ONSHORE-OFFSHORE TRANSPORT AND BEACH PROFILE CHANGE

by

MASATARO HATTORI
Professor of Coastal Engineering, Chuo University, Tokyo, Japan

and

RYOICHI KAWAMATA
Research Assistant, Environmental Research Center,
University of Tsukuba, Ibaragi Prefecture, Japan

ABSTRACT

In this paper a model is presented to describe onshore-offshore sand transport in the surf zone. The model is based on the physical consideration that when the net transport attains a state of equilibrium, the power expended through gravitational force in suspending sand grains is balanced by that due to the uplifting force arising from the turbulence generated by breaking waves.

Two important parameters controlling sand transport are the dimensionless fall-time parameter and bottom slope. Using these parameters, the direction of onshore-offshore transport and the beach profile in the surf zone are expressed as

$$(H_0/L_0)\tan\beta \Big/ \frac{w_s}{gT} \begin{array}{c} < \\ = \\ > \end{array} 0.5 \quad \begin{array}{l} \text{(onshore transport; accretive profile)} \\ \text{(neutral; equilibrium profile)} \\ \text{(offshore transport; erosive profile)} \end{array}$$

INTRODUCTION

The aim of this study is obtain a better understandings of the mechanism governing onshore-offshore sediment transport and the transformation of beach profiles resulting from sediment transport across the surf zone. In treating coastal processes, sediment transport is usually divided into longshore and onshore-offshore components. It is generally believed that the longshore component controls relatively long-term systematic profile changes, whereas the onshore-offshore component has a marked connection with short-term profile changes, observed during either storm or post-storm wave climates.

The onshore-offshore shift of sand in the surf zone plays a very important role in shoreline migration as well as in the transformation of beach profiles. In other words, the beach profile has great bearing on coastal phenomena related to littoral sediment transport.

Since 1949, after Johnson proposed a criteria for beach profile classification in terms of the wave steepness in deep water, much effort has been devoted to clarify the mechanism of the profile change for two-dimensional beaches. Rector(1954), Iwagaki and Noda(1962), Nayak(1971), Watts(1954), Dean(1973); and Sunamura and Horikawa(1974) proposed certain parameters related to beach transformation and the direction of net sediment transport. The authors(1979) also obtained criteria for classifying the beach profile in terms of the "delay distance" (Kemp, 1960) and "surf similarity parameter" (Battjes, 1974). However, onshore-offshore processes, especially in the surf zone, have not yet been fully understood even under constant wave conditions.

Since the mechanics of sediment transport in the surf zone is more complex than in the offshore zone, all the relevant parameters can not be taken into account in a model description. In this paper, a model is developed on the basis of the concept of the balance of power expended on sand grains suspended by breaking waves.

DESCRIPTION OF MODEL

The turbulence generated by breaking waves acts as a stirring agent for suspending sediment particles. Using available field data of kinematic energy and momentum fluxes in the surf zone, Thornton(1978) presented a relationship between the ratio of the turbulent velocity intensity to the wave-induced velocity intensity and a parameter corres-

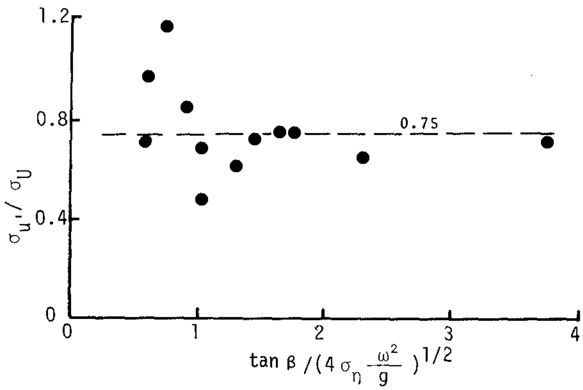


Fig. 1 Ratio of turbulent to wave-induced velocity intensity (Thornton, 1978)

ponding to the offshore paramter $\xi_0 = \tan\beta/\sqrt{H_0/L_0}$ (Battjes, 1974). His result is given in Fig. 1, in which σ_u, and σ_U are the standard deviations of the turbulent and wave-induced velocities, σ_η is the standard deviation of the free surface calculated from the spectrum of the waves, ω is the angular frequency, and $\tan\beta$ is the bottom slope. Figure 1 indicates that the velocity ratio is almost constant regardless of the breaking type, which is represented by the value of the abscissa (Galvin, 1972).

Based on Thornton's result, the stirring power, P_s, for suspending sand grains due to turbulence as the stirring agent is written as Eq.(1),

$$P_s = a'W\,\hat{u}\,\tan\beta, \tag{1}$$

in which W is the submerged weight of sand grains, $\hat{u}$ is the maximum wave-induced velocity, $\tan\beta$ (= h_b/X_b) is the bottom slope in the surf zone, h_b is the water depth at the breaking position, X_b is the width of the surf zone, and a' is a constant. Notations used are shown in Fig. 2.

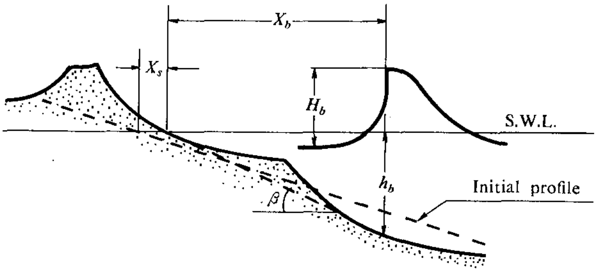


Fig. 2 Definition sketch.

Using the linear long wave theory, we have Eq.(2) as an expression for the maximum wave-induced velocity,

$$\hat{u} = 2\pi\ (H_b/L_b)\ gT, \tag{2}$$

where H_b and L_b are the wave height and length at the breaking position, T is the wave period, and g is the gravitational acceleration. Substituting Eq.(2) into Eq.(1), we have Eq.(3) for the expression of P_s,

$$P_s = a''\ W\ (H_b/L_b)\ g\ T\ \tan\beta, \tag{3}$$

where a" is a constant.

Since it is considered that the resisting power against lifting sand grains from the bottom is due to the gravitational force, the resistive power expended on sand grains is written as Eq.(4),

$$P_r = a'''W\, w_s(d), \tag{4}$$

in which $w_s(d)$ is the fall velocity of a sand grain of diameter d, and a''' is a constant.

If the stirring power, P_s, is greater than the resisting power, P_r, sand grains tend to keep in suspension due to breaking waves. Then, suspended sand grains would be transported seaward in the form of a sand cloud by wave-induced currents (Sunamura, 1980). If, on the other hand, the resisting power is greater than the stirring one, sand grains tend to roll and jump on the bottom surface. Then, sand grains are shifted shoreward as bed load.

It is, therefore concluded that the predominant or net direction of onshore-offshore sand transport, which has a close connection with beach profile change, can be described with the ratio of the above two powers, P_s and P_r. Combining Eqs.(3) and (4), the ratio P_s/P_r is written as

$$\frac{(H_b/L_b)\tan\beta}{w_s(d)/(gT)} \begin{array}{c} < \\ = \\ > \end{array} C' \quad \begin{array}{l} \text{(onshore transport)} \\ \text{(neutral)} \\ \text{(offshore transport)} \end{array}, \tag{5}$$

in which C' is a constant.

As is well known, there are many difficulties in measuring wave and sediment processes within the surf zone, both in the laboratory and in the field. Most of the available data are usually represented by the wave characteristics in deep water and the median diameter of the sediment particles.

Wave steepness at the breaking position depends on the beach slope and incident wave steepness in deep water may be calculated within the limits of linear wave theory. Accordingly the wave steepness in Eq.(5) can be replaced with that in deep water. In addition, we write $w_s(d_{50})$ in place of $w_s(d)$ in Eq.(5), where $w_s(d_{50})$ is the fall velocity of sand grains determined from the median diameter of the sediment particles. Then Eq.(5) is rewritten as follows,

$$\frac{(H_0/L_0)\tan\beta}{w_s(d_{50})/(gT)} \begin{array}{c} < \\ = \\ > \end{array} C \quad \begin{array}{l} \text{(onshore transport)} \\ \text{(neutral)} \\ \text{(offshore transport)} \end{array}, \tag{6}$$

in which C is a constant to be determined from laboratory and field data. It is noticed that Eq.(6), the final expression of the present model, is quite similar to the criterion proposed by Dean(1973), in which the effect of beach slope was not included.

By using the relation $L_0 = (g/2\pi)T^2$, Eq.(6) can be written as

$$\frac{H_0}{w_s(d_{50})T}\tan\beta \begin{matrix} < \\ = \\ > \end{matrix} \frac{1}{2\pi}C. \quad (7)$$

Equation (7) indicates that two important parameters control onshore-offshore sand transport in the surf zone; the dimensionless fall-time parameter, H_0/w_sT, (SPM, 1977), and the relative width of the surf zone, $\tan\beta$. Dean (1973) also pointed out the importance of the quantity $H_0/(w_sT)$ for the prediction of accreted or eroded profiles.

COMPATIBILITY OF THE PRESENT MODEL

The present model emphasizes the importance of the beach slope for onshore-offshore sediment transport. Before discussing the validity of the model, it must be shown to be compatible with general observation both in laboratory experiments and in nature.

The beach slope in the surf zone may depend on the size of the beach material, the energy level of waves incident on the beach, the steepness of incident waves, the rate of percolation and the degree of sediment sorting of the beach, and the change in water level (Komar, 1976). Among these factors, the dependence of grain size on the beach slope has been investigated by geologists (Bascom, 1951; King, 1972; SPM, 1977).

The following has been deduced from previous studies:

(1) The beach slope of the foreshore depends mainly on grain size, and tends to increase with the median grain diameter. In addition, laboratory experiments with movable beds reveal that the specific gravity of beach material is an important parameter controlling the beach slope (Nayak, 1970). These facts imply that beach slope depends predominantly on the fall velocity, which is a function of the size, shape and specific gravity of the sediment particles.

$(\tan\beta \sim w_s(d))$

(2) For a given grain size, low-energy beaches have larger slopes than high-energy beaches.

(3) The effect of wave period (or, in effect, wave length) on the beach slope has been examined with both laboratory experiments and field investigations. The results indicate that the beach slope tends to increase with decreasing wave period.

$(\tan\beta \sim 1/T \text{ or } \tan\beta \sim 1/L)$

(4) The relationship between beach slope and steepness of inciddent waves is that the beach slope becomes flatter with increasing wave steepness (Rector, 1954; King, 1972).

$(\tan\beta \sim 1/(H/L)$

Combining the above results, we obtain the following relationship for the beach slope,

$$\tan\beta \sim \frac{w_s(d)/T}{(H/L)} , \tag{8}$$

which is essentially equivalent to Eq.(6).

TEST EQUIPMENT

In order to verify the present model and to determine the constant appearing in Eq.(6), laboratory experiments were performed in a two-dimensional wave tank, 0.4 m wide, 0.7 m deep, and 16 m long, with a glass wall on one side of the entire length. Figure 3 shows the general arrangement of the test equipment.

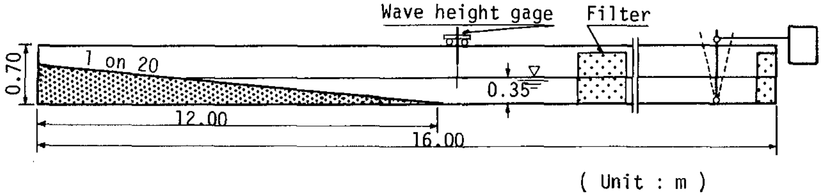


Fig. 3 General arrangement of test equipment.

The experiments were performed using monochromatic waves generated by a flap-type wave maker installed at one end of the tank. The incident wave height was measured by a capacitance type wave gage placed just offshore from the toe of the model beach. The breaker height was measured with a small capacitance type wave gage mounted on a carriage capable of moving with constant speed along the centerline of the tank. The horizontal distance from a base line on the model beach to the breaking position was measured with a ruler.

Beaches for the experiments were molded to an initial slope of 1 on 20 by using natural sand or Amberlite, a kind of plastic grain. The fall velocity of the bed materials was measured by means of a settling tube. Physical properties of the bed materials are given in Table 1.

Table 1 Physical properties of bed materials.

Bed Material	Amberlite	Natural Sand
Median Diameter (mm)	0.55	0.22
Specific gravity in Air	1.33	2.70
Fall Velocity (cm/sec)	3.20	2.60

Each experiment was performed in a series of runs. Beach profiles were surveyed along the centerline of the tank after each run using a specially designed bottom-touch type (Hattori and Kawamata, 1979). Immediately after starting a run, measurements of the incident wave height, and breaking characteristics were taken. Wave characteristics in the uniform depth of 0.35 m were determined from the threshold condition of sediment movement proposed by Horikawa and Watanabe(1967).

EXPERIMENTAL RESULTS AND DISCUSSIONS

As Sunamura and Horikawa(1974) have pointed out, from previous results obtained both in the laboratory and in the field, there exists some difficulty in grouping beach profiles into bar and step types according to the conventional criteria, because of the complexity of the beach configuration and of the tendency for shoreline migration. Figures 4 and 5, examples of the experimental results, show time changes of beach profiles of the accretive type. Arrows pointing toward the still water level represent the breaking position. As seen in Fig. 4, a break-point bar (King, 1972) moved shoreward gradually. It was noticed from the experiments that the breaking position also moved with the bar. When the migrating bar reached the beach face, the shoreline advanced considerably and the beach profile transformed to a step or reflective type profile (Hattori and Kawamata, 1979). On the other hand, sand outside the surf zone was shifted offshore. Due to this sand transport, the water depth around the breaking position deepened progressively, and the beach slope in the surf zone became steeper.

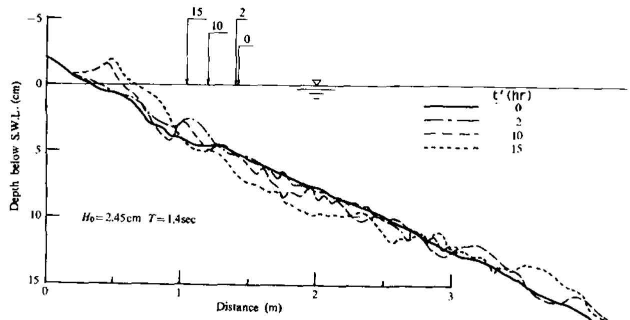


Fig. 4 Profile changes of accretive beach (Amberlite).

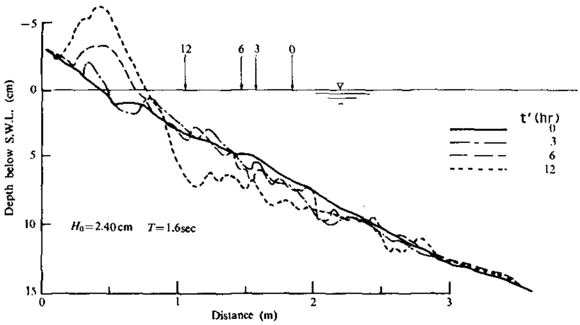


Fig. 5 Profile changes of accretive beach (sand).

Figures 6 and 7 illustrate profile changes of receding beaches. As the coastal berm eroded, sand shifted from the beach face was transported seaward and deposited in the offshore zone. Although an offshore bar sometimes formed at the breaking position, this bar tended to migrate offshore. With retreat of the shoreline, the beach slope within the nearshore zone became flatter and the width of the surf zone broadened in the course of time. It was also observed in the experiments that the breaker wave type changed from plunging to spilling.

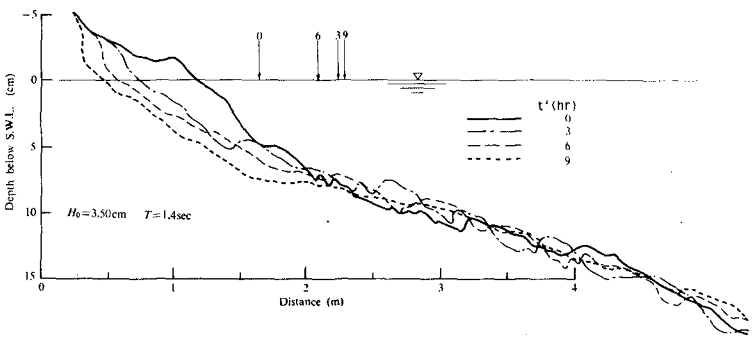


Fig. 6 Profile changes of erosive beach (Amberlite).

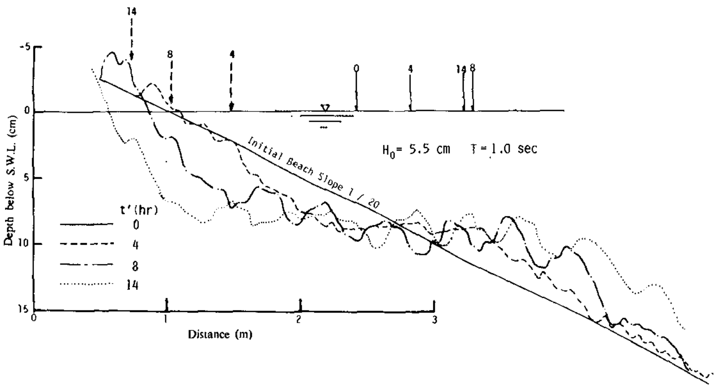


Fig. 7 Profile changes of erosive beach (sand).

When the cumulative time, t', was greater than four hours, waves broke twice: by first spilling and then by plunging at the toe of the foreshore. Under these circumstances, as seen in Fig. 7, a step was formed at the foreshore face and the shoreline migrated seaward. In this figure, broken arrows pointing toward the still water level indicate the breaking position of reformed waves.

CLASSIFICATION OF BEACH PROFILE

On the basis of the experimental results, the authors classified beach profiles into the following three groups as determined by the direction of net sand transport inside and outside the surf zone as shown in Fig. 8.

TYPE I is the accretive beach profile with a step on the foreshore. For this profile a landward sand shift is dominant in the surf zone, and the shoreline advances.

TYPE III is the erosive or storm beach profile without bars. Intense offshore sand transport occurs in the nearshore zone.

On a beach of TYPE II, a bar is formed at the breaking position. This bar sometimes migrates either landward or seaward. Under certain conditions, which depend mainly on the wave characteristics in the nearshore zone, the TYPE II profile transforms to the TYPE I or to the TYPE III profile.

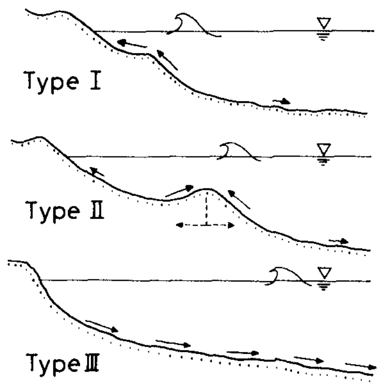
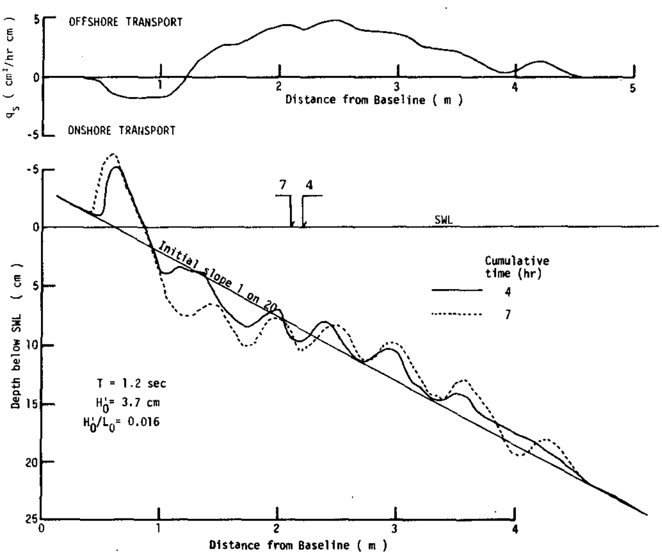


Fig. 8 Classification of beach profiles (Arrows denote the direction of net sand transport).

Figure 9 illustrates the method for determining the direction of net sediment transport adopted in the classification of beach profiles. The bottom figure shows two beach profiles surveyed at a time interval of three hours. From the difference between these two profiles, the rate of sediment transport in the onshore-offshore direction can be computed with the aid of the conservation equation of bottom sediment, given by Eq.(9),

$$\frac{\partial h}{\partial t} = \frac{1}{(1 - \lambda)} \frac{\partial q_s}{\partial x} , \tag{9}$$

in which h is the water depth, q_s is the sediment transport rate in the on-offshore or x direction, λ is the porosity of the bottom sediment, and t is the time. The distribution of the transport rate computed is given by the top figure. The dominant tendency of sediment transport inside and outside the surf zone in Fig. 8 was determined in connection with the beach profiles by calculation with Eq.(9).



Fg. 9 Method for determining transport rate.

EVALUATION OF THE PRESENT MODEL

The evaluation of the present model is made on the basis of shoreline migration from the initial position of each test run, because the shoreline of the TYPE II profile exhibits considerable migratory tendencies. When the shoreline advances, a beach is termed as an accretive profile, whereas when the shoreline recedes, it is termed an erosive profile (Sunamura and Horikawa, 1974).

The criterion for the type of beach profile, erosive or accretive, based on this study is shown in Fig. 10 in terms of $(H_0/L_0)\tan\beta$ and $w_s(d_{50})/gT$. In this figure, the results of many other laboratory experiments are included to cover a wide range of characteristics of waves and bed materials. Open and solid symbols represent the accretive and erosive profiles, respectively.

It is noticed from Fig. 10 that regions of occurrence of the two beach profiles are distinctly separated by the line of C = 0.5, although there exists a mixed region bounded by 0.3 < C < 0.7. The existance of this mixed region seems to have a close connection with the migration tendency of break-point bars.

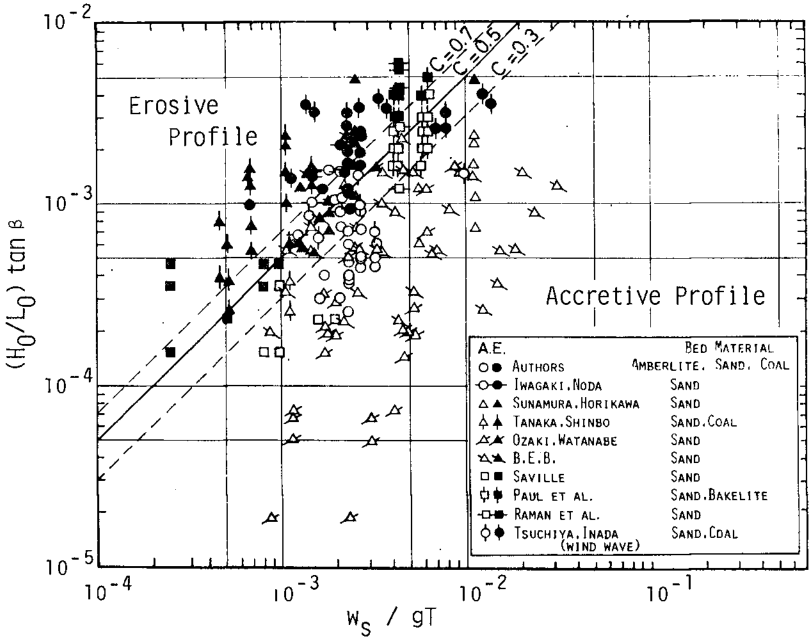


Fig. 10 Classification of erosive and accretive beach profile (Laboratory data).

Various kinds of light-weight bed materials have been widely used for movable bed experiments. Light-weight bed materials behave in very different ways under wave action from natural sand as a bed material (Nayak, 1970). Figure 10, however, indicates that the beach profile in the surf zone can be classified by the present model without respect to the specific gravity of bed materials. This implies that the fall velocity is a very important parameter controlling the beach transformation and sediment transport (Dean, 1973).

In applying results of model experiments to the prototype, we have to consider various factors resulting from the lack of dynamic similitude between the model and the prototype. Among these factors, the scale effect of model experiments and the effect of irregularity of wave characteristics on the onshore-offshore sand transport are examined in this study. Many previous studies have pointed out the importance of scale effects on the formation of beach profiles (Collins and Chesnutt, 1975; Noda, 1972). In the evaluation of the present model, experimental data obtained in a prototype wave tank by Saville(1957) are plotted on Fig 10 in order to obtain knowledge about the applicability of the present model to the prototype.

Tsuchiya et al.(1974) conducted a series of movable bed experiments in a wave tank installed in a wind tunnel. Their data, circles with a vertical bar, are plotted on Fig. 10 to examine the effect of irregularity of incident wave characteristics on beach profiles. In examining the irregularity effect of incident waves, the wave height in deep water in Eq.(6) is replaced with the mean wave height calculated from the significant wave height, which is calculated on the assumption that the wave height frequency distribution in the wave tank is expressible by the Rayleigh distribution function. It is noticed that the transformation of beach profiles under the action of irregular waves also is inferable fairly well from the criterion determined by the experimental results employing monochromatic waves.

The tendency for beach transformation due to changes in incident wave characteristics can be discussed with temporal variations of the C value of Eq.(6) and the shoreline position. The bottom figure of Fig. 11 shows the changes of C value with respect to the dimensionless cumulative time, t/T. The top figure is the time change in the relative displacement of the shoreline, X_s/L_0 (Fig. 2). The following statements are supported by the experiments: For cases of accretive beaches, $C_0 < 0.5$, the C-value tends to move progressively from the initial value to the value of 0.5. C_0 is the value at an initial stage of each test. For erosive beaches, $C_0 > 0.5$, the C-value also shifts toward the value of 0.5. It is therefore concluded that the line of C = 0.5 in Fig. 10 represents not only the criteria for the occurrence of beach profile type, but also the equilibrium condition of beach transformation in the surf zone.

When characteristics of both the incident waves and bottom sediment are prescribed, processes in beach transformations are represented by the vertical shift of data points on Fig. 10. It is apparent from Fig. 10 that the slope of an accretive beach becomes steeper due to the onshore sand transport in the surf zone in approaching an equilibrium beach profile, while the slope on the erosive beach becomes flatter due to the intensive offshore transport.

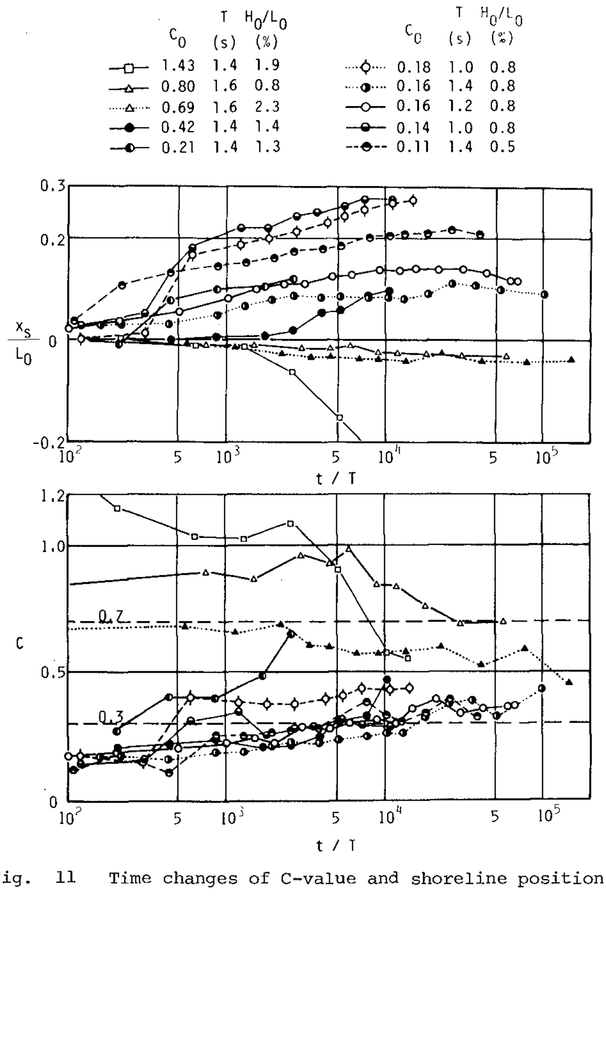


Fig. 11 Time changes of C-value and shoreline position.

BEHAVIOR OF BREAK-POINT BARS

In the classification of beach profiles, it was pointed out that the TYPE II profile occasionally exhibits unusual behavior, which may depend on the migratory tendency of a break-point bar. The occurrence and migratory tendency of break-point bars can be also discussed with the aid of the two parameters of this study. As seen in Fig. 12, a break-point bar is found both on the erosive and accretive profiles.

Most bars on the accretive profile migrate shoreward across the surf zone. Under constant wave conditions, this process is indicated by vertically upward shifts of data points in the accretive profile region of Fig. 12. In contrast, downward shifts of data points in the erosive region indicate the seaward migration of bars due to the intense sand transport beyond the breaking position. It is noticed from Figs. 10 and 12 that the mixed region, $0.3 < C < 0.7$, has a close connection with the growth and reduction of break-point bars, which depends on the direction of bar migration.

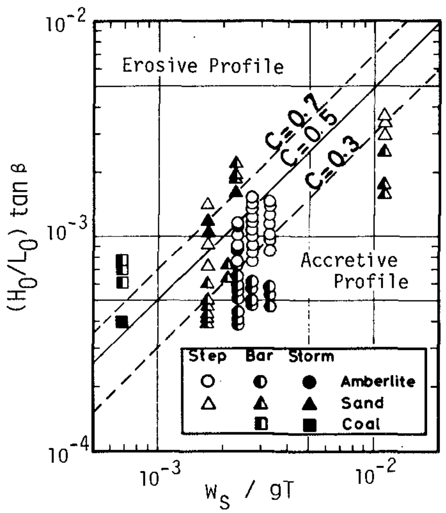


Fig. 12 Occurrence of break-point bars.

APPLICABILITY OF THE PRESENT MODEL TO THE PROTOTYPE

Figure 13 indicates the applicability of the present model to onshore-offshore sand transport in the prototype as well as to beach transformation. Analysis of previous field data, plotted in Fig. 13, is made on the assumption that two-dimensionality holds in shore processes. The examination of beach profiles, erosive or accretive, is decided by the shoreline displacement from its position at the beginning of each investigation term.

In examining the applicability of the model, the wave steepness in Eq.(6) is calculated by a method similar to that used in the examination of the effect of irregularities of wave characteristics as in Fig. 10. Some of the field data did not contain information on the characteristics of the breaking waves. In using such data, the breaking depth is calculated by using the breaker indices proposed by Goda(1970), and the surf zone width is estimated with the aid of a bathymetric chart. When the fall velocity was not prescribed in the data, it was calculated using the diagram for the fall velocity of quartz spheres (Sedimentation Engineering, 1975).

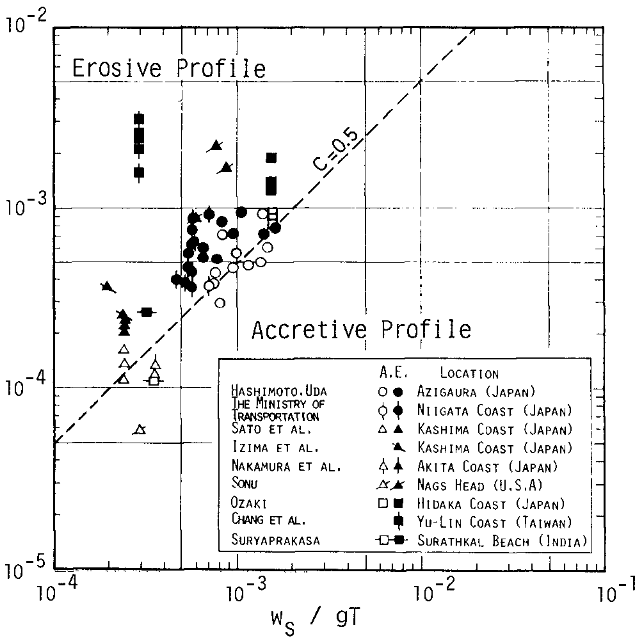


Fig. 13 Applicability of the model to the prototype.

In the analysis of the field data, the effect of time scale on the beach profile change was also included. Field data plotted on Fig. 12, except those of Hashimoto and Uda(1979), were obtained by investigations at intervals of three months or more. Hashimoto and Uda made weekly field surveys of the shoreline configuration and daily observations of the wave climate in the nearshore zone on Ajigaura beach facing the Pacific Ocean.

The long-term profile change appears to have good correlation with the wave height and period averaged over the field investigation. This implies that the beach profile change over the long-term depends on the mean energy level of the incident waves. On the other hand, the profile change over a short-term relates to the high-energy level wave climate during that term. It should be emphasized that the beach profile change in response to the wave field was found inferable from the same relation as that determined from the laboratory data.

CONCLUSIONS

In this study, a model describing onshore-offshore sand transport in the surf zone is developed on the basis of the concept of the balance of power expended on sand gains suspended by breaking waves. The derived relationship, Eq.(6), indicates that both the dimensionless fall-time parameter and the bottom slope in the surf zone, or the surf zone width, are very important parameters controlling on-shore-offshore sand transport.

To evaluate the present model, the authors classify beach profiles into accretive and erosive ones, which are determined by the shoreline migration from its initial position. According to experiments, the regions of occurrence of these two beach profiles are distinctly separated by the line of C = 0.5 (Fig. 10). This C-value also represents the equilibrium condition of profile change of two-dimensional beaches (Fig. 11).

The criterion obtained is as follows:

$$C \begin{array}{c} < \\ = \\ > \end{array} 0.5 \quad \begin{array}{l} \text{(onshore transport; accretive profile)} \\ \text{(neutral; equilibrium profile)} \\ \text{(offshore transport; erosive profile)} \end{array}$$

From comparison with field data (Fig. 13), it is emphasized that this criterion is applicable to the prediction of the beach profile change in the prototype. The importance of the time scale involved in beach profile changes is revealed in the evaluation of the model.

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APPENDIX
ON THE BEACH SLOPE IN THE SURF ZONE

The Shore Protection Manual(1977) provides a criteria for predicting the bar-berm profile in terms of the dimensionless fall time parameter, $F_0 = H_0/w_sT$. In this reference, the dimensionless fall time parameter is plotted against both wave steepness in deep water and wave height to grain size ratio (Figs. 4-29 and 4-30).

According to the results in SPM, the separation between bar-berm profiles, or erosive and accretive profiles, is given by a value of $F_0 = 1 \sim 2$, and the criteria in terms of F_0 is expressible as

$$F_0 \begin{matrix} < \\ = \\ > \end{matrix} 1 \sim 2 \quad \begin{matrix} \text{(deposition onshore, accretive profile)} \\ \\ \text{(deposition offshore, erosive profile)} \end{matrix} \tag{A.1}$$

On the other hand, the criteria obtained in the present study can be rewritten with respect to the dimensionless fall time parameter by using Eq.(7) and putting $C = 0.5$ as follows:

$$F_0 \begin{matrix} < \\ = \\ > \end{matrix} \frac{0.08}{\tan\beta} \tag{A.2}$$

The effect of beach slope on the profile change can be evaluated by combining Eqs.(A.1) and (A.2). For the critical value of the beach profile classification, the beach slope in the surf zone becomes

$$\tan\beta = 1/12.5 \sim 1/25$$

The estimated beach slope is considered to be very reasonable in comparison with previous results obtained in laboratory experiments and in the field (SPM).