CHAPTER 121

BEACH PROFILE CHARACTERISTICS DUE TO THE INCLINED WAVES

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ABSTRACT

The result of a theoretical approach shows that the beach profile characteristics is governed by a modified Iribarren number which includes the effects among the factors of initial beach slope, wave angle and wave steepness. A series of experiments are conducted in a three-dimensional movable bed model on the conditions of two different initial beach slopes, two incident wave angles as well as several erosive wave steepnesses. The relative importance of each factor involved in the parameter is discussed. It is shown that the modified Iribarren number is effective in the analysis of beach profile characteristics under the action of inclined waves. The empirical relationships between beach profile changes and the modified Iribarren number are proposed on the basis of experimental results.

1. INTRODUCTION

A knowledge about the characteristics of beach profiles under the action of waves is of great importance to a number of coastal engineering problems. Various factors such as the

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wave steepness, nearshore current, beach slope and bottom sediment are involved in the beach profile changes. Clarification of these individual factors and evaluation of their mutual interaction are quite important to the determination of the beach profile characteristics. Although much efforts have been devoted to obtain the empirical relationships between the beach profile changes and the different pertinent variables involved in the beach process, a definite solution has not yet been provided because of the complicated nature of the sediment transport in the surf zone.

Previous experimental studies were commonly performed in a two-dimensional wave flume, in which incident waves were normal to the shoreline. In the natural beach, however,the incoming wave often posseses a breaking angle to the shoreline. There are few data on the beach profile changes caused by the inclined breaking waves. Brater and Ponce-Campos(1976) performed a movable bed test in a wave basin with incoming waves oblique to the shoreline, but only the parameter of sand bluff recession was analyzed in his experiments.

The data of the beach profiles complied in this paper are all belong to the erosive type. As shown in Fig.1, the

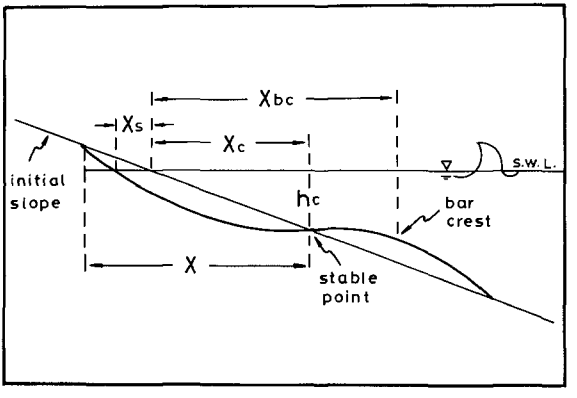

Fig.1 Definitions of beach profile characteristics

items of beach profile characteristics discussed in the present study include the erosion length X, the distance of the stable point X_c, the distance of bar crest X_{bc} and the water depth at the stable point h_c. A modified Iribarren number, $\xi_o^{1/6} \cos\alpha_b$, is proposed based on the concept of wave energy flux to correlate the beach profile changes with the inclined breaking waves, where $\xi_o = \tan\beta / (Ho/Lo)^{1/2}$ is the Iribarren number, $\tan\beta$ is the initial beach slope, Ho and Lo are the wave height and the wave length at deep water respectively, and α_b is the angle of breaking wave. The relative importance of each factor involved in this parameter is discussed. According to the experimental results, the empirical relationships between the beach profile changes and the modified Iribarren number were obtained by applying linear regression analysis.

2. THEORETICAL CONSIDERATION

A non-dimensional length L* is selected to represent the characteristics of beach profile changes. The functional relationship of L* associated with the non-dimensional sediment transport rate is expressed as

$$L^* = f_1(Q_s^*) \tag{1}$$

where Q_s^* is a dimensionless sediment transport rate.

Based on the concept of Bagnold (1963), littoral sand transports are responsible to the wave energy flux. A linear correlation is given by

$$Q_s = k_1 I \tag{2}$$

where Q_s is the volume transport rate, I is the wave energy flux evaluated at the surf zone, and k_1 is a dimensional proportionality coefficient.

As drawn in Fig.2, the wave energy flux F between two wave crests can be written as

$$F = E_b C_{gb} \Delta\ell \cos\alpha_b \tag{3}$$

where E_b is wave energy per unit width, C_{gb} is the group velocity of waves, subscript b represents relative quantities in the breaking point, $\Delta\ell$ is the width between two wave crests. The wave energy flux to a unit shoreline length becomes

$$I = E_b C_{gb} \cos\alpha_b \tag{4}$$

Substitution of Eq.(4) into Eq.(2) gives

$$Q_s = k_1 E_b C_{gb} \cos\alpha_b \tag{5}$$

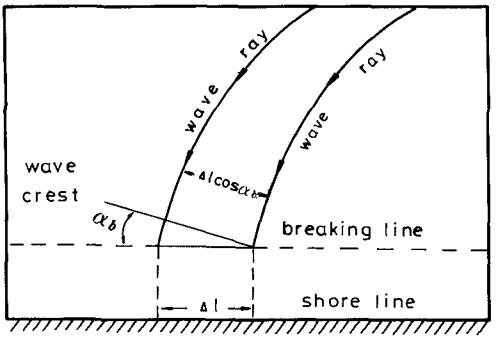

Fig.2 Sketch of the wave energy transmitted on shoreline

From the linear long wave theory, E_b and C_{gb} are evaluated by the following equations, respectively :

$$E_b = 1/8\ \rho g H_b^2 \tag{6}$$

$$C_{gb} = \sqrt{g d_b} \tag{7}$$

in which ρ is the fluid density, g is the acceleration of gravity, H_b the breaking wave height, d_b the breaking water depth. The dimensionless sediment transport rate is formulated in the form of

$$Qs^* = \frac{Qs}{\rho g u_b d_b^2} = \frac{k_1^* E_b C_{gb} \cos\alpha_b}{\rho g u_b d_b^2} \tag{8}$$

where $k_1^* = \gamma' k_1$, is a dimensionless coefficient, γ' is the submerged weight of the sand, u_b is the amplitude of the velocity at the bed in surf zone. For linear wave theory, u_b can be written as

$$u_b = \frac{\pi H_b}{T \sinh \frac{2\pi d_b}{L_b}} \tag{9}$$

where T is the wave period, L_b is the wave length in the surf zone. In the shallow water area, $\sinh \frac{2\pi d_b}{L_b}$ can be expressed as

$$\sinh \frac{2\pi d_b}{L_b} = \frac{2\pi d_b}{L_b} \tag{10}$$

and

$$L_b = \sqrt{g d_b}\ T \tag{11}$$

Insertion of Eqs.(10) and (11) into Eq.(9) yields

$$u_b = \frac{H_b}{2} \sqrt{\left(\frac{g}{d_b}\right)} \tag{12}$$

Combination of Eqs.(6),(7),(8) and (12) leads to

$$Qs^* = k_2 (H_b/d_b) \cos\alpha_b \tag{13}$$

where k_2 is a constant. The ratio of wave height and water depth at breaking point was found to be related to the Iribarren number(Battjes,1974). Based on available experimental data, Sunamura (1980) proposed the relationship

$$\frac{H_b}{d_b} = 1.1\, \xi_o^{1/6} \tag{14}$$

According to Eqs.(13) and (14), the transport rate can be rewritten as

$$Qs^* = k_3\, \xi_o^{1/6} \cos\alpha_b \tag{15}$$

where k_3 is a constant. By comparing Eqs.(1) and (15), we have

$$L^* = f_2 \left(\xi_o^{1/6} \cos\alpha_b\right) \tag{16}$$

It is convenient to assume that the Eq.(16) has the functional form of

$$L^* = a_1 \left(\xi_o^{1/6} \cos\alpha_b\right)^{b_1} = a_1\, \xi_o^{b_2} (\cos\alpha_b)^{b_1} \tag{17}$$

where a_1, b_1 and b_2 are coefficients to be determined by experimental results. It is interesting to note that the physical parameters governing the beach profile changes include the wave steepness Ho/Lo at deep water, the initial beach slope $\tan\beta$ and the angle of breaking wave.

If the incoming waves are normal to the shoreline, Eq.(17) can be simplified as

$$L^* = a_1 \xi_o^{b_2} \tag{18}$$

It has been recognized that the dynamics of the breaking waves in the surf zone is relevant to the Iribarren number (Battjes, 1974; Wang and Yang, 1980). Eq.(18) makes it plausible that ξ_o is also of great importance for beach profile characteristics under the action of normal incident waves. The phase-difference τ/T defined by Kemp(1960) is found to be an important parameter to the beach profile changes (Sunamura and Horikawa,1974), where τ denotes the time for a wave to travel from its breaking point to the uprush limit. An empirical relationship derived by Hsu, Lee and Ou(1986) showed that the parameter τ/T is related to Iribarren number. The usefulness of Iribarren number for the analysis of beach profile changes due to normal incident waves was also confirmed in their studies.

3. EXPERIMENT AND PROCEDURE

The experiments were performed in a three dimensional wave basin of 16m long, 12m wide and 0.7m deep. The testing arrangements for both normal and inclined incident waves are shown in Fig.3 and Fig.4, respectively. The test section of movable bed model were placed with a uniform slope by using fine coal with median diameter of 0.15mm and specific gravity of 2.07.

Two different initial beach slopes (1/16 and 1/25), two wave angles(0° and 30°) as well as several erosive wave steepnesses were selected for the model tests. All experimental conditions are summarized in Table 1. The angles of breaking waves were calculated by the method proposed by Wang and Le Mehaute (1980).

Battjes(1974) clarified the types of breakers on the basis of the classification of Galvin(1968) as follows:

$$\xi_o > 3.3 : \text{surging breaker}$$

$$3.3 > \xi_o > 0.5 : \text{plunging breaker}$$

$$\xi_o < 0.5 : \text{spilling breaker}$$

The experimental data of $\tan\beta = 1/25$ falling in the domain of $0.161 \sim 0.328$ belong to spilling breaker while values of $\tan\beta = 1/16$ ranging from 0.256 to 0.580 correspond to transition between spilling breaker and plunging breaker.

Waves of constant characteristics were generated by a flat type wave maker. Wave characteristics were measured by capacity type wave gauges and a recorder unit. Beach profiles were measured by an electric platform at a half hour time interval along the beach. Normally, it will take three hours for the profile to reach equilibrium condition for normal incident waves. In order to examine the relations between beach profile characteristics and inclined wave behavior inside the surf zone, it is assumed inclined waves will take the same time for reaching the equilibrium conditions.

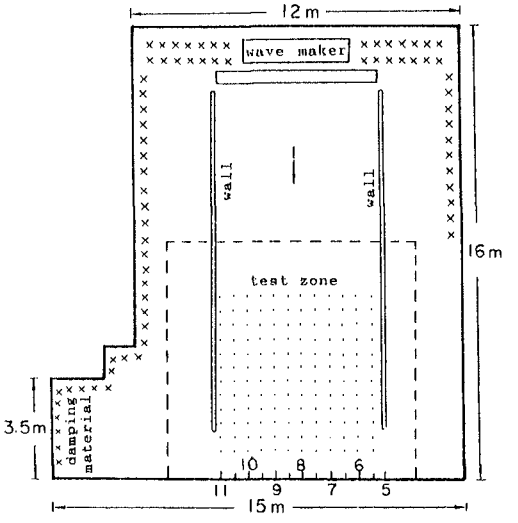

Fig.3 Arrangements of wave basin for normal incident waves

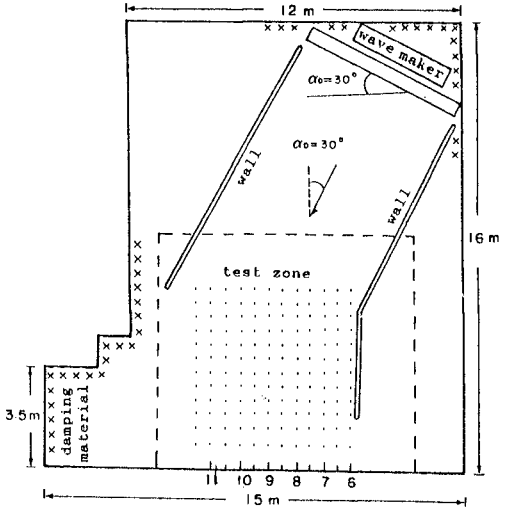

Fig.4 Arrangements of wave basin for inclined incident waves

Table 1 Wave conditions

tanβ	α_0 (deg)	T (sec)	Ho (cm)	Ho/Lo	α_b (deg)
1/16	0°	1.0~1.2	2.84~9.63	0.0182~ 0.0493	0°
1/25	0°	1.0~1.2	2.32~8.28	0.0149~ 0.0619	0°
1/16	30°	1.0~1.2	2.61~10.17	0.0116~ 0.0597	6.8~12.6

Only three successive profiles in the middle part of the movable bed were taken for the analysis of beach profile characteristics because of the boundary effects on the test zone. Only the first type of erosive beach profile (Sunamura and Horikawa,1974) was analyzed in the present study. Fig.5 shows four typical examples of beach profile variation of four successive sections for the cases of different wave steepnesses.

4. RESULTS AND DISCUSSION

Erosion Length

The erosion length, X, is defined as the distance from stable point to the maximum upper erosion point as shown in Fig.1. The understanding of erosion length in sandy beach is essential for shore protection practices. Experiments(Chang, 1982) indicate that the erosion length depends on the location of the breaking point and its value is larger than 0.8 times the distance between the breaking point and the origin point of still water level.

Fig.6 illustrates the relationship between the dimensionless erosion length X/Lo and the wave steepness Ho/Lo. The data of $\tan\beta = 1/30$ plotted here were compiled from Cheng(1974). His experiment were conducted in a two dimensional wave flume. Four lines drawn in this figure were obtained by a linear regression analysis for different initial beach slopes and angles of incident waves. The value of X/Lo increases remarkably as Ho/Lo increases. The data of the inclined incident waves show the same tendency for the cases

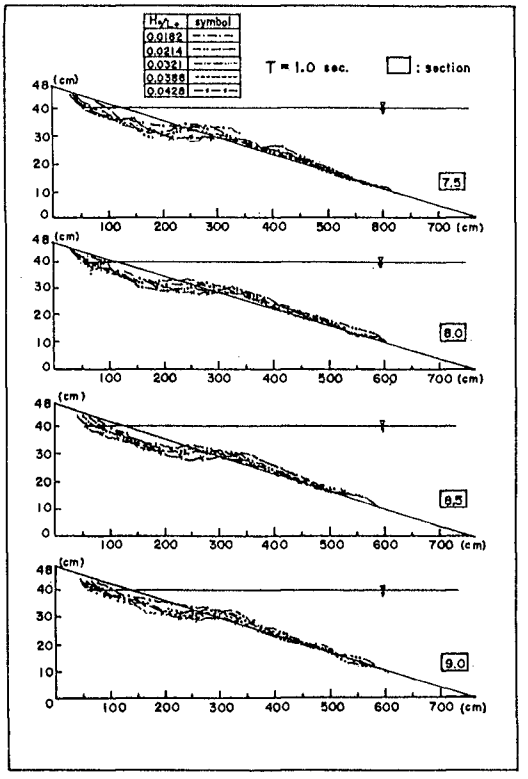

Fig.5 Typical variation of beach profiles for different wave steepnesses ($\tan\beta = 1/16$)

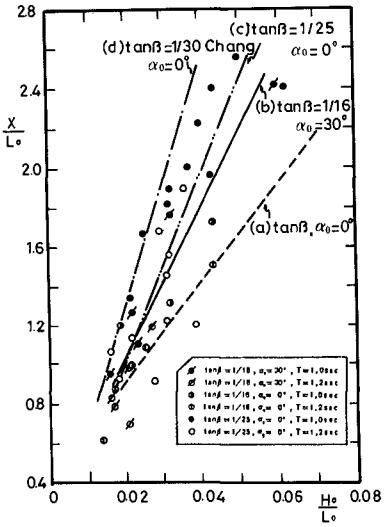

Fig.6 Relationship between X/Lo and Ho/Lo

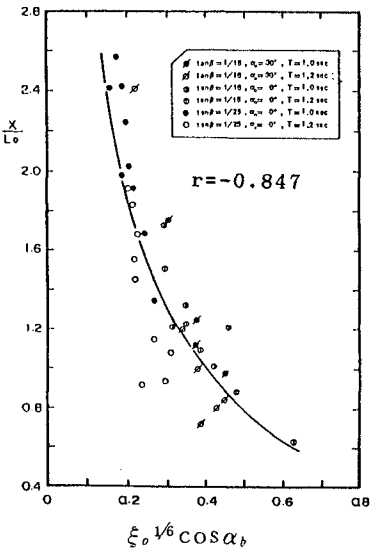

Fig.7 Relationship between X/Lo and $\xi_o^{1/6}\cos\alpha_b$

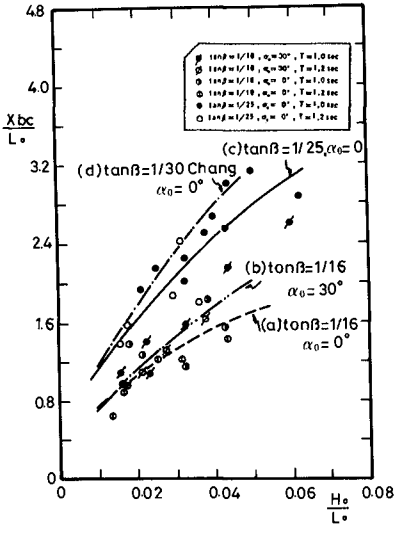

Fig.8 Relationship between X_{bc} /Lo and Ho/Lo

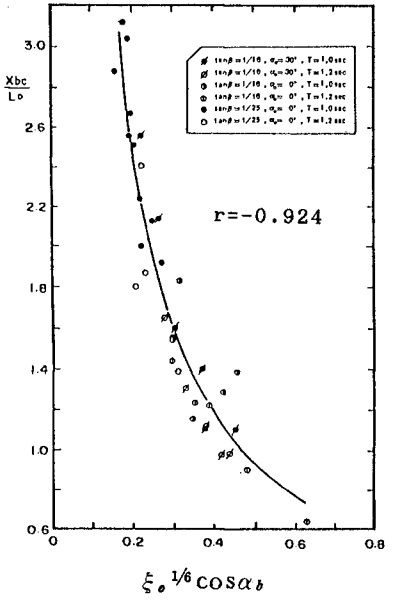

Fig.9 Relationship between X_{bc} /Lo and $\xi_o^{1/6}\cos\alpha_b$

of normal waves. In addition, it is seen that the erosion length increases with milder initial beach slope for normal incident waves. In this case, the effect of initial beach slope on erosion length for larger wave steepnesses is obviously found. For the same initial beach slope, the inclined waves produce greater erosion length than the normal waves. This may be due to the local variation of longshore sediment caused by the inclined waves.

The empirical relationship between the dimensionless erosion length X/Lo and the modified Iribarren number $\xi_o^{1/6}\cos\alpha_b$ as developed from theoretical consideration above is shown in Fig.7. By using linear regression method, the best fit line is given by

$$X/Lo = 0.443\xi_o^{-0.92}\cos\alpha_b^{-5.54} \quad (r = -0.847) \quad (19)$$

where r is the correlation coefficient. The points with larger values of $\xi_o^{1/6}\cos\alpha_b$ qive broadly scattering in Fig.7. This is interpreted as a smaller wave steepness Ho/Lo has larger value of $\xi_o^{1/6}\cos\alpha_b$ for constant beach slope and angle of incoming waves. Under this condition, the beach profile tends to become accretion type as pointed out by Johnson(1949).

The Distance of Bar Crest

The sediment eroded from foreshore is deposited offshore as a longshore bar. The distance of the bar crest X_{bc} is defined as the distance between the bar crest and the origin point of still water level as shown in Fig.1. Laboratory studies were conducted by Horikawa, Sunamura and Kito(1973) to investigate the situation of bar crest response to various wave characteristics. An empirical relationship was proposed on the basis of available experimental data:

$$X_{bc}/Lo = B(Ho/Lo) \quad (20)$$

where B=-67.4+20.5Log(t/T) , is a dimensionless time factor, and t is the time for model test. Hughes and Chiu(1981) performed an experiment in a wave flume. A parameter $H_b/\omega T$ was proposed to analyze the location of bar crest due to severe storms, where ω is the fall velocity of a sediment particle. Experimental results by Chang(1974) indicated the location of bar crest is related to the wave breaking point. His experiments also showed a bar crest is formed outside the wave breaking point and its maximum distance is within 1.6 times the distances between the wave breaking point and the original point of still water level.

Fig.8 gives plots of X_{bc}/Lo versus Ho/Lo for the cases of different initial beach slopes and wave directions. Each curve in the figure is obtained by fitting exponential function for different initial beach slopes and angles of incident waves. The experimental data show that the ratio of

X_{bc} /Lo increases with an increase of Ho/Lo. By comparing curves (a) and (b), it is found that values of inclined waves seemed to be slightly greater than normal waves. Furthermore, it is shown that the initial beach slope has significant effect on the location of bar crest for normal incident waves.

Fig.9 depicts the relationship between X_{bc} /Lo and $\xi_o^{1/6}\cos\alpha_b$. The value X_{bc}/Lo decreases with the increase of $\xi_o^{1/6}\cos\alpha_b$. It is noted that the modified Iribarren number is shown to be highly effective in representing the data by linear regression method. The result is expressed as

$$X_{bc}/Lo = 0.458\,\xi_o^{-1.03}\cos\alpha_b^{-6.20} \qquad (21)$$

Depth and Location of Stable Point

Available experimental and field data of beach profiles indicate that there exists usually a stable point on beach profiles near the breaker zone. At the stable point, sediment of a given size will be in oscillating equilibrium and without net movement. Raman and Earattupuzha(1972) found out a relationship between location of stable point and wave characteristics on the basis of experimental results. Hallermeier(1978) used a sediment entrainment parameter to calculate the water depth of the stable point. Kubo and Tomaki(1981) analyzed the water depth of the stable point from field data.

Fig.10 gives plots of the water depth of the stable point h_c against wave height Ho in deep water. The straight lines in the figure is the linear regression results. The experimental data show that the water depth of the stable point is proportional to the wave height at deep water. From lines (a) and (b), the inclined waves appear to have larger values than normal waves for the same initial beach slopes. The water depth of the stable point increases as the initial beach slope becomes smaller from 1/16 to 1/25. The line obtained by Hallermeier(1978) plotted in the figure shows the similar trend to the case of normal waves for $\tan\beta = 1/25$.

Fig.11 is the relationship between dimensionless water depth of stable point h_c/Lo and the modified Iribarren number $\xi_o^{1/6}\cos\alpha_b$. Although the experimental data scatter broadly over a wide range of $\xi_o^{1/6}\cos\alpha_b$, it is found that a higher value $\xi_o^{1/6}\cos\alpha_b$ leads to a reduction in the value of h_c/Lo. The result of linear regression gives

$$h_c/Lo = 0.011\,\xi_o^{-1.41}\cos\alpha_b^{-8.43} \qquad (r=-0.702) \qquad (22)$$

The correlation coefficient is not good for the reason of random data base.

Fig.12 is a plot of non-dimensional location of the stable point X_c/Lo and the wave steepness Ho/Lo. The effect of the initial beach profile on the location of stable point

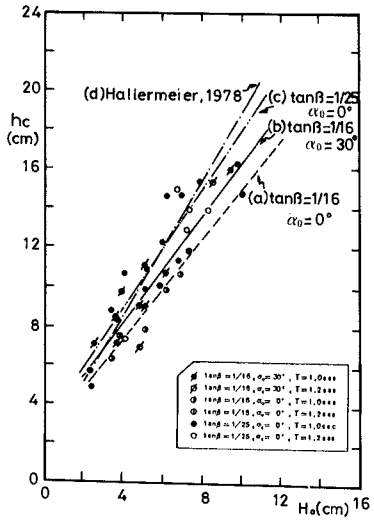

Fig.10 Relationship between h_c and Ho

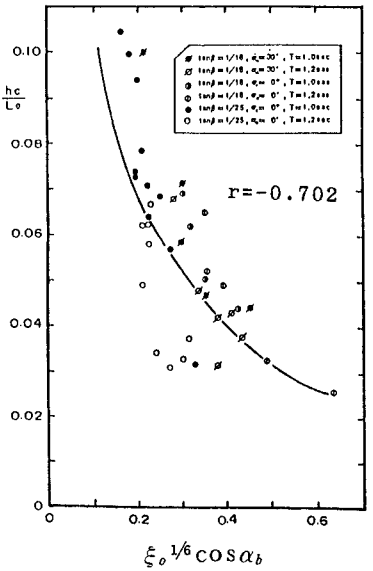

Fig.11 Relationship between h_c/Lo and $\xi_o^{1/6}\cos\alpha_b$

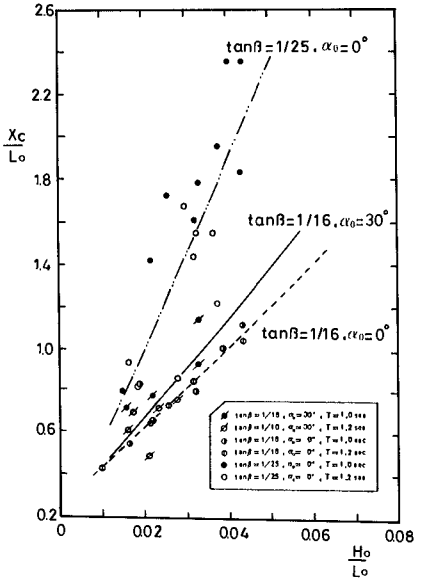

Fig.12 Relationship between Xc/Lo and Ho/Lo

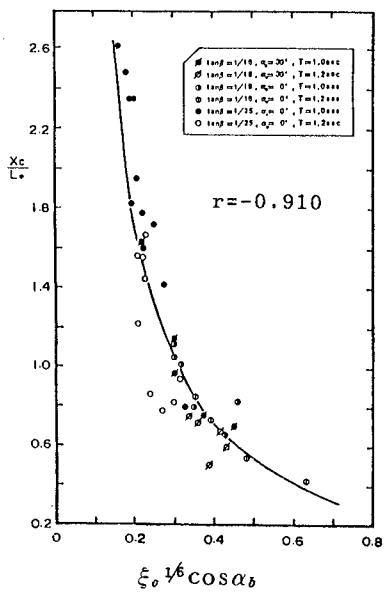

Fig13. Relationship between X_c/Lo and $\xi_o^{1/6}\cos\alpha_b$

for normal waves is obviously found. The inclined waves have larger value than normal waves for $\tan\beta = 1/16$. Fig.13 is a plot of non-dimensional location of the stable point X_c/Lo versus the modified Iribarren number $\xi_o^{1/6}\cos\alpha_b$. The value of X_c/Lo decreases as the value of $\xi_o^{1/6}\cos\alpha_b$ increases. The best fit line in this figure can be expressed as

$$X_c/Lo = 0.211\xi_o^{-1.29}\cos\alpha_b^{-7.74} \qquad (r=-0.910) \qquad (23)$$

A higher correlation coefficient reveals that the location of the stable point can be adequately described in terms of the modified Iribarren number. According Eq.(23), X_c/Lo tends to decrease as α_b increases. This is due to the fact that longshore current is generated by obliquely incident waves and its corresponding longshore sediment transport is dominated in the surf zone.

5. CONCLUSIONS

A theoretical development based on wave energy approach found that the beach profile is governed by a modified Iribarren number. This parameter covers the effects among the factors of the initial beach slope, wave angle and wave steepness. A laboratory movable bed tests were undertaken in the wave basin to find out the relationship between beach profile characteristics and the modified Iribarren number. The analysis of experimental data confirms the usefulness of this parameter in expressing the beach profile changes under the action of inclined waves.

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