

Setup and Swash on a Natural Beach

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Wave setup and swash statistics were calculated from 154 runup time series measured on a moderately steep beach under incident waves varying from 0.4 to 4.0 m significant wave height. When scaled by the incident wave height, setup, swash height, and total runup (the sum of setup and half the swash height) were found to vary linearly with the surf zone similarity parameter $\zeta_0 = \beta(H_0/L_0)^{-1/2}$. The foreshore slope appeared the appropriate value for the calculation of ζ_0 , although the setup data showed some influence of an offshore bar at low tide. For low Irribaren numbers the swash height in the incident frequency band becomes saturated, while for high Irribaren numbers, no such signs of saturations were seen. Thus the infragravity band appears to become dominant in the swash below some value of ζ_0 . For these data, that value is approximately 1.75, although there is considerable scatter associated with that estimate.

INTRODUCTION

The term runup has traditionally been used by coastal engineers to describe the time-varying location of the shoreline water level about still-water level. This quantity is of considerable interest in determining design setbacks for shoreline structures and vulnerability of shoreline protection and natural dunes. It is convenient to split the runup into two components: a super-elevation of the mean water level, called setup, and fluctuations about that mean, called swash. The setup is important to the dynamics of near-shore currents such as longshore currents arising from longshore variations of wave height [Munk and Traylor, 1947; Bowen and Inman, 1969; Gourlay, 1976] and their associated rip currents. Fluctuating water velocities associated with swash contribute to sediment transport and erosion on the foreshore.

WAVE SETUP

The study of wave setup was prompted by the hurricane that hit the east coast of the United States in 1938. At the height of the storm, mean shoreline water elevation at an exposed location at Narragansett Pier was approximately 1 m higher than at the protected shoreline near Newport. A series of laboratory studies followed that demonstrated that water level through the surf zone was significantly elevated by wave breaking [Savage, 1957; Fairchild, 1958; Saville, 1961]. Dorrestein [1961] and Longuet-Higgins and Stewart [1962, 1963, 1964] provided the theoretical explanation of setup, demonstrating that the gradient of excess momentum flux associated with wave breaking (radiation stress) in the surf zone must be balanced by a slope of mean sea level.

Bowen *et al.* [1968] assumed that wave height in the surf zone, H , is limited to a constant proportion γ of the total water depth $h + \eta$, where h is the still-water depth and η the local setup. This led to an explicit expression for the setup gradient in the surf zone:

$$\frac{\partial \eta}{\partial x} = -K \frac{\partial h}{\partial x} \quad K = (1 + 2.67 \gamma^{-2})^{-1} \quad (1)$$

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The maximum setup $\bar{\eta}_M$ will occur at the shoreline and will be

$$\frac{\bar{\eta}_M}{H_b} = 0.3\gamma \quad (2)$$

if the setdown (depression of mean sea level outside the surf zone) is included [Battjes, 1974] or

$$\frac{\bar{\eta}_M}{H_b} = 0.38\gamma \quad (3)$$

if only the setup above the sea level at the break point is of interest. We will present data concerning the latter ratio, as our measure of still-water level—a tide gauge—is located just outside the break point, in the setdown region. However, whether we measure still-water level in the setdown region or far offshore may not have a significant bearing on the results in light of the data of Bowen *et al.* [1968], which showed setdown to be significantly less than expected. Bowen *et al.* also presented laboratory data to show that the breaking parameter γ in equation (3) is only a function of a surf similarity parameter ζ_0 , to be defined later.

Laboratory evidence [Bowen *et al.*, 1968; Van Dorn, 1976] support these setup relationships, although experiments with random waves give somewhat smaller nondimensional setup values [Battjes, 1974]. Interestingly, both Bowen *et al.* [1968] and Van Dorn [1976] found that the setup slope very close to the shoreline was significantly steeper than predicted by (1). Bowen *et al.* related this to a residual wave height at the shoreline (a standing wave) and predicted that the setup slope should approach the beach slope asymptotically. Measurements of the maximum setup should then be rather sensitive to the offshore position of sampling or, as will be mentioned later, to the height of the runup sensor above the bed.

Few field measurements of setup exist. Dorrestein [1961] measured setup across the surf zone on a barred beach under waves with offshore significant wave heights of 0.8–1.6 m. However, his measurements of maximum setup were taken from a location with mean total water depth 0.15 m. Judging from the results of Bowen *et al.* [1968], shoreline values could be significantly larger than Dorrestein found. Also, he estimated mean sea level as the result of a 72-s average from an offshore sensor. Guza and Thornton [1981] pointed out that

the standard deviation of setup estimates made by using such a short offshore sampling time often exceeded the estimates.

The most complete set of wave setup data from a natural beach is that of *Guza and Thornton* (1981). They present 11 estimates taken from a low-slope beach ($\beta = 0.02$) under incident wave heights in the range 0.6–1.6 m. They found the setup at the shoreline to be about $0.17 H_s$, where H_s is the deep water significant wave height. However the data show considerable scatter. Also, the offshore pressure sensors used to estimate still-water level were not located with reference to an experiment benchmark. Thus their vertical displacement from reference had to be determined from the data by using a least squares model that assumes a linear dependence of setup on incident wave height. To obtain a reasonable fit, they had to neglect one of the data points out of hand. It is unclear how meaningful the data would have been with the inclusion of the outlier. It should also be noted that they measured runup by using a dual-resistance wire sensor positioned 0.03 m above the bed. Comparison of their technique with the time-lapse photography technique used here is discussed in the measurements section of this paper and in *Holman and Guza* [1984]. Even with the deficiencies mentioned above, the 11 estimates presented by *Guza and Thornton* [1981] represent the most complete field data set to date.

SWASH OSCILLATIONS

The statistics of swash have been studied extensively both in the laboratory and, to a lesser extent, in the field. *Guza and Thornton* [1982] contains a thorough summary of past research. We will only discuss results relevant to this work.

Miche [1951] proposed that monochromatic waves in the surf zone can be considered to be composed of both a progressive component, which is dissipated by breaking across the surf zone and has zero amplitude at the shoreline, and a standing component, which has a maximum shoreline amplitude a_s . A number of laboratory studies [*Moraes*, 1970; *Battjes*, 1974; *Guza and Bowen*, 1976; *Van Dorn*, 1978] have found a_s to be limited by a surf similarity parameter

$$\epsilon_s = a_s \sigma^2 / g \beta^2 \leq \text{constant} \quad (4)$$

where the constant has been reported in the range 1–3; σ is the incident wave radian frequency, g the acceleration due to gravity, and β the beach slope. Thus the swash amplitude should be independent of incident wave height. *Hunt* [1959] showed laboratory evidence that the total runup R_T is proportional to a different version of the surf similarity parameter, the Iribaren number ζ_0 :

$$\frac{R_T}{H_s} = \frac{(\bar{\eta}_M + 0.5R_S)}{H_s} = C \zeta_0 \quad (5)$$

where

$$\zeta_0 = \frac{\beta}{(H_0/L_0)^{1/2}} = (\pi/\epsilon_0)^{1/2}$$

and R_S is the significant swash height; H_0 and L_0 are the deep-water wave height (taken later to be the significant height) and wavelength, respectively; and C is an empirical constant.

Broadband incident waves, as exist on natural beaches, will give rise to a spectrum of swash. *Huntley et al.* [1977] proposed that incident wave frequencies would each saturate as equation (4), implying that each frequency band acts independent of the others. This leads to the prediction of a σ^{-4} spectral decay through the incident band. They present runup data

from four beaches that support the hypothesis. *Guza and Thornton* [1982] also find that the incident band of the spectrum reaches a saturation level, although they find a σ^{-3} frequency dependence.

Amplitude modulations in nonmonochromatic incident waves can also give rise to low-frequency motions in the swash [*Gallagher*, 1971; *Symonds et al.*, 1982]. Various field studies have investigated the nature of these motions, which are wavelike and may be in the form of either edge waves [*Huntley*, 1976; *Wright et al.*, 1979; *Sasaki et al.*, 1976; *Huntley et al.*, 1981; *Katoh*, 1981; *Holman and Bowen*, 1984] or standing incident waves [*Suhayda*, 1974; *Symonds*, 1982]. Several spot measurements of surf beat amplitude have been made [*Munk*, 1949; *Tucker*, 1950; *Goda*, 1975; *Holman and Bowen*, 1984], but only *Guza and Thornton* [1982] present field data showing a functional relationship between low-frequency swash amplitude and incident wave height. Using a superset of the data mentioned in the setup discussion, they found

$$R_s^v(\text{cm}) = 3.48(\text{cm}) + 0.71 H_s(\text{cm}) \quad (6)$$

with the slope of the relationship depending only on the growth of the infragravity energy, the incident band always being saturated. (*Holman* [1981] presented data that also suggested a linear relationship, although his data were from mid-surf-zone flowmeters and were harder to interpret. He also presented qualitative arguments to explain such a linear relationship.)

In this paper we will present data from 154 different runup time series collected on a natural beach under a variety of incident wave and beach conditions. We find ζ_0 to be a very important variable in predicting runup, influencing both the setup and swash oscillations. Under most conditions the local foreshore slope is the relevant slope for the calculation of ζ_0 , but at low tide the offshore sand bar becomes important.

FIELD MEASUREMENTS

The data presented herein were collected as part of a joint field experiment involving investigators from the United States Geological Survey, Oregon State University, the University of Washington, and the U.S. Army Corps of Engineers to understand surf zone sediment transport processes under storm conditions. The experiment took place at the Army Corps of Engineers Field Research Facility (FRF), located in the middle of a 100 km uninterrupted stretch of barrier islands, approximately 2 km north of Duck, North Carolina. The beach typically exhibits a bimodal grain-size distribution, with a medium sand (0.25 mm) mixed with a coarse shell fraction (0.75 mm). The foreshore is steep, with an average slope of approximately 1:10 (Figure 1). Throughout most of the experiment a single bar was present approximately 50 m offshore, although its position and amplitude varied in response to storm events. Bar morphology varied from linear to crescentic. The main feature of the FRF is a 560-m-long pier which extends offshore to the 8-m depth contour. The pier provided an ideal instrument platform but, as indicated in Figure 2, does cause some interruption to the natural beach contours [*Miller et al.*, 1983]. *Birkemeier et al.* [1981] gives a complete description of the site and available facilities.

Runup data were collected by using longshore-looking time-lapse photography from super-8 movie cameras mounted on scaffolding on the pier, approximately 13 m above mean sea level. Large markers were placed in pairs, spaced 10 m in the cross-shore direction, every 50 m down the beach for 300

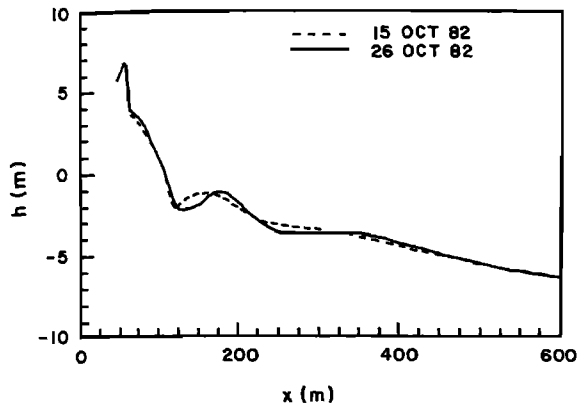


Fig. 1. Example beach profiles for a location 517 m south of the pier for October 15 (mid-experiment) and October 26 (immediately after the experiment). These are not the extreme profiles for the period; the bar position and morphology varied strongly during the experiment. (Data from Coastal Environment Research Center [1982]).

m on either side of the pier. Additional single markers were placed at odd multiples of 25 m. These served as a basis for the beach profile grid and provided scale for the film images. A data run usually consisted of running two movie cameras synchronously, one pointed to the north and one to the south. A frame was shot every second for a total run length of 35 min, or 2100 frames. Slight differences in the digitizing interval were corrected by carefully timing the length of each run,

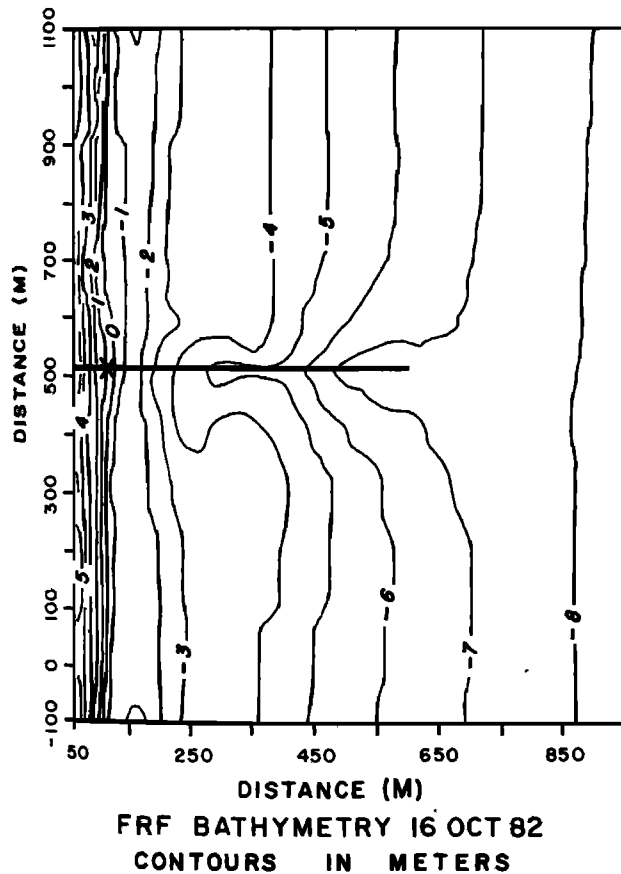


Fig. 2. FRF bathymetry from October 16, 1982, showing the pier (heavy line) and the camera locations (large cross). Data presented in the paper are for longshore locations ranging from 50 to 300 m on either side of the pier. (Bathymetry data from Coastal Environment Research Center [1982]).

counting the number of frames taken, and calculating the average Δt . Laboratory studies have shown no noticeable drift in this number through a 35-min period.

Digitization of the film data for any of the longshore locations is accomplished with a computer-assisted digitization scheme described in Holman and Guza [1984]. Replicate digitizations by different operators, performed on a number of films, showed the standard deviation on setup and significant swash height measurements presented here to be approximately 10%. Intercalibration of the film technique with the dual-resistance wire runup sensor on a low-slope beach showed some systematic differences in measured means and standard deviations, with the film technique registering a slightly higher mean and a 35% larger standard deviation (83% larger variance) than the wire sensor [Holman and Guza, 1984]. This is partly related to the sensitivity of the wire sensor to the height of the wire above the beach and partly to the subjective interpretation of rundown of the films. The latter point will be discussed further in the results section of this paper.

Beach surveys were carried out by using the FRF Zeiss Elta-2 electronic total station system. This gives profile data, corrected to mean sea level, with an accuracy of better than 0.5 cm over the area of filming. These data were used to transform the raw cross-slope runup data to a vertical signal. All data presented in this paper will be in terms of the vertical component of runup.

Incident wave data were collected from a wave-rider buoy positioned 3 km offshore in approximately 20-m depth. Incident significant wave height is calculated as 4σ , where σ is the standard deviation of a 20 min time series. Incident period is the peak period from the spectrum. Tide data is provided by a NOAA tide gauge attached to the end of the pier. Raw tide gauge data, consisting of spot measurements of sea surface elevation every 6 min, showed a standard deviation of 0.04 m during storms. Mean sea level was estimated from the average of the six consecutive measurements corresponding to the data run. The tide gauge was outside the surf zone for all but the largest storms.

OBSERVATIONS

Data were collected over a 3-week period in October 1982. Two storms occurred during the experiment, with significant wave heights ranging from 0.4 to 4.0 m, periods from 6 to 16 s, and foreshore slope variations of a factor of 2. In short, data were collected over a wide portion of the relevant parameter space. A summary of incident wave statistics for the duration of the experiment is shown in Figure 3.

Sixty-one films have been digitized, most at two longshore locations 100 and 150 m from the camera. Some films, where longshore variability has been apparent, have been analyzed intensively, with up to nine ranges being digitized. A total of 154 runup time series are discussed in this paper. After digitization of a runup time series and transformation to the vertical component, the mean $\langle \eta \rangle$ and the standard deviation σ are found. From this the setup $\bar{\eta}$ is calculated as $(\langle \eta \rangle - \text{tide})$ and the significant swash height R_s^0 as 4σ .

SETUP RESULTS

Figure 4 is a plot of setup against incident significant wave height for the entire data set. (In fact, two of the 154 estimates, both from low-wave days, were negative. These do not appear on the setup plots but are included in later plots of total runup.) A general positive trend is apparent, although the data

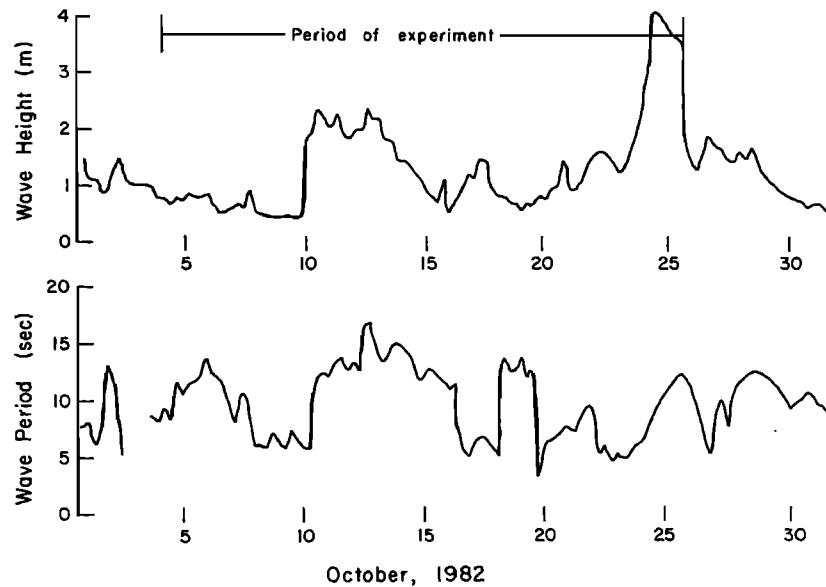


Fig. 3. Incident significant wave height and period for the duration of the experiment as measured by an offshore wave rider in 20-m water depth [Coastal Environment Research Center, 1982]. Two major storms occurred: October 10-13 and 24-26.

are quite scattered, particularly at small H_s . A linear relationship, such as found by Guza and Thornton [1981], is not obvious.

In Figure 5 the setup data are reparameterized, now plotting nondimensional setup $\bar{\eta}/H_s$ against the surf similarity parameter ζ_0 . The beach slope used in the calculation of ζ_0 is the local foreshore slope appropriate to each longshore location (calculated as the mean slope over the range ± 2.5 m from the mean runup). The scatter is reduced. It is apparent that nondimensional setup is dependent on ζ_0 . A single value, such as is commonly quoted in the literature, is not valid for all incident wave conditions.

The scatter is even further reduced if consideration is given to the tides. The data were split into three sections corresponding to low, mid, and high tides. The cutoff tidal elevations were arbitrarily taken as 0.25 and 0.70 m of a total measured range during the experiment of -0.35 to 1.10 m. The setup data are plotted by tide in Figure 6 (a, b, c). Least square fit coefficients and standard error of the coefficients are listed for the setup data in Table 1. Both high- and mid-tide data show significant trends in nondimensional setup with ζ_0 , indicating that setup under spilling breakers and during storms (small ζ_0) will be a smaller fraction of incident wave height than under plunging breakers. The data of Guza and

Thornton [1981] have been included in the high tide plot (Figure 6a), assuming a beach slope of 0.023 and a wave period of 12 s in all cases (reasonable approximations according to Guza). Their data fall slightly below the regression line but are within the typical scatter of the present data. The low tide data do not show any significant trend with ζ_0 . This may indicate an influence of the offshore bar morphology on the setup process. Interestingly, Guza and Thornton's data follow the trend of our data much more closely using the mean surf zone beach slope than using the foreshore slope, again supporting the observation that setup may depend on more than just the beach face. This is in contrast to the swash data, where the local foreshore slope appears most important.

The actual magnitudes of the nondimensional setup deserve some comment. While the functional form of equation (3) is supported by the data (showing nondimensional setup to depend on the Irribaren number through the breaking parameter), the required magnitudes of γ are much larger than are normally found on natural beaches. Part of the reason may be due to the asymptotic increase in setup slope near the shoreline, as noted by Bowen *et al.* [1968]. This implies that measured shoreline values of setup will always be higher than predicted by theory and that the amount in excess will depend on proximity to the shoreline. Holman and Guza [1984] also

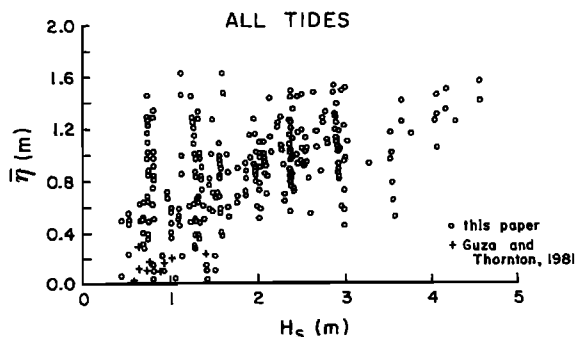


Fig. 4. Setup versus incident significant wave height for all data runs. The data of Guza and Thornton [1981] are included for comparison.

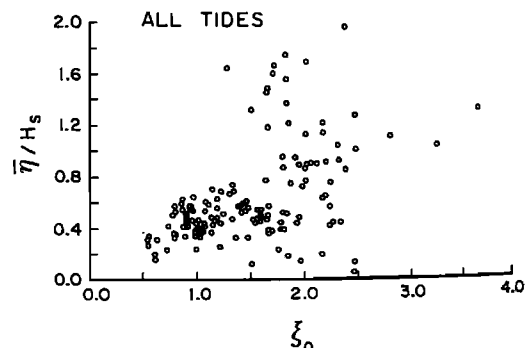


Fig. 5. Nondimensional setup (scaled by incident significant wave height) plotted against the surf similarity parameter ζ_0 .

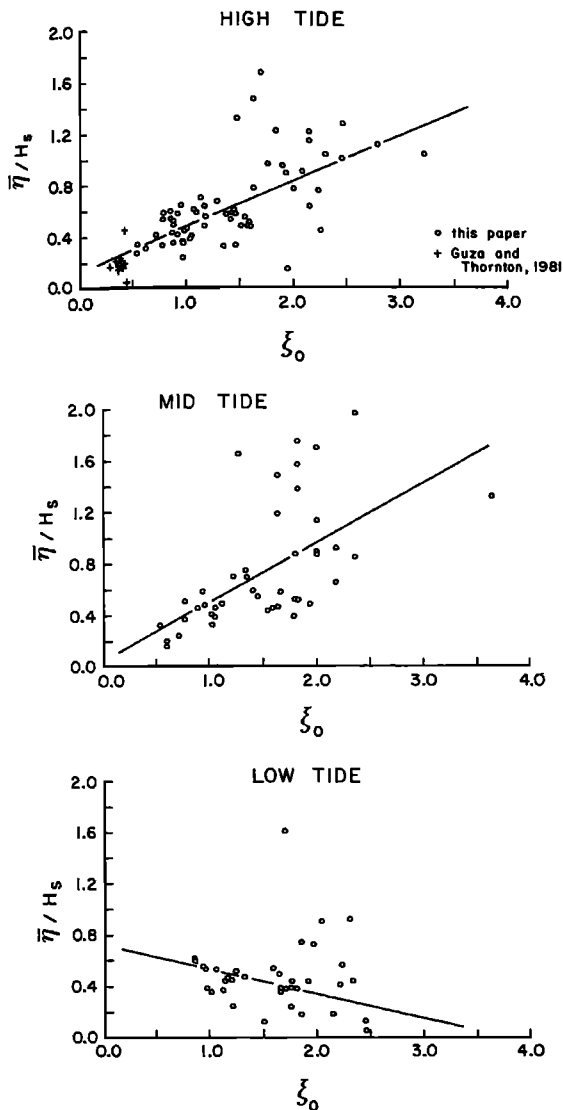


Fig. 6. (a) Nondimensional setup versus the surf similarity parameter ξ_0 for high tide runs only. The data of Guza and Thornton [1981] are included for comparison. (b) Same as 6a, except for mid-tide runs only. (c) Same as 6a, except for low-tide runs only.

noted this, finding that setup elevations measured via the time-lapse photography technique (measuring in an effective water depth of approximately 0.5 cm) were higher than when a dual-resistance wire sensor (measuring 3.0 cm above the bed) was used. Clearly, the kinematics of this asymptotic region deserve further study.

SWASH RESULTS

Figure 7(a, b, c) show the plots of nondimensional swash R_s/H_s against ξ_0 for the three stages of the tide. Table 1 gives the least squares regression coefficients for the plots. The data are well described by this parameterization; there is little scatter. These data then indicate that choosing a single value for nondimensional swash height, such as had been indicated for various laboratory studies (equation (4)) or for the data of Guza and Thornton [1982] (equation (6)), is only suitable for a limited range of incident wave conditions, a possibility anticipated by the latter authors. As alluded to in the paragraph above, the swash data show no difference with the tide, indicating that the foreshore slope determines the swash dynamics

TABLE 1. Regression Coefficients From Runup Statistics

	Slope	Intercept
<i>Setup, $\bar{\eta}/H_s$</i>		
High tide	0.35 ± 0.05	0.14 ± 0.07
Mid tide	0.46 ± 0.10	0.06 ± 0.16
Low tide	-0.20 ± 0.12	0.73 ± 0.07
<i>Swash Height, R_s/H_s</i>		
High tide	0.88 ± 0.06	-0.06 ± 0.08
Mid tide	0.92 ± 0.12	-0.03 ± 0.19
Low tide	0.87 ± 0.13	-0.15 ± 0.22
<i>Total Runup, R_T/H_s</i>		
High tide	0.80 ± 0.06	0.11 ± 0.09
Mid tide	0.93 ± 0.13	0.04 ± 0.21
Low tide	0.24 ± 0.08	0.65 ± 0.14
<i>Incident Band Swash Height, R_s/H_s</i>		
All tides	0.69 ± 0.04	-0.19 ± 0.06
<i>Infragravity Band Swash Height, R_s/H_s</i>		
All tides	0.53 ± 0.05	0.09 ± 0.08

The abscissa is ξ_0 in all cases.

for these data. This is reinforced by the data of Guza and Thornton [1982]. When plotted by using the mean beach slope across the surf zone, the data fell well above the regression line. However, when the beach face slope was used, the data fell well within the scatter of our data.

TOTAL RUNUP

Finally, Figures 8a, 8b, and 8c plot the total runup R_T/H_s , expressed as a nondimensional ratio to H_s , versus ξ_0 for the three tidal stages. As expected, the mid and high tide data show a significant trend, while the low tide data are more weakly dependent on ξ_0 (Table 1). In all cases the plots are well constrained, with relatively little scatter.

It is of interest that this relationship, proposed by Hunt [1959] on the basis of laboratory experiments, should work on this field data. One possible explanation lies in the potential ambiguity of distinguishing between setup and swash. A difficulty in the time-lapse photography technique used here to collect runup data lies in the somewhat subjective interpretation of the swash rundown. While the wave runup is usually easily distinguished by a foam line, the rundown is complicated on natural beaches by percolation and other factors. Replicate digitizations of the same film show that the point chosen as the rundown location in each frame is generally reproducible to within 10%; however, whether that point represents the "true" rundown is unknown (it is not even clear what the true rundown is). The dual-resistance wire sensor used by Guza and Thornton [1981, 1982] suffers from the same fault, although their sensor is at least objective; choosing the farthest landward point at which the water depth is at least 3 cm. Interestingly, variance in the statistical quantities arising from this ambiguity is somewhat self-compensating. If the digitizing technique follows the rundown "too quickly," the result will be a low estimate of setup but a large value of significant swash height. Similarly, following the rundown too slowly will yield a high setup but low swash height. In either case the quantity expressed by the total runup removes the ambiguity by adding the quantities. As it represents the typical maximum swash excursion, a quantity easily seen in the films, and as it has no ambiguity as described above, it should be statistically the most reliable runup statistic.

We attempted to test the idea that the potential ambiguity in definition of rundown could be leading to scatter in our

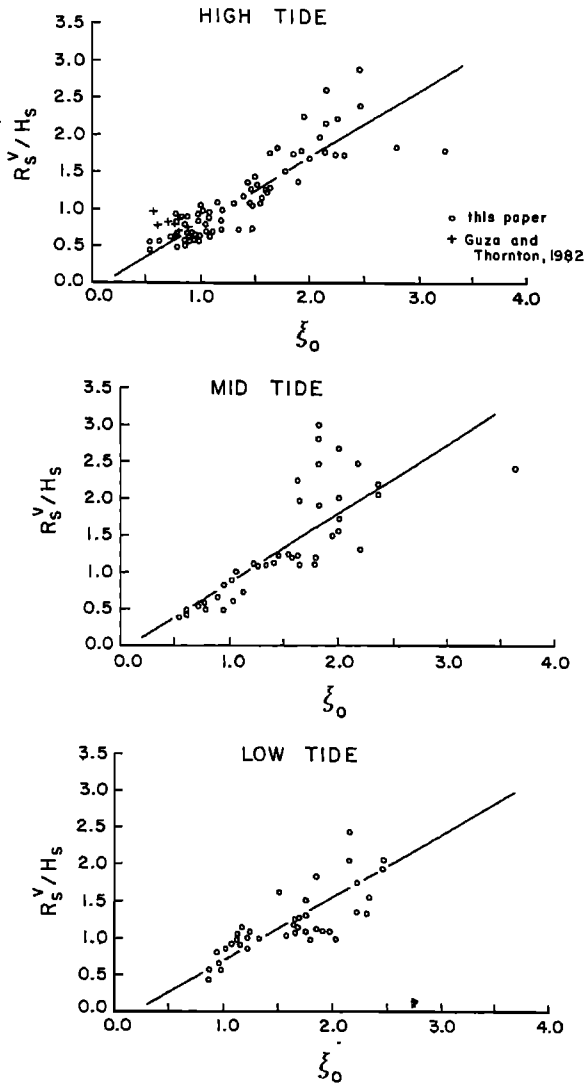


Fig. 7. (a) Nondimensional significant swash height as a function of surf similarity parameter ξ_0 for high-tide runs only. The data of Guza and Thornton [1982] are included for comparison. (b) Same as 7a, but for mid-tide runs only. (c) Same as 7a, but for low-tide runs only.

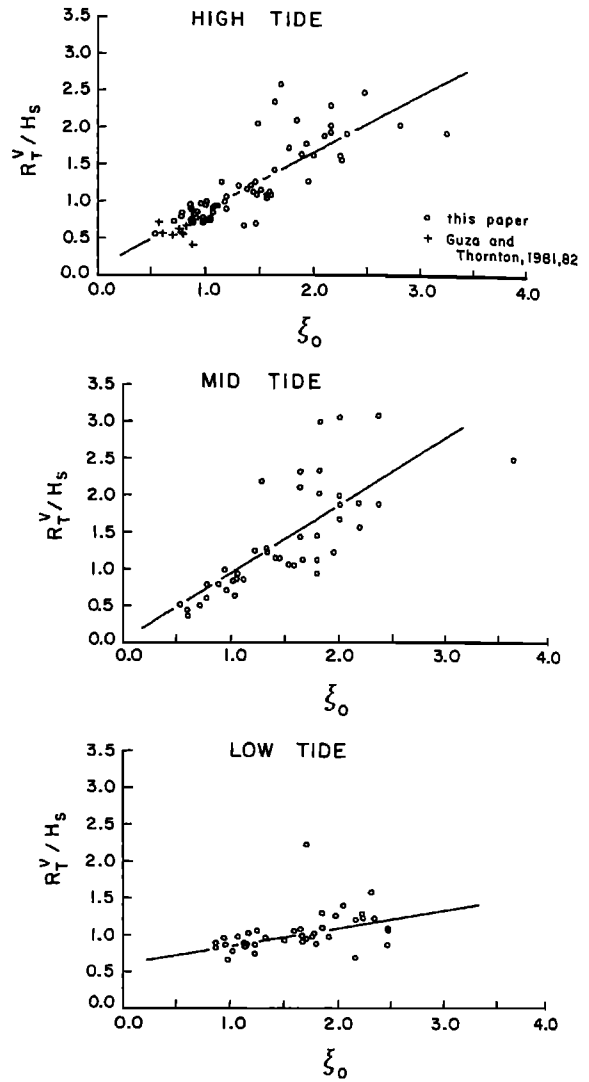


Fig. 8. (a) Variation of the total runup (scaled by incident significant wave height) as a function of the surf similarity parameter ξ_0 for high-tide runs only. The combined data of Guza and Thornton [1981, 1982] have been included. (b) Same as 8a, but for mid-tide runs only. (c) Same as 8a, but for low-tide runs only.

data. This was done by performing a least squares regression on the nondimensional swash data, judged the better behaved of our statistics, then adding the residuals from the regression to the setup. If the scatter in the setup is a result of this ambiguity, then this operation should reduce that scatter. This worked only for the low tide data, the high and mid tide data actually becoming worse. This gives us some faith in our digitizing criteria; if the scatter of the data when plotted against ξ_0 can be taken as a criteria of "goodness" of the data, then this test shows we resolve the rundown without allowing ambiguity between setup and swash.

IMPORTANCE OF THE INFRAGRAVITY BAND

Empirical data discussed earlier from both laboratory and field suggest that the incident and infragravity swash bands respond differently to changes in the incident wave. This was particularly evident in the data from Guza and Thornton [1982], where they showed the incident band to saturate while the infragravity band varied linearly with incident wave height. To test this result, spectra were run on all our data and the total variance split at 0.05 Hz, the lower frequency vari-

ance being referred to as infragravity, while the higher frequency was called the incident band. Significant swash heights appropriate to the variance in each band were then calculated. Figures 9a and 9b show the significant swash height for the incident and infragravity bands, respectively, plotted against incident significant wave height. The data are very scattered, agreeing with the conclusion stated earlier that this is not a good parameterization of the data. Nevertheless the incident band swash height shows little trend with H_s , in agreement with the idea of saturation, while the infragravity band appears to be some positive function of H_s .

Figures 10a and 10b show the nondimensional swash plotted against ξ_0 . This is clearly a better parameterization of the swash process for these data. The least squares regression (coefficients listed in Table 1) shows the infragravity band to assume increasing importance at low ξ_0 (during storms for this data set). In fact, linear solution from the regression lines shows that the infragravity band dominates for $\xi_0 < 1.75$, although errors in this value may be large, given the similarity of the two regression slopes and the scatter associated with each. Sasaki and Horikawa [1975] also distinguished an infra-

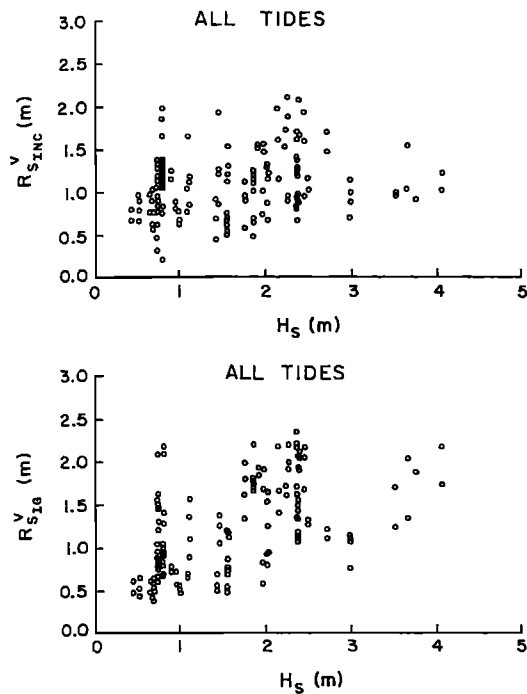


Fig. 9. (a) Significant swash height versus incident significant wave height for the incident wave band ($f \geq 0.05$ Hz) for all data runs. (b) Same as 9a, but for the infragravity frequency band ($f < 0.05$ Hz).

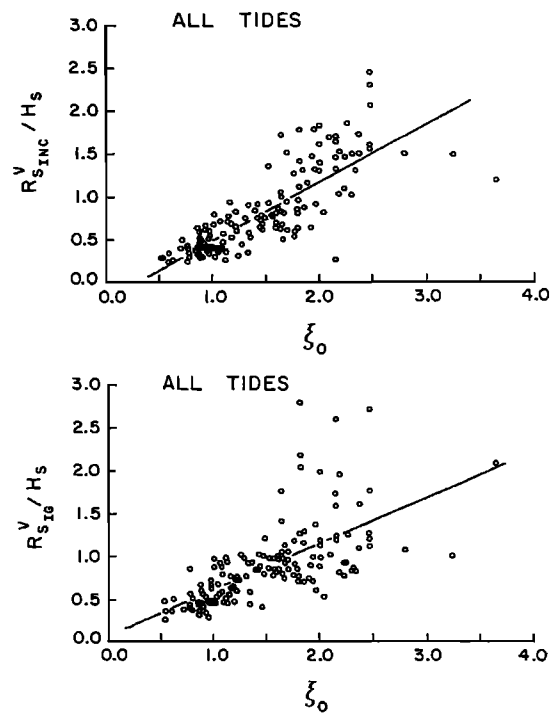


Fig. 10. (a) Nondimensional significant swash height versus ξ_0 for the incident frequency band ($f \geq 0.05$ Hz). (b) Same as 10a, but for the infragravity frequency band ($f < 0.05$ Hz).

gravity regime for ξ_0 less than some value, in their case 0.23. However, their criterion of infragravity dominance appears based on rip current spacing. It is also unclear how they select a value of beach slope.

In order to clarify the differences in dynamics for these two bands, as suggested by Figure 10, the data were ordered in terms of Iribarren number, and dimensional plots made for separate ranges of ξ_0 . Figures 11a and 11b show incident and infragravity band swash data, respectively, for Iribarren numbers from 0.5 to 1.0 (49 points) while Figures 12a and 12b are for Iribarren numbers in the range 1.25–1.75 (44 points). The low Iribarren number data now look remarkably similar to the data of Guza and Thornton [1982]. The incident band swash is apparently saturated throughout the incident wave height range, while the infragravity band is not. However, for higher Iribarren number the incident band swash shows no such saturation for the wave heights measured. Note that there is a great deal of overlap in incident wave height between these groups. Thus, despite apparent dissimilarities, the data set of Guza and Thornton [1982] and this data set are consistent, with the Guza and Thornton [1982] data forming the low Iribarren number limit to the data presented here.

LONGSHORE VARIABILITY OF STATISTICS

Six films were digitized extensively in the longshore direction (seven to nine longshore locations) to allow examination of the natural longshore variability of runup statistics. In general the setup showed about 50% more variability than the swash height, the average standard deviation for setup being 26%, that for significant swash height 17%. In addition the degree of variability appeared positively correlated with ξ_0 , although this observation is based on little data, and the data that was examined was often chosen because it exhibited longshore variability.

The variability was not generally random but showed longshore patterns of nodes and antinodes. This could be related to longshore variable wave motions, such as standing edge waves, or could be a function of longshore rhythmicity in the beach topography. In fact, theoretical models predict that the latter may result from the former [Bowen and Inman, 1971; Guza and Inman, 1975; Holman and Bowen, 1982]. This is clearly an important problem and one we intend to pursue in the future.

DISCUSSION

The surf similarity parameter ξ_0 , or other versions of the same quantity, have been used to successfully parameterize a number of surf-zone processes, including depth at breaking, breaker type, number of waves in the surf zone, and others [Galvin, 1972; Battjes, 1974]. Bowen et al. [1968] state: "the quantity $\tan \beta (H_0/L_0)^{-1/2}$, which occurs in the criterion for the breaking of a wave on a beach, and also in the empirical relation for the vertical runup R, seems to be particularly relevant to the description of conditions in the surf zone." It is not surprising, then, that ξ_0 is important to setup and swash.

The choice of an appropriate beach slope is not obvious. These data show setup to be influenced, at least partially, by the large-scale beach slope (in that the presence of the offshore sandbar seems important at low tide), although use of the foreshore slope for mid and high tides reduces the data scatter. Swash, on the other hand, is best parameterized by using the foreshore slope. While this seems reasonable for the incident band, it is perhaps surprising for low-frequency waves whose dynamics occur over a larger scale. We, unfortunately, have only two full subaqueous beach surveys for the entire 3-week period, so we cannot experiment with alternate beach slope definitions.

The apparent agreement with the data of Guza and Thornton [1982] is a mixed blessing. The intercalibration study of

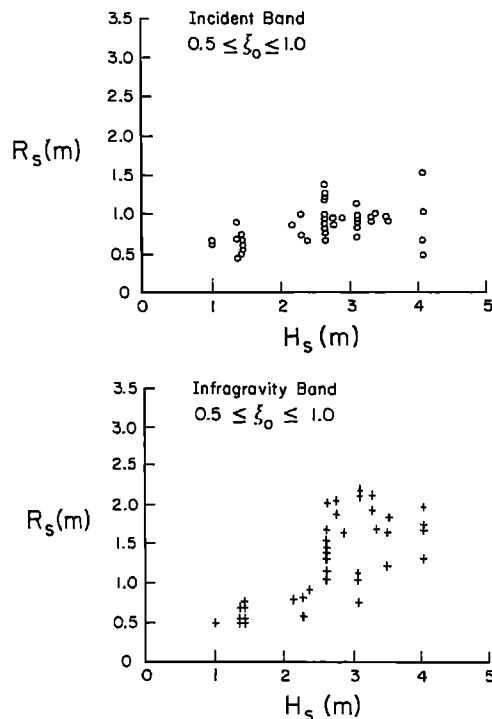


Fig. 11. (a) Dimensional incident band swash data for low Iribaren numbers ($0.5 < \zeta_0 < 1.0$). Forty-nine data points lie in this range. (b) Same as 11a, but for the infragravity band swash data.

Holman and Guza [1984] indicated that the two measurement techniques used, time-lapse photography and the dual-resistance wire sensor, gave systematically different results. This means that, while Guza and Thornton's [1982] swash data are presently slightly above the regression line, they should, in fact, be 35% higher if the intercalibration factor is included.

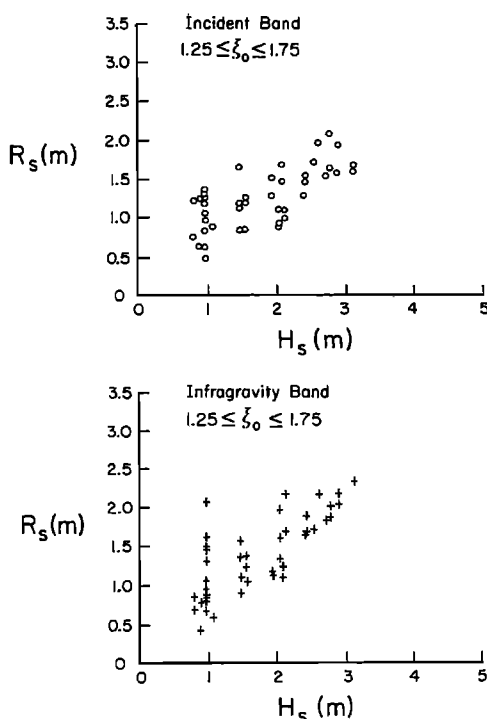


Fig. 12. (a) Dimensional incident band swash data for high Iribaren numbers ($1.25 < \zeta_0 < 1.75$). Forty-four data points lie in this range. (b) Same as 12a, but for the infragravity band swash data.

CONCLUSIONS

Runup on natural beaches appears to depend on the surf similarity parameter $\zeta_0 = \beta/(H_0/L_0)^{1/2}$. When scaled by incident wave height, both setup and swash height decrease with decreasing ζ_0 (usually associated with storms). Thus, while both setup and swash will be largest during storms in dimensional terms, they are nondimensionally smallest (things could be worse). Choice of an appropriate beach slope remains a problem. The foreshore slope seems proper for incident and, surprisingly, infragravity swash, while the offshore bar system seems to have at least some influence on setup at low tide.

For low Iribaren numbers the incident band becomes saturated, while for high Iribaren numbers, no signs of saturation were observed. The infragravity band shows a monotonic increase with wave height for all Iribaren numbers. Thus the infragravity band starts to dominate the swash variance for ζ_0 less than some value, found here to be approximately 1.75, although errors associated with this value could be large.

The total runup height, the typical height of the runup maxima above mean sea level, is well parameterized by ζ_0 , as was found in laboratory studies by Hunt [1959]. One advantage of this variable is that it removes the ambiguity in defining rundown. The hypothesis that scatter in the setup data was related to this ambiguity was tested and rejected.

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