CHAPTER 47

LABORATORY STUDY OF WAVE TRANSFORMATION ON BARRED BEACH PROFILES

Ernest R. Smith[1] and Nicholas C. Kraus[2]

ABSTRACT: In previously reported laboratory experiments, the authors found that incident waves with the same characteristics in deep water break differently on barred and plane-sloping beaches. For example, waves of greater steepness that plunge on plane beaches tend to collapse on barred beaches, and plunge distance on barred profiles is about half that on a plane sloping beach for a given wave steepness. In the present study, wave height transformation, reflection, and runup of monochromatic and random waves are investigated for barred and plane beach profiles in a wave tank, with deep-water wave steepness varied from 0.0085 to 0.09. For monochromatic and random waves, wave-height to water-depth ratios are higher for waves breaking on bars, whereas just seaward of breaking these ratios are lower than on a plane beach. For plane and barred beaches, the ratios unite in the inner surf zone, and the magnitude and shape of wave spectra are the same at fixed points outside and inside the surf zone, except just shoreward of the break point, where the spectrum on a barred profile has the same shape but contains less energy. Despite differences in breaker-related quantities on barred and plane beach profiles, runup, reflection, and wave height transformation in the surf zone on barred profiles are mainly controlled by the plane beach slope on which the bar or reef is located, with only minor influence by a bar, even for extremely-shaped obstacles such as reefs.

INTRODUCTION AND BACKGROUND

Most laboratory studies on wave transformation, runup, and reflection have been conducted on plane sloping beaches. In the field, however, linear bars are common, and waves will transform differently over barred profiles as compared to plane beaches. To elucidate these differences, the authors conducted an extensive laboratory study to examine breaking and broken wave properties on barred and terraced profiles, and the results were compared to those obtained for plane slopes. Results determined from video records were

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(1) Research Hydraulic Engineer, and (2) Senior Scientist, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA.

presented in Smith and Kraus (1991) and in a report (Smith and Kraus 1990) that covers the experiment procedure and results. The present paper focuses on selected results determined from the digital wave gage data, and some analyses from the project report are extended.

As motivation, we consider breaker type and plunge distance on barred and plane slopes (Smith and Kraus 1991). Galvin (1968) expressed breaker type transition values in terms of beach slope m, wave height H, and wave period T. Battjes (1974) re-expressed the transition values in terms of the surf similarity parameter, $\xi_o = m(H_o/L_o)^{-1/2}$, in which H_o and L_o are wave height and wavelength in deep water, respectively. Smith and Kraus observed different transition values of breaker type on single-bar profiles than determined by Battjes for plane slopes. Transition values between breaker types on barred profiles and plane slopes are shown as a function of ξ_o in Fig. 1. Transition values are lower for barred profiles, which means some waves that would spill on a plane slope plunge if a bar is present, and some plunging waves on plane slopes collapse on a barred profile.

Plunge distance X_p of breaking waves differs on plane and barred beaches (Smith and Kraus 1991). Fig. 2 plots plunge distance normalized by breaker height H_b, and the visually fit solid line for barred profiles as a function of ξ_o. The dashed line represents the predictive equation for plane slopes determined by Smith and Kraus. Plunge distance was 60 to 70 percent shorter over bars than over plane slopes. Differences in breaker height and depth, and splash distance between plane slopes and barred profiles were also found. On the basis of these findings, in the present work, the digital data of water surface elevation are examined to investigate wave transformation, runup, and reflection on barred and terraced (shelf) profiles, and the results are compared to those for plane sloping beaches.

PROCEDURE

Data collection was conducted in a 45.70-m-long, 0.46-m-wide, and 0.91-m-high glass walled tank (Fig. 3). The tank contained a 1 on 30 smooth concrete-capped slope, which was separated from the wave generator by a 21-m-long horizontal section. Monochromatic and random waves were produced by an electronically controlled hydraulic system that drove a piston-type wave board. Water surface elevation was recorded at eight double-wire resistance-type gages. Gage 1 was located 9.1 m from the wave generator, Gages 2 and 3 were placed seaward of the bar and positioned to measure wave reflection according to the method of Goda and Suzuki (1976), Gage 4 was placed at the incipient break point, and Gages 5 through 8 were distributed through the surf zone. The water surface elevation was analyzed to obtain statistical wave heights and periods, and spectra.

Deep-water wave steepness H_o/L_o in part controls breaking wave characteristics. Therefore, it was desirable to generate waves with a wide range of steepnesses. A fixed water level (0.38 m) was maintained in all tests and allowed generation of relatively high waves while minimizing the effect of surface tension. Five design monochromatic wave conditions were selected (H_o/L_o = 0.09, 0.07, 0.05, 0.03, 0.0088) through consideration of a diagram given by Galvin (1970, his Fig. 8) for delineating domains where periodic waves, single and multiple solitons, and breaking waves exist to obtain periodic breaking waves without contamination by soliton generation. Three random wave conditions were also developed from an input JONSWAP spectrum for spectral peak periods T_p of 1.0, 1.5, and 1.75 sec, with significant wave heights H_s of 11.3, 14.3, and 13.7 cm, respectively, in the horizontal section of the tank.

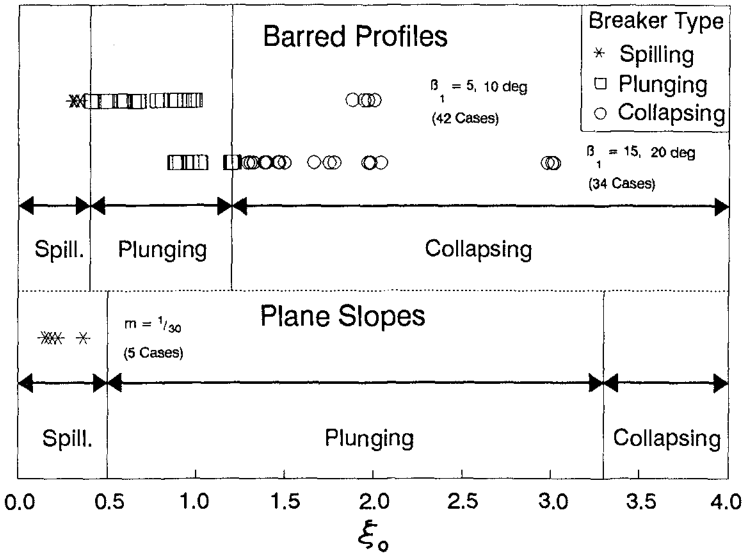

Fig. 1. Breaker type classification for plane and barred slopes (Smith & Kraus 1991)

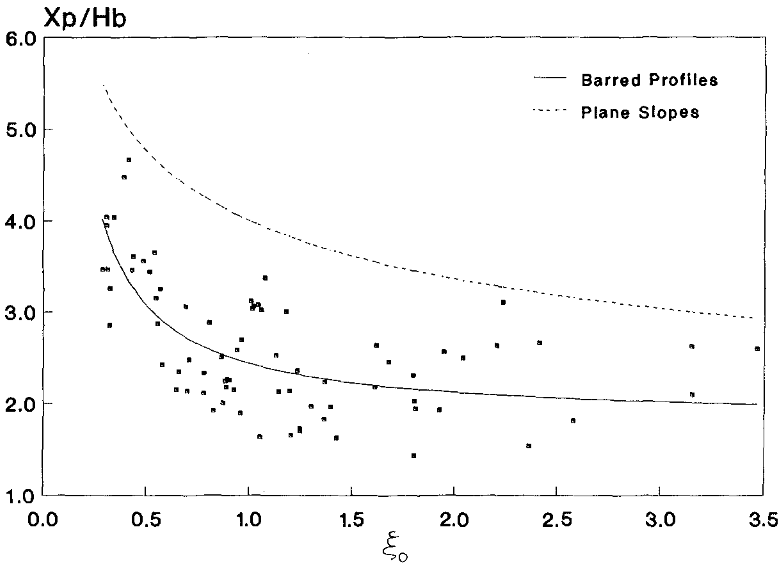

Fig. 2. Plunge distance on plane and barred slopes (Smith & Kraus 1991)

Submerged solid triangular-shaped objects were installed on the 1-on-30 slope to represent natural barred profiles, terraced profiles, and artificial reefs. The geometry of the objects was selected based on large wave tank studies and field measurements of bars (Larson and Kraus 1989). Seaward bar angles β_1 varied from 5 to 40 deg, and shoreward angles β_3 ranged from 0 deg (terrace) to 40 deg. The steeper seaward angles were included to observe breaking waves on shapes that approximate those of submerged breakwaters or reefs. The size and placement of the bars were determined based on findings of Larson and Kraus.

Bars used in the study were constructed of marine plywood, with the seaward and shoreward faces connected with strap hinges. For longer bars, legs were attached under the structure to minimize flexing of the faces due to wave action. Openings created at the crest by the seaward and shoreward faces and the sides of the bar against the tank wall were sealed to maintain a flush surface and minimize leakage. Steel plates were installed under the bar to prevent it from floating or moving when subjected to wave action.

Wave data were collected for 2 min at 50 Hz for monochromatic-wave tests, but only 15 successive waves were analyzed. The analyzed portion of the record began after waves reflected off the concrete slope and ended before reflected waves from the board had returned to the bar. This procedure eliminated contamination of the data by waves reflected off the board, yet simulated the natural reflection of waves by the beach and bar or reef. Random waves were recorded at 20 Hz and analyzed for 500 waves. Because the wave height and period varied, a long record was required to obtain a statistically strong confidence interval for the wave spectrum. Reflection and re-reflection between the beach and the wave board could not be avoided in the random-wave tests.

In summary, 108 tests were performed with regular waves, of which five tests were with a plane slope, and 12 tests were performed with random waves, of which three tests were with a plane slope. Table 1 summarizes the design test conditions. The table shows nominal values for design which were approximated in actual tests.

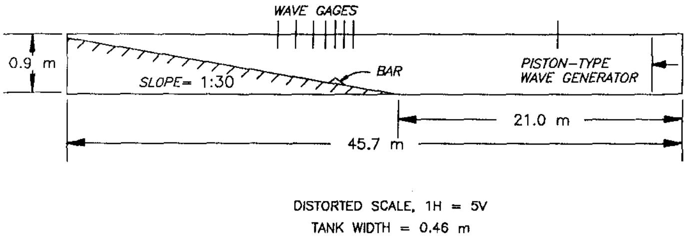

Fig. 3. Definition sketch for tank arrangement

Table 1. Test Design[a] Parameters

Monochromatic Waves				
H_o/L_o	T sec	H cm	β_3 deg	β_1 deg
0.09	1.00	13.1	0, 20, 30, 40	5, 10, 15, 20, 30, 40
0.07	1.00	10.1	0, 20, 30, 40	5, 10, 15, 20, 30, 40
0.05	1.50	16.2	0, 20, 30, 40	5, 10, 15, 20, 30[b]
0.03	1.75	13.7	0, 20, 30, 40	5, 10, 15, 20
0.0088	2.50	9.1	0, 20, 30, 40	5, 10, 15
Random Waves				
$(H_s/L_p)_o$	T_p sec	H_s cm	β_3 deg	β_1 deg
0.078	1.00	11.3	20	5, 10, 15
0.044	1.50	14.3	20	5, 10, 15
0.03	1.75	13.7	20	5, 10, 15

[a] Nominal values for design purposes which were only approximated (see Smith and Kraus (1990) for complete data listing)
[b] One test conducted with β_1 = 30 deg, β_3 = 20 deg

Note: H = wave height measured at the wave maker in depth of 0.38 m
H_s = significant wave height measured at the wave maker in depth of 0.38 m
T_p = peak wave period measured at the wave maker in depth of 0.38 m

RESULTS

Wave Reflection

Miche (1951) developed a theoretical relation for the reflection coefficient K_r for smooth plane slopes. He assumed the reflected portion of wave energy corresponded to a critical deep-water wave steepness $(H_o/L_o)_{cr} = (2\beta/\pi)(sin^2\beta/\pi)$ in which β is the slope angle. Miche defined the quantity $(H_o/L_o)_{cr}$ as the wave steepness to obtain complete reflection, and wave energy that exceeded this value was assumed to be dissipated. Wave reflection was expressed as $K_r = (H_o/L_o)_{cr}(H_o/L_o)^{-1}$ if $H_o/L_o > (H_o/L_o)_{cr}$, and $K_r = 1$ if $H_o/L_o < (H_o/L_o)_{cr}$. Miche stated that actual reflection coefficient values would be lower than theoretical values because of viscosity and roughness, and recommended a multiplicative factor of 0.8 to calculate reflection coefficients for smooth, plane slopes.

Battjes (1974) re-expressed the equation of Miche (1951) to obtain K_r as a function of the surf similarity parameter:

$$K_r = 0.1\xi_o^2 \quad (1)$$

Reflection coefficients calculated from wave data at Gages 2 and 3 are shown as a function of ξ_o, using β_1 as input, in Fig. 4. Also shown are the predicted values of Miche and Battjes, using the reduction coefficient of 0.8. The data are scattered and show overlapping of values for different seaward bar angles. Values obtained by the Miche equation produce a steep curve that approaches a perfectly reflected wave for bar and wave conditions if $\xi_o \approx 1$. The Battjes equation underpredicts the measured K_r at low values of ξ_o (including the plane slope data), and overpredicts K_r at higher ξ_o values. In general, the data show near constant reflection, whereas the Miche and Battjes equations give increasing values of K_r with increasing ξ_o. Measured K_r were also compared to the Miche and Battjes predictions using the 1/30 plane slope to calculate ξ_o, but both equations gave significantly lower values. Neither the equation of Miche nor that of Battjes estimates K_r well for barred profiles over the range of ξ_o values. These equations were developed for plane slopes and, as Fig. 5 illustrates, are not valid if the bottom topography is irregular.

Seelig and Ahrens (1981) developed an equation to determine K_r for plane smooth slopes, plane beaches, and breakwaters, as

$$K_r = \frac{\alpha}{1+\frac{\chi}{\xi^2}} \tag{2}$$

in which α and χ are empirical coefficients, and equal to 1.0 and 6.2, respectively, for plane smooth slopes. The recommended values of Seelig and Ahrens were used in Eq. 2 to compare to the measured plane-slope K_r values, but the equation greatly underpredicted the measured values. However, for our data, Eq. 2 gave good predictions if values of α and χ were 0.22 and 0.02, respectively.

Reflection coefficients for barred profiles were grouped according to shoreward angle and plotted as a function of ξ_o, calculated using $\tan\beta_l$ in place of m as the bottom slope. Linear regression was performed on the α and χ values that best fit the data for each group as a function of $\tan\beta_3$. The resulting equations for determining the empirical coefficients for use in Eq. 2 for barred profiles are $\alpha = 0.19 + 0.07\tan\beta_3$ and $\chi = 0.23 + 0.19\tan\beta_3$. The correlation coefficients r^2 of the regression analysis were 0.99 and 0.95 for α and χ, respectively. Fig. 5 shows predictions of Eq. 2 as a function of ξ_o using calculated α and χ values for the shoreward angles used in the study. Reflection coefficients differ by 5 percent for higher values of ξ_o, but are identical for lower values. Because reflection coefficients were found to be nearly constant, it is concluded that reflection on barred beaches is mainly dependent on the primary slope of the beach and the wave steepness, and only weakly dependent on seaward and shoreward bar angles.

Wave Runup

Hunt (1959) gave an expression for wave runup R as a function of slope, wave height, and wave period, which was re-expressed by Battjes (1974) as a function of the surf similarity parameter, as

$$\frac{R}{H_o} = 1.0\xi_o \tag{3}$$

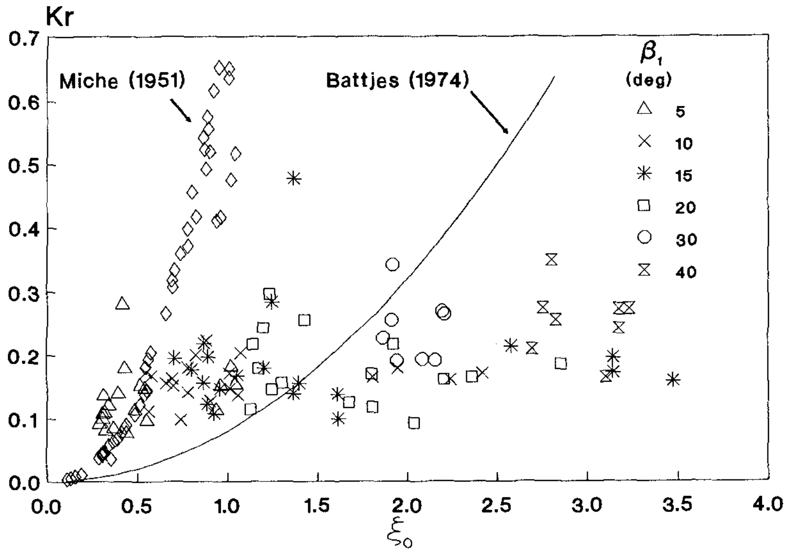

Fig. 4. Measured reflection coefficient vs. surf-similarity parameter

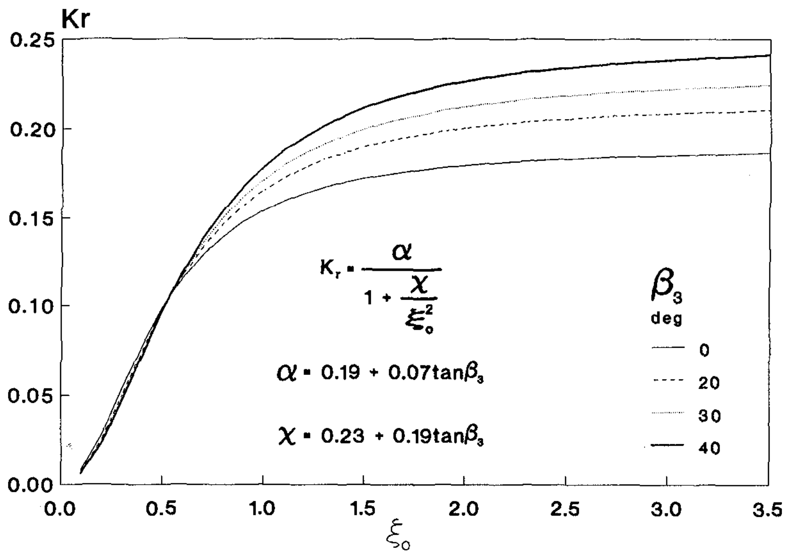

Fig. 5. Empirical curves for reflection coefficients for a 1/30 plane slope with a bar

in which the empirical coefficient value of 1.0 was determined from Hunt's results to be valid for plane, smooth slopes. (Runup is defined as the combination of a superelevated mean water level, called setup, and a time-dependent oscillation called swash.) Hunt recommended smaller values depending on slope roughness. Measured values of runup normalized by deep-water wave height display no dependence on surf similarity parameter if ξ_o was calculated using $\tan\beta_1$ as the primary angle. Runup normalized by wave height was plotted versus the surf similarity parameter using the 1/30 slope as the primary angle to determine ξ_o (Fig. 6). The data show increasing R/H_o with ξ_o. The line shown in Fig. 6 represents the average value of $(R/H_o)/\xi_o$, which was 0.76, and is approximately the value (0.78) given by Hunt for a 1.0-mm grain size slope. The discrepancy between Eq. 3 and measured values may be attributed in part to the slope used in the present study not being as smooth as the slope used by Hunt, but this hypothesis could not be confirmed.

Ahrens (1981) developed the following equation for average wave runup for random waves,

$$\frac{R}{H_{s_o}} = 0.84\xi_o \tag{4}$$

in which H_{so} is the significant deep-water wave height. Average runup for random waves and the calculated values by Eq. 4 were plotted as a function of ξ_o, calculated using β_1. Predictions by Eq. 4 estimate runup well for the plane-slope cases, but underpredict runup for cases with bars. Runup for barred profiles nearly equals that for plane slopes and is independent of ξ_o. However, Eq. 4 gives better results if the plane slope is used to calculate ξ_o (Fig. 7).

Holman and Sallenger (1985) analyzed field data of runup for a mildly barred beach. Although there was wide scatter in the data, they concluded that runup depended on ξ_o. However, the choice of slope with which to calculate ξ_o was unclear. The foreshore slope appeared to be appropriate for data taken at high tide and mid-tide, whereas the bar slope appeared to "have at least some influence" on setup at low tide. It is not evident if the bar was a major cause of wave breaking in their low-tide measurements. The present tests indicate that a bar has a very weak influence, if any, on runup if waves break on the bar. In agreement with Holman and Sallenger, the foreshore, or wide-area slope, appears to be the best quantity to use in correlating runup with ξ_o; however, only one slope (1/30) was used in the present study, so this conclusion can only be tentative.

Breaking Waves

Figures 8 and 9 show average wave height $\overline{H}$ (monochromatic waves) and root-mean-square (rms) wave height H_{rms} (random waves), respectively, normalized by local still-water depth h as a function of distance from the shoreline at the still-water level. Wave decay for identical wave conditions is shown in each figure for plane (solid line) and irregular profiles (dashed lines). The tests conducted with bars show a significant increase of $\overline{H}/h$ and H_{rms}/h over the bar. The increase results from shallower water at the bar and higher waves by (nonlinear) shoaling over the bar. Wave height to water depth decreases directly shoreward of the bar because the water is deeper, and a majority of the waves broke on the bar. The ratio increases as water depth decreases in the surf zone for all tests, including tests on the plane slope. The figures indicate that wave height does not decay uniformly through

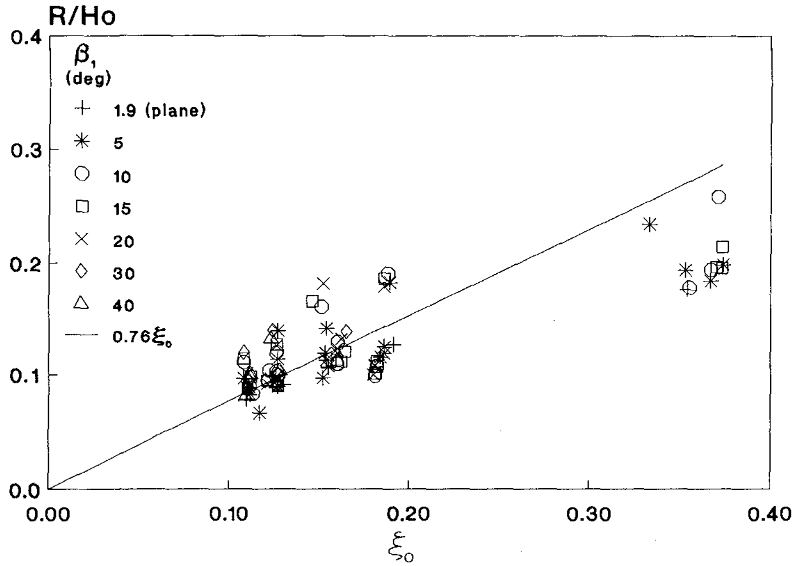

Fig. 6. Runup on barred and plane slopes (monochromatic waves)

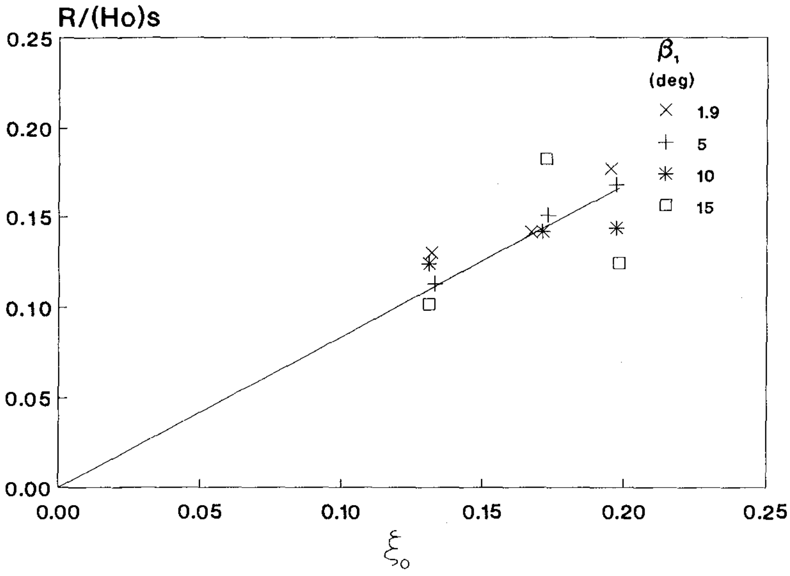

Fig. 7. Runup on barred and plane slopes (random waves)

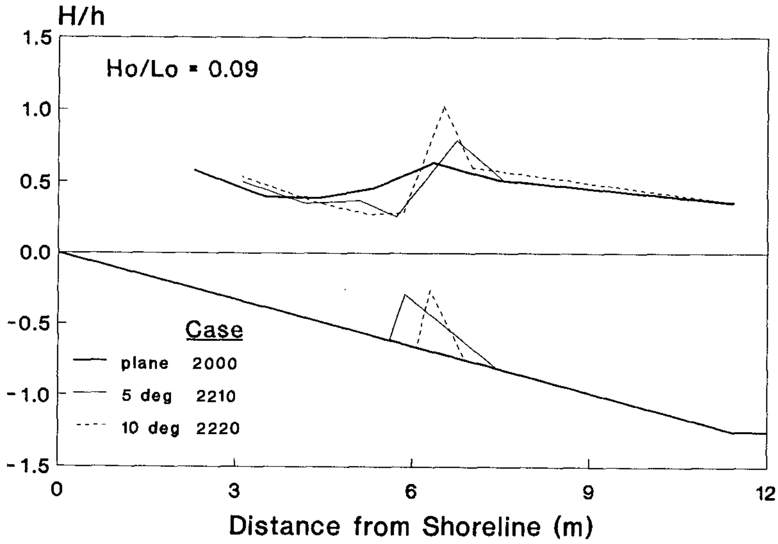

Fig. 8. Wave height on plane slope & two barred slopes, H_{so}/L_p = 0.09 (mono. waves)

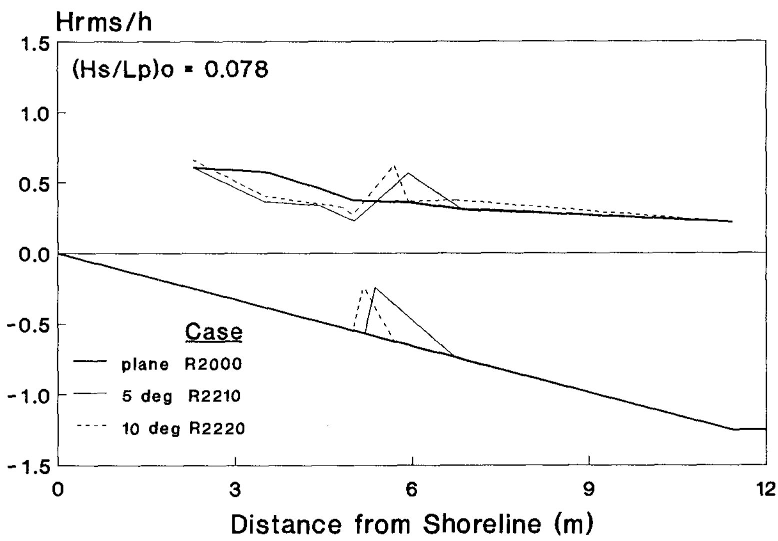

Fig. 9. Wave height on plane slope & two barred slopes, H_{so}/L_p = 0.078 (random waves)

the surf zone for either barred profiles or plane-sloping beaches. Figs. 8 and 9 show that the wave height to water depth ratio is the same in the inner surf zone for barred profiles and plane slopes, despite appreciable differences near breaking. Although the ratio is identical in the inner surf zone, visual observations showed that for most tests broken waves on plane slopes remained as bores through the surf zone, whereas most broken waves on the barred profile reformed.

Maximum wave height H_{max}, significant wave height, and rms wave height were calculated from the time series of the random wave trains and were plotted versus distance from the still-water shoreline in Figs. 10 and 11. The deviation between H_{max}, H_s, and H_{rms} decreased as the waves entered shallower water, indicating the waves become constant in height in the inner surf zone. This behavior has also been shown in other random wave studies, such as Thompson and Vincent (1984) for a plane-slope laboratory beach, and by Ebersole and Hughes (1987) for a barred profile in the field, and by Battjes and Beji (1992) for an irregular-bottom laboratory beach.

Transformation of Wave Spectra

Wave spectra showed surprisingly little variation at fixed points along the profile for plane and barred slopes. Fig. 12 shows spectra for selected gages in two tests with the same gage locations and deep-water waves (random waves, H_s = 14.3 cm, T_p = 1.5 sec). The spectra were averaged over 16 frequency bands. Gage 2 was located in the shoaling zone seaward of significant breaking, Gage 4 was located in a region of significant breaking (on top of the bar in the case of the barred profile), Gage 6 was located shoreward of the bar in the outer surf zone, and Gage 8 was at the most shoreward measurement point in the inner surf zone where many waves had reformed. Two spectra are plotted for each gage, one for the barred slope and the other for the plane slope; these spectra are difficult to distinguish, having the same magnitude and shape, except for Gage 6, located directly shoreward of significant breaking. At Gage 6, energy in the vicinity of the peak frequency for the barred profile is greatly reduced, as is the energy of the low-frequency seiching mode. This result was pointed out in a different way in Figs. 8 and 9, as a decrease in rms wave height. (Note, in Fig. 12, the energy density is given in units of ft^2/Hz, where 1 ft = 0.3048 m.)

CONCLUSIONS

For monochromatic and random waves, wave-height to water-depth ratios were higher for waves breaking on bars than on plane slopes because of increased wave height and reduced water depth. Directly shoreward of breaking, the ratio for barred profiles was less than the plane slope. Wave-height to water-depth ratios increased in the surf zone for cases with and without bars and were identical in the inner surf zone. Although the wave height and spectra were approximately equal in the inner surf zone for both barred and plane beaches, broken waves on the plane slope tended to remain as bores through the surf zone, whereas most broken waves on barred profiles reformed. Maximum, significant, and root-mean-square wave heights of random waves became constant in height in the inner surf zone. Similarly, for the same deep-water wave condition, the energy content and shape of wave spectra were preserved from deep water to the inner surf zone, except in a region directly shoreward of the break point, where the spectra on barred profiles contained less energy than that on a plane slope.

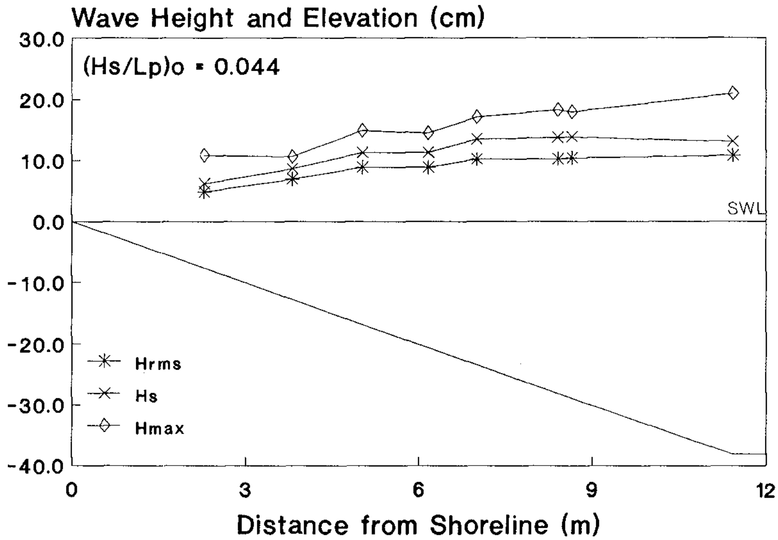

Fig. 10. Statistical wave heights on a plane slope, $(H_s/L_p)_o$ = 0.044 (random waves)

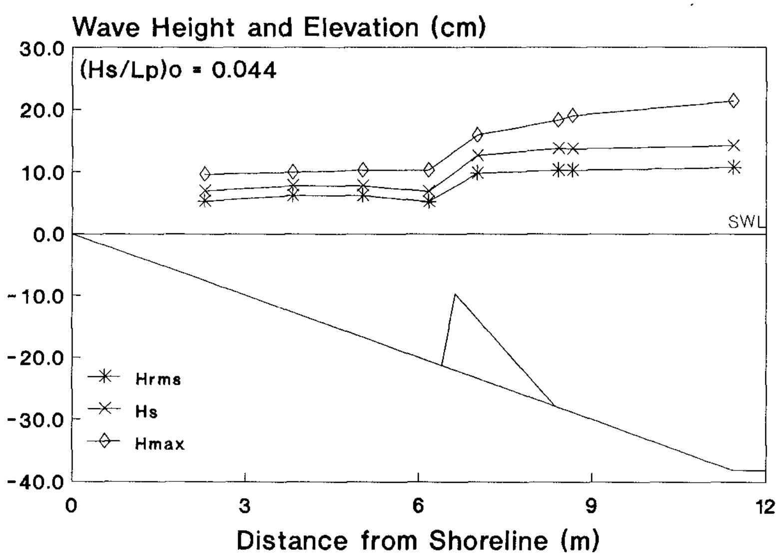

Fig. 11. Statistical wave heights on a barred slope, $(H_s/L_p)_o$ = 0.044 (random waves)

Reflection coefficients were found to be nearly constant across all tests. Reflection was controlled mainly by the plane bottom slope, and only weak variations in K_r were attributable to the seaward and shoreward bar angles. Barred profiles, including extreme bars or reefs, did not alter runup, which was controlled by the plane slope. For monochromatic waves, the measurements followed the runup equation of Hunt (1959) for beaches with 1.0-mm sand grain size. An equation of Ahrens (1981) well predicted average runup for random waves on barred profiles, with the bottom slope in the equation given by the plane slope. In summary, despite differences between breaker-related quantities on barred profiles and plane slopes, wave runup, reflection, and transformation in the inner surf zone on barred profiles were controlled by the plane bottom slope, with only minor influence by the bar, even for extreme (unnatural) bars.

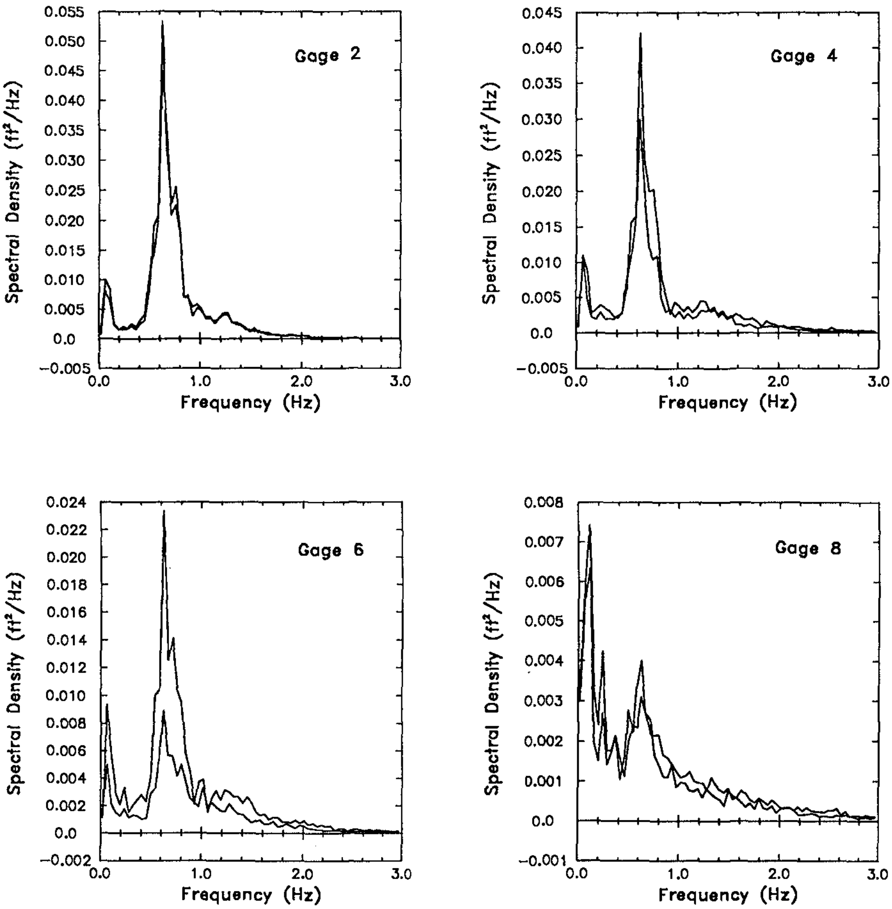

Fig. 12. Wave spectra on barred and plane slopes $(H_s/L_p)_o$ = 0.044 (random waves)

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