcoast area, a statically stable beach can be obtained easily. While, if there is a slight sediment supply, it is rather difficult to create equilibrium as in a dynamically stable beach. This is due to the difficulty in locating, sizing and shaping a proper headland. If there are two dominant wave directions, the

shape of beach will change, so that the concept of setback line defined by Purpura (1972) can be introduced. In the seaward area beyond this line, any construction, excavation or damage to dunes or vegetation is prohibited along with driving vehicles on the dunes.

## VI. CONCLUSIONS

The methodology of beach erosion control is discussed on the basis of the characteristics and mechanism of littoral sediment transport. The following two approaches appear best.

- (1) In the offshore zone: It is very important to control waves by one of two methods; that is, decrease of breaking depth (equivalent to decrease of wave height) and decrease of incident angle of waves. Practically, some coastal structures such as submerged breakwaters and offshore breakwaters can induce wave breaking, therefore reducing the wave power in the offshore zone. In order to decrease the incident angle of the wave, the overall direction of shoreline should be slightly inclined.
- (2) In the nearshore zone: Using the analogy of a stable channel as in rivers, the following three methods appear effective in obtaining a stable beach; (a) decreased discharge of the longshore currents, (b) increased coarseness of sediment and (c) decrease of the surf zone width.

Moreover, it is found that the "land rule" is very important in selecting the method of beach erosion control. The principles of beach erosion control at any location reflect the availability of construction materials, so that engineers need to understand the physical background to the beach erosion control already developed at different coastal environments.

Applying the above discussion, improvements in traditional and newly developed beach erosion control works are proposed through the analysis of their functions.

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(Received September 24, 1988; revised March 20, 1989)