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Wave transformation on a coral reef

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Abstract

Wave transformation of regular waves was measured in a laboratory model of a fringing reef with a steep face and an outer reef-top slope gradually decreasing in the landward direction. Data was obtained for various wave conditions and water levels. A nonlinearity parameter, $F_{co} = g^{1.25}H_o^{0.5}T^{2.5}/h_e^{1.75}$, based upon one proposed by Swart and Loubser (1979), is proposed as a suitable parameter for classifying wave transformation regimes on this reef. In particular, when $F_{co} > 150$, waves plunge on the reef edge and the amount of wave energy reaching a shore or structure is small ($< 16\%$). When $F_{co} \leqslant 100$, waves spill on the reef-top but the greater part of their energy is transmitted over the reef-top. The maximum values of the wave height to water depth ratio on the reef-top were found to be consistent with Nelson's analyses for laboratory and field data which indicate that the maximum stable wave height to depth ratio H/d on a horizontal bottom never exceeds 0.55 for shallow water waves ($F_c > 500$). The experimental data confirms that the maximum value of H/d decreases when F_c decreases but that it also increases when the bottom slope increases.

1. Introduction

Coral reefs occur in the tropical regions of the Pacific, Indian and Atlantic Oceans as fringing reefs surrounding island and continental land masses, as barrier reefs and as separate atolls and island reefs (Davies, 1972). In the Great Barrier Reef region off northeastern Australia reefs are used as platforms for locating navigation aids and weather stations. As tourism expands various structures are being provided for visitors to observe and experience the reef environment and some reef-top islands (cays) have had tourist resorts located on them (Gourlay, 1983a,b). In the Great Barrier Reef region and elsewhere among the island nations of the Pacific and Indian Oceans, boat access channels and harbours have been dredged in reefs and breakwaters, seawalls, groynes and causeways constructed to protect or link various facilities located on reefs or reef-top islands (Gourlay and Flood, 1981; Gourlay, 1983b; Coleman, 1991). The formation and shoreline stability of reef-top islands is primarily determined by wave action (Gourlay, 1988).

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The design of reef-top structures requires an understanding of how waves break on reefs and how they are transformed as they travel across the reef-top. With regard to the Great Barrier Reef region Dexter (1973) developed a computational scheme for shallow water reef-top waves which was applied to the design of automatic weather stations, while Nelson and Lesleighter (1985) carried out physical model experiments to determine design wave parameters for navigation aids. More recently Young (1989) attempted to investigate in the field the attenuation of waves as they propagate across a reef platform. Subsequently, successful field measurements of waves breaking on a reef and propagating into a lagoon were obtained by Hardy et al. (1991a,b) and Hardy and Young (1991). Other studies of waves on reefs elsewhere have been made by Roberts et al. (1975), Lee and Black (1979), Gerritsen (1981a,b), Kono and Tsukayama (1980) Roberts (1981) and Jensen (1991). A summary of the results of these studies has been presented by Gourlay (1991).

Coral reefs commonly grow to about mean low tide level and in their mature form of a planar reef are essentially horizontal. Hence at low tide waves will break on the reef edge and no significant wave energy will be propagated across the reef-top. However, at high tide depth-limited waves are able to propagate across the reef-top. In the Great Barrier Reef region tide ranges may be as great as 3 to 4 m and water depths of 2 to 3 m over reefs at high tide are common. During the passage of cyclones storm surge could increase these depths by 0.3 to 0.5 m or more depending upon the intensity and path of the cyclone. Under such conditions it is essential for design purposes that the maximum depth-limited wave condition be reliably predicted.

Current coastal engineering practice (CERC, 1984) adopts a value of the breaker height to water depth ratio $H_b/d_b = 0.78$ for the limiting case of a horizontal bottom*. This value is based upon solitary wave theory (Munk, 1949). In a series of papers Nelson (1983, 1985, 1937, 1994) has shown that, when all available laboratory data for waves propagating over a horizontal bottom are considered, the maximum value of H_b/d_b never exceeds 0.55. In his last paper he has extended this analysis to the field data obtained by Hardy et al. (1991a,b) and again has found that, when allowance is made for the effects of tides and infragravity waves on the magnitude of the mean water depth, the maximum value of H_b/d_b never exceeds 0.55 on a horizontal bottom. Since the wave energy reaching a structure is proportional to the wave height squared, the use of $H_b/d_b = 0.78$, rather than 0.55, overestimates the wave energy reaching a structure by a factor of 2. Hence current practice may be unnecessarily conservative.

This paper presents an analysis of laboratory experiments on wave transformation over a natural reef profile and provides further evidence that maximum depth-limited wave heights on a horizontal reef are less than those estimated using current coastal engineering practice. Other aspects of wave transformation on reefs are also examined.

2. The prototype reef

The reef for which experiments were made is a fringing reef located on the southern side of Hayman Island, a continental island in the Whitsunday Group in North Queensland

*See Appendix — Notation for definition of all symbols used in this paper.

(Fig. 1). The geological structure of the reef has been described elsewhere by Hopley et al. (1978, 1983). The typical reef profile adopted for the experiments is shown in Fig. 2. The reef face with a slope of 1 to 4.5 rises from a depth of − 14 or − 15 m to the reef edge at an elevation of about + 1.9 m*. The reef-top is initially sloping but the slope reduces away from the edge until the reef-top becomes horizontal 170 m from the reef edge. The total reef width is of the order of 800 m.

The reef is exposed to a maximum fetch of 30 km in a southwestward direction and wave conditions were hindcast using standard methods for various average recurrence intervals

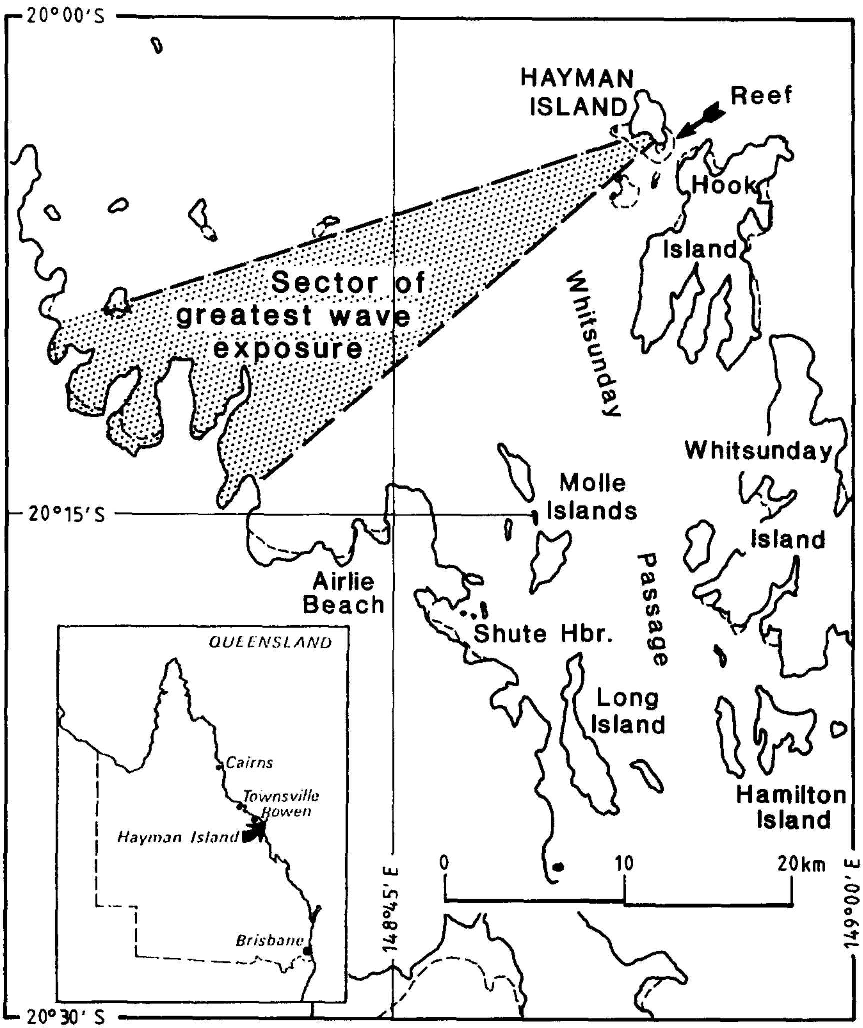

Fig. 1. Location of Hayman Island.

*Project datum is 4.67 m below mean sea level.

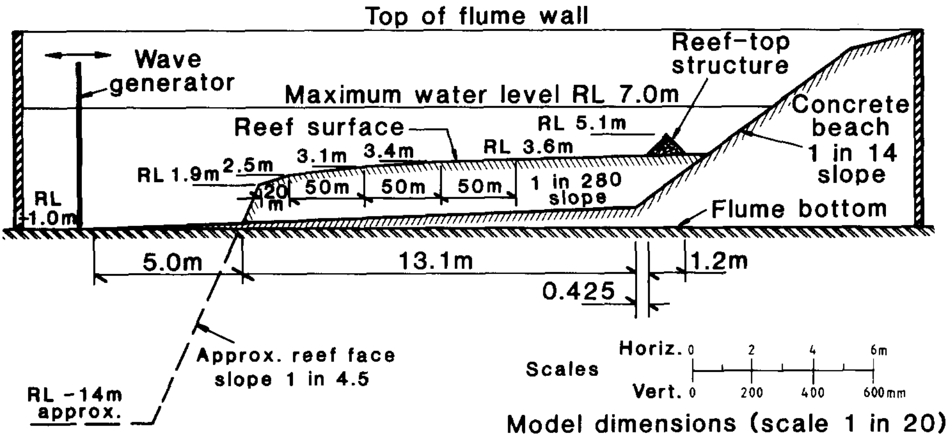

Fig. 2. Reef profile and model arrangement.

up to 50 years. The mean spring tide range is about 3 m. Four water levels were chosen for experiments corresponding to highest astronomical tide (HAT), mean high water springs (MHWS), mean high water neaps (MHWN) and mean sea level (MSL). In each case 0.3 m was added to allow for storm surge.

3. The laboratory model

The wave transformation experiments were made in a 1 in 20 scale two dimensional model of the Hayman Island reef profile (Fig. 2). The model was located in a wave flume 30 m long and 0.9 m wide. The maximum water depth was 0.4 m and this required the offshore water depth to be shallower than in reality. The reef face was cut off at an elevation of -1 m. The model profile was formed in cement mortar with a brushed surface finish. The offshore bottom in front of the model reef had a slope of 1 in 280.

The model had been constructed to investigate the stability of a proposed reef-top structure located 270 m from the reef edge. This structure, which was submerged when the tide was above mean level, had negligible influence upon the breaking and transformation of the waves offshore from it.

Experiments were made with regular waves generated by a suspended wave paddle of the Ransford type (Biesel and Suquet, 1951, pp. 485–487) actuated through a crank and connecting rod mechanism.

Waves were measured using capacitance wave height probes (Moore, 1964). The offshore incident and reflected waves were measured from the antinodal/nodal pattern of the partial standing wave in front of the reef. Thirteen measurements spaced at intervals of one twelfth the local wave length calculated from small amplitude wave theory were made for each experimental condition. Wave heights at each location were the average of 20 individual waves. For analysis purposes the incident wave height H_i was converted to an equivalent deep water value H_o, using small amplitude wave theory. On the reef, waves were measured

Table 1
Test conditions Hayman Island reef model

Test number	Water level[a] m	Water depth			Wave period T, s	Incident wave height H_i, m	Deep water wave height H_o, m	Reflection coefficient –	F_{co} (Eq. 4) –
		reef edge h_e, m	average h_a, m	reef top h_r, m					
1.1	7.0	5.1	4.0	3.4	6.8	3.34	3.61	0.054	221
1.2					6.6	3.18	3.45	0.076	208
1.3					5.9	2.40	2.63	0.033	137
1.4					5.4	2.00	2.19	0.040	100
1.5					4.7	1.54	1.60	0.039	62
1.6					3.8	1.01	1.05	0.073	28
3.1	5.7	3.8	2.7	2.1	6.7	3.34	3.57	0.036	368
3.2					6.6	3.04	3.26	0.026	339
3.3					5.9	2.61	2.84	0.161	239
3.4					5.4	1.93	2.11	0.114	165
3.5					4.7	1.47	1.60	0.047	101
3.6					3.8	0.99	1.04	0.061	48
2.1	5.0	3.1	2.0	1.4	6.8	3.22	3.39	0.037	533
2.2					6.7	3.17	3.35	0.044	510
2.3					5.8	2.80	3.03	0.100	338
2.4					5.4	1.90	2.07	0.126	234
2.5					4.7	1.46	1.60	0.048	146
2.6					3.8	0.96	1.02	0.062	68

[a]Water level is measured relative to project datum which is 4.67 m below mean sea level.

at locations determined by visually observed changes in wave conditions, e.g. breaking, plunge point, end of surf zone, etc.. The number of locations where reef-top waves were measured was not the same for each experiment.

Offshore water level was controlled by a constant head tank connected to the flume by a piezometer tapping. This was necessary to prevent the offshore water level changing as a consequence of the build-up of wave set-up on the model reef. Wave set-up was not measured initially but subsequently six piezometers spaced at 60 m (prototype) intervals were installed in the model reef. Wave set-up measurements were made for the same wave conditions for which wave transformation measurements had been made. The wave set-up results will be discussed in a subsequent paper. In the present analysis the measured wave set-up has been used to determine the actual water depth over the reef.

The experimental programme actually undertaken consisted of three test series, each corresponding to a given tidal condition (Time did not permit one tide condition, MHWS, to be studied). For each test series six wave conditions were measured. All were of approximately the same wave steepness ($H_o/L_o \approx 0.048$). Conditions for each experiment are given in Table 1. Experimental data is given in Tables 2–4*. All experimental values are

*Different symbols are used in the various figures to distinguish data from the three test series — test series 1, squares; test series 2, triangles; test series 3, circles. Each test series corresponds to a different value of the relative depth parameter h_e/h_i.

Table 2
Experimental data. Series 1: water level 7.0 m. $h_e=5.1$ m; $h_a=4.0$ m; $h_r=3.4$ m; $h_i=8.0$ m. Data plotted on figures as squares

Expt No.	1.1		1.2		1.3		1.4		1.5		1.6	
H_o, m	3.61		3.45		2.63		2.19		1.66		1.05	
T, s	6.80		6.62		5.90		5.41		4.69		3.84	
x m	H m	d m	H m	d m	H m	d m	H m	d m	H m	d m	H m	d m
−6	3.52	6.41	3.00	6.43	2.36	6.47	1.96	6.43	1.56	6.43	1.04	6.44
4	3.44	4.95	3.24	4.97	2.68	5.01	1.96	4.97	1.44	4.97	1.00	4.98
9 or 10	3.92	4.77	3.72	4.82	3.08	4.83	–	–	–	–	–	–
14	3.96	4.66	3.32	4.68	–	–	2.16	4.67	1.48	4.67	0.96	4.68
18	–	–	3.28	4.58	–	–	–	–	–	–	–	–
24	–	–	–	–	2.36	4.49	–	–	–	–	–	–
34	2.60	4.38	2.72	4.40	2.20	4.38	1.88	4.32	1.56	4.32	0.96	4.33
54	1.80	4.21	1.80	4.23	2.12	4.15	–	–	–	–	–	–
64	–	–	–	–	–	–	2.16	3.96	–	–	–	–
74	1.88	4.05	2.00	4.08	1.96	3.96	2.40	3.87	–	–	–	–
84	–	–	–	–	1.92	3.90	2.20	3.81	–	–	–	–
94	1.72	3.95	1.48	3.97	1.80	3.85	2.12	3.76	–	–	–	–
104	1.68	3.90	–	–	1.88	3.80	–	–	–	–	–	–
114	1.72	3.85	1.76	3.86	1.84	3.74	–	–	–	–	–	–
124	–	–	–	–	1.96	3.69	–	–	–	–	–	–
134	–	–	–	–	1.96	3.66	2.40	3.55	–	–	–	–
154	1.28	3.70	–	–	1.64	3.58	–	–	–	–	–	–
174	–	–	–	–	–	–	2.12	3.44	–	–	–	–
194	1.40	3.64	1.80	3.64	1.24	3.53	2.16	3.45	1.36	3.39	–	–
224	–	–	–	–	–	2.08	3.46	–	–	–	–	
234	–	–	–	–	–	1.76	3.46	–	–	–	–	
244	–	–	–	–	–	1.64	3.47	–	–	–	–	
x_b, m	10 Pl[a]		10 Pl		18 Sp		124 to 154 Sp		–		–	
x_s, m	124		94		124		224 to 234		–		–	

[a]Breaker type. Pl — plunging; Sp — spilling.

presented in prototype units, having been scaled using Froude law similarity for undistorted free surface models where gravity forces predominate.

Subsequent to the completion of the experiments, numerical computations were made with the full reef height. Their results indicate that, apart from reducing wave reflection to some extent, the reduced off-reef water depth in the model did not affect wave transformation and set-up on the reef-top significantly (S. Massel, personal commun., September 1992).

4. Wave shape parameter for classifying wave conditions

Nelson (1983, 1987, 1994) has used a nonlinear parameter F_c proposed by Swart and Loubser (1979) for classifying waves on a horizontal bottom.

Table 3
Experimental data. Series 2: water level 5.0 m. $h_e = 3.1$ m; $h_a = 2.0$ m; $h_r = 1.4$ m; $h_i = 6.0$ m. Data plotted on figures as triangles

Expt No.	2.1		2.2		2.3		2.4		2.5		2.6	
H_o, m	3.39		3.35		3.03		2.07		1.60		1.02	
T, s	6.75		6.66		5.81		5.36		4.69		3.80	
x m	H m	d m	H m	d m	H m	d m	H m	d m	H m	d m	H m	d m
−6	3.32	4.48	2.96	4.45	2.68	4.50	1.92	4.43	1.48	4.43	0.96	4.45
4	3.12	3.02	3.04	2.99	2.64	3.04	2.24	2.97	1.76	2.97	1.00	2.99
8	–	–	–	–	–	–	–	–	1.84	2.85	–	–
14	2.72	2.72	2.68	2.69	2.20	2.74	1.48	2.67	1.48	2.67	1.04	2.69
24	1.64	2.54	–	–	–	–	–	–	–	–	–	–
34	1.56	2.47	1.36	2.45	1.16	2.49	1.08	2.39	1.08	2.35	1.00	2.33
44	–	–	–	–	–	–	1.04	2.30	–	–	–	–
54	In.16	2.33	–	–	–	–	0.96	2.22	1.08	2.15	–	–
74	0.88	2.21	0.88	2.21	1.16	2.23	0.80	2.07	0.92	1.97	1.00	1.88
94	–	–	–	–	–	–	–	–	–	–	1.00	1.77
104	–	–	–	–	–	–	–	–	0.88	1.79	–	–
114	1.24	1.98	0.52	2.00	–	–	0.84	1.83	0.88	1.72	1.16	1.66
134	–	–	–	–	–	–	–	–	0.84	1.63	0.76	1.57
154	0.68	1.80	0.72	1.83	–	–	0.80	1.66	0.76	1.55	0.68	1.49
164	–	–	–	–	–	–	–	–	0.68	1.52	0.64	1.45
174	–	–	–	–	–	–	–	–	0.80	1.50	0.60	1.43
194	0.80	1.75	0.56	1.77	0.44	1.77	0.52	1.60	0.52	1.51	0.68	1.44
234	0.60	1.75	0.48	1.77	–	–	–	–	–	–	–	–
x_b, m	8 Pl[a]		6 Pl		0 Pl		4 Pl		8 Sp		74 Sp	
x_s, m	74		104		74		54		74		164	

[a]Breaker type. Pl — plunging; Sp — spilling.

$$F_c = \frac{g^{1.25} H^{0.5} T^{2.5}}{h^{1.75}} \tag{1}$$

F_c can be related to the shallow water form of the Ursell parameter U as follows

$$U = \frac{HL^2}{h^3} = \frac{gHT^2}{h^2} \tag{2}$$

since $L = CT$ and $C = \sqrt{gh}$ in shallow water. Hence

$$F_c = U\left(\frac{L}{H}\right)^{0.5} \tag{3}$$

in shallow water.

According to Nelson (1994), "the main implication of F_c is that waves of equal F_c have

Table 4
Experimental data. Series 3: water level 5.7 m. $h_e = 3.8$ m; $h_a = 2.7$ m; $h_r = 2.1$ m: $h_i = 6.7$ m. Data plotted on figures as circles

Expt No.	3.1		3.2		3.3		3.4		3.5		3.6	
H_o, m	3.57		3.25		2.84		2.11		1.60		1.05	
T, s	6.70		6.62		5.90		5.40		4.69		3.84	
x m	H m	d m	H m	d m	H m	d m	H m	d m	H m	d m	H m	d m
−6	3.88	5.14	3.00	5.13	2.72	5.14	2.04	5.13	1.40	5.13	1.00	5.13
4	3.72	3.68	3.36	3.67	3.00	3.68	2.20	3.67	1.64	3.67	1.04	3.67
8 or 9	3.68	3.56	–	–	3.08	3.56	–	–	1.80	3.52	–	–
14	3.16	3.38	2.88	3.37	2.60	3.38	2.40	3.37	1.88	3.37	1.00	3.37
24	–	–	–	–	–	–	–	–	1.64	3.14	–	–
34	1.96	3.14	1.72	3.13	1.64	3.10	1.44	3.07	1.40	3.02	1.00	3.02
44	–	–	–	–	–	–	–	–	1.40	2.90	–	–
54	–	–	–	–	1.29	2.94	1.20	2.87	1.40	2.78	1.00	2.78
64	–	–	–	–	–	–	1.08	2.77	1.40	2.67	–	–
74	1.24	2.89	1.44	2.88	1.16	2.78	1.04	2.70	1.16	2.58	1.00	2.57
84	–	–	–	–	–	–	–	–	0.96	2.53	–	–
94	–	–	1.24	2.77	1.08	2.67	–	–	1.32	2.48	0.92	2.45
104	–	–	–	–	–	–	–	–	1.08	2.43	–	–
114	1.12	2.68	1.12	2.67	1.04	2.55	0.68	2.47	0.64	2.38	1.00	2.33
134	–	–	–	–	–	–	–	–	–	–	1.00	2.23
154	1.00	2.51	0.92	2.50	1.08	2.38	0.72	2.30	0.44	2.23	1.12	2.15
174	1.36	2.45	1.56	2.44	0.92	2.32	0.76	2.24	–	–	0.96	2.10
194	1.20	2.45	1.08	2.44	0.92	2.32	0.96	2.25	0.44	2.18	1.04	2.11
214	–	–	–	–	–	–	–	–	–	–	0.96	2.11
234	0.92	2.45	1.00	2.43	0.84	2.32	0.52	2.25	0.28	2.18	0.84	2.11
244	0.88	2.45	0.88	2.43	0.96	2.32	0.64	2.25	0.36	2.18	0.84	2.11
x_b, m	8 Pl[a]		−6 Pl		8 Pl		12 Pl		14 Sp		164 Sp	
x_s, m	114		104		99		78		34		238	

[a]Breaker type. Pl — plunging; Sp — spilling.

approximately the same relative wave shape''. Furthermore, F_c can also be used to define shallow, intermediate and deep water conditions, i.e.

Shallow water waves $500 > F_c$
Intermediate depth water waves $10 < F_c < 500$
Deep water waves $F_c < 10$

For application to wave transformation on reefs, F_c will be defined by conditions occurring at the reef edge, assuming the waves breaking on the reef are deepwater ones. Hence

$$F_{co} = \frac{g^{1.25} H_o^{0.5} T^{2.5}}{h_e^{1.75}} \tag{4}$$

where h_e is the water depth at the reef edge (Fig. 3).

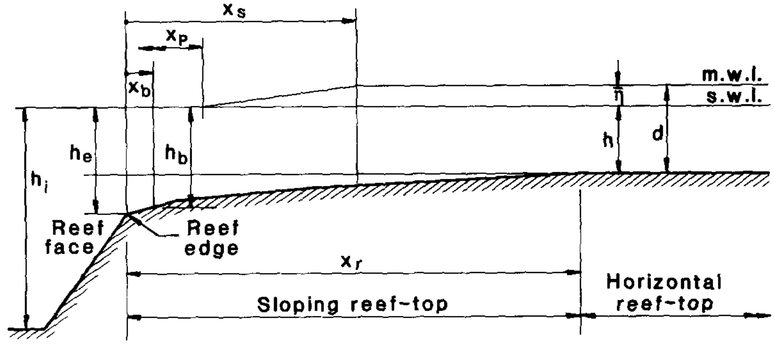

Fig. 3. Definition of terms.

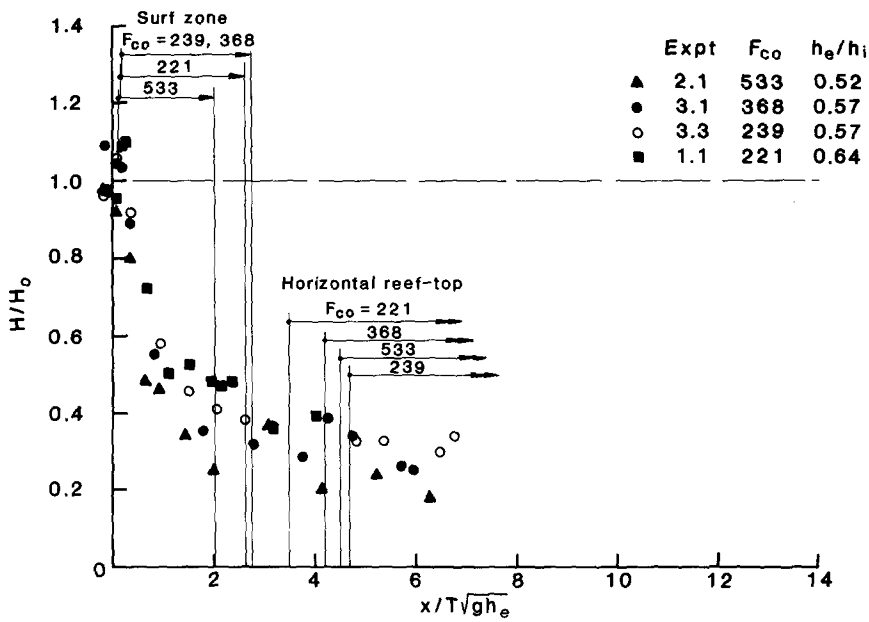

Fig. 4. Wave transformation on reef-top. Waves plunging on reef edge ($530 > F_{co} > 160$).

5. Wave transformation through surf zone

Following Nelson and Lesleighter (1985), the transformation of waves as they break, become a moving surge and then reform as oscillatory waves propagating over the reef-top, is shown in a plot of the dimensionless wave height H/H_i as a function of relative distance $x/(T\sqrt{gh})$. For a horizontal reef-top $x/(T\sqrt{gh})$ represents the number of small amplitude

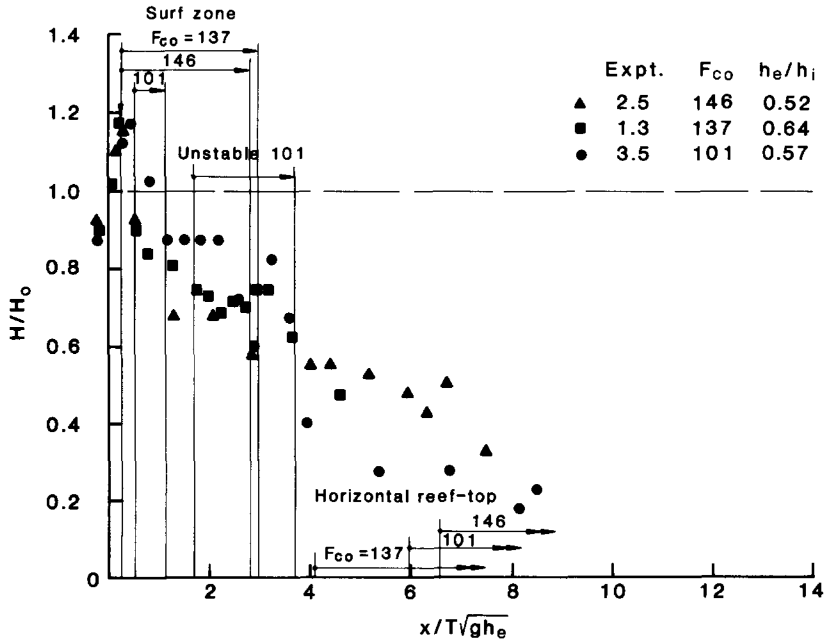

Fig. 5. Wave transformation on reef-top. Waves spilling on outer reef-top ($150 > F_{co} > 100$).

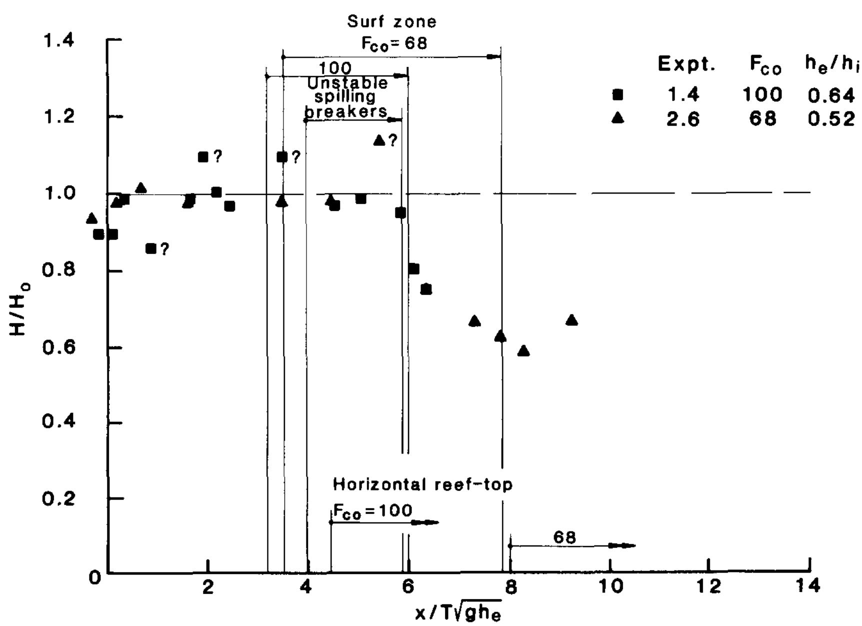

Fig. 6. Wave transformation on reef-top. Waves spilling on gently sloping reef-top ($100 > F_{co} > 65$).

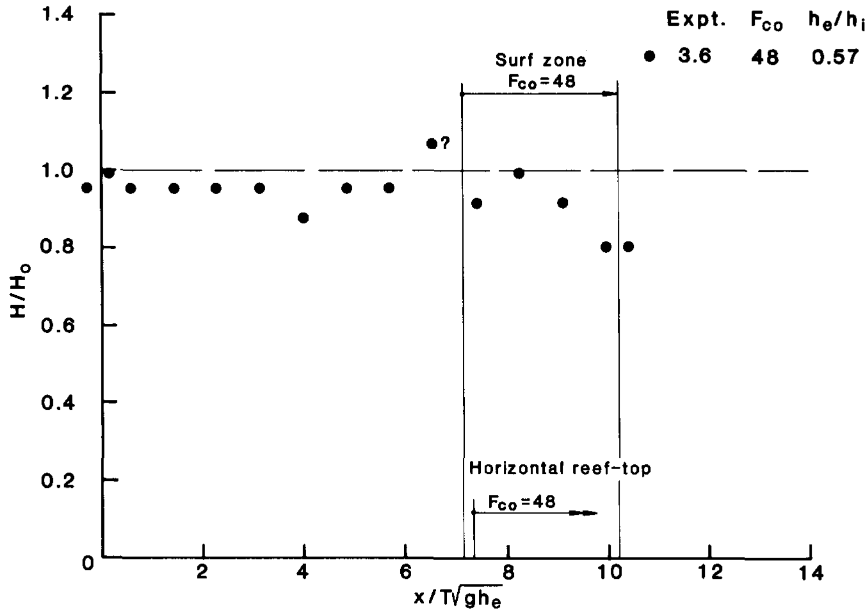

Fig. 7. Wave transformation on reef-top. Waves passing over reef-top with negligible breaking ($65 > F_{co} > 25$).

waves between the reef edge and a given location. As for the definition of F_{co} for a coral reef, H_i is replaced by H_0 and h by h_e in this analysis.

For each individual experiment H/H_0 was plotted as a function of $x/(T\sqrt{gh_e})$. These plots were then ranked in order of decreasing F_{co}. A logical and consistent pattern was clearly evident with four basic wave transformation regimes. These are shown on Figs. 4 to 7 which include 10 of the 18 experiments undertaken. The extent of the surf zone for each experiment is shown at the top of each figure and the point where the horizontal reef-top commences is shown above the horizontal axis. The latter point occurs at a different value of $x/(T\sqrt{gh_e})$ for each experiment.

For $530 > F_{co} > 160$ (Fig. 4) the waves plunge on the reef edge and dissipate significant wave energy in the outer surf zone between the break point and the plunge point. The magnitude of H/H_0 at break point, plunge point and for the reformed waves tends to increase as F_{co} decreases. Since H_0/L_0 ($=2\pi H_0/gT^2$) is approximately constant for these experiments a decrease in F_{co} is equivalent to a decrease in H_0/h_e. Waves with larger values of H_0/h_e break further seaward on the reef face and dissipate a greater proportion of their energy than waves with smaller values of H_0/h_e. For waves plunging on the reef edge, the magnitudes of H/H_0 on the reef-top also generally decrease with decreasing values of the depth ratio h_e/h_i.

For $150 > F_{co} > 100$ (Fig. 5) the waves increase in height as they cross the reef edge and then break by spilling on the outer reef-top. The amount of energy dissipated is not as great as for waves plunging on the reef-edge. Consequently the reformed waves at the landward end of the surf zone are higher.

For $100 > F_{co} > 65$ (Fig. 6) the waves pass over the reef edge without breaking and their height remains almost constant before they become unstable and break by spilling further inshore on the gently sloping reef-top.

For $65 > F_{co} > 25$ (Fig. 7) the waves may just become unstable on the horizontal reef-top or pass over it without breaking. Clearly for smaller values of F_{co}, waves on the reef-top approach deep water conditions and their propagation is not significantly influenced by the reef.

Reef-top breaking conditions are different to those on a plane beach. However, the breaking conditions on the reef face and sloping reef-top are not dissimilar to those over an offshore bar. Smith and Kraus (1991) have recently presented experimentally derived criteria for breaker type on barred profiles, based upon the surf similarity parameter ξ_o, ie
spilling breakers occur when $\xi_o < 0.4$
plunging breakers occur when $0.4 < \xi_o < 1.2$
where

$$\xi_o = (\tan\alpha) / \sqrt{H_o/L_o} \tag{5}$$

and $\tan\alpha$ is the bottom slope. These criteria are not the same as those proposed by Battjes (1974) for plane beaches.

For $H_o/L_o \approx 0.048$ in these experiments and
(i) reef edge slope of 0.030, $\xi_o = 0.138 \rightarrow$ spilling breakers
(ii) reef face slope of 0.25, $\xi_o = 1.14 \rightarrow$ plunging breakers

The breaking behaviour on the Hayman Island reef model in the first two transformation regimes is consistent with Smith and Kraus criteria for breaker types on barred profiles.

5. Relative energy dissipation

The relative energy dissipation on the reef-top as a consequence of the transformation and dissipation processes is shown on Fig. 8. Taking energy as proportional to H^2, E/E_o at $x/(T\sqrt{gh_e}) = 5$ is plotted as a function of F_{co}. There is some uncertainty concerning the correct value of E/E_o for some tests (indicated by ?) because of the lack of experimental observations in the vicinity of $x/(T\sqrt{gh_e}) = 5$ and some values are extrapolated. Hence the trend of the data on Fig. 8 is indicated by a scatter band rather than a single line. Nevertheless, apart from the two experiments where $F_{co} = 100$, the trend is very clear. For waves plunging at the reef edge ($F_{co} > 160$) energy dissipation within the first five wave lengths from the reef edge is substantial. For $F_{co} = 200$ between 85 and 90% of the energy is dissipated while, for $F_{co} > 500$, 95% is dissipated. The laboratory experiments of Nelson and Lesleighter (1985) for which $F_{co} > 590$ give 93 to 98% energy loss. Field measurements behind a continuous offshore reef by Roberts (1981) showed 92 to 97% energy loss depending upon tide level. Kono and Tsukayama (1980) found similar values from their field observations when waves were steep.

On the other hand for $F_{co} < 160$, when waves are spilling on the reef-top, the proportion of wave energy dissipated decreases rapidly as F_{co} reduces. The only significant inconsistency in the data occurs for the two experiments where $F_{co} \approx 100$. In this case the particular shape of the reef-top creates a situation where the waves in experiment 1.4 at the higher water level ($h_e/h_i = 0.64$) pass over the reef edge without breaking, shoal, become unstable

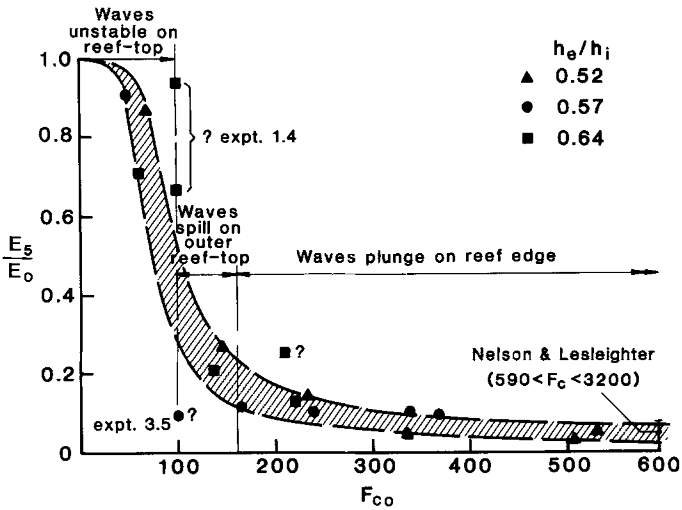

Fig. 8. Relative energy dissipation at $x/(T\sqrt{gh_e})=5$ as a function of F_{co}.

and continue to propagate with slight spilling and apparently negligible energy loss. As discussed later there is reason to believe that the measured wave heights in this experiment are increased by reflection either from the beach at the end of the flume or cross oscillations. Adjusting the value of E/E_o to that equivalent to the maximum possible H/d on a horizontal bottom makes this experiment consistent with the others. With regard to the experiment 3.5 at the lower water level ($h_e/h_i=0.57$), breaking occurs by spilling at the reef edge and there is a region of instability on the gently sloping portion of the reef edge where significant energy dissipation occurs. Such indeterminacy is unlikely to occur on a horizontal reef-top where reef-top wave heights cannot be increased by shoaling after the wave has crossed the reef-edge. It is also possible that the different breaking behaviour in these two experiments is associated with slightly different values of the relative depth ratio h_e/h_i.

When F_{co} decreases below 100 substantial wave energy is transmitted across the reef-top as the breaking process becomes less intense and the waves approach the deepwater condition.

6. Surf zone hydraulics

6.1. Surf zone regions

Using the ideas of Svendsen (1984), the author previously has divided the surf zone on a plane beach into three regions (Gourlay, 1992).

(i) Outer region

In this region there is rapid change in wave shape as the surf roller is developing. There is no significant change in momentum flux and the reduction in wave height is associated with transformation of potential energy into kinetic energy. Wave set-down is usually constant in this region. For plunging breakers the width of this region is approximately identical to the plunge distance of the breakers.

(ii) Inner region

In this region the surf roller developed in the outer region becomes a bore or moving hydraulic jump which travels landward over the seaward flowing undertow. Dissipation of energy and set-up begin at the transition between inner and outer regions.

(iii) Swash region

This is the region where the uprush–backwash cycle occurs on the beach face. The uprush–backwash cycle is essentially an oscillation superimposed on the maximum surf zone mean water level or set-up.

When breaking conditions on a horizontal or near horizontal reef are considered it is found that similar zones can be found whenever waves break upon the reef edge. There is an outer region where the waves break at the reef edge (plunging) or on the outer reef-top (spilling). However, while theoretical analysis has not been undertaken, it is probable that conditions in this region are different to those on a plane beach because of the strong seaward return flow over the reef edge causing significant energy dissipation under certain conditions (Nelson and Lesleighter 1985). Smith and Kraus (1991) also noted that under certain conditions ($\xi_o > 0.85$) return flow over submerged bars altered the breaking conditions.

On a horizontal or near horizontal reef the inner region corresponds to the region where the breaking surge propagates over the reef top and this region ends where the breaking surge dissipates and oscillatory waves reform. Observations on the Hayman Island model and on an idealised two dimensional reef model show that wave set-up reaches a maximum at the end of the inner region where energy dissipation by wave breaking ceases (Gourlay, in preparation).

When waves break on the horizontal or near horizontal reef-top ($F_{co} < 100$) there is only one surf zone region where waves become unstable and excess energy is dissipated by spilling without the formation of a bore.

In the reef situation the third surf zone region, the swash zone, may be nonexistent if there is no land present. This will be the case for a platform type reef in open ocean. Alternatively, in the case of a fringing reef or a platform reef or atoll with a reef-top island (cay), the swash zone will be decoupled from the outer and inner surf zone regions and there will be a separate breaker zone on the cay beach. Usually the latter will be either a steep beach where the swash zone dominates or an intermediate slope beach on which waves plunge (Gourlay, 1992, Table 3).

6.2. Surf zone width

Figs. 4 to 7, showing H/H_o as a function of $x/(T\sqrt{gh_e})$, also give the location of the break point, the estimated location of the boundary between inner and outer surf zones x_p and the observed end of the surf zone x_s. To facilitate comparison with other work, x_p is measured from the breakpoint, whereas x_s is measured from the reef edge rather than the actual break point. Both quantities are difficult to determine because of instabilities in the breaking and transformation processes which cause them to vary with time. In some of these experiments the inconsistencies may be caused by reflection from either the submerged structure located on the horizontal reef-top or the beach at the end of the flume.

6.3. Outer region (plunge distance)

For those experiments where an outer region was observed, its width was found to be of the order of one reef-top wave length, i.e. $x_p/(T\sqrt{gh_e}) \approx 1.0$, with a range from 0.77 to 1.08. Nelson and Lesleighter's (1985) data gives a similar order of magnitude.

Earlier studies on a plane beach by Galvin (1969) indicate that x_p is proportional to breaker height H_b as well as being influenced by the bottom slope. More recently Smith and Kraus (1991) have found that on barred profiles

$$\frac{x_p}{H_b} = 0.63\xi_o^{-1.00} + 1.81 \tag{6}$$

The outer edge of the Hayman Island reef-top is not horizontal. The outermost 20 m have a slope of 1 in 33 ($\tan\alpha = 0.03$) and the next 50 m a slope of 1 in 83 ($\tan\alpha = 0.012$). It is over this region that the wave plunges or spills and develops into a bore. For $H_o/L_o = 0.048$, equation 6 gives the following values of x_p/H_b:

$$\begin{aligned} \frac{x_p}{H_b} &= 6.4 \quad \text{for } \tan\alpha = 0.03 \\ &= 13.3 \quad \text{for } \tan\alpha = 0.012 \\ &= 8.4 \quad \text{for } \tan\alpha = (0.03 + 0.012)/2 \\ &= 9.8 \quad \text{for } \tan\alpha = 0.017 (1 \text{ in } 58) \end{aligned}$$

Observed values from the Hayman Island experiments lie within the range

$$6.2 < \frac{x_p}{H_b} < 13.1$$

with an average value of 9.1.

Clearly while outer surf zone region widths on the Hayman Island reef are consistent with other experimental data, no consistent simple means of predicting this distance is available. If scaled in terms of breaker height, x_p is very sensitive to the bottom slope and hence shape of the outer reef-top and reef edge. Scaling in terms of the reef-top wave length is much less sensitive.

6.4. Total surf zone width

The surf zone width x_s measured from the reef edge to the furtherest distance travelled by the breaking surge is generally within the range $2 < x_s/(T\sqrt{gh_e}) < 3$. Again there is no consistent correlation with any other parameter but values are generally consistent with the maximum bounding line given by Nelson and Lesleighter (1985). Fig. 9 shows both Hayman Island data and Nelson and Lesleighter's data. The former are given only for waves which break at the reef edge ($F_{co} > 200$ or $H_o/h_e > 0.6$).

The bounding condition which gives a maximum value for x_s at which oscillatory waves reform is given by the following equation

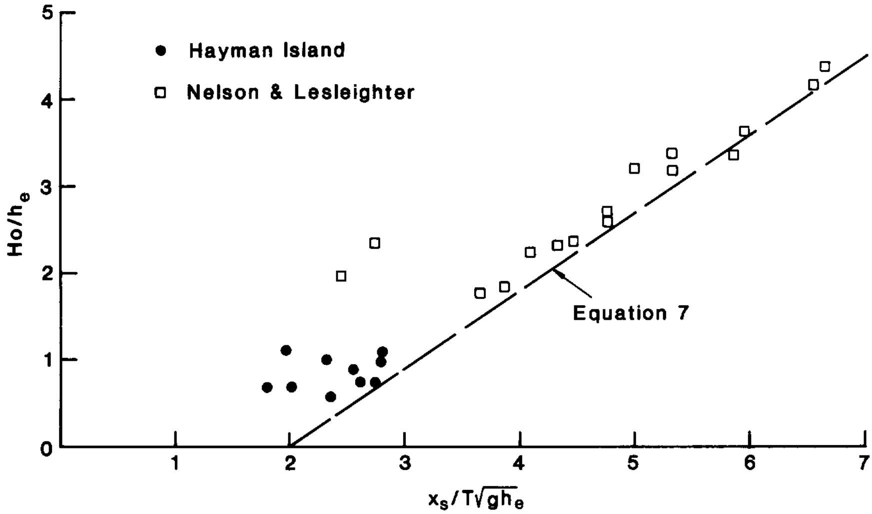

Fig. 9. Distance from reef edge to oscillatory wave reformation.

$$x_s/(T\sqrt{gh_e}) = 2 + 1.1H_o/h_e \qquad (7)$$

Eq. 7 applies only when waves plunge at the reef edge. If waves break on the sloping reef top, the magnitude of $x_s/(T\sqrt{gh_e})$ at which waves reform will generally be larger than that given by Eq. 7, i.e. experimental points will lie to the right of the bounding line on Fig. 9.

When $H_o/h_e < 0.4$ waves pass over the reef edge without breaking. Depending upon the extent of the sloping reef top and the difference in elevation between the reef edge and the reef top, the waves may or may not continue to propagate over the reef top without breaking.

7. Variation of breaking conditions with relative submergence

It is well known that the amount of wave energy transmitted over a submerged offshore breakwater and hence the amount of protection it gives depends upon its relative submergence h/H_i (e.g. Adams and Sonu, 1987; Powell and Allsop, 1985). A coral reef functions in a similar way, protecting reef-top islands and structures.

In Fig. 10 H/d for both breaking and reformed waves is plotted as a function of relative submergence h_e/H_o. For the breaking waves H is the wave height and d ($=h$) is the actual depth at the break point. For the reformed waves H is the wave height at the end of the surf zone at distance x_s from the reef-edge and d ($=h+\bar{\eta}$) is the actual depth including set-up $\bar{\eta}$ at that point. In some cases values of H and d have been obtained by interpolation. Breaking conditions on the reef are clearly significantly affected by the relative submergence of the reef. For the particular reef profile modelled and wave steepness $H_o/L_o = 0.048$, waves break by plunging on the reef edge when $h_e/H_o \leqslant 1.8$ and by spilling when

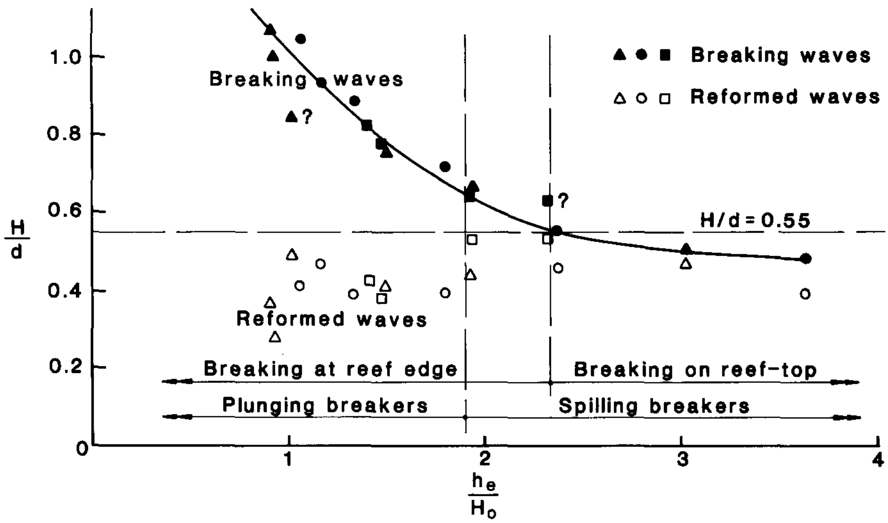

Fig. 10. Conditions for wave breaking and reformation as functions of relative submergence.

$h_e/H_o > 1.8$. At or about $h_e/H_o \approx 2.3$ to 2.4 different breaking conditions may occur depending upon whether the wave breaks on the seaward edge of the reef-top or further inshore.

In the first case (expt 3.5), maximum energy dissipation occurs as the waves initially break by spilling on the outer steeper portion of the reef-top, then reform as the slope flattens and subsequently become unstable again as they propagate over the reef-top. By the time they reform again, the waves are quite small ($H/d \approx 0.27$).

In the second case (expt 1.4), minimum energy dissipation occurs since the waves are small enough to pass over the outer reef-top without breaking and just reach maximum height further inshore. Their reformed wave height on the horizontal reef-top is close to the maximum possible value, which in this case is about 0.5 when $F_c = 100$ (Nelson, 1994, Fig. 1). This second situation corresponds to the offshore wave conditions which result in the greatest amount of energy propagating over the reef-top at a particular tide level.

The distinction between reef-edge and reef-top breaking conditions becomes clearer when H/d for breaking and reformed waves is plotted as a function of F_{co} (Fig. 11)*. Also shown on this figure is Nelson's (1994) limiting curve for maximum H/d on a horizontal bottom.

For waves breaking by plunging, H/d at the break point is of the order of 1.0 at $F_{co} \approx 500$ and decreases to about 0.7 at $F_{co} \approx 160$. The corresponding reformed waves at the end of the surf zone have values of H/d of the order of 0.4 and all fall below the limiting curve for a horizontal bottom.

When $F_{co} < 140$ the waves begin to spill at the reef-edge or rather on the outer steeper portion of the reef-top. At breaking H/d is initially 0.63 when $F_{co} \approx 130$ to 140 and the reformed waves have H/d values very close to the limiting curve for a horizontal bottom. At smaller values of F_{co} ($\leqslant 100$) the waves pass over the reef-edge and break further

*Since H_o/L_o is constant for these experiments, F_{co} is equivalent to $(H_o/h_e)^{1.75}$ multiplied by a constant.

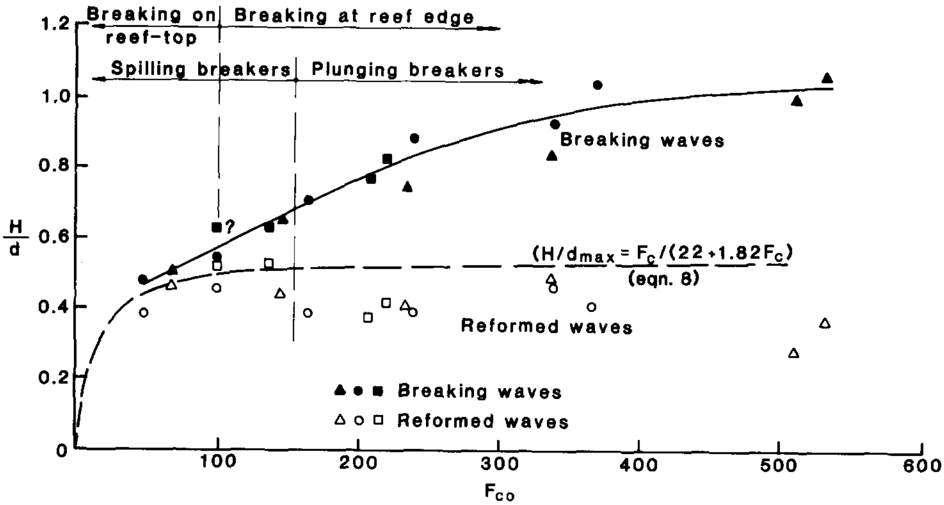

Fig. 11. Conditions for wave breaking and reformation as functions of F_{co}.

inshore on the sloping reef-top. These spilling breakers have H/d values very close to the limiting values for a horizontal reef-top. The break point values are somewhat higher but this is consistent with the fact that the reef-top has a variable slope between 1 in 83 and 1 in 250 for which the maximum limiting value of H/d will be greater than for a horizontal bottom condition (Nelson, 1987).

8. Maximum values of *H/d* on reef-top

Recently Nelson (1994) has shown that the maximum stable wave height to depth ratio H/d of reformed waves measured in the field on a horizontal reef-top is 0.55. This value is the same as that obtained from laboratory experiments using regular waves (Nelson 1983, 1985) and irregular waves (Riedel and Byrne, 1987). This limiting value of $H/d=0.55$ applies to shallow water waves for which $F_c > 500$. It becomes smaller at smaller values of F_c, that is for intermediate depth waves*.

Since the Hayman Island reef-top is not horizontal and almost all the experiments had F_{co} values less than 500, a simple direct comparison with the field data from John Brewer Reef (Hardy et al., 1991a,b) cannot be made. However, detailed examination of the Hayman Island experimental data shows that this data also is consistent with Nelson's conclusions, provided that the influence of bottom slope and wave shape (F_{co}) is taken into account.

The variation of H/d across the reef-top is given in Figs. 12 to 15 for the same representative conditions as in Figs. 4 to 7. In this case, because the position on the actual reef-top is important, H/d is plotted against x/x_r where $x_r = 170$ m is the width of the nonhorizontal

*A similar maximum H/d value was also found earlier by Galvin (1970, Fig. 5a) in his study of finite amplitude shallow water waves on a horizontal bottom. Galvin's maximum H/d values of the order of 0.55 to 0.6 occurred at small relative depths, i.e. with shallow water waves and were associated with the breakdown of the periodic waves into two or more waves resembling solitary waves (solitons) travelling at speeds dependent on their height.

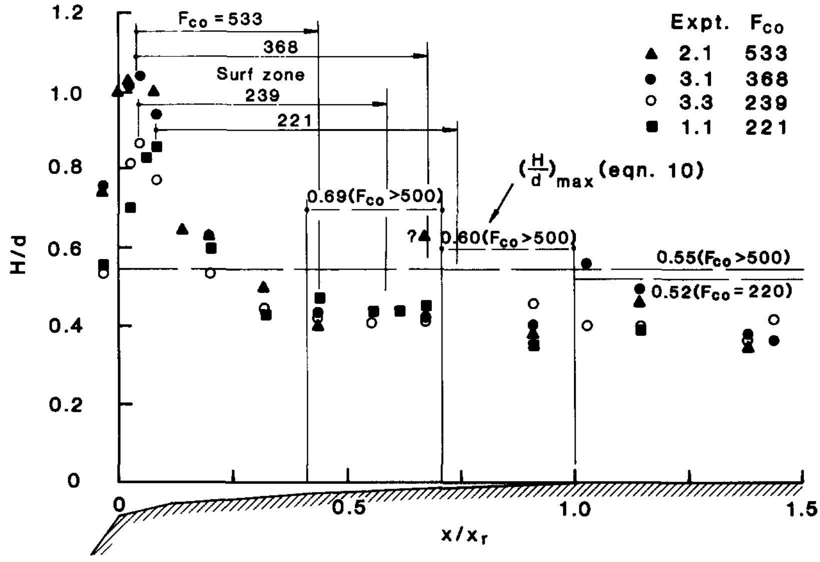

Fig. 12. H/d as a function of reef-top location $530 > F_{co} > 160$.

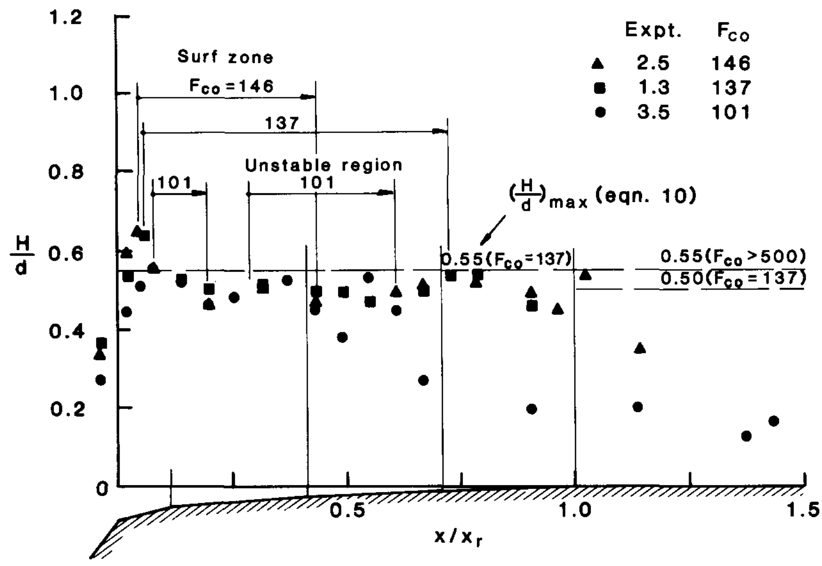

Fig. 13. H/d as a function of reef-top location $150 > F_{co} > 100$.

portion of the reef-top. Values of the mean depth d have been calculated by adding the measured wave set-up to the still water depth h. The ratio H/d is found to vary in distinctive patterns which depend upon the magnitude of F_{co} and shape (slope) of the reef-top (Table 5).

For waves breaking at the reef-edge ($F_{co} > 220$), the magnitude of H/d at the break point

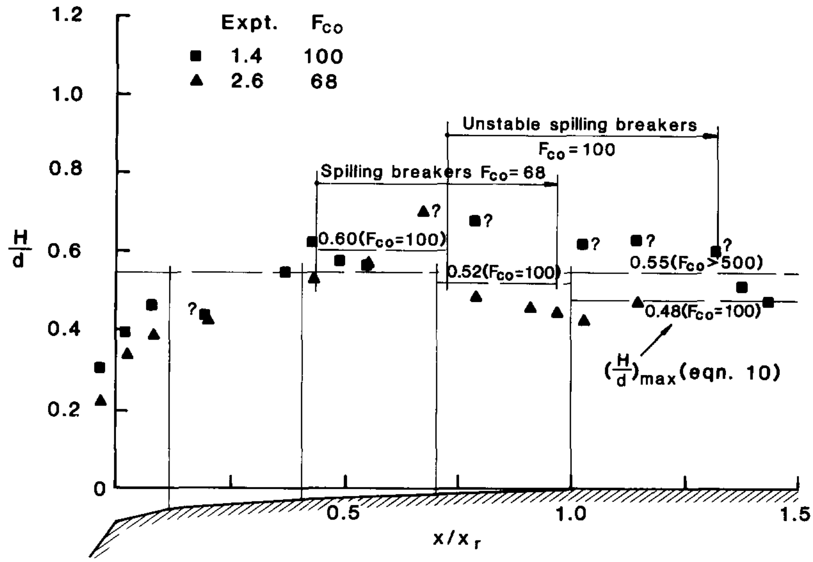

Fig. 14. H/d as a function of reef-top location $100 > F_{co} > 65$.

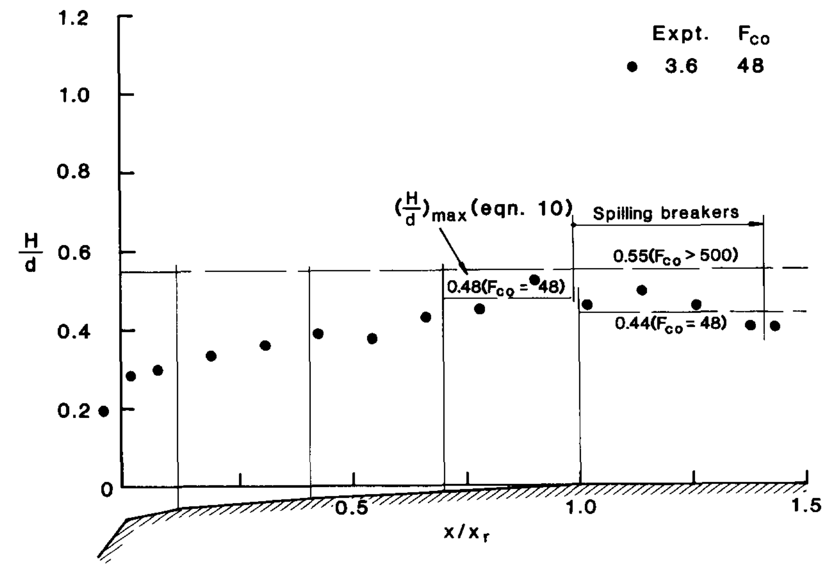

Fig. 15. H/d as a function of reef-top location $65 > F_{co} > 25$.

varies between about 0.8 and 1.1, depending upon the value of F_{co} (Fig. 12). These values of H/d are similar to the upper bound values obtained in the field near the reef edge at John Brewer Reef (Hardy et al.. 1991a, Figs. 13 and 14). At the end of the surf zone H/d is of the order of 0.4, which is similar to the value found by Horikawa and Kuo (1966) for waves travelling over a horizontal bottom after breaking at the top of a 1 in 5 slope, a situation not

Table 5
Values of H/d on reef-top

F_{co}	Breaker conditions		H/d[a]		
	Type	Location	at x_b	at x_s	at x_r
>300	Plunging	at reef edge	1.0	0.4	$\leqslant 0.55$
240 to 220	Plunging	at reef edge	0.85	0.4	–
150 to 130	Spilling	on outer reef-top	0.65	0.55	–
≈ 100 case 1	Spilling	on outer reef-top	0.55	0.49 to 0.52[b]	0.2
≈ 100 case 2	Spilling	on sloping reef-top	0.63	–	0.62
≈ 70	Spilling	on sloping reef top	0.57	–	0.47
≈ 50	Spilling	on horizontal reef-top	–	–	0.44

[a]Values of H/d at break point x_b, at end of surf zone x_s, at beginning of horizontal reef-top x_r.
[b]Unstable.

dissimilar to the Hayman Island reef with its 1 in 4.5 reef face slope. In this situation the energy dissipation process within the turbulent breaking surge or bore has been particularly effective, resulting in the reformed waves at the end of the surf zone having H/d values significantly lower than those for maximum stable depth limited waves on the sloping reef top (see Eq. 10 below).

When waves do not break at the reef edge, they pass over it and travel over the sloping reef-top, their height tending to increase because of shoaling, until they become unstable and break. This is usually the case when $F_{co} < 150$. In virtually all cases, the limiting wave-heights on the Hayman Island reef model are within the maximum envelope curves given by Nelson.

For a horizontal bottom the maximum limiting value of H/d is a function of F_c (Nelson, 1994), i.e.

$$\frac{H}{d} = \frac{F_c}{22 + 1.82F_c} \tag{8}$$

which for shallow water waves, $F_c > 500$, gives a maximum value of

$$\frac{H}{d} = 0.55$$

For a nonhorizontal bottom, Nelson (1987) gives the maximum (shallow water) limiting value of H/d as a function of bottom slope, i.e.

$$\frac{H}{d} = 0.55 + 0.88\exp(-0.012\cot\alpha) \tag{9}$$

where α is the bottom slope angle.

Thus Eq. 9 indicates that the maximum value of H/d increases as the bottom slope ($\tan\alpha$) increases, whereas Eq. 8 indicates that the maximum value of H/d decreases as F_c decreases. At the present time a comprehensive expression for the maximum value of H/d as a function of both F_c and $\cot\alpha$ has not been established. However for the purposes of this analysis, it has been assumed that the maximum value of H/d on relatively flat slopes, e.g. $\cot\alpha > 100$, can be estimated by combining Eqs. 8 and 9 as follows

$$\frac{H}{d} = [0.55 + 0.88 \exp(-0.012 \cot\alpha)] \frac{F_c}{12 + F_c} \tag{10}$$

Limiting values of H/d calculated from Eq. 10 are plotted on Figs. 12 to 15. However, when waves break on the outer portion of the sloping reef-top, i.e. $\cot\alpha < 100$, the magnitudes for the maximum value of H/d calculated from Eq. 10 appear to be much too large.

Alternatively, the maximum values of the breaking waves may be compared with the empirical results obtained by Smith and Kraus (1991) for waves breaking over a bar or artificial reef. They found that H/h at the break point ($\approx H/d$) was a function of the surf similarity parameter ξ_o, i.e.

$$\frac{H_b}{h_b} = 0.41 + 0.98\xi_o \qquad \text{for } 0.3 \leqslant \xi_o \leqslant 0.85 \tag{11}$$

$$\frac{H_b}{h_b} = 1.45 - 0.22\xi_o \qquad \text{for } 1.6 \leqslant \xi_o \leqslant 3.5 \tag{12}$$

There was considerable scatter within the intervening range $0.85 < \xi_o < 1.6$. They suggest that the decrease in H_b/h_b at the larger values of ξ_o is associated with return flow under the breaking wave which causes breaking before the depth-limited condition is reached. Such a situation certainly occurs when waves break on the edge of a coral reef. In these circumstances there is often a strong return flow over the reef edge prior to the arrival and breaking of the next wave.

Applying Eqs. 11 and 12 to breaking conditions on the Hayman Island reef model, $H_o/L_o \approx 0.048$ and the slope of the reef face $\tan\alpha = 0.222$. Hence for breakers plunging on the reef face, Eq. 12 gives $H_b/h_b = 1.23$.

For breakers spilling on the reef-top which has a slope of $\tan\alpha = 0.030$ at its seaward edge, Eq. 11 gives $H_b/h_b = 0.55$.

When compared with observed values of H/d at breaking ($\approx H/h$) in Figs. 12 to 15 it is found that the latter all fall within the range 0.55 to 1.23. However, if Smith and Kraus' relationship for $\xi_o < 0.85$ is based upon an upper bound rather than a mean trend of H/h values, Eq. 11 can be rewritten as

$$H_b/h_b = 0.55 + 0.87\xi_o \tag{13}$$

For $H_o/L_o \approx 0.048$ and $\tan\alpha = 0.030$, this gives $H_b/h_b = 0.67$ for waves spilling on the seaward edge of the reef-top. Maximum observed values for experiments where this occurred are 0.64 and 0.65. Values of H_b/h_b calculated from Eq. 13 for the flatter parts of the reef-top are also similar to experimental values.

In the few cases (for example, experiment 1.4 with $F_{co} = 100$) where individual H/d values observed in the Hayman Island reef model exceeded the values given by Eq. (10) based upon Nelson's limiting conditions, it is probable that either reflection from the structure/spending beach or cross oscillations within the flume have increased the wave height above the maximum limiting value possible without any reflection.

9. Conclusions

1. The parameter $F_c = g^{1.25}H^{0.5}T^{2.5}/h^{1.75}$, when calculated using offshore wave height H_o and reef-edge depth h_e is proposed as a suitable parameter for classifying wave transformation on a near horizontal coral reef.

2. For the particular reef profile at Hayman Island
- waves initially plunge on the reef edge and dissipate almost all their energy within five wave lengths of the reef edge when $530 > F_{co} > 160$;
- waves spill on the outer reef-top when $150 > F_{co} > 100$;
- waves spill further inshore on the reef-top when $100 > F_{co} > 70$;
- waves either just break on the horizontal reef-top or pass over it without breaking when $50 > F_{co}$.

3. The relative amount of energy E/E_o reaching a shore or structure on the reef-top is small (0.15) when $F_{co} > 150$, and becomes even smaller (0.05) when $F_c > 500$. However, E/E_o increases rapidly once F_{co} falls below 100, becoming 1 when $F_{co} < 10$ (deep water waves).

4. The relative plunge distance x_p/H_b at the edge of the reef has values of the same order of magnitude (6.5 to 11.5) as those on barred beach profiles of similar slope. x_p is also of the order of one reef-top wave length, i.e. $x_p/(T\sqrt{gh_e}) \approx 1.0$.

5. The experimental data from the Hayman Island reef model is generally consistent with that from Nelson and Lesleighter (1985) with regard to the maximum distance from the reef edge at which oscillatory waves reform ($=x_s$).
For $H_o/h < 0.4$, waves pass over the reef-top without breaking;
For $H_o/h > 0.4$, $x_s/(T\sqrt{gh}) = 2 + 1.1H_o/h$.

6. Maximum H/d values on the reef-top are consistent with the experimental work of Nelson (1987, 1994). For $\cot\alpha > 100$, the maximum limiting value of H/d can be approximated by combining Nelson's two limiting equations for the influence of F_c and $\cot\alpha$ in the following equation

$$\frac{H}{d} = [0.55 + 0.88\exp(-0.012\cot\alpha)]\frac{F_c}{12 + F_c}$$

7. On a slightly sloping reef-top there is a range of wave conditions where breaking conditions are unstable. For the conditions considered this occurred when $F_c \approx 100 \pm 30$. This instability is a consequence of potentially maximum H/d conditions occurring within the sloping reef-top zone where shoaling causes increasing wave heights. If the wave breaks close to the reef-edge, very effective energy dissipation occurs. However, if the wave does not break but propagates at the maximum possible depth-limited wave height much less dissipation occurs.

8. The absolute amount of wave energy reaching a shore or structure on the reef-top is determined by the water depth over the reef-top where that depth includes the effects of tide, wave set-up, wind set-up, surf beat, storm surge etc. For a horizontal reef-top, both field and laboratory data show that the maximum wave height never exceeds 0.55 times the water depth. Use of $H/d = 0.55$ results in energy density ($\propto H^2$) predictions for reef-top waves being about one half those predicted using current practice which assumes the maximum value of H/d on a horizontal bottom is 0.78.

9. In some situations ($F_{co} > 220$) energy dissipation at the reef edge and in the surf zone bore reduces the wave height at the end of the surf zone to a value less than that of the maximum possible depth limited wave. Hence, in such situations, the reformed waves travelling over the reef-top will have H/d values less than 0.55.

10. As the experiments on the Hayman Island reef model were all made with a wave steepness $H_o/L_o \approx 0.048$, further investigations are required to confirm the generality of the preceding conclusions for other wave steepnesses, as well as other reef-top profiles.

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Appendix — notation

d mean water depth including wave set-up
d_b breaker depth
g gravitational acceleration
h still water depth
h_a average still water depth over sloping section of reef-top
h_b breaker depth relative to still water level
h_e still water depth at reef edge
h_i off-reef still water depth
h_r still water depth over horizontal reef-top
x distance from reef edge
x_b breaker distance
x_p plunge distance
x_r width of sloping section of reef-top
x_s width of surf zone
C wave celerity
E wave energy density
E_o deepwater wave energy density
F_c wave nonlinearity parameter (see Eq. 1)
F_{co} wave nonlinearity parameter as defined for conditions at the edge of a coral reef (see Eq. 4)
H wave height
H_b breaking wave height
H_o off-reef wave height (equivalent deep water value)

L wave length
L_o deepwater wave length
T wave period
U Ursell number (see Eq. 2)
α bottom slope angle;
$\bar{\eta}$ wave set-up;
ξ_o deepwater surf similarity parameter (see Eq. 5)

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