CHAPTER 243

Field Measurement of Bed Roughness for Waves on an Off-Shore Reef

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Abstract

This paper takes advantage of fortuitous, near ideal conditions which existed for a subset of field data, to obtain the hydraulic roughness of the surface of a coral reef platform. This was accomplished by observing the transformation of natural, unbroken, oscillatory wave trains, propagating over the reef top in water of constant depth, where wave bed friction damping was the only active wave transformation process. The paper also demonstrates that while coral reefs may be perceived as being much rougher than sandy beds, they may in fact be no rougher in hydraulic terms, than many sandy beds experiencing the same wave and water depth conditions.

Introduction

The bed friction factor (f) associated with wave motion, is a function of a Reynolds number and a relative roughness.

$$f = \phi_1\left(R_e, \frac{r}{a}\right) \tag{1}$$

R_e is the Reynolds number associated with the oscillatory water movements at the bed as estimated from linear wave theory.

$$R_e = \frac{aU}{v} \tag{2}$$

a is the amplitude of the oscillatory bed movements, U is the amplitude of the periodic bed velocity, and v is the kinematic viscosity of the fluid. r/a is the relative roughness where r is the hydraulic roughness. For all turbulent flow conditions, the friction factor can be expressed in the form of Eq. 1. However,

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for all prototype wave conditions of engineering significance, the oscillatory flow at the bed is always fully developed rough turbulent flow (Jonsson, 1963 and 1966; Swart, 1974). In this regime the friction factor is independent of Reynolds number, reducing Eq. 1 to Eq. 3 for field conditions.

$$f = \phi_2\left(\frac{r}{a}\right) \tag{3}$$

On a movable bed, both r and a are variables, depending on the wave and water depth conditions, the changes in r being caused by the variability of bed form (Nelson, 1989 and 1995).

On fixed beds, such as coral reef platforms, a still varies with wave and water depth conditions, but r remains constant. A measured value of this fixed roughness is far more useful than a measured value of friction factor. The latter is only applicable to wave and water depth conditions that produce the same value of a existing when the measurement was made, while the hydraulic roughness value can be used to obtain wave friction factors for all wave and water depth conditions.

This paper presents values of reef top hydraulic roughness derived from the observed transformation of natural random waves, propagating in water of constant depth, over the fixed bed of a platform coral reef. The resulting values are to some extent site specific. However, from an engineering viewpoint, the use of a measured roughness that can be varied by visual comparisons and reasoning, is far more desirable than the use of a *guesstimate*.

Experiment Description

The experimental data were collected from John Brewer Reef, located inside the line of the Barrier Reef approximately 70 km north east of Townsville, Australia. The reef is elliptical in shape (6 km by 3 km - see Fig. 1) with a major axis approximately normal to the prevailing south easterly winds. The windward reef platform is a continuous reef flat 200m to 300m wide and uniform in elevation at a level approximating Lowest Astronomical Tide. High tide water depths over the reef platform seldom exceed 3m. Seaward of the windward edge, the reef drops rapidly to a depth of about 50m below the reef platform, while the lagoon enclosed by the whole of John Brewer Reef averages about 10m in depth.

Wave and current measuring instruments were deployed on the windward side of the reef (Fig. 1). WR1 was a Waverider buoy located about 500m seaward of the reef front and transmitted incident wave data to a receiver located in the floating hotel. ZP1, ZP2, ZP3 and ZP4 were 6m high, surface piercing wave transducers known as Zwarts Poles (Zwarts, 1974). These were aligned normal to the reef front and parallel to the prevailing south east winds. ZP1 and ZP4 are of special interest to this study. ZP1 was 27m from the reef front while ZP4 was located at a further interval of 141m. Most of the time the line of Zwarts Poles was located along the line of the reef top wave orthogonal but there were some exceptions at high tide during incident wave events with very low energy.

Each wave sample collected from WR1 contained 2048 readings at intervals of 0.391 seconds (sample length about 14 minutes). Each wave sample from each Zwarts pole contained 4800 readings at an interval of 0.25 seconds (sample length about 20 minutes). Data sets consisted of wave samples collected concurrently from all 5 wave instruments with the recording commencement times for each instrument being identical. The interval at which data sets were recorded was sometimes 1 hour and at other times 2 hours.

CM1 was an S4 electromagnetic XY current meter that measured reef top currents. Every 10 minutes it took 120 readings at 0.5 second intervals of both the easterly and northerly velocity components and logged the average.

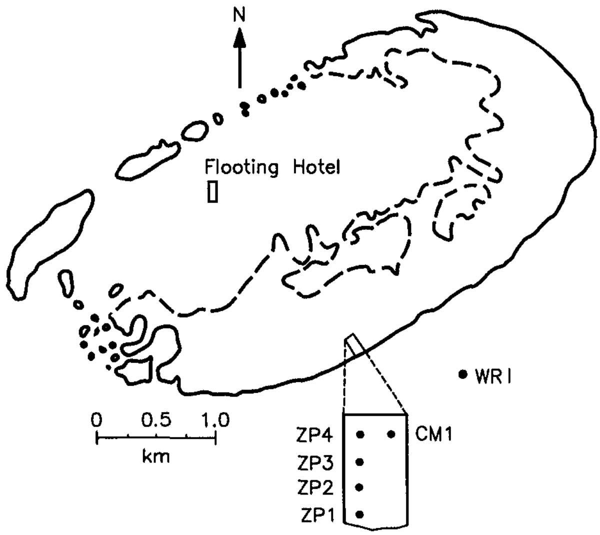

Fig. 1 John Brewer Reef and Instrument Locations

Data Selection

The extraction of bed friction effects from other interacting sub-processes, increases the uncertainties incorporated in the results, the preferred option being to have a prototype location and wave motion where bed friction damping is the only active sub-process. Some of the John Brewer Reef Zwarts Pole data conformed with this requirement. The water depths were, for all practical purposes, uniform eliminating the effects of shoaling and refraction. There were no barriers around which diffraction could occur, and careful selection of data sets ensured that the effects of wave breaking were all but eliminated.

The data base used in this study contained 72 consecutive data sets, some times recorded at one hourly intervals, and at other times, two hourly intervals. They spanned a sustained period of high incident wave energy and some periods of low incident wave energy, both coupled with large tide ranges. This provided a wide range of reef top wave and water depth combinations. These data are presented as a time series in Fig. 2.

Incident high wave energy events were dominated by sea states with peak energy periods of between 4 and 6 seconds with direction determined by the dominant south east wind. During low energy events, when the sea state was minimal, longer peak energy periods were observed when small amounts of wave energy from distant sources became significant relative to the local sea state. The direction of this longer period wave energy was unknown and it was necessary to eliminate it from the data records. All characteristic spectral wave parameters have been restricted to the wind wave component by only considering wave frequencies greater than or equal to 0.16 Hz.

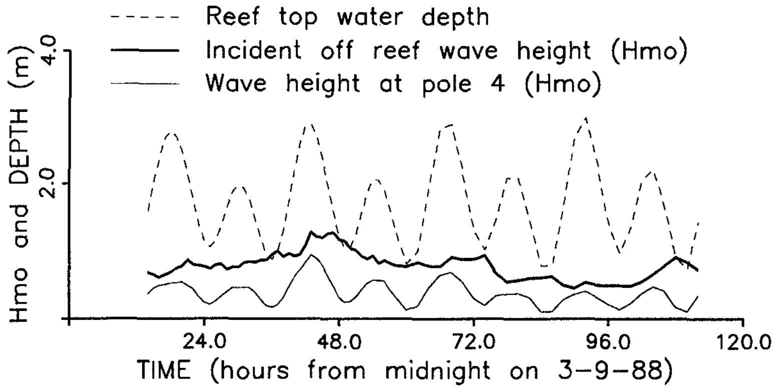

Fig. 2 Wave and Tide Summary

The selected subset of wave records were to be free of wave breaking influences, with the wave energy dissipation over the flat bed between ZP1 and ZP4 (Fig. 1) due only to bed friction damping. However, for most data sets at John Brewer Reef, waves broke at the reef edge due to depth limiting effects and dissipated energy, primarily through the turbulence associated with the breaking process, until stable wave heights compatible with reef top water depths were attained. The waves then reformed into stable oscillatory waves. It was established that even the largest waves in any of the recorded incident wave trains, reformed into oscillatory waves before reaching ZP4 (Nelson, 1994). However, this was not the case at ZP1 making it necessary to delineate which data sets were largely free of breaking waves at this station. These will obviously be those biassed towards lower incident wave energy and larger reef top water depths.

This screening was made using the criterion of Nelson (1994) for the maximum stable oscillatory wave heights sustainable over horizontal beds, namely Eq. 4, and the fact that this criterion was shown to be applicable to the individual waves of a naturally occurring random wave train.

$$\frac{H}{h} = \frac{F_c}{22 + 1.82F_c} \tag{4}$$

F_c is a non-linearity parameter after Swart and Loubser (1979), as defined in Eq. 5. F_c values less than 10 indicate deep water waves, those between 10 and 500 indicate transitional water depth waves, and values greater than 500, shallow water waves when H/h approaches a value of 0.55.

$$F_c = \frac{g^{1.25} H^{0.50} T^{2.50}}{h^{1.75}} \tag{5}$$

Waves with larger H/h ratios can exist on horizontal beds but these would be turbulent breaking waves losing height rapidly by the turbulent dissipation of energy.

A wave by wave analysis of all 72 wave records at ZP1 determined the H/h population for each record and the value of F_c associated with each H/h value. This took into account the effect of tide and infragravity wave activity in varying the effective water depth on which the wind waves were superimposed, since the maximum wave height that could be sustained varied with time because local water depth was time dependent. The F_c value assigned was based on the wave height and water depth associated with each wave and the wave period equal to the lapsed time between the crest of this wave and the crest of the previous wave (see Nelson, 1994 for greater detail).

The results for all 72 wave records were compared with the criterion of Eq. 4. Wave records with little or no wave breaking were those for which none (or at least very few) of the observed values of H/h exceeded the value given by Eq. 4 when using the observed value of F_c. Based on this criterion 20 wave records were available for further consideration.

A further 6 of these 20 records were rejected because the reef top wave orthogonal was not sufficiently aligned to the line of wave poles. There remained 14 acceptable data sets.

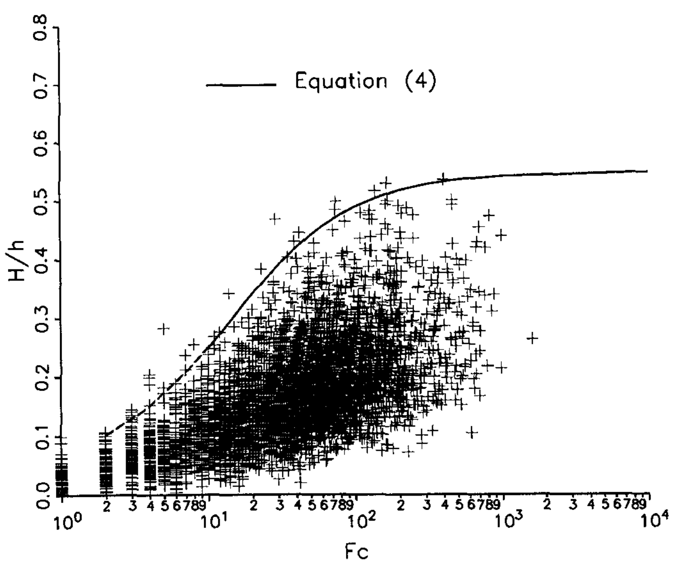

Fig. 3 ZP1: H/h versus F_c for all Waves in all 14 Data Sets

Fig. 3 shows the results for all waves in all 14 data sets plotted on the H/h versus F_c plain. The solid line is Eq. 4 and the dotted line is the deep water wave steepness limit at F_c values less than 10. The average number of waves per wave record is 357, and on average, only 1 or 2 waves per record significantly exceeded the envelope curve. While it is possible some waves did break at H/h values less than the envelope curve (Nelson 1987), it is reasonable to assume that this impact was slight, and that for the 14 selected data sets, all wave energy dissipation between ZP1 and ZP4 was due to bed friction damping only.

Table 1 summarises the characteristic parameters associated with the adopted 14 data sets. The data set number is the location of the data set within the consecutive order of the original 72 data sets. The day and time indicate the common instrument commencement time for the recording of each data set. H_1 and H_4 are respectively the spectral estimates of significant wave height (H_{mo}) of the wind wave component at ZP1 and ZP4 and H is the mean of these two values. T_p is the mean of the four peak energy periods at ZP1, ZP2, ZP3, and ZP4 for the wind wave component. h is the mean, reef top water depth during the data set.

Table 1
Observed Reef Top Parameters - September 1988

Data set	Day	Time (hrs)	$^*H_1$ (m)	$^*H_4$ (m)	H (m)	$^*T_p$ (s)	h (m)
02	4	1500	0.544	0.418	0.481	4.280	1.865
03	4	1600	0.536	0.446	0.491	3.443	2.273
04	4	1700	0.521	0.461	0.491	4.455	2.555
07	4	2000	0.570	0.496	0.533	4.265	2.343
17	5	0600	0.559	0.429	0.494	4.025	1.843
49	6	1800	0.625	0.582	0.604	3.975	2.693
50	6	2000	0.641	0.599	0.620	4.265	2.758
55	7	0600	0.379	0.319	0.349	4.932	1.948
56	7	0800	0.361	0.315	0.338	5.200	1.935
60	7	1600	0.337	0.257	0.297	3.880	1.505
65	8	0200	0.253	0.125	0.189	4.020	0.828
66	8	0400	0.323	0.210	0.266	4.265	1.208
67	8	0600	0.407	0.349	0.378	3.595	1.905
68	8	0800	0.539	0.456	0.498	3.710	2.078

* Based on all frequencies $\geq$ 0.16 Hz

Reef Top Wave Energy Dissipation Factors

Two wave related friction factors are in common use. The wave friction factor (f_w) is defined by Eq. 6.

$$\tau_{max} = 0.5\rho f_w U^2 \tag{6}$$

τ_{max} is the maximum bed shear stress due the horizontal oscillatory water particle velocities at the bed and ρ is the water density. The determination of f_w requires the direct or indirect measurement of bed shear. The wave energy dissipation factor (f_e) is defined in terms of the time averaged rate of wave energy dissipation due to bed friction as given in Eq. 7.

$$\frac{dE_f}{dx} = (\tau u)_{mean} = \frac{2}{3\pi}\rho f_e U^3 \tag{7}$$

E_f is the wave energy flux, τ is the instantaneous bed shear stress, u is the instantaneous bed velocity, and U is the amplitude of the of the bed velocity variations. The determination of f_e requires the measurement of wave energy loss over a known distance.

The second of the above procedures was adopted at John Brewer Reef, but in so doing it is important to note the following. The two wave related friction factors are different according to how they are defined and measured. However, it has been shown that for fully developed rough turbulent oscillatory flows, $f_w \approx f_e$ (Jonsson, 1963; Swart, 1974; Nielsen, 1992; Raudkivi, 1988). The oscillatory flow at the bed is fully developed rough turbulent flow for all prototype wave conditions of engineering significance. Therefore, for all practical purposes, the field estimates of f_e can be interchanged with f_w. This will be important when estimates of the reef top hydraulic roughness are made.

f_e can be evaluated two ways. The first considers the attenuation of the total energy using only characteristic spectral parameters. The second considers the attenuation of individual frequency components in the spectrum, based on the assumption that these components travel independently of all other spectral components and that there are no non-linear interactions. Experimental limitations dictated the use of the first method. Despite the difficult and hostile environment, the field measurements of small total energy deficits between poles 1 and 4 displayed good consistency and trends. To deal with still smaller energy deficits within individual frequency components introduces anomalies due to the lesser confidence associated with these components relative to that of the total wave energy measurement.

In water of constant depth, the loss rate of wave energy per unit surface area (left hand side of Eq. 7) can be expressed as,

$$\frac{dE_f}{dx} = \frac{\rho g C_g}{8}\frac{dH^2}{dx} \tag{8}$$

where C_g is the group velocity and g is the acceleration due to gravity. The right hand sides of Eqs. 7 and 8 can be equated, integrated, and re-arranged to yield the solution for f_e shown in Eq. 9, and can be applied directly to the John Brewer Reef data shown in Table 1. Δx is the distance between ZP1 and ZP4 namely 141m.

$$f_e = \frac{3g}{8\pi^2}\frac{(H_1 - H_4)}{H_1 H_4}\frac{C_g}{\Delta x}(T_p sinh\,(kh))^3 \tag{9}$$

The resulting values of f_e are shown in Table 2. Also shown are the associated values of a, U, and R_e obtained using the values of H, h, and T_p given in Table 1.

A plot of f_e versus R_e is shown in Fig. 4. At first glance the scatter appears considerable with f_e values of between 0.1 and 0.2 over a Reynolds number range

Table 2
Derived Reef Top Parameters - September 1988

Data set	Day	Time (hrs)	a (m)	U (m/s)	R_e (-)	f_e (-)
02	4	1500	0.323	0.474	153000	0.164
03	4	1600	0.206	0.376	77000	0.218
04	4	1700	0.281	0.396	111000	0.150
07	4	2000	0.304	0.449	137000	0.132
17	5	0600	0.308	0.480	148000	0.162
49	6	1800	0.279	0.441	123000	0.090
50	6	2000	0.314	0.463	145000	0.082
55	7	0600	0.273	0.348	95000	0.152
56	7	0800	0.283	0.342	97000	0.120
60	7	1600	0.202	0.327	66000	0.177
65	8	0200	0.194	0.303	59000	0.207
66	8	0400	0.234	0.344	80000	0.190
67	8	0600	0.196	0.342	67000	0.144
68	8	0800	0.253	0.428	108000	0.143

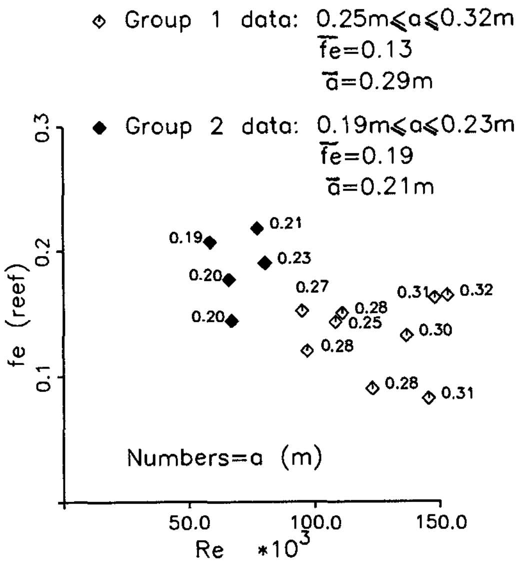

Fig. 4 f_e versus R_e - Reef Data

of between 50000 to 150000. To some extent, the perceived scatter is more apparent than real, accentuated by the linear scales. More common practice is to use log log axes for such plots (e.g. see Fig. 5), masking the extent of the scatter. While much of the scatter must remain unexplained, some can be attributed to the different characteristic values of relative roughness associated with each data set, and the dependence of f_e on that value (see Eq. 3). The values shown beside each point are the a values given in Table 2. These alone are an indicator of relative roughness ($= r/a$) because the reef top roughness remains unchanged for all data sets. Based on this indirect measure of relative roughness the results can be divided into two groups. Group 1 data has a values between 0.25m and 0.32m (mean=0.29m) and a mean f_e value of 0.13. Group 2 data has a values between 0.19m and 0.23m (mean=0.21m) and a mean f_e value of 0.19.

Analyses demonstrated that the small prevailing pole line current that existed on the reef (average value of 0.06 m/s for the 14 data sets) would have had little influence on the computed values of f_e shown in Table 1.

Reef Top Hydraulic Roughness

Kamphuis (1975) used an oscillating water tunnel to measure the maximum shear stresses on a smooth bed and 5 different artificially roughened beds. The shear stress values, measured using a shear plate incorporated in the bed, enabled the computation of wave friction factor, f_w (Eq. 6). Kamphuis summarised the results in a friction factor diagram reproduced here in Fig. 5. The results are consistent with the friction factor being independent of Reynolds number for fully rough turbulent flow. In this region, f_w and f_e (the wave energy dissipation factor) are for all practical purposes, interchangeable as indicated on the vertical axis of Fig. 5. The John Brewer Reef data in Fig. 4 fall well within the fully rough turbulent region of Fig. 5 ($0.1 < f_e < 0.2$ and $50000 < R_e < 150000$) and can be used to estimate values of reef top hydraulic roughness in conjunction with Fig. 5.

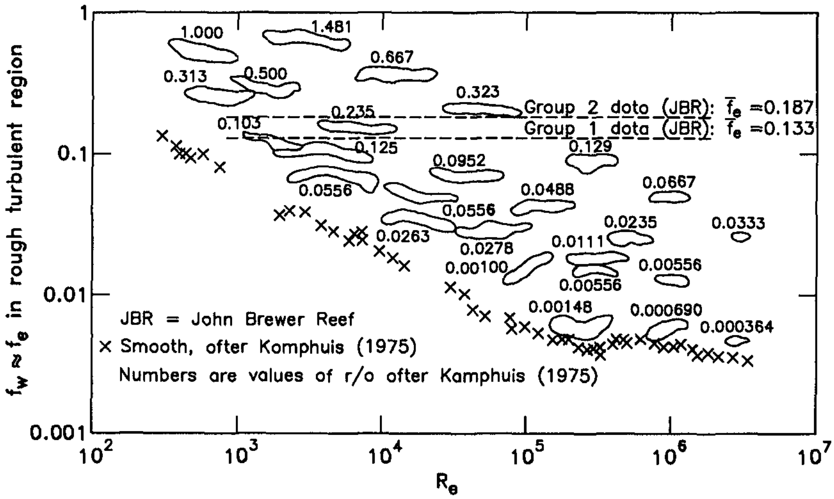

Fig. 5 f_e versus R_e (after Kamphuis, 1975)

The group 1 data has a mean f_e value of 0.130, corresponding to a relative roughness (r/a) value in Fig. 5 of about 0.2. Based on the mean a value of 0.29m for the group 1 data, the hydraulic roughness (r) of the reef top is estimated as $0.2 \times 0.29 = 0.06$m. Similarly for group 2 data, the mean values of $f_e = 0.183$ and $a = 0.21$m lead to values of $r/a \approx 0.3$ and $r = 0.3 \times 0.21 = 0.06$m. Hence, one estimate of the reef top roughness is 0.06m.

A second independent estimate of hydraulic roughness can be made using the work of Jonsson (1963) who developed the following implicit equation for fully rough turbulent oscillatory flow over a fixed immobile bed.

$$\frac{1}{4f_w} + log\left(\frac{1}{4\sqrt{f_w}}\right) = -0.08 + log\left(\frac{a}{r}\right) \tag{10}$$

Swart (1974) presented Eq. 11 as an explicit alternative to Eq. 10. The author has replaced f_w in Swart's equation with f_e as has been previously justified in this paper for fully rough turbulent flow.

$$f_e = exp\left(5.213\left(\frac{r}{a}\right)^{0.194} - 5.977\right) \tag{11}$$

Fig. 6 shows the John Brewer Reef data over-plotted with curves corresponding to fixed values of r computed from Eq. 11. These show that the best estimate of reef top hydraulic roughness is 0.07 m, and this closely approximates the previous estimate of 0.06m.

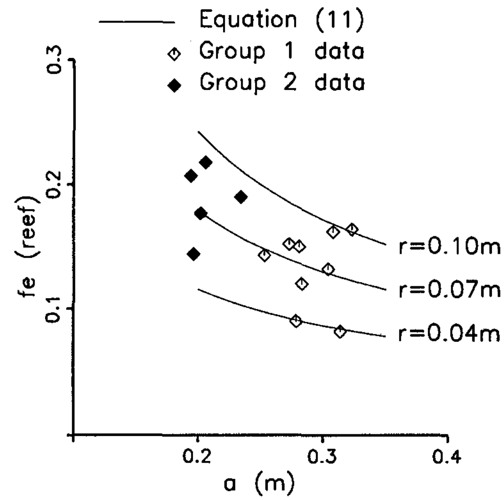

Fig. 6 f_e versus a - Reef Data

Movable Sand Bed Equivalents

An interesting comparison has been made between the influence of this fixed reef surface on wave damping and that of a movable bed of sand using the dimensionless function of Nelson (1995). This expresses the wave energy dissipation factor (f_e) and the physical state of a movable bed as a function of two dimensionless parameters namely $T_c = T\sqrt{g/D}$ and $D_c = D/a$. A range of bed particle sizes were used in the function for each reef top wave and water depth condition listed in Table 1. It was found that movable bed f_e values, comparable with the observed fixed bed reef top values, occurred most consistently when the bed particle size was equal to 0.6 mm. The comparative results are shown in Fig. 7.

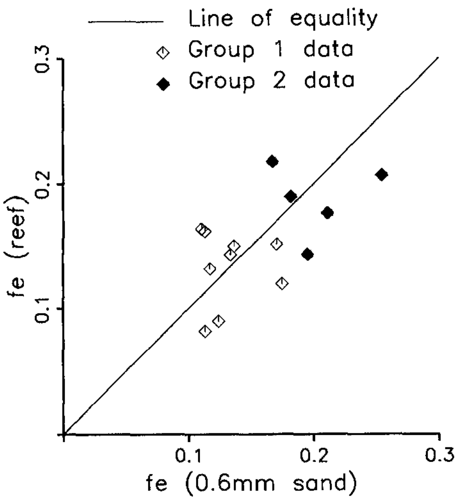

Fig. 7 Movable Bed versus Reef Top Friction Factors

The scatter in the plot results from the fact that a movable bed of given particle size no longer has a constant roughness because the bed form varies with the prevailing wave and water depth conditions. Nevertheless, the comparison demonstrates that while coral reefs may be perceived as being much *rougher* than sandy beds, they may in fact be no rougher, in hydraulic terms, than many sandy beds.

Comments and Conclusions

Field observations have enabled the hydraulic roughness for the fixed bed of a coral reef platform to be determined. In so doing, advantage has been taken of fortuitous and near ideal conditions, where natural trains of random, stable and unbroken oscillatory waves were propagating in water of constant depth, such that wave bed friction damping was the only active wave transformation process present. The roughness estimate of 60mm to 70mm was based on small total energy deficits measured over a known length of wave orthogonal.

The measured fixed bed roughness value is of more use to wave transformation modelers than any of the measured values of wave friction factor. The latter change with wave and water depth conditions while the former remains unchanged, so that the applicable relative roughness and wave friction factor can be determined no matter what wave and water depth conditions prevail.

The measured hydraulic roughness value is transferable to other similar reefs. If differences between reefs are perceived, the measured roughness is a datum value that can be varied based on visual comparisons and reasoning.

The paper has demonstrated that, while coral reefs may be perceived as being much rougher than sandy beds, they may in fact be no rougher in hydraulic terms than many sandy beds experiencing the same wave and water depth conditions.

Acknowledgements

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Appendix 1. References

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