WAVE ATTENUATION AND WAVE SET-UP ON A COASTAL REEF

by

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ABSTRACT

In attempting to specify criteria for the design of structures on coastal reefs, it was found that no adequate method existed to derive those criteria from the deep water wave conditions.

In order to fill the gap, a program of measurements and analysis was initiated at the University of Hawaii.

The program consisted of prototype and laboratory measurements. Great emphasis was placed on reliable field data, which were collected on Ala Moana Reef, in Honolulu.

Laboratory investigations on the behavior of waves on shallow reefs are subject to scale effects; verification from field observations is required to obtain reliable results. As a result of this study, a mathematical model was developed for the calculation of wave attenuation and wave set-up on a shallow reef, using the incident waves in the ocean as boundary conditions.

This paper discusses the general behavior of waves approaching a shallow reef and presents some essential characteristics of the mathematical model. The study is limited to waves approaching the shoreline at right angles.

The results of this study can be extended to breakwaters with wide, submerged berms.

1. INTRODUCTION

In Hawaii many coastal areas have a relatively low elevation and require protection against wave attack by storm waves. In some of these areas a shallow coral reef extends between the shoreline and the deeper water. The reef may be biologically alive or dead. Such coastal reef offers significant protection to the coast; the large ocean waves will break on the edge of the reef and the wave that reaches the coastline is of reduced magnitude. Not only is wave energy lost in the breaking process but attenuation of wave height also takes place due to friction along the bottom.

After the breaking of waves on the reef's seaward edge, regeneration of waves may occur over the reef, creating waves of lower height and shorter period. If wind blows over the reef in shoreward direction, wind energy is transferred into wave energy but the growth of wind generated waves over the shallow reef is limited by the depth of the water.

The effect of wave breaking and wave attenuation on a shallow reef, however, also has another aspect: it generates a setup of the mean water level over the reef and near the coastline. The increased water depth in turn results in greater wave heights near the shoreline. Onshore winds may further increase the depth of water near the shoreline and in this way also contribute to a potentially greater wave height.

The depth over a reef usually varies in the direction parallel to the shoreline, giving rise to differences in setup along the coast. The resulting gradients of the mean water level drive a mean current system. Such currents are of major importance with regard to the transportation of coastal sediments, and also for the onshore-offshore mixing of the water leeward of the reef and the ocean waters. Quantitative knowledge of the setup is required for a prediction of these currents and their effects.

Knowledge of the setup and the wave characteristics leeward of a reef is furthermore necessary in numerous engineering endeavors, such as the assessment of beach stability or the design of coastal structures, as well as the prediction of the dynamic response of ships or the design of marine terminals in waters partly protected by a reef. The existing grave uncertainties with regard to the design parameters mentioned above has led to a widespread practice of producing conservative results, which needless to say, results in unnecessarily high costs.

In view of the preceding discussion it was proposed to carry out a study on the attenuation of ocean waves on a reef and of the associated wave setup.

In addition to a theoretical analysis of the problem the study would consist of a field study and a laboratory study.

It was believed that a scale model study in a wave flume would in intself not be conclusive and that data from the field, properly analyzed, would be required to arrive at reliable answers.

A comparison between field and model data would furthermore provide interesting information regarding possible scale effects.

2. WAVE TRANSFORMATION ON A SHOALING BOTTOM AND A HORIZONTAL OR SLIGHTLY SLOPING REEF

Waves moving from deep into shallow water are subject to transformation, which may take different forms, whether the waves are monochromatic or random and whether they are breaking or not breaking.

The following general characteristics have been documented.

a. Periodic waves propagating into shallow water are likely to demonstrate cnoidal characteristics (Svendsen and Buhr Hansen, 1976).

b. A solitary wave progressing over a sloping bottom onto a shelf or reef, with no breaking occurring, demonstrates a remarkable behavior in that the initial wave disintegrates into a train of solitary waves of decreasing amplitude. These are called solitons. (Madsen and Mei, 1969; Johnson, 1972).

c. For waves approaching a beach or a shallow reef, breaking occurs when the wave height over depth ratio assumes a critical value. The behavior of breaking waves has been documented by many experimental studies (e.g. Galvin, 1968). Battjes (1974) found that the similarity parameter $\xi_o = \frac{\tan\alpha}{\sqrt{\frac{H_o}{L_o}}}$, in which α represents the slope and H_o and L_o respectively the deep water wave height and wave length is a characteristic parameter useful in describing breaking wave characteristics.

d. The behavior of random waves after breaking over a sloping bottom or on the edge of a natural reef is not well documented in the literature. These are the type of waves that are particularly relevant to this study. At the study site incident waves usually have a narrow-band spectrum, often showing distinct wave group behavior.

As the waves shoal and break, secondary waves are typically formed and are indicative of a nonlinear wave process. Because of the wave height variation in the (random) waves the zone in which initial breaking occurs extends over a certain width; a consequence of this is that the fraction of breaking or broken waves in a wave record varies over the breaking zone.

Energy dissipation leading to a reduction in wave height is primarily due to bottom friction and breaking. When the bottom is porous, percolation losses may become important. The wave attenuation is primarily at the expense of the energy near the peak frequency of the spectrum. At the same time nonlinear energy transfer takes place from the peak frequencies to higher and lower frequencies.

The lower frequency energy components demonstrate themselves in the surf beat which is induced by the height modulation of the breaking waves and the corresponding variation in shoreward mass transport. The higher frequency waves are generated in the breaking process in the form of secondary waves riding on the crests of the primary waves.

As a result of these transformations, the mean period of the waves inside the reef is considerably lower than the period of the incident waves outside the reef.

The decrease in wave energy is associated with a rise in the mean water level over the reef (wave set-up). Low frequency waterlevel variations may be observed as the dynamic part of the wave set-up.

It has been the objective of this study to quantify the above processes and to provide the design engineer with the tools to calculate the relevant design conditions.

For a mathematical model to adequately describe the behavior of random waves after breaking, the following aspects need consideration:

- energy losses due to wave bottom friction and percolation;
- energy losses due to wave breaking;
- the fraction of breaking waves in a wave record, as a function of location

- exchange of energy from medium to lower and higher frequency components of the wave spectrum;
- wave set-up and wave set-down.

Within the framework of this paper it will not be possible to give adequate coverage to all aspects of these transformations. Most attention will be given to wave energy dissipation and wave set-up.

Empirical coefficients from the mathematical model are verified from the analysis of the field and model observations. The experimental set-up is described in the following section.

3. EXPERIMENTAL SET-UP

3.1 Field Experiments

The field experiments were conducted on a shallow reef at Ala Moana Park, in Honolulu, Hawaii. Site conditions, bathymetry, and measurement stations are shown in Fig. 1. In all stations, except Station 6, waves were measured with a capacitance wave gage (Black, 1978). In Station 6 where heavy breaking occurred, wave heights were obtained by filming the motion of a tethered buoy from a location offshore.

For the determination of wave set-up best results were obtained from visual readings of the mean water level using five separate manometers, fixed to the reef bottom and carefully levelled from a bench mark on shore (Wentland, 1978). At the study site the offshore bottom consists of a stable coral reef, whereby the (dead) coral heads produce a rough surface.

3.2 Model Experiments

The model experiments were conducted in the outdoor wave flume of the J.K.K. Look Laboratory. The flume is 54 m long and 1.22 m wide. Maximum water depth is about 1.0 m. Waves are generated with a parabolicly shaped plunger type wave generator; the maximum wave height is about 0.3 m, whereas wave periods range from 0.5-4.0 sec. Only regular waves can be generated. The vertical walls partly consist of glass panels, which allow visual inspection of the wave phenomena from outside.

The size of the tank allowed the construction of a 1:12 scale model of the outdoor reef site, whereby 130 m of the actual reef could be simulated. Waves were measured with capacitance wave gages in positions corresponding to the field stations. The waves were recorded on two channel wave recorders and on magnetic tape.

For the measurement of wave set-up in the tank best results were obtained by visual readings of manometers, attached to the outside of the flume and connected with 3 mm plastic tubes mounted inside to the side-wall of the tank, with their openings close to the bottom.

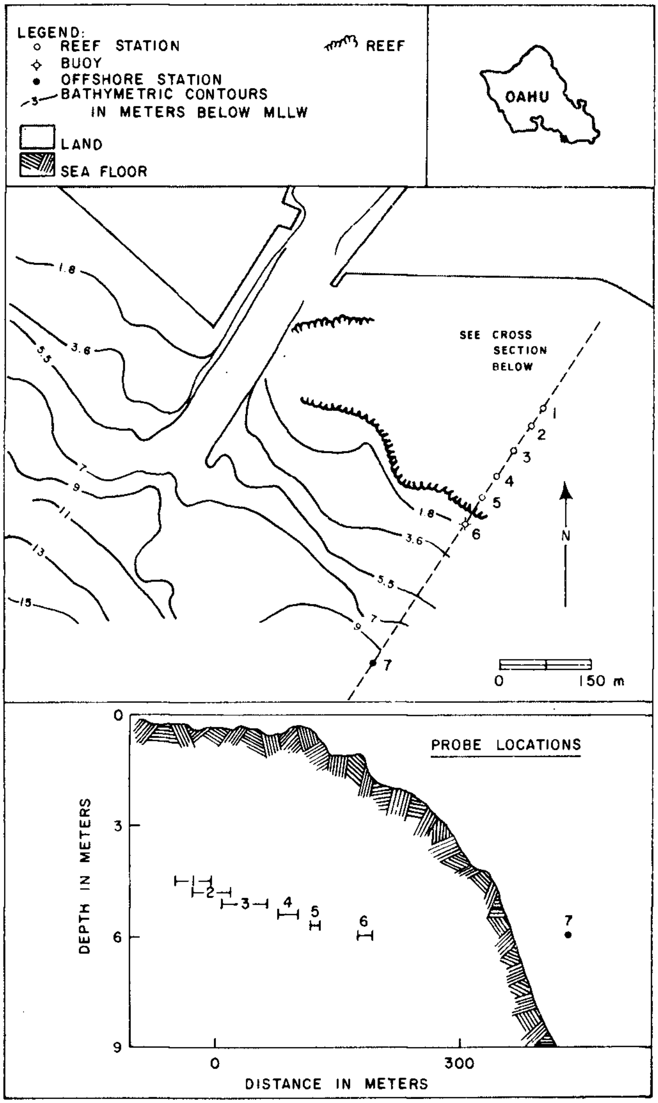

Figure 1 Offshore bathymetry and measurement stations at Ala Moana Reef, Honolulu

4. RESULTS OF INVESTIGATIONS

4.1 Background

Prototype measurements were taken at Ala Moana Reef, Honolulu, at a site where the bottom consists of coral reef. It has been assumed that energy losses due to percolation are negligible at this site and need not be taken into consideration. Energy losses therefore are limited to losses due to bottom friction and to breaking.

Observations at the study site furthermore show that under most conditions waves approach the shoreline at near right angles. The effect of refraction on changes in wave heights can then be ignored. Consequently in all our analysis the waves were treated as a two-dimensional problem.

Because of variations in reef elevation some wave refraction did occur across the reef. Since the experimental set-up did not provide quantitative information on these three-dimensional effects they could not be taken into consideration in the analysis. It was found, however, that at times, certain observations were adversely affected by this aspect of the problem.

For waves moving perpendicular to the coast the process of wave attenuation is governed by the equation:

$$\frac{dF}{dx} = -(\varepsilon_f + \varepsilon_b) \qquad (1)$$

where F is the energy flux per unit of width,
x is the direction of wave propagation (perpendicular to coastline),
ε_f is the rate of energy dissipation per unit of (horizontal) area due to friction, and
ε_b is the rate of energy dissipation per unit of (horizontal) area due to breaking.

Equation (1) assumes a steady state condition where the variation of the mean energy with time equals zero.

In monochromatic waves (laboratory conditions) variations in wave height can be directly obtained from Eq. (1); however because of strong nonlinearities, values for mean energy and energy flux have to be used as they apply to nonlinear waves. Both the value of the mean energy and of the velocity of propagation of the waves near and after breaking are affected by the nonlinearity of the waves, so that linear expressions need to be modified.

In random waves the situation is even more complicated; besides nonlinearity, the variation in wave heights and wave period pose additional problems to define dissipation parameters. (Gerritsen, 1980).

One of the objectives of the study is to evaluate the numerical values of ε_f and ε_b so that a mathematical model for wave attenuation can be developed.

The wave set-up on the reef is governed by the equation (Battjes, 1974):

$$\frac{dS_{xx}}{dx} + \rho g(h_o+\bar{\eta}) \frac{d\bar{\eta}}{dx} + \bar{\tau} = 0 \tag{2}$$

where S_{xx} is the radiationstress component, perpendicular to the shoreline,
h_o is the mean depth,
ρ is the density of the water,
g is the acceleration of gravity,
$\bar{\eta}$ is the time-averaged value of the wave set-up, and
$\bar{\tau}$ is the mean value of the bottom shear stress.

In the above expression for wave set-up it is assumed that the mean mass transport velocity equals zero.

In most previous studies (Battjes, 1974, Van Dorn, 1976) the authors have neglected the contribution of $\bar{\tau}$ to the wave set-up.

From analyzing wave set-up on a reef, there is some evidence that the contribution of $\bar{\tau}$ is not entirely negligible, and needs to be taken into consideration.

In the calculation of S_{xx}, the linear formulation is usually accepted, although the nonlinearity of the waves will also have an effect on the value of the radiationstress.

In this study we have also used the linear expression of S_{xx} for the analysis of data.

4.2 Energy Losses Due to Bottom Friction

In the literature extensive information is available in the bottom friction in low amplitude, harmonic waves. (Jonsson, 1963, 1966; Riedel, et al., 1972; Kajiura, 1964, 1968).

The concepts introduced by these authors have been extended to waves under shoaling and breaking conditions, whereby the assumption was made that even under breaking waves the orbital velocities near the bottom retain oscillatory characteristics (Gerritsen, 1979).

It can be shown, that both the nonlinearity of the waves and the turbulence induced by breaking will affect the numerical value of the bottom friction coefficient, if the latter is based on a linear wave formulation. (Gerritsen, 1979).

The wave bottom shear stress coefficient f_w is here defined by the equation

$$\tau = f_w \frac{1}{2} \rho U_b |U_b| \tag{3}$$

where U_b is the instantaneous value of the orbital velocity near the bottom. Linear assumptions give the following value for the energy dissipation rate ε_f:

$$\varepsilon_f = \frac{2}{3} f_w \frac{\rho}{\pi} \left(\frac{\pi H}{T \sinh kh}\right)^3 \tag{4}$$

where k is the wave number. From field and model data, numerical values of the friction coefficient f_w have been obtained.

It appears that the results follow the general trends established by Jonsson and others surprisingly well. (Gerritsen, 1979) The values of the bottom friction coefficient seem to be only slightly larger than for linear waves, possibly with the exception of plunging breakers where turbulence affects the wave boundary layer and higher values of f_w may be expected.

Values of f_w for prototype conditions usually ranged between 0.1 and 0.5, indicating that the role of friction in energy dissipation in the breaking zone is of considerable significance.

4.3 Energy Losses in Breaking and Broken Waves

The problem of energy dissipation in breaking waves is highly complex and so far no completely satisfactory solution has been proposed.

A number of investigators have used the similarity between a breaking wave and a bore as a model for energy dissipation. (e.g. LeMéhauté, 1962, Battjes and Jansen, 1978). Such approach has also been followed in this study. Utilizing an analysis on bore propagation by Schönfeld (1955) the following expression for the rate of energy dissipation can be derived (Gerritsen, 1979)

$$\varepsilon_b = \frac{\zeta}{8\pi\sqrt{2}} \rho g \omega H^2 \tag{5}$$

In this expression ω is the angular wave frequency, and ζ is a dimensionless energy dissipation coefficient, which is a function of the Froude number, the ratio between wave height and depth in front of the breaker and of the fraction of energy dissipated by turbulence. The latter is highest for a plunging breaker and lowest for a spilling breaker.

Expected values of the coefficient ζ range between 0.3 and 0.6, which is in agreement with experimental results.

4.4 Energy Losses in Random Breaking Waves

For monochromatic waves a breaking point can be defined using conventional methods. This in turn defines the width of the breaking zone, over which energy dissipation due to breaking occurs. In this analysis, the similarity parameter $\xi_o = \frac{\tan\alpha}{\sqrt{\frac{H_o}{L_o}}}$ plays an important role. Battjes (1974) has shown that there is a relationship between the value of ξ_o, the ratio between wave height and depth at the breaking point. The value of ξ_o is also indicative of the type of breaker that can be expected.

In random waves the above analysis is useful for a wave-by-wave analysis of wave dissipation when wave observations are available at successive stations. Such approach has been used to experimentally determine the values of f_w and ζ.

For prediction purposes, however, this approach is less useful because of lack of wave data across the surf zone.

For the calculation of energy dissipation in breaking waves in a predictive manner two methods can be considered:

(1) Calculation of the transformation of the wave spectrum when waves move into shallow water and across the reef after breaking. Utilizing this method the effects of shoaling, and energy dissipation and of energy shifts in the wave spectrum must be considered. (Gerritsen, 1980)

(2) A simplified method, which is based on the mean energy of the wave spectrum, appears to give adequate results for engineering purposes. This method is based on the attenuation of the root mean square wave height and does not take into account energy shifts between frequency components.

In this paper the discussion will be limited to the second method. In order to calculate the energy dissipation due to breaking, the fraction of breaking waves at various locations in the breaking zone must be predicted. Battjes and Jansen (1978) developed a method, based on the truncated Rayleigh distribution, to describe the frequency distribution of waves in the surf zone. This model assumes that the wave height at the point of breaking is limited by depth and that the higher waves of the distribution are reduced to the maximum possible wave height corresponding to that depth.

In evaluating Battjes and Jansen's model to describe our experimental data a difficulty emerged in relation to the assumed truncated distribution. In reality wave heights in the breaker zone do not conform to such a distribution. The distribution is continuous rather than truncated and may be described by a two parameter Weibull distribution.

The concept of a maximum wave height for a certain depth has been verified. Indeed the presence of such maximum could be assumed to exist and could be expressed by

$$H_m = \gamma_m h \tag{6}$$

where H_m is the maximum wave height and γ_m a proportionality parameter, depending on ξ_o. The prototype experiments showed γ_m to vary between 0.46 and 1.11 with mean values for each station (see section 3) varying gradually from $\gamma_m = 0.81$ for station 5 to $\gamma_m = 0.60$ to station 1.

Because of the difference between the actual distribution (Weibull) and the assumed distribution (Truncated Rayleigh) the probability of occurrence of H_m was expectedly much smaller in reality than predicted in Battjes and Jansen's model for the same value of H_m. A correction is therefore required.

For random waves Eq. (5) is modified to:

$$\varepsilon_b = Q \frac{\zeta^2}{4\sqrt{2}} \rho g \, \overline{f} \, H^2 \tag{7}$$

where Q is the fraction of broken waves at a given location and $\overline{f}$ a mean frequency of the waves obtained from the first order moment of the wave spectrum.

The reduction parameter Q is related to the ratio $\frac{H_{rms}}{H_m}$, and may be calculated from Battjes and Jansen's model, if a correction factor is applied. (Gerritsen, 1980)

The modified equation is:

$$\frac{1-Q}{y^2 \ell n\ Q} = -\left(\frac{H_{rms}}{H_m}\right)^2 \quad (8)$$

where y is the correction factor involved; the latter may be obtained from

$$y = 0.71(Q-1)^2 + 1 \quad (9)$$

Equations (8) and (9) are to be seen as being of empirical nature fitted to observed data.

Results of some measurements and calculations are shown in Figs. 2 and 3. The observations were made on August 25, 1976. The location of the measurement stations is shown in Fig. 1.

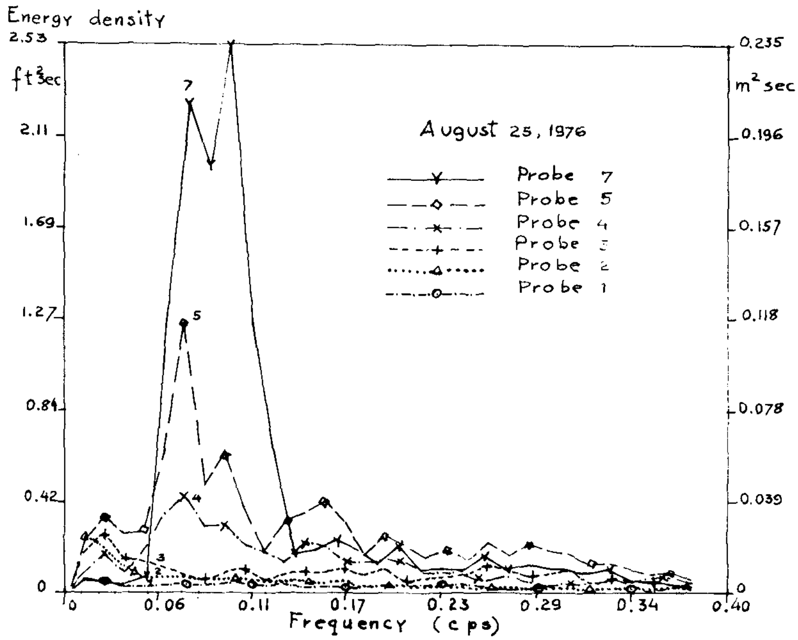

Figure 2 Calculated Wave Spectra for Stations on Ala Moana Reef

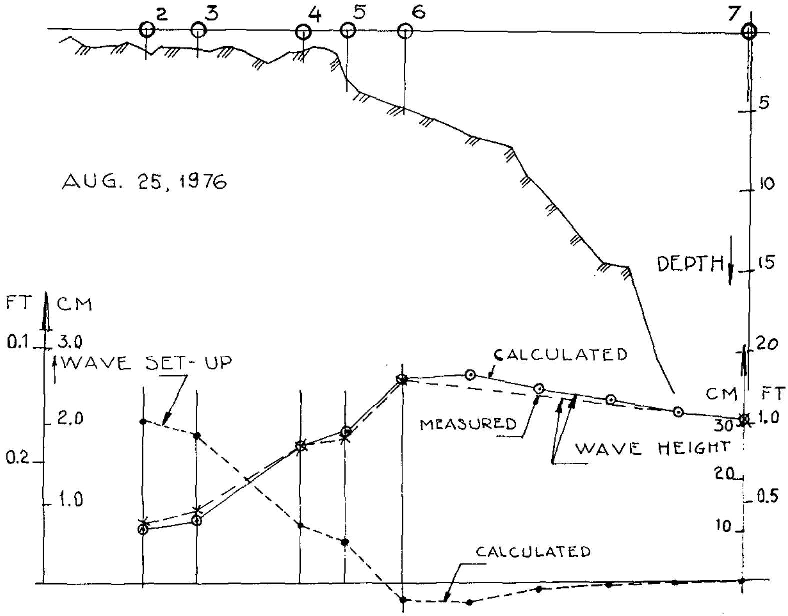

Figure 3 Root Mean Square Wave Heights from Measurements and Calculations

Figure 2 shows calculated wave spectra for the various measurement stations. It shows the sharp decline in energy densities around the peak frequencies, and the shift of energy to low and high frequencies.

Part of the shift is an apparent shift and may not be real; it is due to the Fourier analysis applied to nonlinear wave forms.

The higher frequency components may not represent free harmonics, but they may be bound in phase to the principal wave.

Figure 3 shows the results obtained from the above described dissipation model. Calculated values of H_{rms}, obtained directly from the wave records, and obtained from the dissipation model are both shown. For the latter the root mean square wave height at the offshore station was used as input for the calculations.

Satisfactory agreement between the data from observations and from the model is obtained if the correct values of the dissipation coefficients are introduced into the calculations.

4.5 Wave Set-Up

Analysis of model investigations

Measurements on wave set-up were carried out in the field as well as in a hydraulic model (scale 1:12), allowing a comparison between the two types of measurements. However waves in the laboratory were restricted to the monochromatic type which made the comparison less than ideal.

The range of test conditions in the field measurements was limited, therefore the broader scope of the model data was used as the basis of verification.

An overall view of the test results indicated that both the mean relative waterdepth over the reef $\frac{h_s}{H_i}$ and the wave steepness parameter $\frac{H_i}{gT^2}$ were playing a role in the wave set-up phenomenon. In these parameters H_i is the incident wave height and T the incident wave period. These values were taken at the offshore station. An attempt was made to define a single parameter (most likely a combination of the two other parameters mentioned), that would function as a governing parameter for the wave set-up on a reef.

A suitable parameter of this kind is:

$$\chi = \frac{gT^2 H_i}{h_s^2}$$

which appears to be a modified Ursell parameter, for shallow water.

In Fig. 4 the dimensionless maximum wave set-up on the reef $\frac{\bar{\eta}_{max}}{H_i}$ is plotted against χ. Although there is considerable scatter the solid line may represent a unique relationship. Much of the scatter is probably due to inaccuracies in the reading of the manometers, particularly for low values of the wave set-up. As the values of the wave set-up get larger the scatter seems to become smaller.

It may be noted that χ is related to relative reef depth and wave steepness:

$$\chi = \frac{gT^2 H_i}{h_s^2} = \frac{1}{\frac{H_i}{gT^2} \cdot \left(\frac{h_s}{H_i}\right)^2}$$

so that

$$\frac{\bar{\eta}_{max}}{H_i} = \mathrm{fct}\left[\frac{H_i}{gT^2}, \frac{h_s}{H_i}\right] \tag{10}$$

A graphical representation of (10) can be accomplished in two manners:

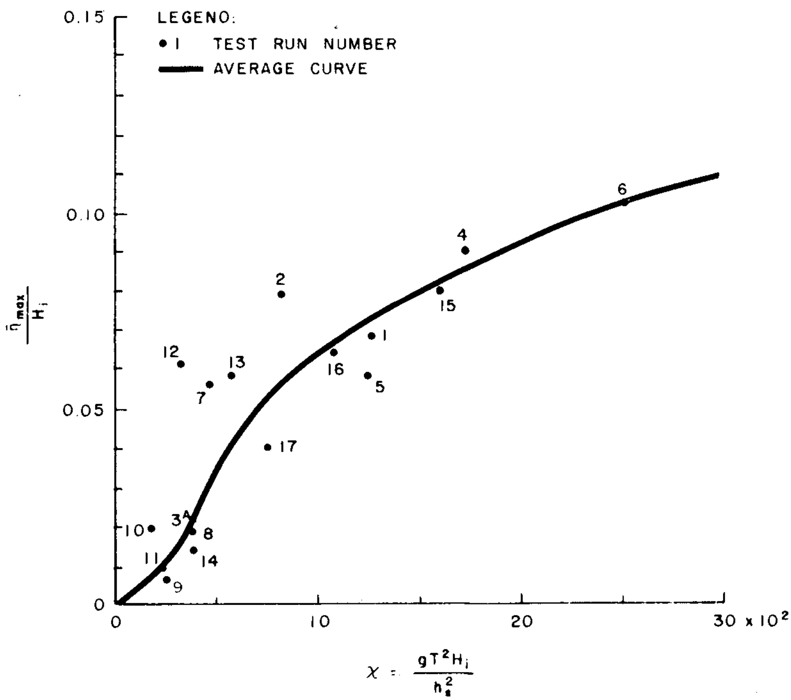

Figure 4 Maximum dimensionless wave set-up on reef versus χ

(1) $\frac{\bar{\eta}_{max}}{H_i}$ as function of $\frac{h_s}{H_i}$, with $\frac{H_i}{gT^2}$ as a variable parameter;

(2) $\frac{\bar{\eta}_{max}}{H_i}$ as function of $\frac{H_i}{gT^2}$, with $\frac{h_s}{H_i}$ as a variable parameter.

In view of the space limitations for the paper only the second representation is shown. (Figure 5)

The scatter that was observed in Fig. 4 is visible again in Fig. 5.

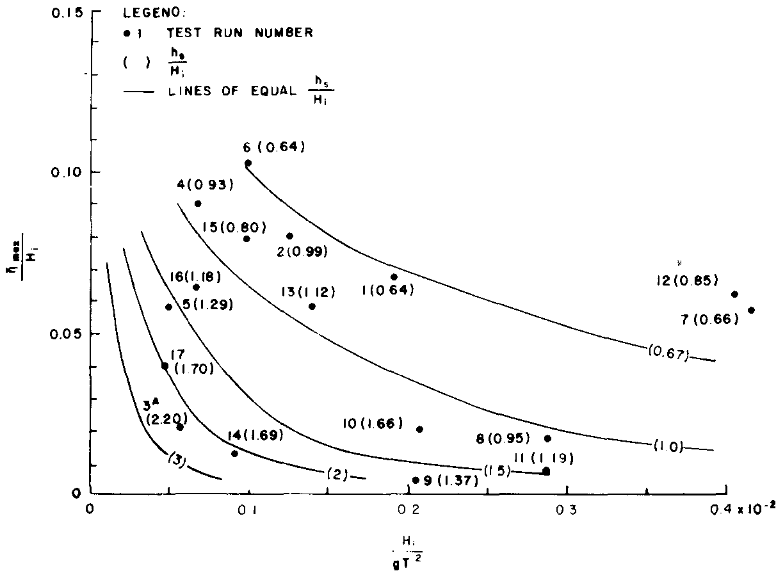

Figure 5 Maximum Dimensionless Wave Set-Up on Reef as a Function of the Wave Steepness Parameter

Verification of hydraulic model with theory

For the verification of the model with theory, a numerical integration of (2) was used. The computations were carried out in two different ways: by letting the mean shearstress $\bar{\tau}$ be equal to zero and by letting it be different from zero. In the latter case its value was adjusted until satisfactory agreement between observation and theory was obtained.

For the numerical integration of Eq. (2) the gradient in mean wave energy must be known in order to determine $\frac{dS_{xx}}{dx}$. For this the dissipation equations developed in the previous sections, were applied.

The results of this analysis indicated that a positive shearstress $\bar{\tau}$ must be introduced to obtain satisfactory agreement between observation and theory. If this positive shearstress is not applied theoretical values are too high and do not agree with observed values.

A positive shearstress is indicative of a resultant watermotion toward the coast in the bottom layers. The nature of this will have to be investigated in future studies. The analysis further showed that reasonable agreement between observation and theory was usually obtained when a shearstress proportional to the (negative) gradient of the radiationstress

$$\bar{\tau} = - B \frac{dS_{xx}}{dx} \tag{11}$$

was introduced.

B is a numerical coefficient for the model for which a mean value $B_m = 0.36$ was found.

Comparison between field and model data

It is unfortunate that the extensive 1976 field measurements provided inaccurate information on wave set-up.

Improved measurements were taken in 1978, although without the simultaneous wave data that characterized the measurements in 1976. In 1978 wave measurements were limited to the offshore wave station.

Over a total of about 14 days of measurement the maximum wave set-up on the reef was found to be 10.7 cm.

Wave set-up values were found from the difference in waterlevel elevation on the reef and in the small harbor behind the reef. The latter is connected with the ocean by a 6 m deep channel. (It was assumed that the wave set-up inside the harbor, compared to the instantaneous mean sealevel in the ocean, would be negligible).

Utilizing available field data and comparing measurements with theory, the coefficient B of Eq. (11) for field conditions could be determined. It was found that $B_p = 0.17$ which is less than the value found for the model.

This difference suggests a difference in resultant bottom shear stress between model and prototype possibly related to a difference in circulatory water movement.

In the field surface drift velocity measurements near reef stations showed low and variable currents (between 0.03 and 0.1 m/sec) usually westerly in longshore direction, occasionally directed shoreward. Onshore mass transport, is expected to have been very small. However velocities near the bottom were not measured and consequently no information is available regarding the resultant current conditions near the bottom.

In the model resultant mass transport to the shore must necessarily be zero, but a resultant shoreward bottom current may nevertheless still be present. An imperfection of the model: return ground waterflow through a not completely sealed bottom, and a porous reef may have had some lowering effect on the wave set-up, which consequently may have increased the value of B_m.

The difference in the values of B for the model and prototype may be considered as a scale effect of the model, and may be used to calculate corrections on the model data.

The results are presented in Fig. 6. In this figure the average of four field observations under approximately equal conditions is also shown, which plotting fits the corrected model data well.

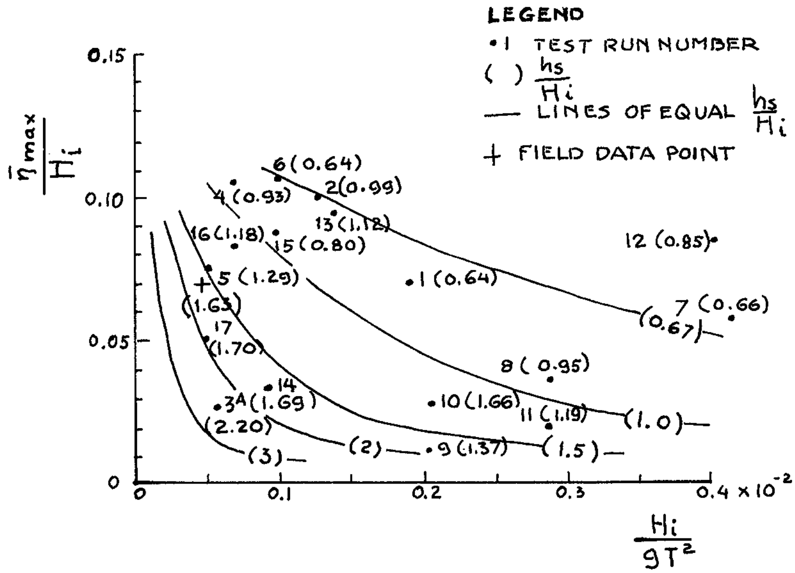

Figure 6 Dimensionless maximum wave set-up on reef versus wave steepness parameter from model, corrected for scale effect

5. CONCLUSIONS AND RECOMMENDATIONS

1. Waves breaking on a coral reef are subject to energy dissipation due to bottom friction losses and breaking losses.
2. The linear wave bottom friction coefficient is affected by the nonlinearity of the waves and by near bottom turbulence.
3. In spilling breakers the wave friction coefficient is of the same order of magnitude as the value of this coefficient in nonbreaking waves.
4. In plunging breakers the overturning jet affects the turbulence of the near bottom fluid motion, and a considerably higher friction coefficient may be expected.
5. Wave friction coefficients in the breaking zone, obtained from the reef measurements are usually between 0.1 and 0.5.

6. The similarity with the bore is utilized to define a breaking loss coefficient ζ. Its value is usually between 0.3 and 0.6 depending on the type of breaker.
7. The randomness of broken waves is an important element in the calculation of wave energy dissipation. A modified Battjes-Jansen model gives adequate results.
8. Wave set-up on a shallow reef is governed by a dimensionless parameter
$$\chi = \frac{gT^2H_i}{h_s^2}$$
which may be considered as a modified Ursell parameter.
9. Experimental evidence suggests that the resultant shearstress $\overline{\tau}$ cannot be neglected in the calculation of wave set-up.
10. More research is required to obtain a full understanding of the physical phenomena. The study of the resultant shearstress $\overline{\tau}$ in the wave set-up equation is particularly recommended.

6. ACKNOWLEDGMENTS

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