Coastal Engineering Technical Note

WAVE ATTENUATION OVER REEFS

PURPOSE: To describe a methodology for calculating wave attenuation over reefs.

BACKGROUND: The transformation of waves across coral reefs is a complex problem, including the processes of refraction, shoaling, breaking, energy dissipation by bottom friction, and reflection. As waves pass from deep water over a steep reef face onto the reef flat, the waves become highly nonlinear. Wave energy is dissipated due to breaking, but energy is also transferred to both higher and lower frequencies in the wave spectrum, and the spectral shape becomes flat (Young 1989, Hardy and Young 1991). The peak wave period shoreward of the reef face may become shorter as higher harmonics are transmitted as free waves (Lee and Black 1978), or the period may increase as surf-beat dominates the spectrum. Breaking waves induce a setup of the water surface over the reef, and differences in breaking characteristics along the reef can cause variations in wave setup, producing significant longshore currents. Although it may seem that wave reflection off a nearly vertical reef would be significant, field data (Young 1989, Roberts et al. 1975) have shown reflected wave height to be on the order of only 10 percent of the incident height (due to the porosity of the reef). Energy losses due to bottom friction are usually negligible in wave transformation across sandy beach profiles, but may be significant over shallow, rough reef flats where the bottom friction coefficient may be an order of magnitude larger than for a sandy bed (Roberts et al. 1975, Gerritsen 1980).

For engineering purposes, the most significant wave transformation process on a reef is generally depth-limited breaking. Design wave heights for a breaking wave on a structure are often determined from a bottom slope-dependent maximum height-to-depth ratio at the toe of the structure (or just offshore). Over a flat reef, this would predict breaking wave heights of 0.78 times the depth. This breaking wave height ratio is overly conservative for design wave heights on the shoreward edge of a wide reef or in the lagoon behind. The concept of a constant height-to-depth ratio in the surf zone is incorrect; prototype data show the height-to-depth ratio varying between 1.1 and 0.4 across reefs (Gerritsen 1980, Hardy et al. 1990). Similar to the case of waves breaking on a barred beach, waves on a reef flat will break, dissipating energy, and then reform as they travel across the reef. The wave height will decay quickly on the outer portion of the reef until it reaches a stable value. On the inner portion of the reef, the reformed wave will decay slowly due to bottom friction. The breaking and reformation process is strongly dependent on the width of the reef and the water depth over the reef. To accurately estimate wave heights on the reef or in a lagoon, it is necessary to model transformation across the entire reef and to represent wave setup (driven by the gradient in wave height). Wave height estimates based only on incident wave conditions and still water depths over the reef will not be reliable across the entire reef.

Wave breaking and reformation on a reef is similar to the process on a barred beach. Gerritsen (1980) first applied wave breaking methods developed for mildly sloping beaches to reefs, with the inclusion of dissipation due to bottom friction. Gerritsen applied the random breaking wave model developed by Battjes and Janssen (1978), but found that the truncated Rayleigh distribution of wave heights assumed by Battjes and Janssen was a poor representation of broken waves over a reef. Young (1989) used a similar approach, but included a check to "turn off" wave breaking when the height-to-depth ratio was

less than 0.78 to simulate wave reformation.

Dally, Dean, and Dalrymple (1985) developed a wave breaking and reformation model which has been extensively verified for plane beaches, composite beach slopes, and barred beach profiles. The model is based on the transformation of individual waves, but may be applied to a random wave field using a statistical approach. The statistical approach requires specification of the wave height distribution in the offshore region, but does not impose a specified distribution in the surf zone. The advantages of the Dally, Dean, and Dalrymple model are: a) extensive verification for a variety of beach configurations, b) no a priori specification of the wave height distribution in the surf zone, and c) the individual wave approach allows calculation of the wave height distribution and statistical wave height parameters (H_{rms}, $H_{1/3}$, $H_{1/10}$) in the surf zone. Due to these advantages, the Dally, Dean, and Dalrymple model is recommended to calculate wave attenuation over reefs.

METHODOLOGY: The methodology described here includes the processes of wave shoaling, refraction, depth-limited breaking, and bottom friction. The assumptions include: linear wave theory, steady-state wave conditions, Rayleigh wave height distribution in the offshore, and longshore homogeneity. The method neglects energy shifts within the wave spectrum, wave-current interaction, and wave reflection and scattering.

The steady-state energy balance equation governing wave propagation is given by

$$\frac{d(ECg\cos\theta)}{dx} = \frac{\kappa}{d}[ECg - ECg_s] + \frac{\rho C_f}{6\pi}\left(\frac{2\pi H}{T\sinh kd}\right)^3 \qquad (1)$$

where

E = wave energy ($= \rho g H^2/8$)
x = cross-shore coordinate (+ offshore)
κ = empirical decay coefficient (0.15)
H = wave height
k = wave number
g = gravitational acceleration
Cg = group velocity
θ = wave direction relative to shore normal
d = total water depth
T = wave period
ρ = density of water
C_f = bottom friction coefficient
ECg_s = energy flux associated with stable wave height H_s, where $H_s = \Gamma d$ and $\Gamma \approx 0.4$

The first term on the right side of Equation 1 is the energy dissipation due to wave breaking (Dally, Dean, and Dalrymple 1985), and the second term is energy dissipation due to bottom friction (Gerritsen 1980, Thornton and Guza 1983). The application of Equation 1 to calculate random wave transformation across reefs is based on the approach of Kraus and Larson (1991). The input parameters required include the cross-shore profile of the reef and the offshore wave period, mean direction, and root-mean-square height (H_{rms}). The wave breaking parameters (height-to-depth ratio for incipient breaking (γ), κ , and Γ) and bottom friction coefficient must also be specified (Gerritsen suggests values of $C_f = 0.05$ to 0.25 for coral reefs). From the specified offshore H_{rms}, a Rayleigh distribution of wave heights is determined. Individual wave heights are randomly chosen from the Rayleigh distribution, and each individual wave is transformed independently. Wave angles are calculated by Snell's law, wave setup is calculated from the cross-shore balance of momentum, driven by cross-shore gradients in wave height (Longuet-Higgins and Stewart 1964), and wave height is calculated from Equation 1. The wave height statistic H_{rms} is determined across the reef by combining the transformed individual waves. Other wave height statistics, e.g., $H_{1/3}$ or $H_{1/10}$, may also be calculated. Generally 100 or more individual waves are required for

stable mean statistics.

RESULTS: Limited validation of the method described above was performed using laboratory data from an unpublished CERC flume study with a configuration replicating the reef at Agat, Guam, and field data from Yonge reef (Young 1989). The laboratory study was conducting in an eighteen-inch-wide flume consisting of 21.3 m of flat bottom, 1.5 m of 1/5 slope, 10.2 m of 1/30 slope, 12.9 m of reef flat, and 3.3 m (covered with wave absorber) of 1/30 slope. The water depth in the deepest portion of the flume was 0.68 to 0.64 m with a depth on the reef flat of 0.05 to 0.005 m. Wave periods ranged from 1.1 to 2.5 sec and heights ranged from 0.02 to 0.12 m. The model was applied with the standard breaking parameters (κ = 0.15 and Γ = 0.4) and an incipient breaker index γ = 1.0 (a breaking index of 0.8 is commonly used on gently sloping beaches, but an index of 1.0 is more appropriate for steeper reef slopes). The bottom friction coefficient was set to 0.01 which is a typical value for smooth slopes such as the lab configuration. Figures 1 through 3 show selected results for the laboratory data. The agreement between laboratory measurements and model results is excellent. The solid line is the modeled wave height, the symbols are the measured wave height, the chain-dot line is the modeled setup, and the dotted line is the still-water level. These results are typical for water depths greater than 3 cm on the reef flat. For shallow water depths, the model underpredicted the (small) measured wave heights. For very shallow depths, the wave energy at the incident frequency is almost entirely dissipated and low-frequency energy (which is not included in the model) dominates. Figure 4 is a scatter plot of the calculated versus measured results for 69 laboratory tests (345 data points). The figure shows the good correlation for the higher wave heights (depths greater than 3 cm) and the underprediction of the low wave heights (depths less than 3 cm).

Figure 5 shows results from a field experiment conducted on Yonge reef, part of the Great Barrier Reef in Australia. This is one of four cases reported by Young (1989). The incident H_{rms} = 2.05 m and the depth over the reef was 1.05 m. The wave measurement was taken in the lagoon on the leeward side of the reef. The wave breaking parameters used in the model were identical to those applied for the laboratory cases, and the bottom friction coefficient was 0.05 which is equivalent to the value suggested by Young. As in the case of the laboratory results, the model compares well with the measurement.

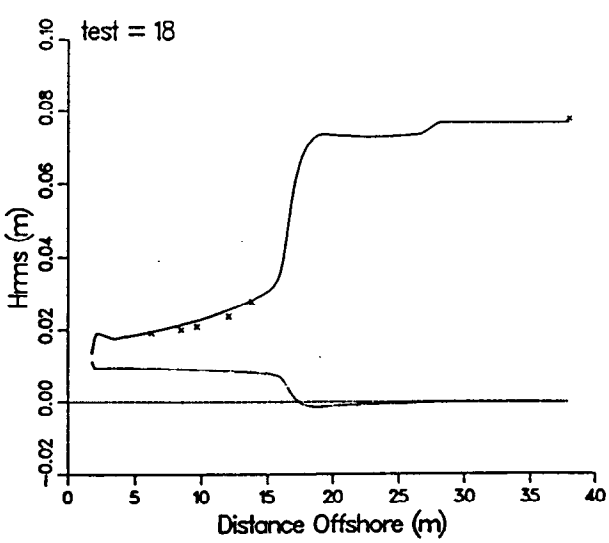

Figure 1. Laboratory test 18, Agat, Guam.

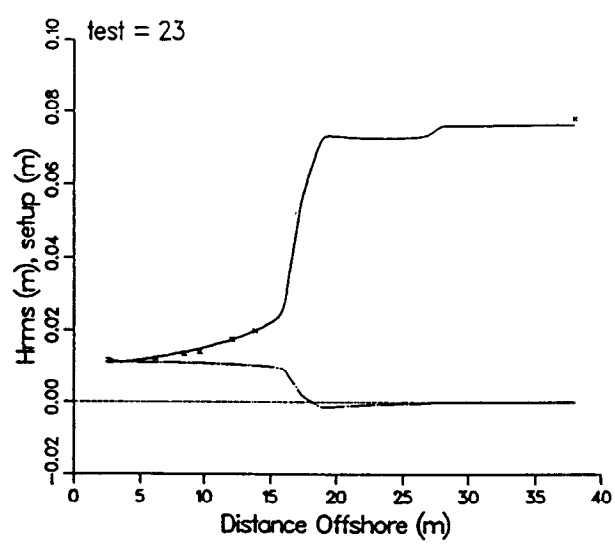

Figure 2. Laboratory test 23, Agat, Guam

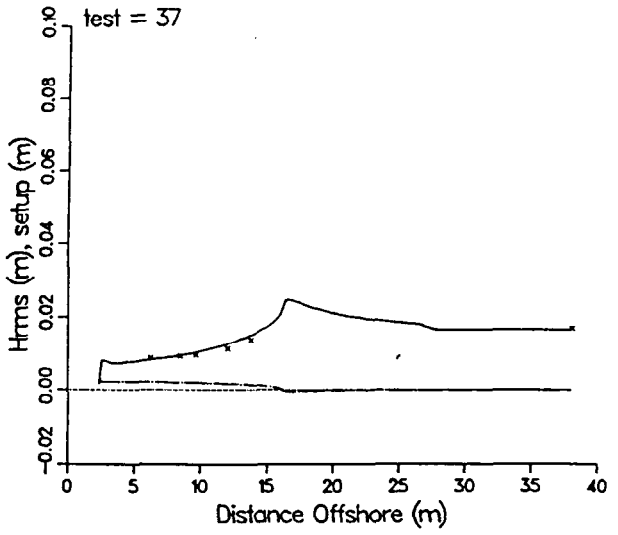

Figure 3. Laboratory test 37, Agat, Guam.

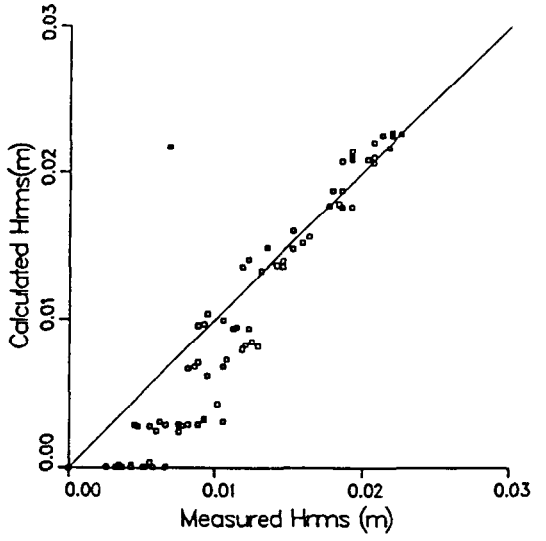

Figure 4. Calculated vs. measured laboratory results.

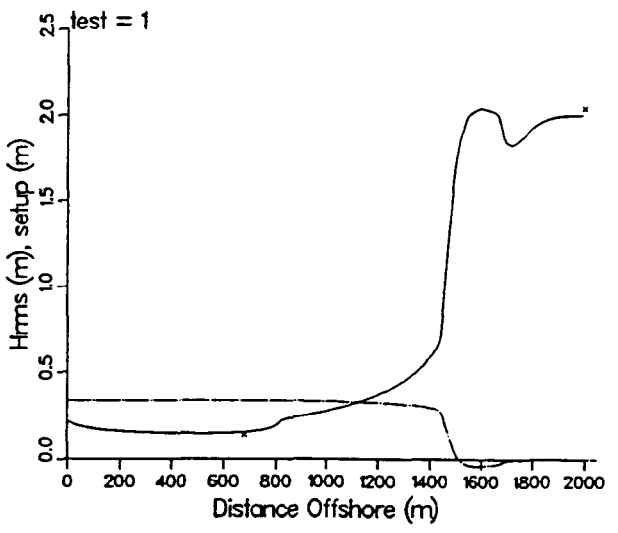

Figure 5. Field test August 1985, Yonge Reef, Australia (Young 1989).

SUMMARY: For engineering purposes, the breaking wave model of Dally, Dean, and Dalrymple can be used to calculate the attenuation of waves over reefs. For very small water depths over the reef, the model may underpredict wave height as nonlinear processes dominate. The inclusion of bottom friction in the energy balance equation improves estimates of wave height across the reef flat, but may not be critical for engineering application. There are insufficient measurements to give general guidance of bottom friction coefficients, so site-specific field measurements are recommended to determine C_f. The breaker model without bottom friction is available in the PC-based computer program NMLONG (Kraus and Larson 1991, CETN-I-47). An executable copy of NMLONG is available from Dr. Nicholas C.

Kraus, USAE Waterways Experiment Station CV-CS, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. For additional guidance on applying the model to reefs, contact Jane McKee Smith (601-634-2079).

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