# CHAPTER 120

## CARIBBEAN BEACH-FACE SLOPES AND BEACH EQUILIBRIUM PROFILES

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**ABSTRACT**

Field measurements performed on two Caribbean islands revealed that two-dimensional nearshore bottom morphology is well represented by Dean's (1977) model of the beach equilibrium profile, $h = A\ x^m$, where h is depth below mean water level at a distance x offshore and A is a scale factor. For the curvature, m, we obtained an average value of approximately m = 1/2 through least squares curve fitting of observed profile data, yielding a more concave and therefore steeper profile inshore than m = 2/3, the average previously reported by Dean for quartz sand beaches in the United States. Furthermore, an objective measure of beach steepness was found to be $A^{1/m}$, a quantity which utilizes both of Dean's parameters and which may serve as a surrogate for the beach-face slope, tan $\beta$, on highly concave beaches. Reasonable correlations were found between $A^{1/m}$ and the environmental parameter, $H_b^2/gDT^2$, where $H_b$ is breaker height, D is sediment grain size, T is wave period and g is gravitational acceleration. Improved prediction of Caribbean beach slopes and beach equilibrium profiles is an important practical result.

**INTRODUCTION**

Beaches on the islands bordering the Caribbean Sea differ in at least two respects from beaches in temperate zones: (1) they consist mainly of skeletal calcium carbonate sands of marine origin rather than quartz and feldspar-rich detrital sands, (2) much of the time they experience fairweather waves of relatively low energy and steepness produced either locally by trade winds or received as swell from distant storms (Wilson, 1969; Wilson et al., 1973; Terwindt et al., 1984). Mean tidal range is also minimal (less than 20 cm) within the eastern Caribbean basin (Kjervfe, 1981) around which most of the Caribbean islands are located.

As a result of coastal processes dependent on these factors, Caribbean island beaches typically have a steep, concave-upward profile and lack an offshore bar and bar-related surf zone. Morphodynamically, they exemplify the reflective beach state (Wright and Short, 1984; Wright et al., 1985) wherein incident waves are strongly reflected and thus are conducive to nearshore standing wave motions at subharmonic frequencies. Exceptions do exist. Dissipative surf zones with offshore

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bars and plunging breakers are occasionally seen and certain beaches contain an abundance of black sands rich in ferromagnesian minerals rather than pure calcium carbonate. Pocket beaches lying between rocky headlands are more common than long, straight beaches, however, and the former may have steeper slopes due in part to the absence of strong longshore currents (Bailard, 1981).

Our research interests throughout this study have focused on the question of predictability among various elements of Caribbean beach morphology and the extent to which this knowledge may prove useful in beach construction or restoration projects. Among these elements, none has appeared more promising than the quantitative description of the two-dimensional form of beach profiles in approximate equilibrium with existing environmental parameters including wave height and period, and sediment grain size.

## DESCRIPTION OF THE STUDY ENVIRONMENT

Ten carbonate beaches were selected for study on the island of Sint Maarten/St. Martin (Netherlands Antilles/ French West Indies) located in the extreme northeast corner of the Caribbean Sea at the top of the Lesser Antillean arc system (Figure 1). Additional beaches were surveyed on the island of Curacao (Netherlands Antilles) located at the

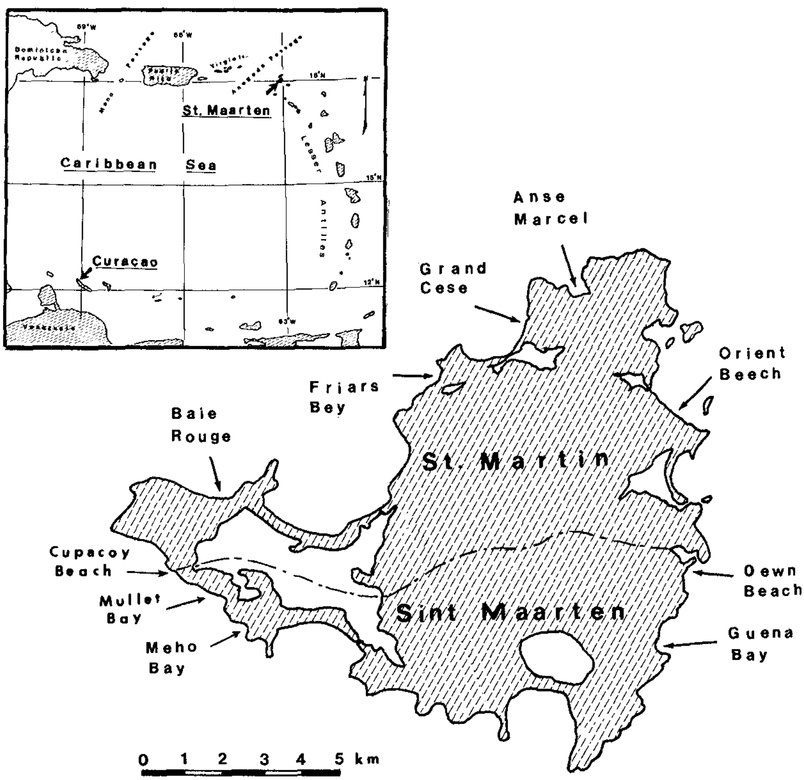


Figure 1. Location of Study Area and Beaches Surveyed.

southern margin of the Caribbean Sea near Venezuela. Due to the extremely narrow shelf (150 to 200 meters wide) surrounding almost the entire coast of Curacao, only one of its beaches possessed a fully covered, natural sand bottom (Playa Abao) suitable for the purposes of this study. Sint Maarten/St.Martin lies at the western boundary of an elongate, raised shoal platform known as the Anguilla Bank, a feature approximately outlined by the 100-meter depth contour, beyond which depths in excess of 500 m are quickly reached.

Beaches along the southwest side of Sint Maarten are fully exposed to deep water waves (100-meter depth contour less than 2 kilometers from shore). Wave energy reaching this coast consists mostly of ocean swell from the Caribbean Sea, or the Atlantic via the Anegada Passage, mixed with only intermittent local wind waves due to ample protection from dominant northeast and easterly trade winds (Netherlands Antilles Meteorological Service, 1981).

The eastern side of the island is bordered by an extensive shallow platform wherein the 30-meter depth contour lies approximately 5 kilometers from shore. The coastline here is generally rocky or fronted by reefs. Numerous pocket beaches are found along the east coast behind reef platforms. Beaches on the north side of St. Martin are characterized by relatively low energy conditions since this side fronts the narrow and sheltered Anguilla Channel between Sint Maarten and the neighboring island of Anguilla. Deep water waves in this region have a mean height of approximately 1.5 - 2.0 meters; about half of all waves have a period of 6 seconds or less and about one-third have a period of between 6 and 9 seconds (U.S. Naval Weather Service Command, 1974).

Curacao differs from Sint Maarten/St. Martin in having little or no shelf. A submerged terrace about 60 meters deep occurs a short distance offshore, in some places only 125 meters from the shoreline. Consequently, very few natural beaches are able to retain sand cover and most consist of coral rubble at the foreshore and step. The only exceptions are found among a few small pocket beaches located at the heads of narrow limestone cliff re-entrants prevalent at the northwest corner of the island, the largest example of which is Playa Abao. Curacao lies within the trade wind belt at a latitude where the dominant winds are from the east. Deep water wave height averages about 1 meter with more than half of all waves having periods of 6 seconds or less (U.S. Naval Weather Service Command, 1974). Swell waves with periods of 9 seconds or more are rare.

## DATA COLLECTION METHODS

Beach profiles from the backshore to the wave step were measured with an automatic level and metric surveyor's rod. The nearshore profile from the approximate still water line (depth zero) to an offshore distance of approximately 120 meters was surveyed by divers who carried the profile out to depths of 4 to 6 m where the sand cover on the offshore bottom typically begins to thin. At one beach (Playa Abao) the entire profile was surveyed using rod and level measurements. At all other beaches, depths were measured by divers using an electronic depth gauge. The depth sensing device consisted of a Senso-Metrics model SP91 pressure sensor (accurate to approximately $\pm$ 4 cm) mounted in a clear plastic tube containing batteries, amplifier circuitry and a digital voltmeter displaying the depth in centimeters. Wave filtering was done by visually averaging the readout over several wave periods.

Distances to marks on the bottom were measured using a 50-meter fiberglass tape and depths were recorded at each mark. Taped (slant) distances were later corrected to horizontal distances in a surveying program written for a portable computer. Divers also collected bottom samples in small plastic vials and recorded the sample numbers and depth-distances on an underwater slate together with descriptions and measures of bedforms. Sediment samples were later introduced into a rapid sand analyzer to determine size characteristics based on the formulation of Gibbs et al. (1971). The graphic mean size and Inclusive Graphic Standard Deviation of Folk and Ward (1957) were used to represent sediment size in this study.

Bulk density determinations were made using selected carbonate sand samples which revealed an average density of approximately 2.65 $g/cm^3$, the density of quartz. Although pure crystals of calcite and aragonite have a greater density than quartz, most of the carbonate sands examined consisted of porous coral fragments and broken plates of calcareous algae (Halimeda sp.), sediments similar to those described by Folk and Robles (1964).

Following each beach survey, a sample of breaking wave heights ($H_b$) and breaker periods (T) were recorded using the metric survey rod and a stop watch. Mean breaker period and root-mean-square breaker height were then calculated for each site. Water temperature was also recorded and found to be nearly constant at 28.5°G.

BEACH EQUILIBRIUM MODEL

Among the processes that drive the cross-shore exchange of sediment between the beach and the nearshore region are: asymmetric waves, rips, combined wave and steady current flow, downwelling and upwelling, gravity flows and "groupy" waves (Wright, 1987). The temporal and spatial expression of the nearshore seabed morphology is influenced simultaneously and at different times by at least all of these processes. Dean (1977) argued that the details of the individual processes could be neglected and the offshore profile of equilibrium modelled in terms of very simple propositions regarding "destructive" or sediment-mobilizing forces that mold the bed profile. Dean showed that the time-integrated, two-dimensional equilibrium profile over an unspecified distance seaward could be modelled by the power equation

$$h = A x^m \tag{1}$$

in which h is the depth below still water level expressed as a function of x, the distance seaward from the shoreline. "A" is a scale parameter numerically equal to the depth at a unit distance from shore whereas "m" is a parameter representing the degree of profile concavity (m<1), convexity (m>1) or a plane profile (m=1). The theoretical values obtained for the parameters in equation (1) vary according to the way in which the destructive forces are expressed: assuming uniform energy dissipation per unit volume in the surf zone gives m = 2/3, whereas m = 2/5 results from assuming either uniform alongshore shear stress or uniform energy dissipation per unit surface area in the surf zone.

Bowen (1980), using an energetics model of suspended sediment transport based on symmetric wave orbital motion and a "perturbation" or drift velocity in the nearshore zone, also obtained an expression for the equilibrium beach profile similar to equation (1) with an m = 2/3 exponent. However, by including a higher harmonic term to simulate asymmetrical wave orbital motion, Bowen obtained a new approximation of $h \cong g(5.7wx/\sigma^2)^{2/5}$ where w is the grain settling velocity of the beach sediment and $\sigma = 2\pi/T$ is the wave radian frequency. This equation, which is valid for both the surf and nearshore zones, yields an $m = 2/5$ exponent and implies that the parameter A should be a function of the wave period in addition to sediment grain size or settling velocity.

Based on least squares fitting of equation (1) to some 502 profiles measured from the shoreline to approximately 365 meters offshore (3 to 5-meter depths) along the U.S. East and Gulf coasts, Dean (1977) adopted a mean value of $m = 2/3$ to be used as a functional constant although m for individual profiles ranged from about 0.2 to 1.2 in value. Justification for selecting $m = 2/3$ was based in part on the apparent Gaussian distribution and observed central tendency of the 502 m-values reported by Dean and partly for the convenience of examining variations in A with m held fixed. The latter variation was attributed to a functional relationship between A and the grain diameter, D (Moore, 1982; Dean, 1983) or to the equivalent settling velocity, w, of the bed sediment. Dean (1987) recently noted a close fitting of available A and w data from detrital (quartz) sand beaches by an empirical equation given as $A = 0.067\ w^{0.44}$, where A has units of meters$^{1/3}$, (since m was fixed at 2/3) and w is in cm/s.

The use of particle settling velocity rather than particle size would appear to be more in keeping with governing fluid dynamic processes but this assumes that w has been determined with the necessary adjustment for the in-situ water temperature, a correction that may show considerable variation from one beach (or season) to the next. Particle settling in the Stokes (viscous) range increases by more than 50 percent as water temperature increases from 5 °C to 20 °C, extremes not at all uncommon in the temperate zone. Water temperatures are, of course, higher and less variable in tropical regions (nominally 25 °C to 30 °C); Hydraulic-equivalent grain sizes should be larger there when compared with grains of the same physical size in colder, temperate regions. Meaningful grain settling velocity data should therefore be based upon stated field (not laboratory) water temperature, a practice not commonly evident at present in the literature.

Dean's theoretical arguments leading to the general expression for the equilibrium profile (equation (1) with $m = 2/3$) are strictly applicable to dissipative surf zones although the profiles used by Dean to verify the model and support the choice for m extend well beyond the surf zone into the nearshore region. Since Dean's field examples mainly represent beaches with dissipative surf zones, other surf-zone types may contain exceptions to the $m = 2/3$ "rule", and, if so, it is of interest to know under what conditions they may occur. The singular dependence of the A parameter on either particle size or sediment settling velocity may also require further examination; one intuitively expects the A parameter to be a function of wave characteristics as well as beach sediment properties.

**The Equilibrium Profile on some Caribbean Beaches**

The fitting of equation (1) to the observed profile data obtained at our study sites was, in general, quite successful. In a typical example from Mullet Bay, shown in Figure 2, the fitted profile is designated as FP3458 in which the parameters determined by least squares methods are $A = 0.34$ and $m = 0.58$. In Figure 3 (Baie Rouge), the fitted profile is FP6550 ($A = 0.65$, $m = 0.50$).

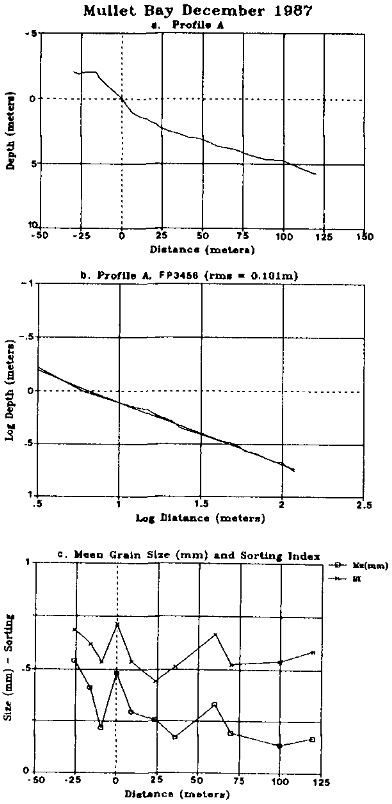


Fig. 2 Beach Profile Data, Mullet Bay

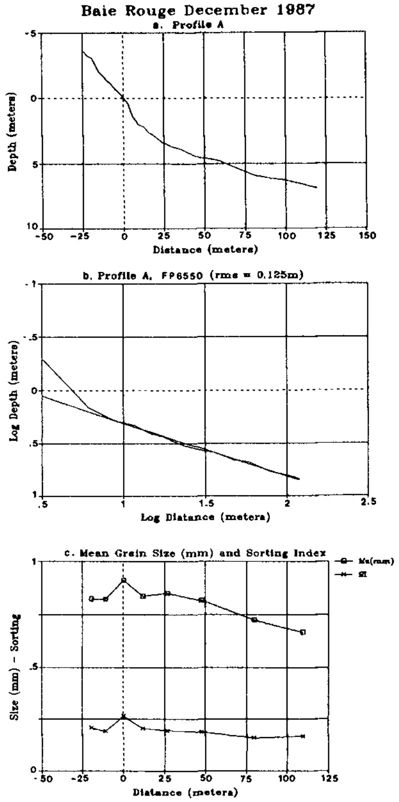


Fig. 3 Beach Profile Data, Baie Rouge

Only one measured beach profile, that of Guana Bay (Figure 4) on Sint Maarten, failed to achieve a reasonable fit. The reason for the deviant shape is presently unclear but the Guana Bay beach differed from all others in being fully dissipative and habitually displaying a wide surf zone with large, plunging breakers approximately 50 meters offshore; the profile, however, steepens markedly beyond this point and thereafter resembles the shape that other profiles have closer to shore. Guana Bay lies between headlands on the windward side of the island and is the only windward beach not protected by an offshore reef.

Table 1 contains the fitted values of the parameters A and m together with root mean square deviations of the observed profile points from the least squares line of best fit. It is noted that the mean value of m for the eleven fitted profiles (two profiles, A and B, were measured at Maho Beach) is approximately 0.55 with a standard deviation of $\pm$ 0.10. The present sample of Caribbean beach profiles is perhaps too small to warrant a definitive statement on the exact distribution of m-values for this population. However, if the assumption of normality is made, one can infer (using the Student's t statistic at the 0.995 level of confidence, one-tailed test) that the population mean is less than 0.67, the m-mean reported by Dean (1977).

Table 1. Summary of Parametric Values for Surveyed Beaches on Curacao, Sint Maarten, Netherlands Antilles and St. Martin, French West Indies.

| BEACH | m | A | tan $\beta$ | $A^{1/m}$ | fit rms | D1 | D2 | $H_b$ | T |
|---|---|---|---|---|---|---|---|---|---|
| Playa Abao | 0.544 | 0.356 | 0.08 | 0.150 | 0.069 | 0.25 | 0.13 | 20.0 | 5.0 |
| Maho(A) | 0.502 | 0.431 | 0.12 | 0.187 | 0.071 | ..no data | | ..no data | |
| Maho(B) | 0.470 | 0.487 | 0.13 | 0.216 | 0.080 | 0.40 | 0.31 | 32.5 | 9.0 |
| Mullet Bay | 0.580 | 0.338 | 0.11 | 0.154 | 0.101 | 0.41 | 0.21 | 44.2 | 9.8 |
| Cupecoy Beach | 0.637 | 0.301 | 0.14 | 0.152 | 0.130 | 0.53 | 0.35 | 51.8 | 10.1 |
| Baie Rouge | 0.498 | 0.650 | 0.13 | 0.421 | 0.125 | 0.85 | 0.78 | 39.2 | 12.2 |
| Friars Bay | 0.512 | 0.416 | 0.19 | 0.180 | 0.098 | 0.25 | 0.13 | 12.0 | 10.0 |
| Grand Case | 0.432 | 0.506 | 0.15 | 0.207 | 0.229 | 0.50 | 0.27 | 10.0 | 9.5 |
| Anse Marcel | 0.479 | 0.395 | 0.16 | 0.144 | 0.139 | 0.25 | 0.15 | 13.0 | 10.0 |
| Orient Bay | 0.773 | 0.135 | 0.09 | 0.075 | 0.212 | 0.22 | 0.47 | 32.4 | 7.3 |
| Dawn Beach | 0.610 | 0.246 | 0.16 | 0.100 | 0.297 | 0.29 | 0.35 | 49.2 | 7.3 |
| AVERAGE | 0.549 | | | | | | | | |
| STD.DEV. | 0.097 | | | | | | | | |

m, A: Least squares parameters for fitted model profile, $h = A x^m$.
tan $\beta$: Beach-face slope
fit rms: Root-mean-square deviation from model profile in meters.
D1: Beach-face mean sand size in mm.
D2: Nearshore mean sand size in mm.
$H_b$: Breaker height (rms) in cm.
T: Breaker period in sec.

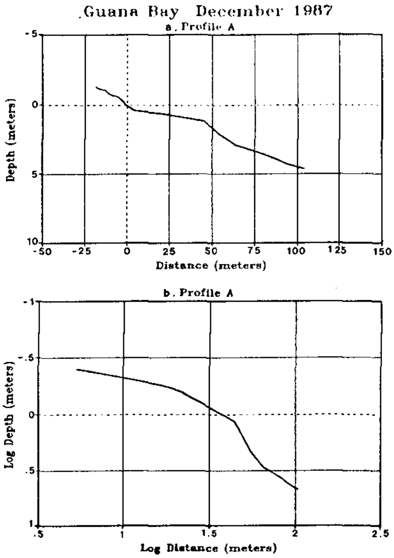


Fig. 4 Beach Profile Data, Guana Bay

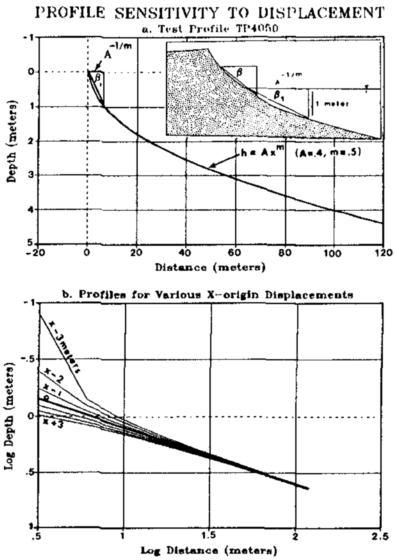


Fig. 5 Simulated Profiles with x-origin Displacements from shoreline zero

**Profile Sensitivity to Measurement Error**

Field profiles modelled by equation (1) require the precise location of the h,x reference or "zero" point. The vertical reference is taken to be the mean water level averaged over the diurnal tidal period and the horizontal reference is found as the intersection of mean water level at the shoreline. Due to the extremely small variation in tidal range (including "weather" tides) at the study locations, we considered that the major error in defining the profile reference would be the error associated with the elimination of gravity wave motion. Consequently, we found the point of sea level intersection on the beach foreshore by visual estimation, choosing a point just above the lower limit of the swash zone. Since depths below mean water level were obtained with a pressure gauge, we assumed these measures to be independent of horizontal distance. To test the sensitivity of the measured profiles to possible errors in reference location, a typical beach profile was simulated using representative model parameters ($A = 0.4$ and $m = 0.5$) to produce a test profile (Figure 5a). Following its construction, the test profile was re-measured (numerically) after each one of a series of fixed x-origin displacements landward and seaward of the reference point. The erroneous profiles, shown in Figure 5b, suggest that measures of real profiles will be most affected by x-origin measurement error occurring in the first 10 meters of the profile but that little change will be noted seaward of that point. Fitting of model profiles in the range $x = 10$ to 100 meters on log-log linear plots will be only slightly affected by a horizontal error of nearly 3 meters in x-origin location.

**Beach Slope based on the Equilibrium Profile**

The parameter A is a potentially useful representation of beach slope or steepness in the nearshore zone since, from equation (1), it is simply the depth at a unit distance from the shoreline. The parameter A in equation (1), however, has units of length$^{1-m}$. It is therefore impossible to compare A values in the same units when m is allowed to vary, as we believe it must in some situations. Basically, this problem arises due to a lack of unique spatial scale. One could, for example, make the variable x in equation (1) dimensionless by dividing it by the distance out to wave base (depth at which which waves initiate bottom sediment motion) but this distance clearly varies as a function of the local wave regime. To achieve standardization, we propose to make horizontal distances nondimensional using $x_1$, the distance seaward to a depth ($h_1$) of one meter, roughly the order of the usual depth at the surf zone limit. At this depth, equation (1) yields a "scaling" distance of $x_1 = A^{-1/m}$ and a new, dimensionless representation of beach slope is obtained as

$$\tan \beta_1 = h_1/x_1 = A^{1/m} \qquad (2)$$

in which both of the fitted curve parameters, A and m, are utilized. The slope angle, $\beta_1$, is given a subscript to distinquish it from $\beta$, the angle of the beach-face slope with which it overlaps (Fig. 5a). The former angle approaches 90° as m approaches 0 (vertical wall) and approaches 45° when $m \gg 1$ (highly convex profile). Therefore, assuming that a two-dimensional beach profile can be represented adequately by equation (1), we conclude that equation (2) is an objective means of expressing the beach slope and is probably intermediate between what is termed beach-face slope (tangent extending from about mid-foreshore to about the low tide mark) and various linear approximations of tan $\beta$ taken across the nearshore region (e.g., Bowen, 1980, Fig. 1.1). For the steep, reflective-type profiles under discussion here, we consider that equation (2) may provide a close approximation to the beach-face slope, tan $\beta$, as discussed in the next section.

**RESULTS AND DISCUSSION**

Nearshore beach slopes, calculated as $A^{1/m}$, are presented in Table 1 along with the corresponding values of beach-face slope, tan $\beta$, obtained from leveling data on the beach-face of the eleven beach profiles of the present study. In several instances the two measures of slope are quite similar but, overall, it is clear that $A^{1/m}$ is more variable, showing greater range of slope values than tan $\beta$.

Values of the dimensionless parameter $H_b/g^{0.5}D^{0.5}T$ were determined for comparison with beach slope, where $H_b$ is breaker height, D is beach sediment grain size, T is breaker period and g is the acceleration due to gravity. Sunamura (1984) has shown that beach-face slope (tan $\beta$) may be quantitatively predicted using

$$\tan\beta = [0.013/(H_b{}^2/gDT^2)] + 0.15 \qquad (3)$$

which was determined from existing laboratory data, or

$$\tan\beta = 0.12/(H_b/g^{0.5}D^{0.5}T)^{0.5} \qquad (4)$$

which was based on field data. Table 2 contains data from the present field experiment in which two sets of $H_b/g^{0.5}D^{0.5}T$ values were determined, one using the mean sand grain diameter from the beach-face and one using the mean grain diameter from the nearshore zone. Samples taken near the wave step were excluded as they usually contained very coarse material of limited extent (e.g., Figure 2c). Plots showing the four combinations of data (tan $\beta$ versus $A^{1/m}$, beach-face versus nearshore sand size) are shown in Figure 6 with the curve for equation (4).

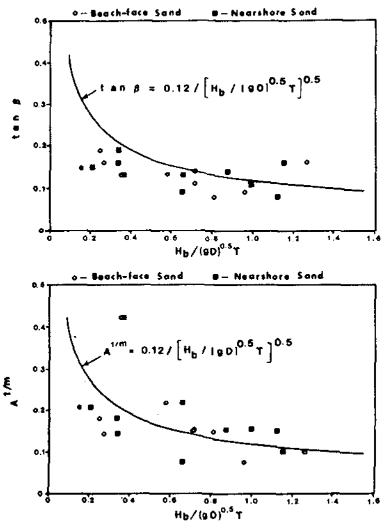


Fig. 6 Beach slope measured as tan$\beta$ and $A^{1/m}$ plotted against the dimensionless parameter $H_b/(gD)^{0.5}T$

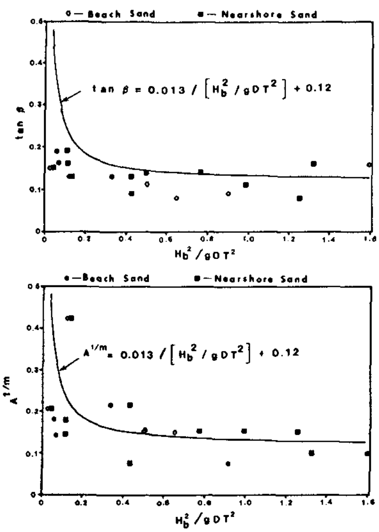


Fig. 7 Beach slope measured as tan$\beta$ and $A^{1/m}$ plotted against the dimensionless parameter $H_b{}^2/gDT^2$

Table 2. Comparison of Beach Slope with functions of $H_b/g^{0.5}D^{0.5}T$

| f1(D1) | f1(D2) | f2(D1) | f2(D2) | tan $\beta$ | $A^{1/m}$ | Beach |
|---|---|---|---|---|---|---|
| 0.150 | 0.204 | 0.023 | 0.042 | 0.15 | 0.207 | Grand Case |
| 0.242 | 0.336 | 0.059 | 0.113 | 0.19 | 0.180 | Friars Bay |
| 0.262 | 0.339 | 0.069 | 0.115 | 0.16 | 0.144 | Anse Marcel |
| 0.352 | 0.367 | 0.124 | 0.135 | 0.13 | 0.421 | Baie Rouge |
| 0.577 | 0.655 | 0.332 | 0.429 | 0.13 | 0.216 | Maho(B) |
| 0.711 | 0.994 | 0.506 | 0.988 | 0.11 | 0.154 | Mullet Bay |
| 0.711 | 0.875 | 0.506 | 0.766 | 0.14 | 0.152 | Cupecoy Beach |
| 0.808 | 1.120 | 0.652 | 1.254 | 0.08 | 0.150 | Playa Abao |
| 0.955 | 0.654 | 0.913 | 0.428 | 0.09 | 0.075 | Orient Beach |
| 1.264 | 1.150 | 1.597 | 1.322 | 0.16 | 0.100 | Dawn Beach |

D1: Beach-face mean sand size in cm.
D2: Nearshore mean sand size in cm.
$f1(D1) = H_b/g^{0.5}D1^{0.5}T$  $f2(D1) = (H_b/g^{0.5}D1^{0.5}T)^2$
$f1(D2) = H_b/g^{0.5}D2^{0.5}T$  $f2(D2) = (H_b/g^{0.5}D2^{0.5}T)^2$

In Figure 6, tan $\beta$ shows little, if any, systematic variation with $H_b/g^{0.5}D^{0.5}T$. The beach slope calculated as $A^{1/m}$ does show the expected variation with the independent variable, allowing for scatter in the data similar to that seen in Sunamura's graphs (Sunamura, 1984, Figures 1 and 2). Although Sunamura attributed some of the scatter to inaccuracies in the measure of tan $\beta$, he pointed to 1) spatial and temporal change in D and 2) temporal changes in $H_b$ and T as the leading sources of error. As expected, less error was associated with laboratory as opposed to field data plots.

The quantity $H_b/g^{0.5}D^{0.5}T$ is in part an index for wave steepness since the numerator contains wave height and the denominator furnishes a length based on joint wave-sediment properties. A similar quantity can be derived as a ratio of wave and sediment-related forces expressed as unit mass accelerations. Taking the numerator as $H_b/T^2$ and the denominator as gD/S where $S = \delta H_b$ is the suspension distance of sand particles above the bottom and $\delta \cong 1$ (Dean, 1973), this ratio is simply the steepness index squared or $H_b{}^2/gDT^2$. Values of the latter appear in Table 2 and in Figure 7 using averages of beach-face and nearshore sand samples, respectively, for the mean grain size, D. This figure shows tan $\beta$ and $A^{1/m}$ plotted against $H_b{}^2/gDT^2$ with Sunamura's (1984) laboratory data curve, equation (3), superimposed in slightly modified form (constant reduction in slope of 0.03) to obtain the apparent best fit to our data. Again, the best dependent or predicted variable appears to be $A^{1/m}$ rather than tan $\beta$ and the corresponding curve of best fit is

$$A^{1/m} = [0.013/(H_b{}^2/gDT^2)] + 0.12 \qquad (5)$$

There is no overly compelling reason to select plots based on beach-face rather than nearshore sediment samples (Figures 6 - 7) as better predictors of beach slope. At first glance it is noted that nearshore sediments are generally finer (e.g., Mullet Bay, Figure 2C) and so produce slightly larger values of $H_b{}^2/gDT^2$. This is not always the case, however. Certain beaches on the windward side of Sint Maarten (Orient Bay and Dawn Beach) contained coarse sands that appear to be rather than beach-face sand sizes would appear to rank them too low on the scale of $H_b^2/gDT^2$. Since beach-face sediment is affected more by the ambient wave regime and less by local variations among nearshore (and offshore) sediment sources, it is considered best to use for determinations of D in equation (5).

## GONGLUSIONS

Practical applications for the above results are immediately obvious. Beach construction or restoration projects in low-energy, carbonate environments of the type described require an estimate of fill type (grain size) and amount necessary to achieve a desired two-dimensional profile over existing bottom. An equilibrium beach profile can be readily determined through use of equation (1) and the necessary estimates for the parameters A and m. Given a suitable estimate for the parameter m, the parameter A is readily calculated from the beach slope, $\tan \beta_1 = A^{1/m}$, predicted by equation (5). Pending further investigation, an appropriate average estimate for carbonate beaches on Caribbean islands appears to be $m = 0.55$.

It has been shown that $A^{1/m}$ provides a useful and objective estimate of beach slope on Caribbean island carbonate beaches (equation 5). The sudden inflection in the left side of the curve in Figure 7 implies that a small change in wave height or steepness in this region will be accompanied by a large change in beach slope. Beaches composed of very coarse sand will be particularly susceptible to such change. This is consistent with reports we have obtained from hotel owners on the western side of Sint Maarten that sudden and often severe subaerial erosion typically occurs in winter when Atlantic storm waves reach this side of the island.

In a definitional sense, $A^{1/m}$ is not equivalent to the mostly subaerial beach-face slope ($\tan \beta$) but is an indicator of the subaqueous nearshore slope ($\tan \beta_1$) as shown in Figure 5a. Nevertheless, on the steep, highly concave and barless beaches studied here, there appears to be ample justification to use $A^{1/m}$ in place of $\tan \beta$ in predictor equations for beach-face slope of the type presented here. Since the parameters A and m are determined by least squares fitting of the observed nearshore profile over most of its length (excluding perhaps the first 6 meters from shore), the measure of $A^{1/m}$ is not only objective but its precision can be judged by goodness-of-fit criteria.

Also, we seem to have observed near agreement between our field results and Sunamura's empirical curve for laboratory results, equation (3). Equation (3) has the same form as equation (5) but differs from it by a constant denoting a small offset in the dependent variable, $\tan \beta_1 = A^{1/m}$; With this minor adjustment, Sunamura's curve appears to fit our data reasonably well when using the squared term, $H_b^2/gDT^2$, as the independent variable. Given the potential use for equation 5 in field applications, it is worth noting that equation 3 is based on a very large collection of laboratory data which fit this curve quite well. Addition data from the field are needed to verify the relationship.

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