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Wave Breaking in Shallow Waters
淺海域에서의 碎波

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Abstract □ A local Iribarren number is suggested for the universal use of breaker type classification, which relates the bed slope to the wave steepness, both being given from the breaking point. The existing Iribarren number uses the wave length at an offshore point, while the local Iribarren number uses the wave length at the breaking point so that it can imply any influences due to current interaction and diffraction. The modified form of Miche's breaking criterion includes a breaking parameter which may be related to the local Iribarren number. Using the modifiedform of Miche's criterion with the local Iribarren number, the inclusion of Doppler effect seems to describe well the wave breaking mechanism in a current-interacted flow on a sloping beach without any additional effects implemented.

要 旨: 어느 조건에서나 쇄파형태를 분류하기 위하여 쇄파점에서의 해저경사와 파형경사의 비를 취한 일반화된 쇄파점 Iribarren 数를 제시하였다. 기존 Iribarren 数는 외해에서의 파장을 취한 반면에 본 논문에서 제시한 Iribarren 数는 쇄파점의 파장을 취하기 때문에 해류와의 합성효과나 회절 영향에 의한 파형경사의 변화를 고려할 수 있다. Miche의 쇄파경계조건은 해저면경사의 영향을 고려하기 위하여 쇄파계수를 사용하여 수정되었는데 이 쇄파계수를 쇄파점 Iribarren 数와의 관계식을 구하여 산정할 수 있다. 수정된 Miche의 쇄파경계조건과 쇄파점 Iribarren 数를 사용한 결과 Doppler 효과만 포함하여 쇄파파고를 잘 산정할 수 있었으며 이 밖에 다른 영향은 무관함을 알 수 있었다.

1. INTRODUCTION

Due to its inherent characteristics, the description of wave breaking heavily depends on the empiricism, though mathematical basis may also be important and theoretical reasoning derives from the mathematical basis. Some rigorous investigations have been made in recent years to understand the fine structure of waves near breaking point (Longuet-Higgins, 1976), but any wave theory may not properly describe the wave motion at the breaking point or after the point. The usage of such models is also doubtful for general purposes on engineering practice. Therefore, it has been common practice to describe the breaking process using an empirical parameter and/or a simple breaking criterion.

The so-called Iribarren number has widely been used to classify the types of breaking waves; surging, plunging, collapsing or spilling, and to estimate the run-up height and reflection coefficient (Battjes, 1984). The Iribarren number is the ratio of beach slope to the square root of wave steepness, but it can vary with the location for the choice of wave parameters, that is, whether they are chosen at the breaking point or at an offshore position. It is, however, found that the wave length was normally taken from the offshore position so that the wave steepness used for the inshore parameter is not considered to be a proper one. For example, the breaking wave condition behind a breakwater will be much less influenced by the offshore wave condition than in the open coast.

The major reason for the improper choice of the wave length is probably due to the difficulty of estimating the wave length at the breaking point in a practical application. The estimation of wave length at a local position is now easily made using personal computers, and in fact the use of local values is more

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convenient than the offshore values for checking the wave conditions in the numerical modelling of wave transformation.

It is here suggested that the value of wave length at the breaking position should be used for the estimation of wave steepness resulting in 'local Iribarren number'. The published laboratory data sets are reanalysed to estimate the local Iribarren number and to classify the types of breaking waves using the new parameter.

The breaking criterion proposed by Miche (1944) is widely used for the estimation of wave height at the breaking point. In recent years it was found that the beach slope and/or wave steepness may also affect the criterion. The Miche's criterion was, therefore, modified to account for the effects including a breaking parameter 's' by several workers. Ostendorf and Madsen (1979) related the parameters with the bed slope, while Battjes and Janssen (1979) with Weggel's criterion (1972) which considers the wave steepness as well as the bed slope. Weggel's criterion is, however, rather complex and found to be unacceptable in deep water condition. In the present study it is proposed that the parameter can be estimated using the Iribarren number. Extensive sets of published laboratory data are re-analysed so that a relationship between the breaking parameter and the local Iribarren number is obtained.

The modified form of Miche's criterion with the effect of Iribarren number is also applied to a laboratory situation of waves propagating against a current on a sloping beach, which was reported by Sakai and Saeki (1986). They found that the breaking parameter decreases from the value of unity when the waves are interacted with the opposing current and argued that it may be related to the unit width discharge ratio defined by eq. (17). In the present study the data was also re-analysed using Doppler relation for the accurate estimation of wave number or wave length, and it appears that the parameter has no relation with the unit width discharge ratio. Discussion is made on this aspect.

2. SURF PARAMETER

Iribarren and Nogales (1949) first introduced a surf zone breaking parameter which relates the wave steepness to the bed slope, i.e.

$$I_i = \frac{m}{\sqrt{H_b/L_o}} \qquad (1)$$

where m is the bed slope, H_b is the breaking wave height, L is the wave length, and the subscript 'o' indicates the offshore condition and 'i' the inshore condition. Galvin (1968) also studied the mechanism of wave breaking in the surf zone. After performing a large number of laboratory experiments for various bottm slopes, he suggested that the different types of breaker could be classified by a parameter which is essentially the same as the one represented by eq. (1). Battjes (1974) has also proposed that the dimensionless parameter may be used for the estimation of various surf zone quantities such as run-up height, set-up height and reflection coefficient as well as the classification of breaking waves, and suggested to call it surf parameter or 'Iribarren number' after the name of the perpson who first introduced.

It is, however, noticed that the inshore Iribarren number I_i does not use the inshore value of wave length but its offshroe value, which results in the improper estimation of wave steepness. The present author suggests that the parameter related to the local wave conditions may be more appropriate for the description of breaking wave characteristics at a certain point. That is, the local Iribarren number 'I_b' is represented by;

$$I_b = \frac{m}{\sqrt{H_b/L_b}} \qquad (2)$$

where H_b and L_b are the local values at the breaking point. It is obvious that when waves are interacted with a current, the wave length at the local point is elongated or squeezed by Doppler effect from the one at the offshore point. It should also be noted that the wave number is not exactly the same as the separation factor given by the dispersion relation when waves diffract behind a structure or in caustics (Battjes, 1968; Yoo and O'Connor, 1988). Therefore, the local number 'I_b' is considered to be better than the semi-inshore number 'I_i' if the local values of H_b and

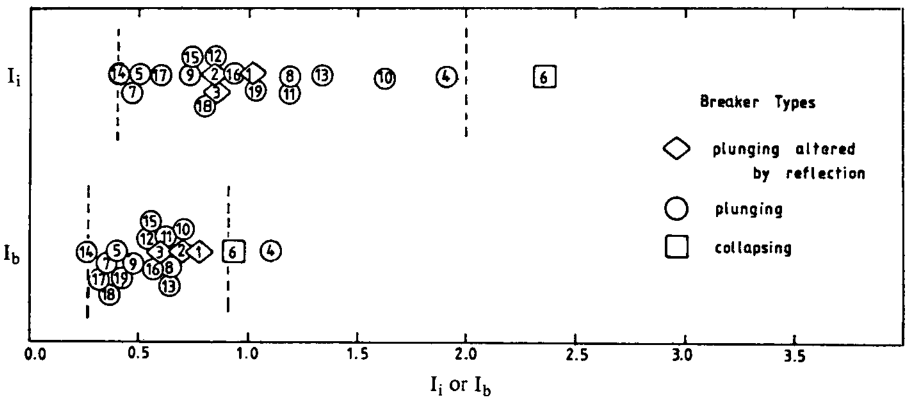

Fig. 1. Breaker type as a function of 'I_i' or 'I_b'

L_b can be determined.

It is now widely accepted that the surf parameter would give an indication of how the waves break, i.e. the type of breaking waves. Using the laboratory data of Galvin (1968), Battjes (1984) proposed the approximate transition values of the inshore Iribarren number may also be a good indicator for the classification. Ignoring any possible experimental errors, the wave number at the breaking point is evaluated using Hedges' semi-empirical dispersion relation, i.e.

$$\sigma^2 = gk \tanh k(d+\beta H) \qquad (3)$$

where σ is the angular frequency, g is the gravity acceleration, k is the wave number, d is the water depth, and β is a constant. Here β is assumed to be 0.78, and when $\beta=1.0$ eq. (3) becomes the dispersion relation for solitary waves.

Fig. 1 shows the comparison between I_i and I_b against the laboratory data obtained by Galvin (1968). Due to the lack of information in Galvin's data, only part of his data has been used for the test. Unfortunately most of the data available are for the plunging type of breakers so that clear transition values may not be determined yet. The figure shows the transition values of I_i equivalent to those suggested by Battjes (1984). That is, plunging if $0.4<I_i<2.0$, surging or collapsing if $I_i>2.0$, and spilling if $I_i<0.4$.

On the other hand using the local Iribarren number, the range of the transition values for the plunging type is very much reduced, and it is noted that one of plunging-type breakers has higher value of 'I_b' than the collapsing-type breaker. Apart from this, the values of 'I_b' for the plunging-type breakers are well concentrated ranging from 0.25 to 0.9. At the present stage, it is, therefore, siggested that:

$$\begin{array}{rl} \text{surging or collapsing} & \text{if } I_b>0.9 \\ \text{plunging} & \text{if } 0.25<I_b<0.9 \\ \text{spilling} & \text{if } I_b<0.25 \end{array} \qquad (4)$$

As one of the plunging-type breakers is found to have the value of 'I_b' higher than 0.9, the upper limit of 'I_b' for the plunging breakers may probably be larger than this value. Although the transition values of 'I_b' are roughly half the values of 'I_i', the value of I_b cannot be replaced simply by half the value of I_i. For example, the 'I_b' value of the data '10' is approximatly half the 'I_i' value of the same data, but the 'I_b' values of the data '1', '2', '3', etc. are shown to be very close to the 'I_i' values of each data, respectively.

3. BREAKING CRITERION

Based on the Stokes wave theory, Miche (1944) produced the breaking criterion for waves in shoaling water as follows:

$$\left(\frac{H}{L}\right)_b = \frac{1}{7}\tanh(kd)_b \qquad (5)$$

As the criterion covers the wide range of water depth from deep to shallow water, it seems to be most popularly used to check the growth limit of waves. In deep water, tanh (kd)$\doteqdot$1 and then the criterion (5) reduces to the deep-water breaking criterion of Michell (1893). On the other had, in very shallow water tanh(kd)$\fallingdotseq$kd and it reduces to (H/d) = 0.90 which is about 20% higher than the breaking criterion for solitary waves, i.e. (H/d) = 0.71 (McCowan, 1894; Galvin, 1969). The gap can be reduced by the modification of the form (5) as explained later.

In the late 1960's it was realized from laboratory evidence that beach slope also influenced the breaking mechanism or criterion. One of the results is as follows:

$$\left(\frac{H}{d}\right)_b = \begin{cases} 1.18 & m \geq 0.1 \\ 0.27+4.6m & m<0.1 \end{cases} \tag{6}$$

after Madsen (1976). The result shows that the steeper the bed slope the higher the relative wave height. The variation in H/d with slope is linear up to about m = 0.1, and above this value significant reflection may occur. The results also show that on a flat bed (m = 0.0) the relative height found on the laboratory experiments is close to the theoretical value.

Further laboratory work was made by Weggel (1972), considering the wave steepness as well as the bed slope. Based on a large amount of data, he proposed the following criterion:

$$\left(\frac{H}{d}\right)_b = b(m) + a(m)\frac{H_b}{L_o} \tag{7}$$

where T is the wave period and

$$a(m) = 6.97[1-\exp(-19m)] \tag{8}$$

$$b(m) = 1.56[1+\exp(-19.5m)] \tag{9}$$

The criterion (7) implies that the wave breaking limit is determined by the wave steepness as well as the bed slope which may simply be represented by the inshore Iribarren number 'I_i'.

In order to include the effects of bed slope and/or wave steepness, the Miche's criterion has been reworked and modified by Ostendorf and Madsen (1979) and Battjes and Janssen (1979) as follows:

$$\left(\frac{H}{L}\right)_b = \frac{1}{7}\tanh(skd)_b \tag{10}$$

where S is a constant or breaking parameter which may be related to the bed slope and/or wave steepness. In this formulation they intended to match eq. (10) to the critreion (6) or (7) in very shallow water. As tanh(skd)$\fallingdotseq$skd in very shallow water, eq. (10) can be reduced to eq. (6) or (7). Ostendorf and Madsen recommended eq. (6) to estimate the value of 's', while Battjes and Janssen recommended eq. (7).

The breaking mechanism is considered to be affected by the relative bed slope to the wave steepness rather than the value of bed slope only, as the wave breakers are classified by using the Iribarren number rather than the bed slope. In this sense the recommendation of Battjes and Janssen is preferred to that of ostendorf and Madsen. There are, however, still some problems remaining as to use Weggel's equation, because it represents insufficient wave condition at a local breaking point. It cannot account for the effects of current-interaction which may alter the wave steepness due to Doppler shifts. It is, therefore, believed that the breaking parameter 's' should be related to the local number 'I_b' instead of the semi-inshore or insufficient-inshore number 'I_i', or Weggel's equation.

The data collected by Weggel (1972), such as those from Bowen, *et al.* (1968), Galvin (1968), Iversen (1953), Weggel and Maxwell (1970) supplemented by other laboratory results (Van Dorn, 1978; Iwagaki, *et al.*, 1978), have been reanalyzed to evaluate the local wave conditions and local parameters at the breaking point. The wave number k or wave length L has been computed using Hedges' semi-empirical dispersion relation (3). Given k or L, H and d, obtained from the laboratory results at the breaking point, the breaking parameter 's' can be estimated, from eq. (10), as follows:

$$\begin{aligned} S &= (kd)^{-1}\tanh(7H/L)_b \\ &= (2kd)^{-1}\ln[(1+7H/L)/(1-7H/L)]_b \end{aligned} \tag{11}$$

The plots of 's' against 'I_i' and 'I_b, are given in Figs. 2 and 3, respectively. As shown in the figures there is a considerable scattering on each graph. This scatter seems to be attributable to several reasons. The quality of the data is not consistent, because the data have been collected from several different sources and the laboratory conditions of flume and instruments are dif-

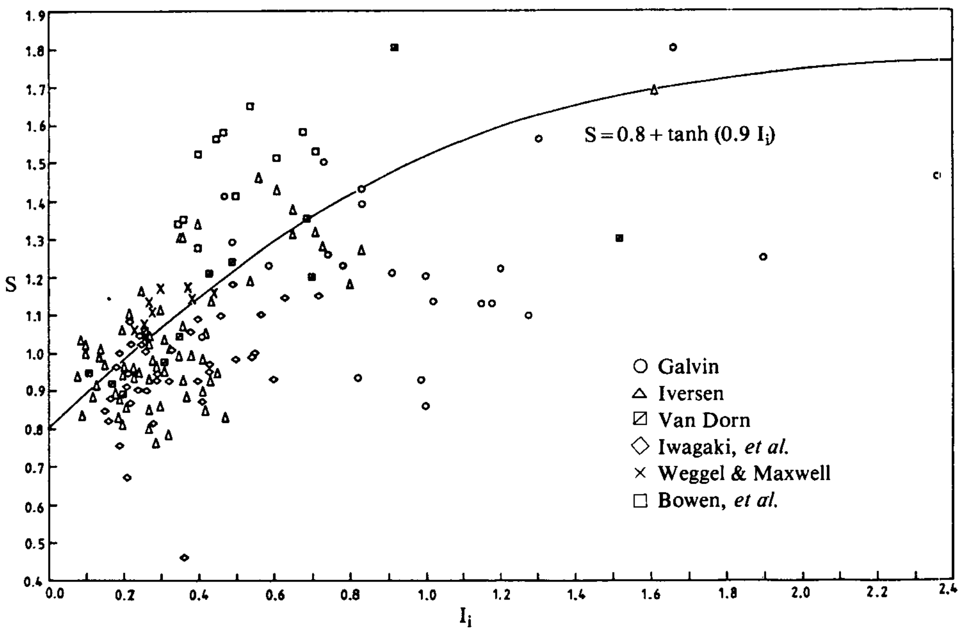

Fig. 2. Variation of breaking parameter 's' agaisnt 'I_i'

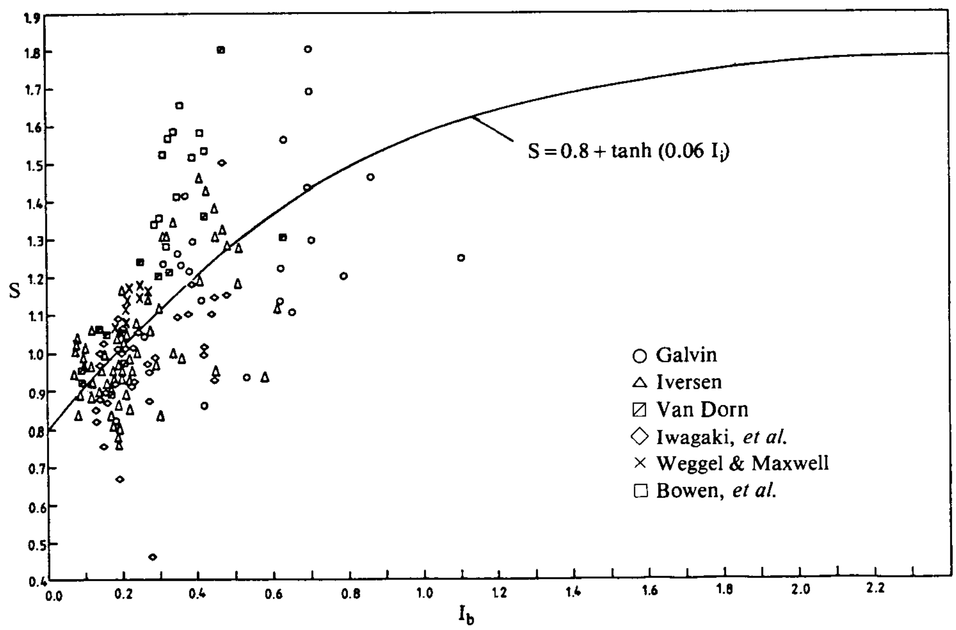

Fig. 3. Variation of breaking parameter 's' against 'I_b'

ferent from each other. Another reason is that the wave length or wave number have not, in fact, been measured but only estimated using the semi-empirical equation (3). Although it has been proved that the semi-empirical equation gives fairly good results, especially when the crest wave height is known, some errors are still expected as the crest wave height has roughly been estimated using the proportionality factor β.

It is also noted that several fvalues of (H/d) from the data of Bowen *et al.,* (1968) and Galvin (1968) exceed the maximum value '1.18' suggested by Madsen (refer eq. (6)). Some of the values reach up to about 1.8. This is regarded to be primarily due to reflection which is probably significant at the high value of Iribarren number. In the present analysis the high values of H/d are included so that the following relations obtained imply the influence of reflection on the growth limit of wave height on a sloping beach.

It is seen that the value of 's' rarely goes down below 0.8, the valve given by the solitary wave theory, and hence this lattermost value can be chosen as the minimum value of s. The maximum value found is 1.8. For small values of the surf parameters I_i and I_b a reasonable correction between s and any of surf parameters could be obtained by a linear funtion. However, the experimental results indicate that when the value of surf parameter becomes infinite the value of s is more or less constant. A hyperbolic tangent function seems to be best for the regression line of this trend:

$$s=a+b\tanh(cI) \qquad (12)$$

where a, b, c are fitting constants and I can be either I_i or I_b. If the minimum value of s is assumed to 0.8 and the maximum value 1.8, the value of a and b are automatically given as a $=0.8$ and $b=1.0$.

Provided that the value of a and b are given, the factor c can be estimated by using a regression analysis. However, in view of wide spread of result, it is felt unjustifed to use a sophisticated fitting analysis. Curve fitting has thus been done by eye and yields the equations:

$$s=0.8+\tanh(0.90I_i) \qquad (13)$$

$$s=0.8+\tanh(1.06I_b) \qquad (14)$$

4. WAVE BREAKING ON AN OPPOSING CURRENT

It has been considered that the effect of current interaction may also influence the breaking mechanism of waves in various ways, particularly when waves encounter an opposing current. First of all wave heights would grow to keep the wave action conservation. At the same time waves might be more easily broken due to sharpened wave steepness, since the wave length is shortened by the Doppler shift of frequency given by:

$$\sigma=\sigma_i+kU \qquad (15)$$

where σ is the apparent angular frequency observed from the fixed sea bed, σ_i is the intrinsic angular frequency observed from the moving flow, and U is the current velocity with negative value for an opposing current. In the case of current interaction, the frequency used in the dispersion relation (3) should now be replaced by the intrinsic or Doppler-shifted frequency σ_i for the proper estimation of the wave number or wave length and thereby wave steepness. When we use the inshore Iribarren number I_i expressed with the wave length at an offshore point L, the effect of Doppler shift is not expected to be included.

When waves meet a current on a sloping beach, further complexity was expected in the mechanism. Sakai and Saeki (1986) has conduced laboratory experiments on the problem, and suggested a dimensionless parameter called 'unit width discharge ratio' for the effect of the opposing current on the wave breaking. They also modified the Miche's breaking criterion similar to but slightly different from eq. (10) as follows:

$$\left(\frac{H}{L}\right)_b=\frac{t}{7}\tanh(kd)_b \qquad (16)$$

In their form a constant α was used instead of t/7. For a very shallow water eq. (16) is essentially the same as eq. (10), i.e. $t\fallingdotseq s$. But for an intermediate water depth they can be different from each other. On the other hand, for a deep water $\tanh(skd)\fallingdotseq 1.0$ when s is of the order of unity. Therefore, eq. (10) reduces to the Michell's breaking criterion without any further implication, while the reduced form of eq. (16) may still imply some effect through the parameter t, i.e. $(H/L)_b=t/7$. Sakai and Saeki (1986) has argued that the constant α or t is closely related to the unit width discharge ratio q* defined as:

$$q^*=\frac{q}{g^2T^3} \qquad (17)$$

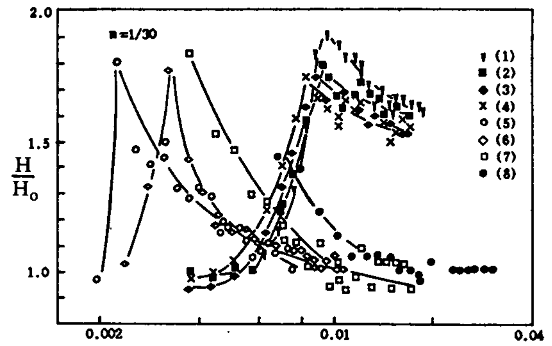

Fig. 4. Breaking wave transformation on opposing current, laboratory data after Sakai and Saeki (1984).

where q is the unit width discharge of current given by Ud. It was shown that the value of α decreases with the discharge ratio from 1/7 (refer Fig. 15 in their paper). There, however, remain some doubts in their estimation of wave length. In the present paper the laboratory data are re-analyzed considering the Doppler relation so that the accurate estimation of wave number or wave length is obtained.

A large number of laboratory data was shown in the paper of Sakai and Saeki, but unfortunately some information is missing for most of the data except the data (1)~(6) as shown in Fig. 4. The data numbered (7) and (8) in the figure are excluded in the analysis because the information given does not provide the breaking limit. The data (1)~(6) with good information are considered in this analysis. The wave number at the breakin point is computed using the Hedges' empirical dispersion relation (3) and the Doppler relation (15) with the depth-mean current velocity $U=q/d$. The breaking parameter 's' or 't' is then evaluated using eq. (11) or eq. (16), respectively, and shown in Table 1, in comparison with the values of 's' estimated using eq. (14) which was determined by regression of the laboratory data for the case of no current interaction.

The values of 't' are found to be more or less than 0.67, while the values of 's' to be more or less than the value of unity. There are found to be some differences between 's' from eq. (11) and 's' from eq. (14), the former being slightly bigger than the latter in all the cases. The ratio ranges from 0.98 to 1.39. It is, however, noticed that the ratio has no relation with the discharge ratio q* nor with any other parameter such as the ratio σ_i/σ. On the other hand the values of t are found to be almost constant, which certainly indicates that the value of t is totally independent of the unit whdth discharge ratio. Consequently the discharge ratio is considered to have no other implication except the Doppler effect.

5. Concluding Remarks

For an application to any complex situation due to irregular topography, coastal structures and/or ambient currents, the existing Iribarren number is considered to be insufficient to represent the characteristics of breaking waves, because the wave length used in the parameter is obtained from an offshore point. The local Iribarren number suggested in the present paper is related to the wave length at the breaking point so that it can properly express the wave condition at the breaking point even when the waves are Doppler-shifted by a current before break-

Table 1. Breaking parameters t, s' and s on various laboratory conditions of waves propagating against opposing current

No.	T sec	d cm	U cm/s	q cm^3/s	H cm	σ sec^{-1}	σ_i sec^{-1}	σ_i/σ	q* 10^3	I_b	t	s'	s
1	1.6	23.1	33.4	771.	17.6	3.93	4.91	1.25	.196	.116	.693	.975	.922
2	1.6	22.6	20.0	452.	18.6	3.93	4.44	1.13	.115	.121	.677	1.034	.928
3	1.6	21.8	13.6	297.	18.8	3.93	4.26	1.08	.075	.123	.674	1.074	.930
4	1.6	20.3	8.3	169.	18.5	3.93	4.12	1.05	.043	.126	.674	1.127	.933
5	2.4	13.6	21.9	297.	15.7	2.62	3.03	1.16	.022	.154	.656	1.385	.962
6	2.0	12.6	23.7	297.	11.3	3.14	3.76	1.20	.039	.154	.595	1.068	.962

Notes; (t from eq. (16), s' from eq. (11) amd s from eq. (14)), laboratory data of Sakai and Saeki (1984) were used for the estimation of breaking parameters.

ing.

The transition values of the local Iribarren number for the classification of breaker type are found, using Galvin's laboratory data, as represented by eq. (4). The ranges of the local Iribarren number I_b are shown to be approximately half the ranges of the inshore Iribarren number I_i. But further laboratory data may possibly be required for the precise measured of the transition values of I_b, since most of the data used in the analysis include only the type of the plunging breakers.

A reasonably good relation was found between the breaking parameter 's' and the local Iribarren number 'I_b' which considers the wave steepness and bed slope both at the breaking point. As the wave steepness is properly estimated using the local wave length, the relation is expected universally applicable to any situation, i.e. when waves are interacted with a current or diffracted behind a breakwater. When the Doppler-shifted wave length is used in the estimation of surf parameter, no other parameter does seem to show any influence on the wave breaking when the waves propagate against a current.

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Symbols

d : water depth
g : acceleration due to gravity
H : wave height
I_b : local or breaking point Iribarren number defined by eq. (2)
I_i : inshore Iribarren number defined by eq. (1)
K : wave number
L : wave length
m : bed slope
q : unit width discharge (= Ud)
q* : unit width discharge ratio defined by eq. (17)
s : breaking parameter defined by eq. (11) (see also eq. 10)
T : wave period
t : breaking parameter defined by eq. (18) (see also eq. 16)
U : (depth-mean) current velocity
α : t/7
β : a constant (see eq. (3))
σ : apparant frequency
σ_i : intrinsic frequency

Subscripts

b : breaking point
i : inshore
o : offshore