CHAPTER 45

Prediction of the maximum wave on the coral flat

Dede. M. Sulaiman[1], Shigeaki Tsutsui[2], Hiroshi Yoshioka[3], Takao Yamashita[3],

Shinichi Oshiro[4], and Yoshito Tsuchiya[5], M. ASCE

Abstract

Beach erosion has become a major problem at coral-sand beaches in Bali, Indonesia, due to the rapid changes in natural environment and utilization of coastal areas. An observation of waves was carried out at Sanur beach in Bali to know what waves are effective for beach processes. The representative waves are predicted by use of the mild-slope and KdV equations with evaluation of the coefficient of bottom friction. Empirical formulae of wave energy dissipation are proposed for taking into account of wave height damping due to breaking on the coral flat. The maximum wave on the coral flat, occurring in the reforming region of waves after breaking near the reef edge, can be decided by the theoretical results of the highest wave of permanent-type on water of uniform depth. Sanur beach has observed swells with a period longer than 15 sec, being incident onto the coral flat without breaking. This maximum wave of non-breaking progressive-type is, therefore, evaluated by the experimental wave height criteria.

INTRODUCTION

Indonesia, one of the largest archipelagos, is located in the tropics and is consisted of about 13,7000 islands. Among them the total area of islands surrounded with the coral reef, such as Bali, is about 1,900,000 km^2. Many rivers in the south parts of Bali island, as shown in Figure 1, supply sand sediment sources into the beach. The length of coastline of Bali is about 430 km, and main coastal engineering problems are beach erosion, river mouth closing, and tidal flood (Syamsudin, 1993). Especially in Sanur, Kuta, and Nusa Dua

[1] Researcher, Research Institute for Water Resources Development, Ministry of Public Works, Bandung, 40135, Indonesia.
[2] Professor, Dept. of Civil Engineering and Architecture, Faculty of Engineering, Univ. of the Ryukyus, Okinawa, 903-01, Japan.
[3] Instructor, Disaster Prevention Research Institute, Kyoto Univ., Uji, 611, Japan.
[4] Graduate Student, Civil Engineering and Architecture, Faculty of Engineering, Univ. of the Ryukyus, Okinawa, 903-01, Japan.
[5] Professor Emeritus, Kyoto Univ., and Professor, Meijo Univ., Nagoya, 468, Japan.

coral-sand beaches, located nearby the southern peninsular of coral limestone forming beautiful steep sea cliffs, beach erosion has become a major problem for which effective countermeasures are needed. There should be interrelation between coastal processes concerned with beach erosion in these beaches and changes in natural environment due to utilization of coastal areas. Clarification of the relation is very useful for other coral-sand beaches to predict what beach processes will occur in the future.

The successful control of coral-sand beach processes requires the knowledge of prediction of the maximum wave on the coral flat, i.e., what waves are the most effective for beach change. As the first step, therefore, an observation of waves, as joint investigation between the Research Institute for Water Resources Development and the Disaster Prevention Research Institute, Kyoto University, has been carried out at Sanur beach. This paper examines changes in wave heights and periods by using wave data, and predicts wave transformation in the coral reef beach, both by the mild-slope and KdV equations, and the maximum wave on the coral flat, where the effects of wave breaking and bottom friction are introduced.

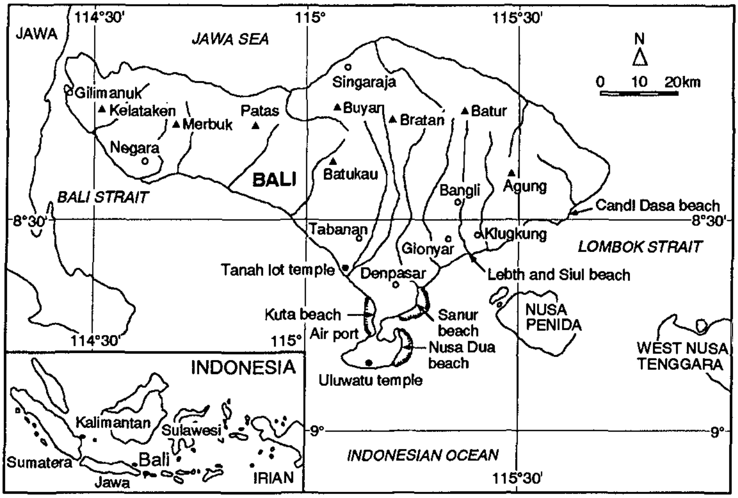


Figure 1. Bali island and coral-sand beaches.

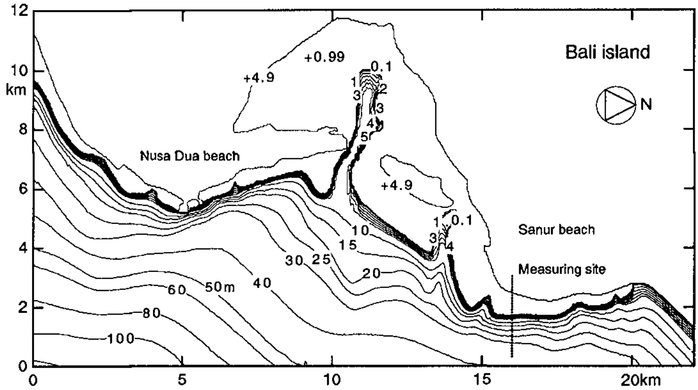
COASTAL ENVIRONMENTS

Field measurements

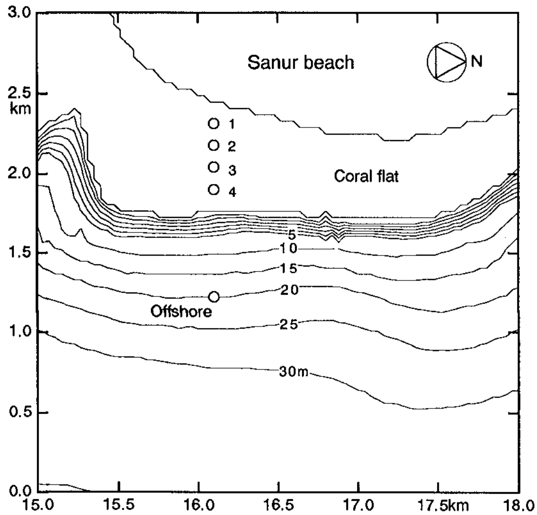
(1) Bathymetry near Sanur coral reef beach and wave measuring stations

As seen in Figure 2(1), Sanur beach is about 7 km long having coral flats, 500 - 800 m wide. The coral reef beach profile is of slope-type, as seen in Figure 2(3), where the water depth increases gently in the outer reef with the bottom slopes of 1/20 - 1/50. This geometric feature is different from that in the Okinawa islands, Japan, where the step and barrier-type coral reefs are formed.

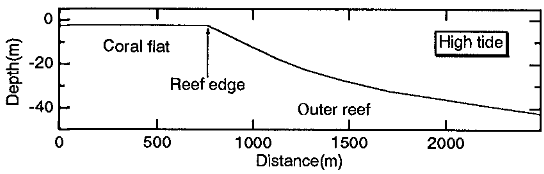
The linear array of five wave gauges was set up perpendicular to the reef edge, as shown in Figure 2(2) by the circles. The offshore station was set up at the location of 20 m water depth for measuring incident waves, and the others (St.1, 2, 3, and 4) were installed on the coral flat at intervals of 100 m from the reef edge. The offshore wave gauge is supersonic-type and those on the coral flat are of capacitance-type.



(1) Bathymetry near Sanur and Nusa Dua beaches.



(2) Wave array installed at Sanur beach, shown by circles.



(3) Beach profile along the course of wave array.

Figure 2. Bathymetry around Sanur beach in Bali and the wave probe linear array.

(2) The period of observation

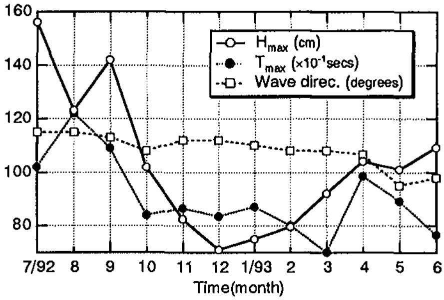


Figure 3. Seasonal variations of incident wave characteristics at Sanur beach.

The seasonal variations of incident wave characteristics at Sanur coral reef beach, shown in Figure 3, indicate significance of the waves in the dry season for the beach process. The wave direction is almost unchanged throughout the year and the maximum wave heights and the corresponding wave periods (H_{max}, T_{max}) in the dry season (June - August) are greater than those in the wet season (December - February). The observation was therefore carried out in the period of July 16 - 19, 1992 under the usual sea conditions. After preliminary measurements on July 16, three runs of measurements were put into operation from 11:00 to 24:00 on July 17, from 9:00 on July 18 to 1:00 on July 19, and from 9:00 to 17:00 on July 19. The sample size of the data used is 20 minutes for all measuring stations, and the data were obtained at intervals of two hours for the offshore station and one hour for the other stations on the coral flat. At the offshore station, in addition, two-directional (NS and EW) water particle velocities were measured for a period of 20 minutes in every two hours, by using the sonic-type current meter.

(3) Wave direction

Figure 4 shows velocity vectors at the offshore measuring station, which were estimated from the two-directional (NS and EW) components of water particle velocities at high (12:00, 24:00) and low (18:00) tides. In the expression, the velocity components are normalized by each maximum value. The predominant directions of currents are ESE and WNW, indicating that offshore waves are incident from the direction of ESE. According to the results of numerical calculation of wave rays (Syamsudin, 1993), waves propagating in the Indonesian Ocean from the direction of SE are coming onto the beach, nearly perpendicular to the reef edge. Judging from the bathymetry of the beach in Figure 2(2) and the velocity vectors in Figure 4, offshore waves can be assumed to be incident normally to the reef edge in the period of the present observation.

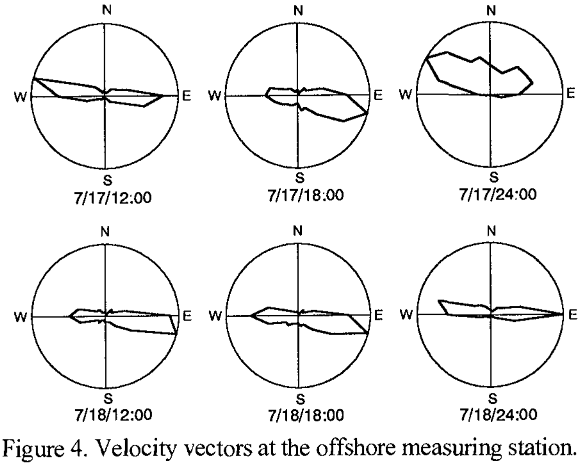


Figure 4. Velocity vectors at the offshore measuring station.

Wave characteristics

(1) Power spectra and wave energy dissipation

According to the tidal record measured at Benoa harbor nearby Sanur beach, the highest tidal level of water rises up to +2.3 m and +2.5 m in the period of July 17 - 18, as shown in Figure 5 by thin solid lines. The water depth at low tide is extremely shallow so that there appear some places dried up. The significant wave heights and periods ($H_{1/3}$,$T_{1/3}$) measured in the reef vary in phase with the tide level, as shown in Figure 5. Waves can enter onto the coral reef at high tidal phase of several hours, but the wave heights decrease gradually due to bottom friction with wave propagation toward the shore. Waves in the reef are, therefore, subjected to the water depth on the coral flat and incident waves at high tide are effective for coral-sand beach processes.

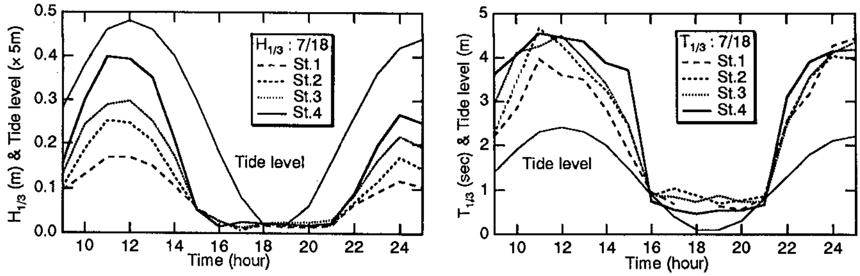
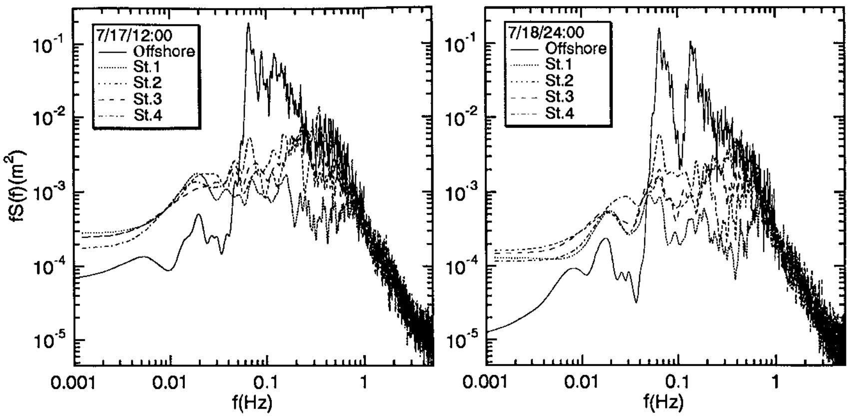


Figure 5. Significant wave heights (left) and periods (right), varying with the tide level on the coral flat (July 18).



(1) July 17 at 12:00 (2) July 18 at 24:00

Figure 6. Frequency spectra for waves in and outside the reef at high tide.

Figure 6 shows typical examples of frequency spectra at high tide on July 17 - 18. In the ordinates, power spectra $S(f)$ are multiplied by the frequency f to obtain dominant peak frequencies clearly (Kai, 1985). The sampling time is 0.5 sec for offshore data and 0.1 sec for data on the coral flat.

Power spectra of offshore waves (solid lines) have several dominant peaks, showing that the waves include swells with a period of about 15 sec and wind waves with periods less than 8 sec. As can be seen in spectra at the stations 1 to 4 on the coral flat, high energy components with periods of 3 - 20 sec in offshore waves decrease suddenly by breaking near the reef edge. Long waves less than 0.05 Hz are then generated clearly on the reef. These long waves might be consisted of two components; incident swells onto the coral flat without breaking near the reef edge and waves generated by nonlinear interaction of incident and reflected waves on the reef, resulting in wave setup (Goda, 1975; Hino et al., 1989). The former can be confirmed in the following discussion on Figure 7. The power spectral shape on the coral flat becomes flat and the spectral width seems to be wider than that of offshore ones. Note, however, that the energy of swells with a period of about 15 sec, though decrease by breaking, is still predominant in the reef, as clearly shown in Figure 6(2). At the lowest tidal phase, on the other hand, the water depth becomes very shallow, and there exist strong offshore-wards currents from the reef edge, as shown in Figure 4. A few waves thus coming into the reef flat, most waves measured on the coral flat are, as shown in Figure 5, wind waves with periods less than 1 sec, of which the energies are very small.

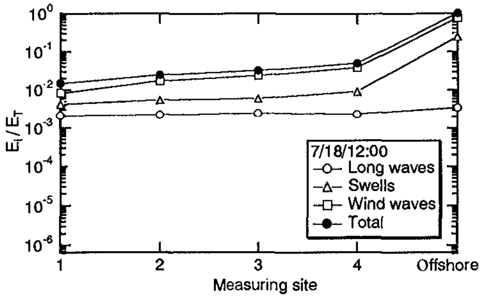


Figure 7. Wave energy dissipation on Sanur coral flat due to wave breaking and bottom friction at high tide (July 17 at 12:00).

If the frequency region of power spectra at high tide is divided into three regions; long waves ($f < 0.04$), swells ($0.04 < f < 0.1$), and wind waves ($f > 0.1$), respectively, each wave energy component E_i changes in and outside the reef due to wave breaking and bottom friction, as shown in Figure 7. The abscissa indicates the measuring stations and the ordinate does the energies relative to the total energy of incident waves, E_T. It is noted that the energy of long waves with periods greater than 25 sec, having small partition rate of the wave energy, are unchanged both in and outside the reef. The result shows that the coral reef in the beach is not effective for dissipating long period waves.

(2) Significant waves

At high tidal phase the significant wave heights and periods ($H_{1/3}$, $T_{1/3}$) change in and outside the reef, i.e., in the wave propagation direction, as shown in Figure 8. The abscissa shows the measuring stations and the subscript 0 denotes quantities of

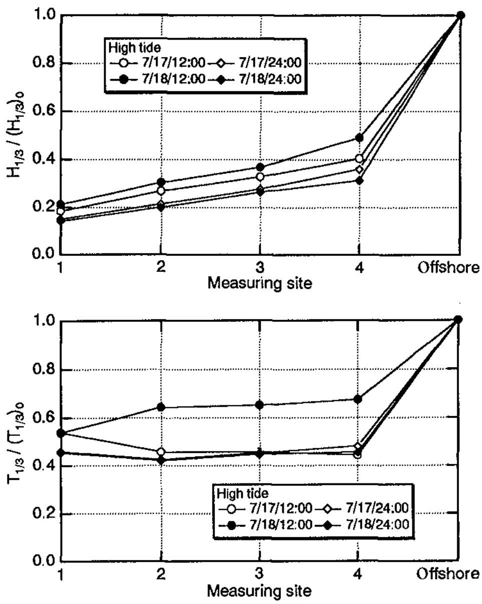


Figure 8. Changes in the significant wave heights (upper) and periods (lower) at high tide.

the offshore incident waves. After entering onto the coral flat, the significant wave heights decrease suddenly by breaking nearby the reef edge, and furthermore decrease gradually due to bottom friction on the coral flat. Similarly, the significant wave periods change suddenly near the reef edge, but they remain nearly constant on the coral flat. The main reasons of decrease in wave period are due to short-period waves generated in the course of wave breaking, and, probably, fission of long-period waves into solitons taking places on the coral flat. The prediction of wave properties should become taking into account of the change in wave period caused both by wave breaking and fission.

PREDICTION OF REPRESENTATIVE WAVE HEIGHTS

Model equations

The mild-slope (MS) and KdV equations are applied herein to predict representative wave heights for irregular waves on the coral flat. The MS equation is useful for estimation of transformation of waves propagating on the step-type reef with bathymetric discontinuity (Tsutsui & Zamami, 1993), as shown schematically on the left in Figure 9. Coral reefs of step-type are formed in the Okinawa islands, but those of slope-type are formed in Sanur beach, as shown schematically in the figure. As the offshore-side bottom slope changes gradually from 1/20 to 1/50, the KdV equation can be applied, but not for the step-type reef. Notice that all the physical quantities in this section are written in dimensionless form by using the representative quantities, the length being the nominal water depth h_0, the time $\sqrt{h_0/g}$, the velocity $\sqrt{gh_0}$, and the acceleration of gravity g.

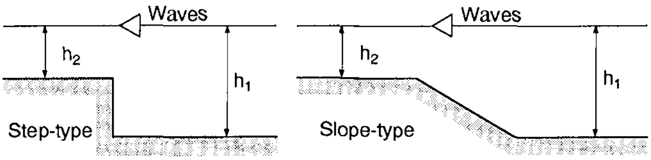


Figure 9. Step and slope-type reefs.

(1) The MS equation

The MS equation with the effects of wave energy dissipation due to wave breaking and bottom friction is given in the form (Dalrymple et al., 1984)

$$\nabla(cc_g\nabla\eta) + \left[(c_g/c)\,\sigma^2 - \mathrm{i}\sigma f_d\right]\eta = 0 \tag{1}$$

where $\nabla \equiv (\partial/\partial x,\ \partial/\partial y)$ is the horizontal differential operator, (x, y) are the horizontal coordinates, c is the wave velocity, c_g the group velocity, η the water surface displacement, $\sigma = 2\pi/T$ the frequency, T the wave period, and f_d the dimensionless coefficient of wave energy dissipation due to breaking and bottom friction. In the present study, after transformation into the two-dimensional form (Tsutsui, 1991), the MS equation (1) is calculated numerically by the finite element method.

(2) The KdV equation

The KdV equation with the effects of wave energy dissipation due to wave breaking and bottom friction is given in the form (Tsutsui, 1986; Yasuda & Nishio, 1990)

$$\eta_x + \frac{3}{2}h^{-3/2}\eta\eta_\xi + \frac{1}{6}h^{1/2}\eta_{\xi\xi\xi} + \frac{1}{4}h^{-1}h_x\eta = \frac{1}{2}\kappa h^{-3/2}\eta_{\xi\xi} - \frac{1}{2}s\,h^{-2}\eta|\eta| \tag{2}$$

with $$\xi = \int h^{-1/2}dx - t \tag{3}$$

where h is the local still water depth, κ the dimensionless coefficient of wave energy dissipation, s the coefficient of bottom friction, and the subscripts denote partial derivatives. Note that the wave energy dissipation is estimated by two terms on the right-hand side of Eq.(2). The term of diffusion, the first term, plays an important role in evaluating the effect of wave height damping due to breaking, and the second term does due to bottom friction. The equation (2) can be calculated numerically by the finite difference method (Tsutsui, 1986).

The sudden decrease in wave periods due to fission of long-period waves into solitons just after wave incidence upon the reef can be confirmed numerically, by making use of the KdV equation without wave breaking and bottom friction. Figure 10 shows an example for a gradually varying reef shown in the bottom of the figure, where U_r is the Ursell number, $\varepsilon \equiv h_2/h_1$ the ratio of the shallower water depth h_2 on the reef to the offshore water depth h_1, H is the wave height, and the subscript i stands for quantities of an incident wave. The wave height and period vary periodically with respect to wave propagation because of nonlinear interaction of solitons. Just after the fission, its period decreases suddenly to a value less than half of the incident wave period. As shown in Figure 8, the value nearly equals those obtained from observation. In the course of wave propagation the wave period becomes longest in the phase of reformation of waves, at which the wave height decreases a little.

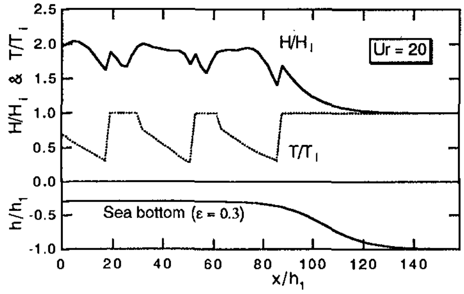


Figure 10. Changes in the wave height and period on the reef due to fission of a wave into solitons.

Coefficient of energy dissipation

In order to use Eqs.(1) and (2) for calculating wave properties on the coral reef, the coefficient of wave energy dissipation due to breaking and bottom friction must be cvaluated. The equation of wave energy conservation is given by

$$\frac{d}{d\xi}\left(Ec_g\right) = -f_d E \tag{4}$$

where E is the total wave energy and ξ is the horizontal coordinate in the direction of wave propagation. We use the expression for the coefficient of wave energy dissipation, f_d, introduced by Izumiya & Horikawa (1984), considering bottom friction, under the assumption of homogeneity of turbulence in the breaker zone. As the total water depth including wave setup is used in the expression, using linear wave theory, it can be modified (Yamashita et al., 1990; Tsutsui & Zamami, 1993) as

$$f_d = \left[\frac{1}{2} C_f^* + \frac{\beta_0}{8} \sqrt{\left(\frac{H}{h}\right)^2 - \left(\frac{H}{h}\right)_s^2} \right] \frac{H}{h} \frac{c_g}{h} \tag{5}$$

in their notations, where $(H/h)_s$ is the minimum wave height relative to the water depth in the wave damping region, C_f^* the coefficient of bottom friction, and β_0 the dimensionless coefficient related with wave energy dissipation due to breaking.

Based on the experimental estimation of the coefficient β_0 for the step-type reef, the wave height distribution in the breaker zone can be estimated correctly (Tsutsui & Zamami,

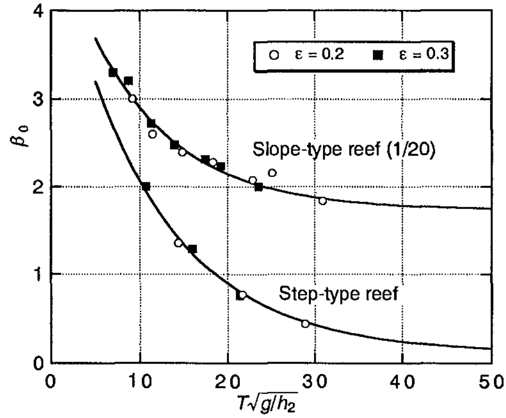


Figure 11. Coefficients β_0 for the slope and step-type reefs.

1993). Similarly, we can determine the coefficient β_0 on the slope-type reef, as shown in Figure 11, where the offshore slope is 1/20 and the abscissa indicates the dimensionless wave period $T\sqrt{g/h_2}$ on the coral flat. In the limiting state of $T\sqrt{g/h_2} \to \infty$, the value of β_0 on the slope-type reef can be approximated as $\beta_0 \approx \sqrt{3}$ (Appendix), by referring to the breaking model for the solitary wave (Le Méhauté,1963). The empirical formulae of the coefficient β_0 are, for the slope-type reef,

$$\beta_0 = 3.27\exp\left[-0.1027T\sqrt{g/h_2}\right] + 1.73, \quad T\sqrt{g/h_2} > 5 \tag{6}$$

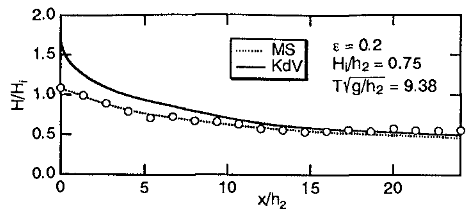
and for the step-type reef,

$$\beta_0 = 4.48\exp\left[-0.0921T\sqrt{g/h_2}\right] + 0.12, \quad T\sqrt{g/h_2} > 5 \tag{7}$$

Figure 12 shows typical examples of experimental wave height distributions for periodic waves on the slope-type reef, comparing with numerical results by the MS and KdV equations without bottom friction. The abscissa is taken as the distance from the reef edge and the ordinate denotes the dimensionless wave height. In the MS equation the coefficient of wave energy dissipation f_d with β_0 given by Eq.(6) is used in estimation of wave damping, whereas the coefficient of energy dissipation in the KdV equation is evaluated by

$$\kappa = f_d/4 \tag{8}$$

to express the effect of wave breaking by the term of diffusion. Generally, for shorter period waves the wave height distributions by the MS equation agree well with experimental ones, whereas



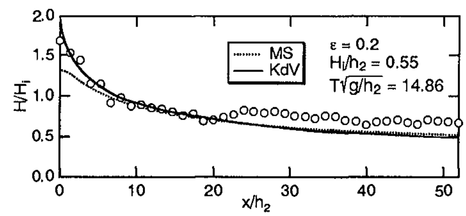


Figure 12. Wave height distributions on the slope-type reef.

the KdV equation gives good estimation of the wave height distributions for longer period waves. This reason is that, for longer period waves, the breaking wave heights at the reef edge estimated by KdV equation are agree fairly with experimental ones, but the MS equation shows to underestimate them. Therefore, the discrepancy between the calculated and experimental values of relative wave height near breaking point becomes remarkably. However, in a region far from the reef edge, both the MS and KdV equations are applicable for wave height estimation after wave breaking.

Wave height prediction on Sanur coral flat

As mentioned previously, wave setup takes place on the coral flat due to wave breaking. Hereafter, the amount of wave setup Δh is assumed to be 30 cm according to the results of

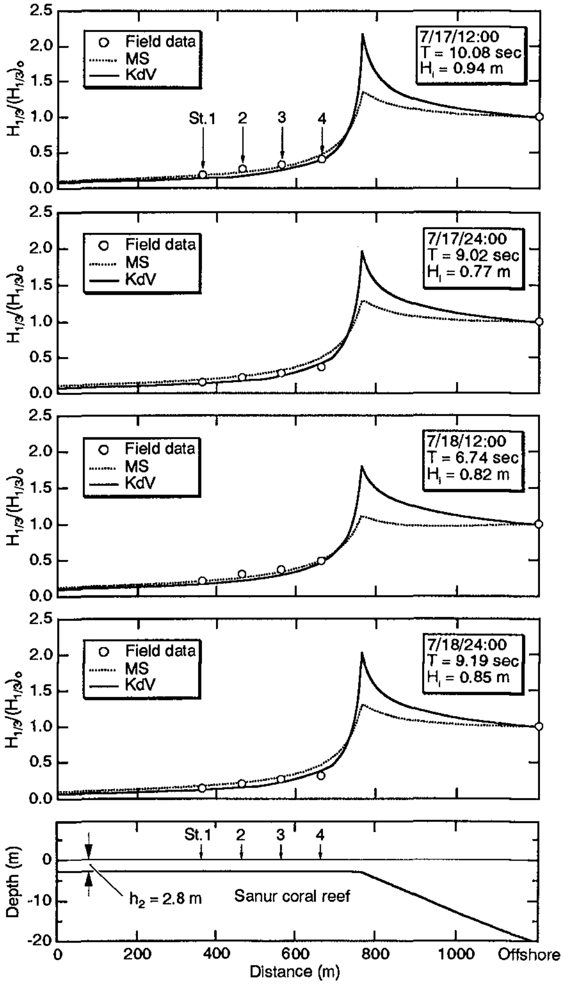


Figure 13. Wave height prediction on Sanur coral flat with the MS and KdV equations.

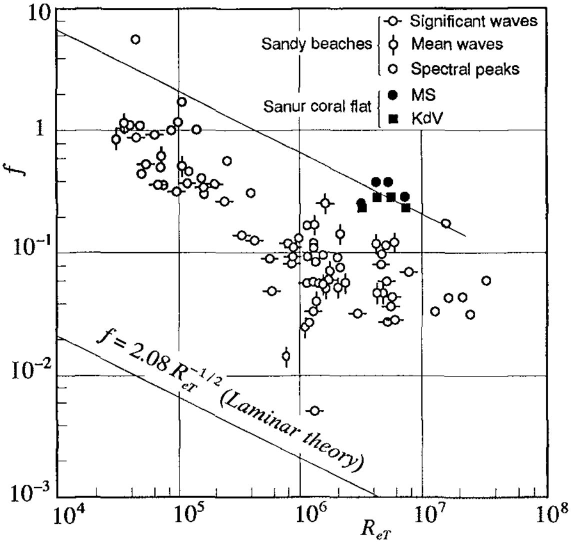


Figure 14. Coefficient of bottom friction on Sanur coral flat.

Goda (1975) and Hino et al. (1989).

When the significant waves on the coral flat at high tide were estimated by the MS and KdV equations, taking into account only of wave damping due to breaking, the values of wave heights were greater than those of observation. The result indicates the significant role of bottom friction to the wave energy dissipation on the coral flat. However, the value of the coefficient of bottom friction in the coral flat is unknown. Therefore, the coefficient of bottom friction was evaluated such that wave heights estimated coincide with the observed data. Figure 13 shows the results of prediction of significant wave heights on the coral flat at the highest tidal level of water, where the distance is taken offshore-ward from the shoreline. Discrepancy in numerical estimations by the MS and KdV equations (solid and dotted lines) becomes remarkably near the breaking point, i.e., the reef edge. The relative distances between the measuring station 4 and the reef edge are within $35 < x/h_2 < 40$, showing that all the measuring stations are located in the region where the damping of wave heights due to breaking is not effective, as shown in Figure 12. The MS and KdV equations, therefore, predict well the wave height distributions observed.

On the bottom friction, as seen in the data for sandy beaches shown by open symbols in Figure 14 (e.g., Iwagaki & Kakimuna, 1962), there exists a linear relation between the coefficient of bottom friction f and the wave Reynolds number $R_{eT} = u_{b\max}^2 T/\nu$, where $u_{b\max} = \sigma H/2\sinh kh$, k is the wave number, and ν is the kinematic viscosity. The values of bottom friction on Sanur coral flat are plotted by the solid symbols (●, ■). The coral flat composed of unevenness is covered by sea glasses so densely that the bottom friction is evaluated greater than those on sandy beaches. The values of bottom friction on the coral flat are not enough to design the relation, but may follow the linear relation shown in the figure by the solid line.

THE MAXIMUM WAVE ON THE CORAL FLAT

Wc consider two kinds of the maximum waves on the coral flat in relation to the rate of wave breaking near the reef edge. Waves of small wave heights can propagate on the coral flat without breaking but the waves may break after propagation of some distances when they become large. The first kind of the maximum wave is then for progressive waves propagating onto the coral flat without breaking. Figure 7 has already indicated the incident possibility of long-period waves into Sanur beach. Due to the low breaking rate of irregular waves at the reef edge, the maximum wave arriving at the shore is therefore subjected to this breaking criterion for progressive waves on the reef. As the results of experiments for periodic waves on the step-type reef (Tsutsui & Zamami, 1993), this breaking criterion is given by

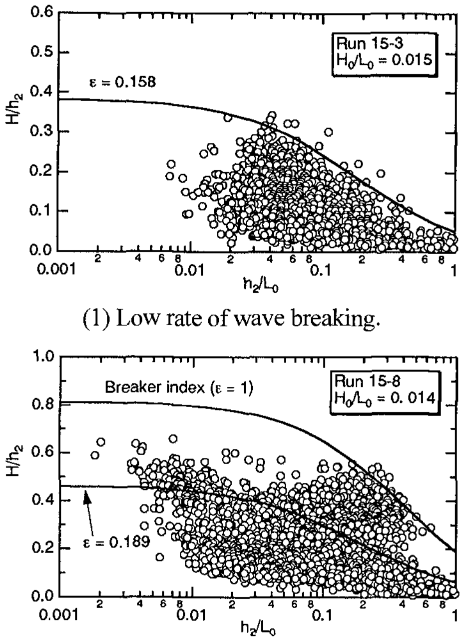
$$\frac{H_b}{h_2} = \frac{c_0}{1 + c_1 \zeta + c_2 \zeta^2}, \qquad \zeta \equiv \frac{2\pi h_2}{L_0} \tag{9}$$

with

$$\left.\begin{aligned} & c_0 = 2.45\ \varepsilon, \quad \text{for } \varepsilon < 0.2 \\ & c_0 = 0.4 \frac{1 + 1.34\sqrt{\varepsilon - 0.17}}{1 + 0.1\sqrt{\varepsilon - 0.17}}, \quad \text{for } \varepsilon \geq 0.2 \\ & c_1 = 1 - 0.6\ \varepsilon, \qquad c_2 = 0.02 \end{aligned}\right\} \tag{10}$$

On the other hand, when incident waves are relatively large to the water depth, they break very close to the reef edge on the step-type reef, forming partial standing waves in the offshore deeper region of the reef, but they break near the reef edge on the slope-type reef. In this case of high wave breaking rates of irregular waves, the second kind of the maximum wave arriving at the shore is subjected to the waves that are reformed after strong wave breaking.

As the results of experiments for irregular waves on the step-type reef, Figure 15 shows examples of the relationship between the wave height relative to the water depth on the coral flat, H/h_2, and the shallowness h_2/L_0, where all the individual waves measured in the reforming region after wave damping due to breaking are plotted by the open circle. In the parameters, L_0 is the wave length in deep water for the individual wave and H_0/L_0 is the wave steepness in deep water for the significant waves. In the upper figure (1), the significant wave height is smaller than the critical wave height shown by the solid line, Eqs.(9) and (10), and it seems that the rate of wave breaking is low. This solid line indicates the maximum wave, which shows the envelope of the data.



(1) Low rate of wave breaking.

(2) High rate of wave breaking.

Figure 15. Maximum waves on the step-type reef according to the rate of wave breaking.

The result in the case of high wave breaking rate is shown in the lower figure (2), where the significant wave height is larger than the critical wave height shown by the lower solid line, and most waves break at the reef edge. The upper solid line with $\varepsilon = 1$ indicates the breaker index for the flat sea bottom (Goda, 1970), an approximation of the highest wave of permanent-type on water of uniform depth (Yamada and Shiotani, 1968), and it becomes the envelope of all the experimental data. Therefore, the maximum wave after strong wave breaking near the reef edge is determined by the breaker index for the flat sea bottom.

Similarly, the relation of the relative wave height H/h_2 on Sanur coral flat and the shallowness h_2/L_0 is shown in Figure 16, where all the individual waves measured at the station 4 near the highest tidal phase are plotted by the open circle. The breaker type near the reef edge is for progressive waves because Sanur beach is of slope-type reef with the offshore slopes of 1/20 - 1/50. Therefore, we can use Eqs.(9) and (10) as the breaking criterion, when the water depth ratio $\varepsilon = h_2/h_1$ is given as the ratio of the water depth h_2 on the coral flat to the offshore water depth h_1, where the shoaling coefficient given by the small amplitude wave theory takes unity, i.e., $h_1/L_0 = 0.057$. The solid lines in Figure 16 show the results. As $h_2/L_0 = 0.017$ - 0.038 and $H/h_2 = 0.303$ - 0.346 for the significant waves, the wave breaking rate is low. Therefore, the curves in Figure 15 indicate the empirical maximum wave on Sanur coral flat with envelopes for the field data. Furthermore, it has been confirmed by laboratory tests that the maximum wave on Sanur coral flat at the high wave breaking rate is also evaluated by the breaker index for the flat sea bottom, as well as for the step-type reef.

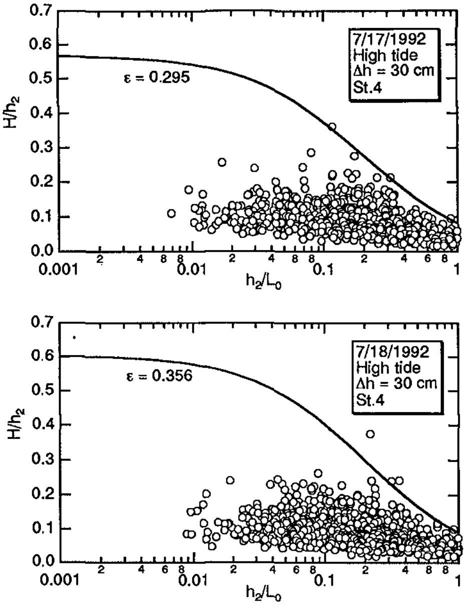


Figure 16. The maximum wave on Sanur coral flat.

CONCLUSIONS

Main conclusions of the present analysis of wave properties and the maximum wave based on the experimental and field data at Sanur coral beach are summarized as:

(1) In Sanur beach, waves in the dry season (June - August) are predominant for the beach process, and they are incident perpendicular to the reef edge. Swells with a period of about 15 sec are most effective for beach change.

(2) The MS and KdV equations with the effects of wave energy dissipation can predict the wave height distribution on the coral flat, when the coefficients of wave breaking and bottom friction are evaluated.

(3) In the case of the low wave breaking rate, the experimental wave height criteria for progressive waves, Eq.(9) and (10), give the maximum wave arriving at the shore without breaking. Contrarily, after full breaking of incident waves near the reef edge, the maximum wave on coral flats can be determined by the breaker index for flat sea bottom.

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Appendix: The coefficient β_0 for the slope-type reef as $T\sqrt{g/h_2} \to \infty$

If the small amplitude wave theory is applied in Eqs.(4) and (5), we have

$$\frac{d}{d\xi}\left(H^2 c_g\right) = -\frac{\beta_0}{8}\left[\left(\frac{H}{h}\right)^2 - \left(\frac{H}{h}\right)_s^2\right]\frac{H^3}{h^2} c_g \tag{A.1}$$

where the effect of bottom friction is neglected. Dividing by $H^2 c_g$ and integrating with respect to ξ within a small increment $\Delta\xi = \xi_2 - \xi_1$ give

$$\frac{H_2}{H_1} = \left(\frac{c_{g1}}{c_{g2}}\right)^{1/2} \exp\left[-\frac{\beta_0}{16}\sqrt{1-\left(H_s/H_b\right)^2}\left(\frac{H_1}{\bar{h}}\right)^2 \frac{\Delta\xi}{\bar{h}}\right] \tag{A.2}$$

where the subscripts 1 and 2 denote quantities at the locations ξ_1 and ξ_2, respectively, and $\bar{h}$ is the mean water depth within the increment $\Delta\xi$.
By introducing the bore model, Le Méhauté (1963) evaluated the energy dissipation rate of solitary wave as a spilling breaker as;

$$\frac{H_2}{H_1} = \frac{h_1}{h_2}\left(\frac{c_1}{c_2}\right)^{2/3} \exp\left[-\frac{\sqrt{3}}{16}\left(\frac{H_1}{\bar{h}}\right)^{5/2} B \frac{\Delta\xi}{\bar{h}}\right] \tag{A.3}$$

$$\text{with } B = \frac{[(1+H/h) - \beta(1+\beta H/h)]}{(1+H/h)(1+\beta H/h)}(1-\beta)^3 \tag{A.4}$$

where β is the dimensionless parameter that defines the range of surface disturbance due to wave breaking and then $0 \le \beta \le 1$. The condition that $\beta = 1$ corresponds to non-breaking ($B = 0$), and $\beta = 0$ to full breaking ($B = 1$). The coefficient B is then call the breaking coefficient. In case of non-breaking, Eq.(A.2) gives the so-called Green's law for long period waves as : $H_2/H_1 \approx (h_1/h_2)^{1/4}$, and Eq.(A.3) gives $H_2/H_1 \approx (h_1/h_2)^{4/3}$. This difference is due to the validity of using the solitary wave theory in analyzing wave motion on a slope. However, Eq.(A.3) is applicable for waves on the coral flat because the coefficients of the exponential terms in Eqs.(A.2) and (A.3) can be approximated as unity. Equation (A.2) must be asymptotic to Eq.(A.3) as $T\sqrt{g/h_2} \to \infty$. Comparing the coefficients in the exponential damping terms gives

$$\beta_0 = \sqrt{3}\sqrt{H_1/\bar{h}}\, D, \qquad D = B\,/\sqrt{1-\left(H_s/H_b\right)^2} \tag{A.5}$$

It is easy to show that the effect of sea bottom slope on the parameter D in Eq.(A.5) through the wave height is very small, by using the breaker index (Goda, 1970) and assuming the breaking point to be the reef edge. Furthermore, waves on slopes steeper than 1/50 break completely (Le Méhauté, 1963). We can thus approximate as $\beta \approx 0$ and $D \approx 1$. Consequently, the coefficient β_0 for longer period waves depends only on the breaking wave height $(H/h)_b$, i.e.,

$$\beta_0 = \sqrt{3}\,\sqrt{(H/h)_b} \tag{A.6}$$

Since $\sqrt{(H/h)_b} = 1.01$ for solitary wave propagating on the gentle slope of 1/20, the coefficient β_0 can be approximated by $\beta_0 \approx \sqrt{3}$ when $T\sqrt{g/h_2} \rightarrow \infty$. Note that the breaking wave height takes values within $0.91 < \sqrt{(H/h)_b} < 1.17$ for the sea bottom conditions varying from the uniform water depth to the slope of 1/10.

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