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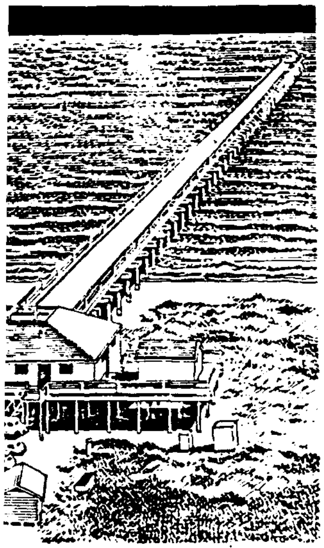

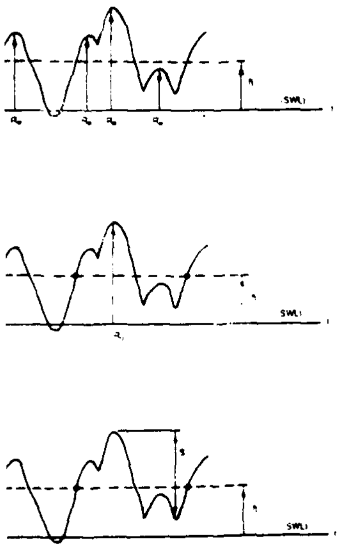

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# ESTIMATING RUNUP ON BEACHES: A REVIEW OF THE STATE OF THE ART

by


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The literature on estimating extreme values of runup on beaches is reviewed. The few available models for estimating beach runup agree with each other and the available data. However, the models are of limited engineering usefulness. Also, the available data are significantly limited. The use of Hunt's Equation to scale beach runup should be carefully examined. Future research on beach runup is recommended and the importance of the engineering applications of such research is outlined.

The extreme beach runup data set of R. A. Holman is published in Appendix B.

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# PREFACE

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This work was performed for the Coastal Engineering Research Center (CERC), WES, under the general supervision of Dr. Yen-hsi Chu, Chief, Engineering Applications Unit, CERC, Ms. Joan Pope, Chief, Coastal Structures and Engineering Branch, CERC, and Mr. Thomas W. Richardson, Chief, Engineering Development Division, CERC. Program Manager was Dr. C. Linwood Vincent, CERC. Technical Monitors were Messrs. John H. Lockhart, Jr., John G. Housley, James E. Crews, and Charles W. Hummer, HQUSACE. Ms. Julie D. Rosati, Engineering Applications Unit, CERC, was the Contracting Officer Representative. Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., were Chief and Assistant Chief, respectively, of CERC.

This report was written by Dr. Scott L. Douglass, Assistant Professor, Department of Civil Engineering, University of South Alabama, Mobile, Alabama. Ms. Brooks A. McLeod, University of South Alabama, assisted in the analysis and preparation of the report. Discussions with Mr. John P. Ahrens, CERC, and Dr. Todd L. Walton, CERC, are appreciated.

COL Larry B. Fulton, EN, was Commander and Director of WES during preparation of this report. Dr. Robert W. Whalin was Technical Director.

CONTENTS

# ESTIMATING RUNUP ON BEACHES: A REVIEW OF THE STATE OF THE ART

## PART I: INTRODUCTION

Runup is the movement of the waterline on a beach. The term "runup" has been used to describe the wave "uprush" or "swash" on coastal structures for at least several decades. It was first the subject of an entire technical paper in 1953, "Wave Run-up on Sloping Structures," by Granthem (1953). In the 1950's, Thorndike Saville and others at the US Army Coastal Engineering Research Center conducted an extensive series of tests of runup on structures. The primary focus of these runup studies was on man-made structures such as dikes, seawalls and revetments. Coastal engineering laboratories around the world have continued to focus on quantifying wave runup on structures.

The related phenomenon of runup on beaches has not received as much attention in the engineering and scientific literature. The engineer tasked with estimating runup on a beach has often adapted some of the available methods for estimating wave runup on structures. This usually entails assuming the beach profile is fixed and applying Hunt's (1959) Equation or the Shore Protection Manual (SPM) (US Army 1984) curves for runup on structures. Saville's (1958) method for composite slope structures has been used in attempts to account for the non-uniform slope found on sandy beaches.

Beaches are not fixed but free to move in response to the incident waves. They have much flatter slopes than man-made structures. The beach slope is not constant across the profile and offshore sand bars which effect the incoming wave energy are often present. Thus, the attempts to apply runup methods derived for structures to beaches have been educated guesses at best.

## Importance of the Problem

Maintaining existing development along the nation's coastlines requires improved techniques for coastal engineering. The extent of runup on beaches is important for a number of coastal engineering and coastal management issues. The limit of runup defines the zone of possible wave damage and thus can be used in the determination of coastal setback lines, the design of the height of man-made beaches and dunes, models of beach and dune erosion during storms, management policy related to the creation of dune fields on developed shorelines, and estimating flooding due to overtopping and breaching of beaches and dunes.

Beach nourishment is the most widely accepted engineering technique for beach management along much of the nation's coastline. Although a wide sandy beach provides protection to landward structures during major storms, quantifying the level of protection is difficult. During storms, sand is moved alongshore and offshore with the net result often being erosion of the beachface and, if present, the sand dune. Several models of sand dune erosion in response to storms have recently been developed. These models are applied in the design of beachfills to determine the required volume of a "sacrificial" sand dune to survive the design storm. They do not provide information on how high the water will run up the beach or how high the dune should be to prevent overtopping.

From a less pragmatic engineering viewpoint, runup on beaches has been investigated to describe the motion of runup in terms of the driving force, the incident waves. Several investigators have described runup in terms of its frequency spectra and discussed the differences between the runup spectra and the incident wave spectra.

The most important dynamics of runup on beaches can be discussed in terms of the effect of waves on a popular children's activity. Sand castles built below the high tide line wash away during the next rising tide. The individual "wave" (runup) which does the most damage to the sand castle is often not the largest incident, offshore wave. The reasons for this lack of one-to-one correspondence between waves and runups on beaches are not entirely clear. Obviously, the interference patterns of individual runups on the beach slope are part of the explanation. Backwash down the slope from the previous runup can decrease and even eliminate the runup from a subsequent, incoming wave. The largest individual runups on structures often occur when two waves combine on the slope at almost the same time. Thus the timing, or phase, of the individual waves on the beachface is critical in the runup process. This interference phenomenon decreases the number of runups relative to the number of incident waves and changes the frequency spectra of the runup relative to that of the waves.

Surf beat, the rise and fall of the average water level inside the surf zone, effects extreme runup on beaches. Surf beat has periods between 30 seconds and several minutes, the "infragravity" range of periods. The highest runups occur when the inshore water level is high due to surf beat and incoming waves can propagate farther inshore. Surf beat has been neglected in the estimation of runup on structures, however, it is much more important on beaches. Many nearshore processes, including runup, have been explained in terms of the energy in the infragravity range. However, the causes and effects of surf beat are an area of active research. Although the sand castle problem may be trivial, the physical processes involved are the important processes of runup on beaches.

## Purpose of this Report

The specific question addressed in this report is, given offshore water level and incident wave conditions for a specific beach, what are the extreme runup levels?

This report will:

- summarize the literature on runup on beaches,
- compare the different methods for estimating extreme runup statistics on beaches,
- discuss the general abilities of these methods to provide engineering guidance,
- provide recommendations for engineering applications for beach and dune design,
- discuss areas for future research on runup on beaches, and,

- discuss the possibilities of future applications of this research to engineering questions related to overtopping of beaches and the resulting flooding of landward areas.

This report will focus on the engineering question of estimating runup extremes on a given beach with given incident wave conditions. Thus, this report will take a rather pragmatic engineering approach to the problem.

## Definitions

The vertical distance from the still-water level (SWL) to the intersection of the water surface and the beach slope is $\eta$, as shown in Figure 1. The time history of $\eta$, $\eta(t)$, can be plotted as in Figure 2. The mean, $\bar{\eta}$, will be above the SWL due to setup in the surf zone. One definition of an individual runup is the vertical distance, $R_p$, between the SWL and each local maximum, or "peak," in the $\eta(t)$ record (Figure 2a). Another definition of an individual runup is the maximum vertical distance, $R_u$, from the SWL between successive upcrossings of the mean, $\bar{\eta}$ (Figure 2b). The peak definition is more common in the literature on runup on beaches. There are four runups by the peak definition but only one by the upcrossing definition for the $\eta(t)$ record given in Figure 2. Individual swash height, $S$, is defined as the vertical minimum-to-maximum distance between successive upcrossings of the mean in the $\eta(t)$ record (Figure 2c). All notation is summarized in Appendix A.

## PART II: LITERATURE REVIEW

This literature review focuses on estimating extreme values of runup on beaches. Some previous influential work on wave runup on structures is discussed as background because several aspects are applicable to runup on beaches. Several of the Dutch papers present models of equilibrium profiles of gravel beaches: a component of these models is the runup. The literature focusing on the spectra of runup on beaches is not included in this review. Oltman-Shay and Hathaway (1989) discuss most of the runup spectra literature in their "tutorial on infragravity motions."

### Wave Runup on Structures

Hunt (1959) summarized the European (Miche 1944, 1951; Iribarren & Nogales 1947) and American (Granthem 1953, Saville 1957) laboratory data available on wave breaking, reflection, and runup on structures. He emphasized an equation relating runup height to wave steepness and structure slope which can be written as,

$$R / H = (\tan \alpha) / (H/L_0)^{0.5} \tag{1}$$

where $R$ is the vertical distance of runup from the SWL, $H$ is the incident monochromatic wave height, $L_o$ is the deepwater wavelength, and $\alpha$ is the angle of the slope of the structure.

A dimensional form of Equation (1) is,

$$R = (HL_0)^{0.5} \tan \alpha \tag{1a}$$

Hunt only considered monochromatic waves, i.e. a single wave train of identical height and period.

The general form of Equation (1),

$$R / H \propto (\tan \alpha) / (H/L_0)^{0.5} \tag{2}$$

is referred to as Hunt's Equation.

Battjes' (1974) doctoral thesis to the Delft University of Technology, and a companion paper (Battjes 1972) provide both an exhaustive literature review of runup and significant original extensions of monochromatic-wave-based methods to irregular seas. He emphasized the importance of the right-hand side of Hunt's Equation. It is not necessary to know both beach slope and wave steepness but it is sufficient to know only the combination,

$$\xi = (\tan \alpha) / (H/L_0)^{0.5} \tag{3}$$

This number is often referred to in the literature as the "surf parameter" or the "Iribarren number".

Van Oorschot and d'Angremond (1968) investigated runup on structures due to incident irregular waves at the Delft Hydraulics Laboratory. The defined runups, $R_z$ , using a zero-upcrossing method with the SWL as the horizontal baseline for determining upcrossing instead of $\bar{\eta}$ . They chose the runup level exceeded by

2% of the runups, $R_{z2\%}$, as a measure of extreme runup. They related $R_{z2\%}$ to a form of Hunt's Equation modified for irregular waves,

$$R_{z2\%} / H_s = C (\tan \alpha) / (H_s/gT_p^2)^{0.5} \tag{4}$$

$H_s$ is significant wave height which is not specifically defined by van Oorschot and d'Angremond but is probably the average of the largest one-third waves at the toe of the slope, $T_p$ is the period of the peak of the frequency spectra of the waves, $g$ is acceleration due to gravity, and $C$ is an empirical coefficient. They found $C$ to be a function of the width of the wave spectrum. Wider incident wave spectra generated higher extreme runups. They investigated fixed, impermeable slopes of 1:4 and 1:6.

Kamphius and Mohammed (1978) investigated runup on relatively steep, smooth structures in the laboratory at Queen's University in Kingston, Canada. They specifically focused on wave steepness and beach slope combinations which would yield highly reflective conditions. Their beach slopes ranged from 1:1 to 1:3. They found $R_{z2\%}$ to be about 2.4 times the average runup. This is slightly larger than would be predicted by an assumption of a Rayleigh distribution of runups. They noticed a slight tendency for the ratio to increase as structure slope decreased.

Ahrens (1981) combined data from three independent studies to describe the runup statistics, $R_{z2\%}$, $R_{zs}$, and $R_{z\,mean}$ in terms of the wave steepness, $H_s/gT_p^2$. $R_{zs}$, the significant runup, is the average of the largest one-third of the runups and $R_{z\,mean}$ is the average of all the runups. Ahrens used results from the studies of van Oorschot and d'Angremond (1968), Kamphuis and Mohammed (1978), and Ahrens (1979). The latter study investigated runup due to irregular waves on a 1:1.5 slope in the laboratory of the US Army Coastal Engineering Research Center in Fort Belvoir, Virginia. Ahrens (1981) presents 2nd-order polynomial regression curves for the three runup statistics for slopes ranging from 1:1 to 1:3. He also presents empirical equations in the form of Hunt's Equation for three runup statistics for a 1:4 slope,

$$R_{z2\%}/H_s = 1.61\ \xi \qquad (5)$$

$$R_{zs}/H_s = 1.25\ \xi \qquad (6)$$

$$R_{z\,mean}/H_s = 0.84\ \xi \qquad (7)$$

where the surf parameter is defined with the significant wave height at the toe of the structure and the deepwater wavelength corresponding to the period of peak energy density of the wave spectrum.

### Mase and Iwagaki (1984)

Mase and Iwagaki (1984) conducted laboratory tests of runup due to irregular waves at Kyoto University. They used impermeable slopes of 1:5, 1:10, 1:20 and 1:30. They investigated a number of different aspects of runup including runup spectra, runup distribution, the effect of wave groupiness on runup, and the ratio of the number of individual runups to incident waves.

They used both definitions of individual runup presented in Figure 2. The ratio of the number of runups defined by the upcrossing method, $R_u$, to the number of runups defined by the peak method, $R_p$, varied from 0.4 to 0.9 depending on beach slope (the ratio decreased as the slope decreased). In other words, there were between 10% and 150% more runups using the local peak definition. $R_{ps}$ and $R_{p\,mean}$ were about 10% and 20% less than $R_{us}$ and $R_{u\,mean}$, respectively.

Mase and Iwagaki looked at the decrease in the number of runups compared to the number of incident waves. The ratio of the number of runups to the number of waves varies from 0.2 to 0.9. Lower ratios occur for lower $\xi$, i.e. for flatter beach slopes.

They plot the logarithm of three statistical representations of runup, $R_{p\,mean}$, $R_{ps}$, and $R_{max}$ against the logarithm of wave steepness for each slope. The data fit an empirical exponential relation between runup and wave steepness of -0.37. This is different than the exponent of -0.5 inherent in Hunt's Equation. They thus present two different empirical formulations for irregular wave runup on impermeable slopes,

$$R^*/H_s = a\ (\tan\alpha)^b\ (H_s/L_0)^c \tag{8}$$

$$R^*/H_s = d\ [(\tan\alpha)/\ (H_s/L_0)^{0.5}]^e \tag{9}$$

where $R^*$ = $R_{p\ mean}$, $R_{ps}$, $R_{u\ mean}$, $R_{us}$, or $R_{max}$ . The empirical coefficients; a , b , c , d , and e ; for these equations for both definitions of individual runup, upcrossing and local peak are given in Table 1. Although neither of the above equations clearly fit the data better than the other, Mase and Iwagaki preferred the latter equation. Apparently they preferred it because it kept the surf parameter, $\xi$ , intact as a scaling parameter.

Mase and Iwagaki found that the highest runup often occurs alone, i.e. not followed or preceded by other large runups. They attributed this to the interference of the backwash of large runups reducing the height of the following runup. They also found little dependence of the runup statistics on incident wave groupiness. They attributed this to the fact that the wave groupiness decreases due to the breaking process before runup.

### Mase (1989)

Mase (1989) adds two more statistical representations of runup to his empirical model from Mase and Iwagaki (1984). He includes coefficients of Equation 9 for $R_{p2\%}$ , the level exceeded by 2% of the runups, and $R_{p(1/10)}$ , the average of the highest 1/10 of the runups. He presents these coefficients in terms of the local peak method of defining runup and does not give the corresponding coefficients for the upcrossing definition. He presents plots of predicted versus measured $R_{p\ mean}$ , $R_{p2\%}$ , $R_{p(1/10)}$ , $R_{ps}$ , and $R_{p\ max}$ that show that the empirical equations fit the data from which they were calibrated well. The correlation between predicted and measured values is 0.98 to 0.99.

Channell et al. (1985)

Channell et al. (1985) present the results of a laboratory experiment at the Hydraulics Research Station in Wallingford, England on runup on permeable, shingle (flat gravel) beaches due to monochromatic waves. The mean grain size for the "pea shingle" used as the beach was 8.2 mm. Initial beach slopes ranged from 1:6 to 1:10 . They found that on the gravel beaches, runup was about one-third of that predicted by Hunt's Equation for smooth, impermeable slopes. They found this result both for waves which were too small to significantly redistribute the gravel and for larger waves which did move the gravel. They also constrained the gravel in wire mesh gabions and subjected this constrained beach to the large waves and found runup to increase significantly. Runup on the constrained beach was about 1.6 times runup on the unconstrained beach for the same wave conditions.

van Hijum and Pilarczyk (1982)

Van Hijum and Pilarczyk (1982) investigated the dynamic equilibrium profile of gravel beaches in the Delft Hydraulics Laboratory. They developed a model for the shape of this profile in terms of wave height and grain size. Their model also includes the angle of wave approach, wave period, and initial beach slope. They were interested in runup because the upper limit of runup is the limit of gravel motion and the limit of their equilibrium profile. For monochromatic waves they use Hunt's Equation. They present an empirical expression for the coefficient (=1 on smooth impermeable slopes, and less on real beaches) in terms of the ratios of wavelength to grain size and wave height to grain size. For runup due to irregular waves on the initial beach slope, they present another empirical equation. Runup is related to grain size, significant wave height and period, and initial beach slope. They also present an expression for wave runup on the equilibrium profile which is a function of wave height and period and grain size only (oblique angle of wave approach is also considered).

van der Meer (1988)

Van der Meer (1988), in his doctoral thesis to the Delft University of Technology, discusses the entire spectrum of profile shapes exposed to wave attack. At one end of the spectrum are static structures such as rubble mound breakwaters with large armor units that do not move due to wave action. At the other end are sandy beaches which are significantly shaped by waves. In between are dynamic revetments and gravel beaches. The larger grain sizes present a static stability problem and the smaller grain sizes present a dynamic stability problem. Van der Meer presents a model of the dynamic profile of the beach during a storm which is a function of wave height and period, grain size, storm duration, water depth, and angle of oblique wave attack. A part of the model is an expression for the berm crest height which can be interpreted as an estimate of extreme runup since the crest forms near the limit of runup. This expression is given as a function of wave height and period, grain size and number of waves. The number of waves appears because the foreshore slope is a function of storm duration.

Carlson (1984)

Carlson (1984), in his doctoral thesis to the University of California, investigated runup on actual beaches on San Francisco Bay. He made movies of the incident waves and the resulting runup at two different locations. He used standard photogrammetric techniques to analyze the water surface elevation and the location of the intersection of the water surface and the beach for the moment in time captured by each individual frame of photography. Ground truth was provided by a series of poles extending from the beach through the surf. The result of this labor intensive method is a time-series history of water level and a coincident time-series history of swash location. From these time-series, Carlson computed distributions, frequency spectra of runup and waves, and coherence between the two. For each day, a time-series of waves and coincident swash is shown graphically.

Carlson does not compute either wave heights or runups in the standard way. He never considers the definition (e.g. zero-upcrossing) of an individual wave or runup in the time-series of water elevation and swash location. He analyzes only $\eta(t)$ , the vertical distance from the SWL to the location of the intersection of the water surface and the beach. Carlson actually measured the horizontal location of the intersection, which could be called $\eta_h$, relative to an arbitrary baseline. This can easily be converted to the corresponding vertical distance from the SWL, $\eta$, if the beach slope is known.

The wave heights measured by Carlson were very small for field conditions. Carlson gives the root-mean-square of the offshore water surface elevation as 3.6 cm and 10.0 cm for his two sets of data. Carlson intentionally did his experiments on days of small waves to avoid any low frequency energy which would be present in rougher seas. The surf zone was very narrow (maximum width of roughly 3 m) because of the small waves and the steep beach (1:9 and 1:12).

Holman (1986)

Holman (1986) investigated the extreme runup statistics on an energetic open-ocean beach at Duck, North Carolina. He filmed the swash zone during three weeks in October 1982 from the US Army Engineer Field Research Facility pier. The individual movie frames were digitized and analyzed. Holman designed the data collection procedures to investigate the spectra of beach runup. He was specifically interested in the energy in the infragravity range (this focus was reported in Holman & Sallenger, 1985). Holman was later approached by the Coastal Engineering Research Center to reanalyze his data focusing on parameterizing extreme runup. Holman (1986) presents the results of 149 runup time-series with incident wave heights and periods ranging from 0.4 to 4.0 m and 6 to 16 sec, respectively. Incident wave data were from a waverider buoy in 20 m depth and a Baylor gage at the end of the pier in 8 m depth.

Holman considered four runup statistics; $R_{p2\%}$; $\eta_{2\%}$, the 2% exceedance value for the time-series of $\eta(t)$ (sampling rate = 1 Hz); $\eta_{max}$, the maximum value of $\eta(t)$; and $S_{2\%}$, the 2% exceedance value for the crest-to-trough vertical excursion of individual swashes as defined by the upcrossing method (Figure 2c). Holman found that each of these four parameters could be explained in terms of $\xi$ defined as,

$$\xi = \alpha / (H_{mo}/L_0)^{0.5} \tag{10}$$

where $\alpha$ = beach slope defined as the average slope in the swash zone, i.e. the beachface or foreshore slope; $H_{mo}$ = spectral significant wave height as measured by the wave gage in about 8m depth; and $L_0$ = linear theory deepwater wavelength corresponding to the period of peak energy density of the wave spectrum. The tangent is dropped from beach slope term in Equation 10 since for the range of beach slopes found on natural sandy beaches, $\tan \alpha \approx \alpha$ ($\alpha$ in radians). Holman found neither wave gage was superior in explaining runup in terms of Equation 10. He presents plots and regression coefficients of each of his four runup parameters versus $\xi$. The regression coefficients for the four parameters with and without setup removed are given in Table 2.[1] Incident wave characteristics are from the Baylor gage in 8 m depth for the regression coeffients given in Table 2.

## Resio (1987)

Resio (1987) reanalyzes Holman's data to apply an extreme value model to runup on beaches. Resio reexamines Holman's wave data and shows that the two sets of data, in 8 m and in 20 m depth, are different in terms of wave height. During some data sets, waves increased in height as they moved into shallower water. During other data sets wave heights decreased between the two gages. Resio claims that this behavior is consistent with shallow water wave transformation theory. Essentially, low steepness waves (swell) waves should increase due to shoaling more than they decrease due to bottom friction and breaking. For high steepness waves (sea) the dissipative processes are dominant. Resio, like Holman, found no preference for either of the two gages for explaining runup with Hunt's Equation.

Resio investigates the use of a third depth for wave data collection, 1.5 m, i.e. well inside the surf zone. He finds that these waves do not explain the $R_{p2\%}$ statistic in terms of $\xi$ as

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[1]The regression coefficients given in Holman's (1986) Table 1 do not fit the data plotted on the corresponding Holman (1986) Figures 6d, 7a, 7b, 7c, and 7d. It is not clear whether the coefficients are in error or the figures are plotted incorrectly (Holman 1989, personal communication). Table 2 of the present report is from Holman's (1986) Table 1a.

well as waves at the two deeper water gages. Resio suggests that offshore wave data explain runup better than inshore wave data. This suggestion is not supported by Resio's analysis since the shallow-water gage data is probably not representative of the wave field where the runup was measured. The gage is a Baylor gage attached to the pier. Large scour holes along the pier offshore of the gage effect the waves reaching the gage. It would indeed be paradoxical if Resio's suggestion were correct. He suggests that it is preferable to go farther away from the location of runup to collect incident wave conditions to explain the runup. Unbiased data such as could be provided by a gage immediately offshore of the location of runup measurements are necessary to make such a suggestion.

Resio applies a generalized extreme value distribution to runup and uses Holman's data to calibrate the model. He compares Carlson's data to the model. Resio's approach extends Holman's approach to include any extreme runup value of interest. Holman only provides information on the 2% statistic and the extreme statistic for a 35-minute duration. Holman did not attempt to generalize his results to a frequency distribution because "it was felt that the small number of data points was insufficient to select the appropriate frequency distribution" (Holman 1986, page 532). Resio reanalyzed Holman's data to do precisely that. Both used the same basic "model" of Hunt's Equation to scale the runup phenomenon with the exception of the choice of wavelength used in the surf parameter.

Resio's model for the large values of runup (the values of most interest) can be written as:

$$R' = 1.25 - 1.05\ (T_r - 0.5)^{-0.19} \qquad (11)$$

or

$$R' = 1.25 - 1.05\ [(1/P_e) - 0.5]^{-0.19} \qquad (12)$$

where $T_r$ = the return period of the runup of interest in number of runups, $P_e = 1/T_r$ = probability of exceedance, $R'$ = the coefficient of a form of Hunt's Equation;

$$(R_p^* - \bar{\eta})/H_{mo} = R'\ \xi \qquad (13)$$

with

$$\xi = \alpha\ /\ (H_{mo}/L_p)^{0.5} \qquad (14)$$

so

$$R' = \frac{(R_p^* - \bar{\eta})/H_{mo}}{\xi} = (R_p^* - \bar{\eta})\ \alpha^{-1}\ (H_{mo}L_p)^{-0.5} \qquad (15)$$

where $R_p^*$ = is the runup statistic of interest as defined by the local peak method, $H_{mo}$ = incident spectral significant wave height, $L_p$ = local wavelength corresponding to the peak period of the energy density spectrum. The location of the incident wave parameters is in water depth of 8 m . Equations 11 and 12 are plotted in Figures 3a and 3b, respectively.

Resio's model does not include $\bar{\eta}$'s effect on the total runup elevation. Although it is not clearly defined in Resio (1987), the dependent variable is as given on the left-hand side of Equation 13 above,

$$(R_p^* - \bar{\eta})/H_{mo}$$

The $\bar{\eta}$ has been removed from the runup elevation (Resio 1989). This is a serious shortcoming for engineering applications. Holman was unable to predict $\bar{\eta}$ based on $\xi$ . Although $\bar{\eta}$ is a manifestation of wave setup in the surf, it is not the usual engineering definition of setup, the average water level at the intersection of the SWL and the beach.

Two examples are given which show how to apply Resio's model with an assumed $\bar{\eta}$ . The examples are chosen to match Holman's conditions for comparison of the two models in the next chapter.

*****************************************************************
EXAMPLE PROBLEM 1:

GIVEN: incident peak wave period, $T_p$ = 10 sec

incident wave height, $H_{mo}$ = 2 m in 8 m water depth

beachface slope = 0.10 (1:10)

storm wave and water level duration = 35 min

$\bar{\eta}$ = 1.0 m

FIND: An estimate of the maximum runup elevation during the storm.

SOLUTION:

1) Calculate the probability of exceedance of interest,

The number of runups during the storm is

N = (35 min) (60 sec/min) / (10 sec/wave) = 210 waves

```
*******************************************
* Note: Resio's method assumes that       *
* (number of waves) = (number of runups)  *
* This is not correct.                    *
*******************************************
```

Therefore, for the maximum runup,

$P_e = 1/N = 1/210 = 0.048$

2) Calculate the Hunt's Equation coefficient from Eqn. 12 or Figure 3b,

R' = 0.872

3) Calculate local wavelength (d = water depth),

$L_0 = (g/2\pi)\ T_p^2 = (9.8\ m/sec^2)/2\pi\ (10\ sec)^2 = 155\ m$

$d/L_0 = (8\ m) / (155\ m) = 0.0516$

from linear wave theory tables, Appendix C of SPM,

d/L = 0.096

so,

$L_p = d / (0.096) = (8\ m) / (0.096) = 83\ m$

4) Calculate maximum runup,

$$R_{max} = R'\ \alpha\ (H_{mo}L)^{0.5} + \bar{\eta}$$

$$= (0.872)\ (0.10)\ [(2\ m)(83\ m)]^{0.5} + \bar{\eta} = 1.12\ m + \bar{\eta}$$

$$= 2.12\ m$$

5) Calculate elevation of maximum runup,

$\text{elevation} = SWL + R_{max} = SWL + 2.12$

where SWL includes the tide level and storm surge.

*******************************************************************

The next example calculates the $R_{p2\%}$ statistic for the same given conditions.

************************************************************
EXAMPLE PROBLEM #2:

GIVEN: The same storm, wave and beach conditions in Example Problem #1.

FIND: The elevation exceeded by 2% of the runups during the storm (runups are defined by local peak method).

SOLUTION:

1) The probability of exceedance of interest, is stated as,

$$P_e = 0.02 \quad (2\%)$$

2) Calculate R',

$$R' = 0.75$$

3) Calculate $L_p$,

$$L_p = 83 \text{ m} \quad \text{(from Ex. Prob. \#1)}$$

4) Calculate runup,

$$R_{p2\%} = (0.75)\,(0.10)\,[(2 \text{ m})(83 \text{ m})]^{0.5} + \bar{\eta} = 1.05 \text{ m} + \bar{\eta}$$

$$= 2.05 \text{ m}$$

5) Calculate elevation of runup,

$$\text{elevation} = \text{SWL} + 2.05 \text{ m}$$

************************************************************

## PART III: COMPARISON OF DIFFERENT METHODOLOGIES FOR ESTIMATING RUNUP ON BEACHES

### Summary of Available Methods

The methods available for estimating runup on beaches are very limited. Holman's method and Resio's extension of Holman's work are the only methods based on actual runup measurements on prototype beaches. Other methods are based on laboratory tests on gravel beaches, impermeable slopes, or revetments. This chapter will focus on these two methods and the laboratory results of Mase. Mase (1989) and Mase and Iwagaki (1984) are based on the same investigation and will be referred to as Mase's work. He measured extreme runups due to irregular waves on slopes approaching the flatness of natural beaches and found many of the phenomena of beach runup.

This chapter will describe how to use Holman's and Resio's methods for engineering applications. Results from the two methods will be compared. The comparison is good as would be expected since Resio calibrated his method with a subset of Holman's data. Mase's equations compare better with Holman's data than previously reported. The problem of choosing an appropriate beach slope for applying Mase's results to prototype beaches is discussed.

## Summary of Available Data

Independent data should be used to evaluate the available methods of estimating beach runup. This is not possible. Essentially, no beach runup data in either raw or partially analyzed form were available for this investigation.

Holman's data is by far the largest set of beach runup data discussed in the literature. It forms the basis for the two models of beach runup. It is "not available" in its raw form of digitized time-series of runups and collocated beach slope and incident wave statistics (Holman 1989, personal communication). Holman's summary statistics of his 149 runs have not been published. Holman (1986) only published dimensionless plots of the data which do not allow for further analysis by other investigators. A summary table of Holman's data was located and expanded through a series of telephone conversations with Dr. Robert Holman at Oregon State University, Dr. Donald Resio at Offshore and Coastal Technologies, Inc. in Vicksburg, Mississippi, Mr. William Birkemeier at the Field Research Facility, and Mr. John Ahrens at WES. This summary table of Holman's 149 data points is given in Appendix B. It includes the location and time of each data run, the extreme runup statistics, computed setup, SWL, beachface slope, and incident wave statistics from the Baylor gage at the end of the pier.

Most of the runup data were collected within 150 m of the pier to the north and the south. The data may have been biased because the wave field was effected by the perturbed bathymetry around the pier (Holman and Sallenger 1984). Bathymetric plots of the area before and immediately after Holman's experiment are shown in Figures 4 and 5. The pier effects on bathymetry extended 100 m to 400 m to either side of the pier. Considering the natural directional spread of energy in a wave field, wave energy from the direction of the pier must have been modified by the pier effects for all of Holman's data.

The pier appears to have affected the runup data measured by Holman. Inspection of the $\bar{\eta}$ results for the two major storms in the data set shows this effect. These two storms account for 80 of Holman's 149 observations and for all of his larger wave observations. During the first part of the storms (10-11 Oct and 24 Oct), waves and winds were driving the longshore current to the south (Mason et al. 1984). Later in both storms (12-13 Oct and 25 Oct), waves and winds came around and longshore current reversed to the north. $\bar{\eta}$ was higher on the updrift side of the pier throughout both storms. A possible explanation is the effect of the bathymetry near the pier on the incident wave field.

Carlson published plots of two runup time-series. Resio used these to check the parameter estimation of his generalized extreme value distribution for runup. He found that one of the data sets fit his distribution and the other data set may have been biased since the incident wave conditions were measured inside the surf zone. Carlson's data set does not reflect open-ocean beach conditions since he measured runup due to very small, locally generated waves incident on an unbarred beach profile. Thus, the agreement with Resio's model is surprising, indeed encouraging, considering the differences in the overall conditions.

Guza and Thornton (1982) measured runup on a beach using gages and reported on the runup spectral characteristics but not the extreme values. It is not known whether their data are available in a raw form for further analysis. More runup data were collected by Holman at Duck, North Carolina in 1985 and 1986 with movie and video systems (Mason 1987). However, analysis of the data is not complete (Holman 1989, personal communication).

## Mase's Equation Compared to Holman's Data

Both Mase (1989) and Holman (1986) state that Mase's equation overpredicts Holman's data by 100%. Mase says that his equation is roughly an upper envelope to Holman's data and that dividing his coefficient by two provides a good fit through the data. Mase attributes the difference to beach permeability but does not support this conclusion. Neither author discusses what the appropriate choice of beach slope for applying Mase's results to Duck, North Carolina. Recall that Mase's equation is based on laboratory data on constant slopes and Holman's data is prototype data.

Figure 6 shows a beach profile at Duck before and during the collection of Holman's data. The depth over the bar is 1.1 m at mid-tide. The profile is reproduced from Holman and Sallenger (1985). Holman's wave heights were $0.4 \text{ m} < H_{mo} < 4.0 \text{ m}$. Since common values for the ratio of spectral significant wave height to water depth at breaking are around 0.5, waves were breaking on the offshore bar for most of Holman's data. The surf zone during storms included all of the profile shown in Figure 6.

Superimposed on the profile in Figure 6 are slopes of $\alpha$ = 0.100, 0.050, 0.014 (1:10, 1:20, and 1:70). These slopes roughly correspond to the beachface, the outer slope of the bar and the entire surf zone during major storms.

Figure 7 shows how Mase's equation for $R_{max}$ compares with Holman's data for the three different choices of beach slope. Figure 7a shows the comparison of Mase's equation, with beach slope of m = 0.1 (1:10), with the envelope of Holman's data (from Holman's 1986 Figure 7c). Figure 7b shows the comparison between Mase's Equation and Holman's data using a beach slope defined as m = 0.05 (1:20). The agreement is good. Figure 6c shows the comparison between Mase's Equation and Holman's data for a beach slope defined as m = 0.0143 (1:70). Mase's Equation underpredicts Holman's data! Thus, depending on the definition of beach slope adopted for describing the Duck profile, Mase's Equation can overpredict, correctly predict, or underpredict the runup measured by Holman.

Choosing the beach slope definition to characterize the natural beach profile of Figure 6 is a problem. Holman used beachface slope to define his surf parameter. His data collection and analysis technique required very accurate knowledge of beach face slope in order to convert from horizontal swash data to vertical swash. Thus, he had good beachface slope data.

The question at hand when trying to use Mase's results is "what single beach slope should be used to correctly model the Duck profile?" By inspection of Figure 6, a 1:10 slope should overestimate runup since it would not account for the wave transformations including breaking and dissipation across the bar. A 1:70 slope should underestimate runup which actually occurs on a much steeper beachface. Thus, the result that the "best-fit" beach slope is somewhere between these two extremes should not be unexpected. Note that the slope which fits the data best corresponds to the slope of the offshore side of the bar in Figure 6.

The beach slope definition is important since $\xi$ has been shown to be a very good scaling parameter for a number of surf phenomenon (Battjes 1974). However, most of the data available during the development of the surf parameter were laboratory data on steep, constant slopes. Since $\xi$ is a scaling parameter, the experimentalist is free to define the exact surf parameter in terms of the wave height, length, and beach slope of his choice. The surf parameter adapted by Holman uses estimates of the three components of $\xi$ from three different locations across the surf zone: beach slope from the beachface, wave height from a depth of 8 m , and a representation of deepwater wavelength. Resio preferred the use of wave height and wavelength from the same location.

Others faced with engineering applications of $\xi$-based methodologies have faced the same problem with respect to beach slope. Inman and Jenkins (1989) believe that swash is best scaled with beach face slope and surf beat is best scaled with the overall beach slope. Dean (1987), in the keynote address to the Coastal Sediments '87 Conference, suggests a way to avoid the difficulties inherent in choosing which portion of the beach profile is appropriate by relating surf parameter to grain size and incident waves.

## Resio's Equation Compared to Holman's Equation

Resio's method should give the same results as Holman's method since it was calibrated with a subset of Holman's data. This section will show that the two methods do agree.

The results of Example Problems 1 and 2 allow a rough comparison of the two methods results. The 35-minute duration is what was measured by Holman and the beach and wave parameters fall within the ranges observed by Holman. Holman's model has R' coefficients of

$$R' = 0.65 \quad (\text{for } R_{max}), \text{ and}$$
$$R' = 0.53 \quad (\text{for } R_{p2\%}).$$

The difference between Holman's coefficients and those from Example Problems 1 and 2,

$$R' = 0.87 \quad (\text{for } R_{max}), \text{ and}$$
$$R' = 0.75 \quad (\text{for } R_{p2\%}),$$

is due to the different definitions of wavelength employed. Holman useo deepwater wavelength and Resio used local wavelength. Conversion can be approximated since wavelength enters Equation 14 as a square root. For this problem (d=8m),

$L/L_0 = 83/155 = 0.54$

Converting Holman's coefficients to a local wavelength definition of psi gives,

$$R' = 0.87\ (0.54)^{0.5} = 0.64 \text{ (for } R_{max}\text{), and}$$
$$R' = 0.75\ (0.54)^{0.5} = 0.55 \text{ (for } R_{p2\%}\text{)}$$

which agree well with those from Resio's method. Thus, Resio's method gives consistent results with Holman's method.

Resio's method allows for more information about the extremes to be estimated. For example, Figure 3 can be used to calculate any of the larger runup statistics. Strictly speaking, Resio's model should be limited to the upper 10% of the runups since that is all that Resio used in the derivation. However, the extreme value distribution used by Resio is related to the Weibull distribution and others have found that a Weibull distribution fits the entire runup distribution. Therefore, the lower limit of the range of probabilities for which Equation 12 is applicable may be much less.

## Summary of Comparisons

The few appropriate comparisons between available runup estimation methods are encouraging. The two methods based on field runup data, Holman's and Resio's, agree with each other as well they should since one is based on a subset of the other's data. Resio found that one of Carlson's data sets fit his model. The application of Mase's laboratory results to this data set is complicated by the problem of choosing an appropriate beach slope. For a beach slope intermediate between the foreshore slope and the overall surf zone beach slope, Mase's equation predicts Holman's data well.

## PART IV: ENGINEERING APPLICATIONS OF BEACH RUNUP ESTIMATES

The development of models to describe runup on beaches may have lagged behind the development of models to describe other coastal phenomenon because of the difficulties inherent in the phenomenon. The limit of runup is dependent upon a number of variables including the water level, incident wave conditions, sediment characteristics, and the beach profile which is constantly changing in response to the waves and water level. This problem of the changing profile or cross-section has not been faced by the engineer tasked with designing a traditional, fixed seawall. (However, this is changing with the recent popularity of flexible revetments designed to deform without loss of function during storms.) The upper limit of runup would seem to be an important component of coastal engineering and coastal zone management decisions since this limit defines the zone of possible wave damage. This chapter will discuss several of the areas of coastal engineering where estimates of runup on beaches can be applied including:

- design of the height of man-made beaches and dunes,
- models of beach and dune erosion during storms,
- management policy related to the creation of dune fields on developed shorelines, and
- estimating flooding due to overtopping and breaching of beaches and dunes.

Engineers may realize other applications if given a reliable, practical model.

Beach and Dune Design

Knowledge of the limit of runup could be applied in several ways to the design and management of beaches and dunes. Design engineers tasked with prescribing the height of a beach berm or dune line could consider both the design water level and the coincident runup. In the crudest application, the height of the beach or dune could be designed as for a fixed structure, i.e. the required height to prevent overtopping would be the design water level with storm surge plus maximum runup. The Federal Emergency Management Agency (FEMA) essentially uses this concept of a "fixed" dune when mapping velocity or V-zones for flood plain mapping in the coastal area. The delineation of these V-zones has important local economic development impacts.

However, since storms will erode the beach and dune and a rational design approach is to include an adequate volume of sand in the dune to survive the design storm erosion event. Kriebel and Dean (1985) and Vellinga (1983) have developed models of storm induced dune erosion that can be used to determine the volume of the required "reservoir of sand." The State of Florida uses a form of Kriebel's model in determining its coastal setback line. Such models can be improved by including runup in the formulation. In fact, Kriebel and Dean (1985) conclude that the first improvement to the model should be the "inclusion of wave runup" on the beachface.

Knowledge of runup on beaches could be applied to the design and management of grassed dune fields. For example, the minimum elevation at which beach grasses and small dunes can be maintained on the beach has been found to be fairly consistent on the barrier island of Ocean City, New Jersey (Weggel, 1988). This minimum elevation is probably related to some recurrence interval of runup. The grasses can tolerate only a certain exposure to waves. Establishing dunes is a significant coastal zone management and policy concern on many developed coastlines.

## "Overtopping" of Beaches and Dunes

Overtopping is a term reserved usually for the water passing over a fixed seawall. As waves break on an overtopped seawall, they wash up (runup) and over (overtopping) the structure. Knowledge of the volume of water overtopping a seawall is needed to design drainage or other flood prevention systems on the landward side. Given the uncertainty of many of the variables contributing to seawall overtopping our ability to estimate volumetric rates of overtopping is rather poor. In a review of the available methodology, Douglass (1984) concluded that overtopping estimates were probably only accurate to within an order of magnitude. Subsequent laboratory tests with irregular waves and several different structure cross-sections at WES have greatly improved our ability to estimate overtopping over fixed structures. With structure-specific laboratory model testing, the accuracy of our estimates of site-specific overtopping are probably primarily limited by the inaccuracies of estimating design storm water level, the single most important overtopping parameter. Prototype overtopping data are needed to evaluate the importance of scale effects in the laboratory results.

The extension of the concept of overtopping of structures to overtopping of beaches or dunes is tenuous and should be approached with many caveats. Essentially, the question is "what happens when the runup on the beach exceeds the crest of the sand dune?" Water from the individual runups flows landward. The big difference between this and the overtopping of structures question is that sand from the dune will be carried landward with the water.

Coastal geologists call this process "overwash." It is a mechanism for barrier island retreat because of the landward transport of sand. Overwash is fairly common during major storms on some barrier islands. It occurs initially at low spots in the dune crest elevation. These low crest areas are often associated with pedestrian pathways to the beach where the vegetation has been killed and the wind has created a "blowout" in the dune crest line. The width of these "breaches" in the dune line can increase during the storm. The very limited quantitative information about overwash is primarily limited to measurements of the volume of sand transported. Fisher et al.(1974) and Leatherman (1977) discuss some simple hydraulic measurements during minor overwash events on Assateaque Island. It is interesting that they report the number of runups that "surged" through the breach in the dune averaged out to be about one per minute. Although they don't discuss the actual time-series, the timing implies that these "surges" could have been driven by energy in the infragravity band.

The practical problem for the coastal engineer is how to estimate flooding on the landward side of a dune when the dune is breached or overwashed. There exists no available guidance to address this problem. Birkemeier et al. (1987) make the only feasible recommendation to FEMA concerning overwash,

> "Because the flooding will be caused by localized dune breaching and overwash (unless the surge level erodes or overtops the dune crest), the depth of flooding is difficult to predict. If the surge is of short duration, the flooding will occur as weir flow, and there will be a drop in water level across the eroded dune. However, once the dune overwashes inland, the maximum surge level should be assumed [as the interior flood level]. Since the overwash process is poorly documented and unquantified, a conservative and recommended approach is to use the maximum flood level if the dune is flooded."

For the case of minor overwash events it is tempting to try to apply overtopping methodologies developed for structures. A model for this condition could be based on Battjes (1974) model for overtopping of structures. Battjes assumed that each individual runup could be explained in terms of the monochromatic form of Hunt's Equation. Battjes' model could be modified by using Resio's (1987) distribution of runup on beaches. Input to the model would have to be an assumed beach profile that is either fixed at a low elevation or changing in time. It could represent a typical post-hurricane profile through the area of breaching. Design SWL must be less than the highest point on the profile for Hunt's Equation to have any physical meaning. With design wave conditions, Resio's model would estimate how many runups would exceed the profile crest. The results of Battjes and Roos (1972) relating the runup to the volume of water on a slope could then be used to estimate the overtopping volume rate per longshore unit width of breach. Because of the unverified nature of such an approach, it could only be assumed to be accurate to within an order of magnitude.

Research Recommendations

Research on runup on beaches should be more focused on specific engineering applications. This can be accomplished without sacrificing the general applicability of the research. Engineers have adapted the available technology to their specific engineering problems. It is telling that the best available data set on beach runup, Holman (1986), was not collected to study beach runup for engineering purposes but in order to study the swash spectra with a mind towards identifying the importance of the infragravity energy in the surf (Holman and Sallenger, 1985). The engineering applications paper derived from this data set, Holman (1986), was a reanalysis of the data that was commissioned by CERC. Although the application of available technology to specific engineering problems is necessary and productive, engineering research matures to studying the problem of interest. The applications for beach runup models discussed above; storm erosion prediction, beach overwash estimation, dune and beach design; are important and current questions in coastal zone management. The use of beaches and dunes for storm protection is not new and will probably play a more major role in the nation's response to accelerated sea level rise.

Future research on beach runup should examine whether or not the scaling relationship of Hunt's Equation is the most appropriate for estimating prototype beach runup. Hunt (1959) developed the equation with laboratory monochromatic wave data. His data showed a clear dependence of runup on both the wave steepness and structure slope. Wave height, wavelength and structure slope are clearly defined in the laboratory with monochromatic waves. However, the definition of each is more complex on prototype beaches.

More importantly, the importance of each term in Hunt's Equation on beach runup data has not been clearly examined. Hunt (1959) had clear evidence that runup varied roughly linearly with the tangent of structure slope but no such relationship has been shown for prototype beaches. Appendix C is a short reanalysis of Holman's data that shows that runup is unrelated to beachface slope. Only one site, Duck, North Carolina, is included in Holman's data set. Data from other sites with different ranges of slopes must be considered in order to determine whether beachface slope should be included in beach runup models.

Mase's results support the idea that the importance of beach slope is exaggerated in Hunt's Equation. Equation 8 separates the slope from wave steepness. Mase found $b=0.7$ . Thus, Mase found runup varies linearly with $(\tan \alpha)^{0.7}$ instead of linearly with $\tan \alpha$. Mase's $b$ is fit to all of the structure slopes he tested (1:5, 1:10, 1:20, 1:30). Examination of Mase and Iwagaki's Figure 10 shows that runup varies with $(\tan \alpha)^{0.4}$ for the two flatter slopes. In summary, slope's influence on runup decreases for flatter slopes.

Another reason why the scaling relation of Hunt's Equation should be questioned is that the dynamics on a prototype beach are different than the dynamics on simple laboratory slopes. In particular, overall beach slope across the entire surf zone width can be much flatter than has been tested in laboratory tests. The presence of offshore bars is very common on prototype beaches and has not been included in most laboratory tests. Waves break on the bar and propagate across the bar as air-entraining, turbulent bores until reaching the deeper water behind the trough where the white-water turbulence ceases and one or more waves continue propagating across the trough. These waves which have reformed in the trough are the waves which break on the beachface and runup. An individual wave, if it can even be identified, can break several times over a distance of hundreds of meters during storm conditions. The final breaking wave which runups up the beach called "shore break," can be a very different wave than the offshore wave both as an individual wave and in terms of spectral description. Similar phenomena have been described on beaches without offshore bars (Guza and Thornton 1982).

On barred profiles, the height of the shore break is controlled by the depth on the bar. The influence of depth across the bar on runup in Holman's data is investigated in Appendix C. Dimensionless depth across the bar, $d/H_{mo}$ , explains runup as well as $\xi$ . Since depth on the bar, $d$ , was not measured by Holman, it is estimated for his data by relating SWL to the profile shown in Figure 6. That such a crude estimate of depth across the bar explains the runup as well as $\xi$ implies that further work on finding a better scaling relationship than Holman's application of Hunt's Equation is warranted.

Research on beach runup should consider the effects and causes of energy in the infragravity portion of the runup spectra. The rising and falling of the water level in the surf zone allows incident gravity waves to propagate farther inshore before breaking and beginning the runup process. Guza and Thornton (1982) found that runup spectra is saturated, i.e. that the amount of energy in the spectra at the frequencies of the incident wind waves is independent of the incident wave height, while the energy at the infragravity frequencies continue to increase with increasing wave height. Mase (1988) found the same results in his laboratory work and showed that they can be explained entirely in terms of the interactions of the waves on the slope. This implies that a runup model separating the two components, call them swash and surf beat, may be useful. For a given offshore water level and a barred profile, waves are depth-limited across the bar during storms. Thus, the swash component of runup could be related to a constant function of the depth across the bar. This would essentially be a measure of the wave height in the trough which could then be combined with the beachface slope and an estimate of the wave period in a surf parameter which should be related to the swash height. The surf beat component could be modeled separately and the two components added to estimate total runup. However, the estimation of the surf beat phenomena on beaches is still an area of active research.

A comprehensive field investigation of beach runup at a specific site could be modeled after different portions of the recent surf zone dynamics experiments at Duck (Mason 1987). Waves and water levels should be measured offshore and at several locations across the surf zone. Specifically, a bottom-mounted wave gage in about 8 m depth with photopoles or bottom-mounted gages on the bar and in the trough are a minimum. Photopoles are painted poles driven into the sand to extend above the water surface to permit movie photography or video recording of the time-history of water surface elevation. Runup should be measured with a video system looking in the alongshore direction. Wind and bottom profile data should also be available. The experiment should be conducted away from the local bathymetric effects of piers, groins, and other coastal structures. All of the recommended methodologies and the required analysis techniques are presently used by CERC so no new equipment or methodologies would have to be developed. Since storms are of particular interest, the problems of working in an energetic surf zone will not be trivial.

It is suggested that such data be collected at more than one site. In particular, Pacific and Gulf coasts should be investigated because of the differences in storm wave climates. A "package" experiment could be put together and moved to several sites around the country. Experiments should be scheduled to catch medium-sized storm events.

Laboratory tests on flat slopes and non-uniform slopes are needed. The controlled environment of the laboratory provides excellent opportunities to investigate specific phenomenon. Laboratory tests are one of the most powerful coastal engineering tools for investigating the physics of complex phenomena. For example, Mase was able to find many phenomena in his laboratory flume that might be attributed to modes of propagation of infragravity energy in prototype experiments.

## PART V: SUMMARY

The phenomenon of runup on beaches has not received as much attention in the engineering literature as the phenomenon of runup on structures. In the absence of specific guidance, the engineer tasked with estimating runup on a beach has often adapted some of the available knowledge of runup on structures. Holman's method and Resio's extension of Holman's work are the only methods based on actual runup measurements on prototype beaches. Holman (1986) describes a large data set on beach runup and provides a model for estimating extreme values of runup. Resio (1987) extended Holman's model by describing the full distribution of extreme values.

Holman's data is published for the first time in Appendix B of this report. Limitations of the data are that they are only from one location during the same month and they may be biased because the wave field incident on the beach may have been affected by the perturbed bathymetry in the vicinity of the pier.

Both Holman and Resio used the same basic "model" of Hunt's Equation to scale the runup phenomenon. Resio used a different choice of wavelength in the surf parameter. Although it provides a useful method for the generalization of Holman's results, Resio's model is of limited immediate engineering value since it does not yield the total runup elevation and it does not account for the fact that the number of runups is less than the number of waves. Resio's method only yields the variation above the mean runup elevation ( $\bar{\eta}$ ) which is difficult to estimate.

Mase (1988, 1989) provides the most significant laboratory contribution to understanding the dynamics of runup on beaches. His experiments with irregular waves on sloping structures show many of the same properties of extreme runup statistics and runup spectra found on natural beaches.

Future research on beach runup should closely examine the scaling relationship of Hunt's Equation as it applies to engineering estimates of runup on beaches. The importance of and definition of each term in Hunt's Equation has not been addressed in detail. The dynamics on a prototype beach are different than those in laboratory tests with monochromatic waves breaking on planar slopes. In particular, overall beach slope across the entire surf zone width can be much flatter than has been tested in laboratory tests. The effects of non-planar beaches on wave breaking has not been adequately considered in runup models.

Both laboratory and field experiments are needed. Field experiments should be modeled after the recent surf zone dynamics experiments at Duck, North Carolina. However, data from other locations would be extremely useful. Focused laboratory experiments are critical in that they can provide explanations of the field results. Mase's work is an excellent example of how the controlled environment of the laboratory can be used to better understand the physics of beach runup.

Research on runup on beaches will be used in the solution of a number of coastal engineering and coastal management problems. Since the limit of runup defines the zone of possible wave damage, this research will be applied to the determination of coastal setback lines, the design of the height of man-made beaches and dunes, models of beach and dune erosion during storms, management policy related to the creation of dune fields on developed shorelines, and possibly estimating flooding due to overtopping and breaching of beaches and dunes.

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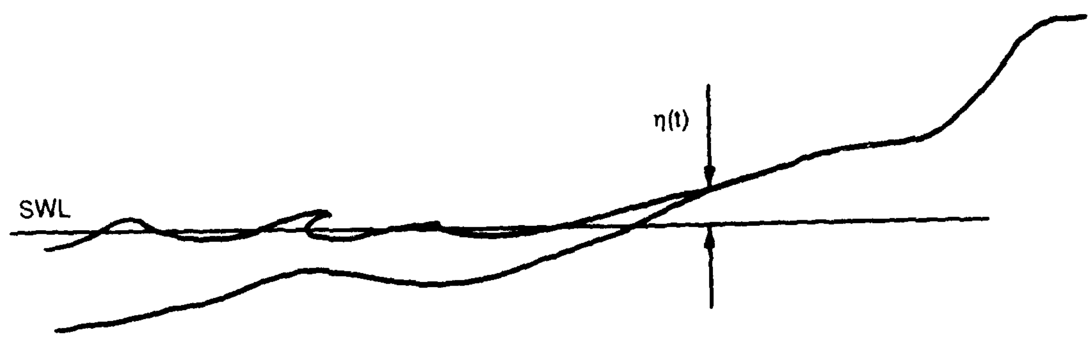
Table 1. Mase's empirical coefficients for Equations (8) and (9). Adapted from Mase and Iwagaki (1984) and Mase (1989).

| Statistic | a | b | c | d | e |
|---|---|---|---|---|---|
| $R_{max}$ | 2.57 | 0.78 | -0.36 | 2.32 | 0.77 |
| $R_{p2\%}$ | - | - | - | 1.86 | 0.71 |
| $R_{p(1/10)}$ | - | - | - | 1.70 | 0.71 |
| $R_{us}$ | 1.34 | 0.69 | -0.36 | 1.50 | 0.70 |
| $R_{ps}$ | 1.31 | 0.70 | -0.36 | 1.38 | 0.70 |
| $R_{u\ mean}$ | 0.99 | 0.67 | -0.36 | 1.09 | 0.68 |
| $R_{p\ mean}$ | 0.95 | 0.70 | -0.33 | 0.88 | 0.69 |

Table 2. Holman's (1986) regression coefficients for runup statistics versus $\xi$ as given by the incident wave conditions in 8 m of water.

| Statistic | slope | intercept |
|---|---|---|
| $\eta_{max}$ | 0.90 | 0.21 |
| $\eta_{2\%}$ | 0.69 | 0.18 |
| $R_{p2\%}$ | 0.78 | 0.20 |
| $S_{2\%}$ | 0.83 | 0.78 |
| $\eta_{max} - \overline{\eta}$ | 0.65 | -0.01 |
| $\eta_{2\%} - \overline{\eta}$ | 0.45 | -0.04 |
| $R_{p2\%} - \overline{\eta}$ | 0.53 | -0.02 |




Fi ure 1. Definition sketch for $\eta(t)$.

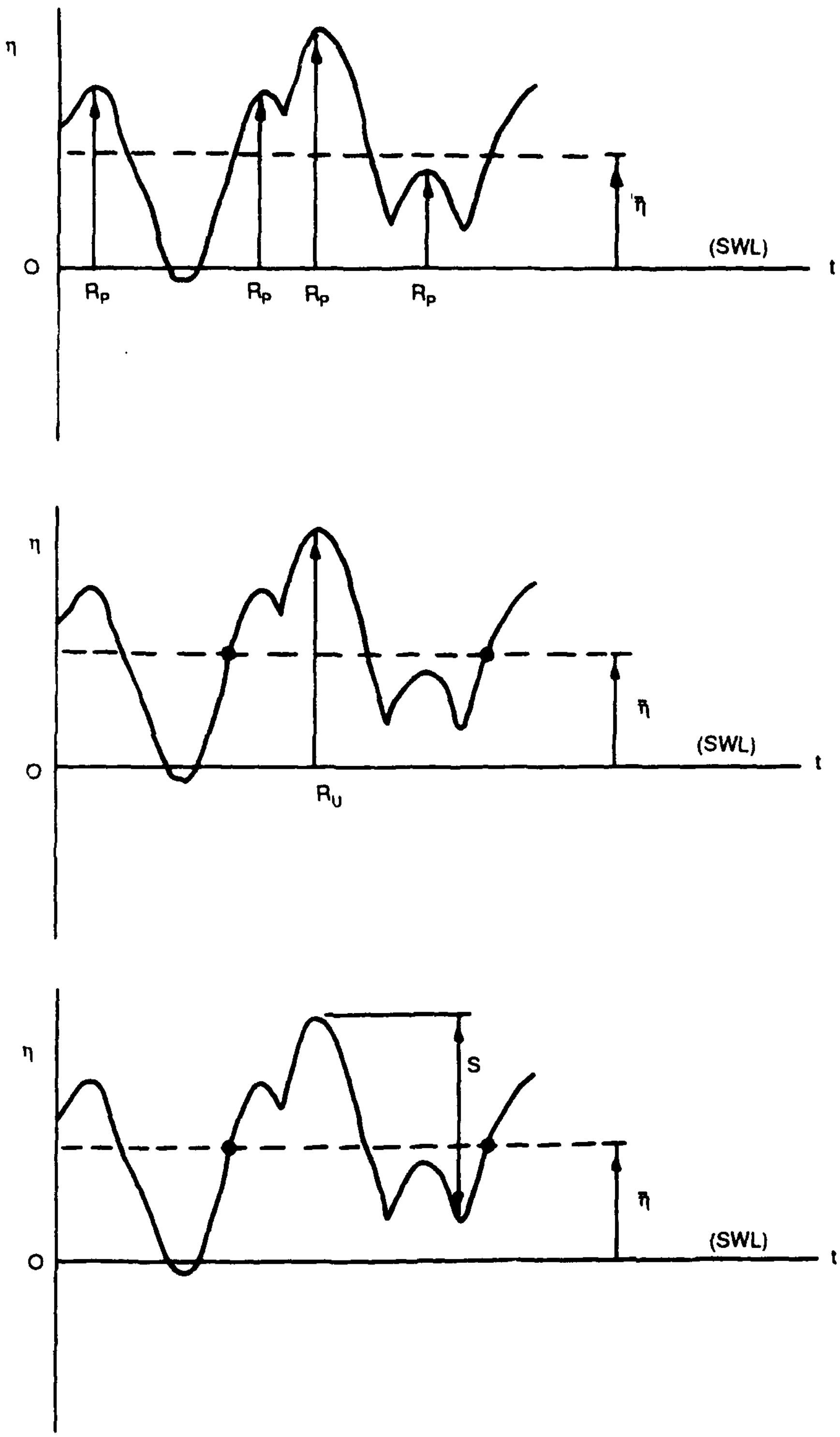



Figure 2. Individual runup definitions: a) local peak definition of runup, $R_p$ , b) upcrossing definition of runup, $R_u$ , c) upcrossing definition of swash height, S.

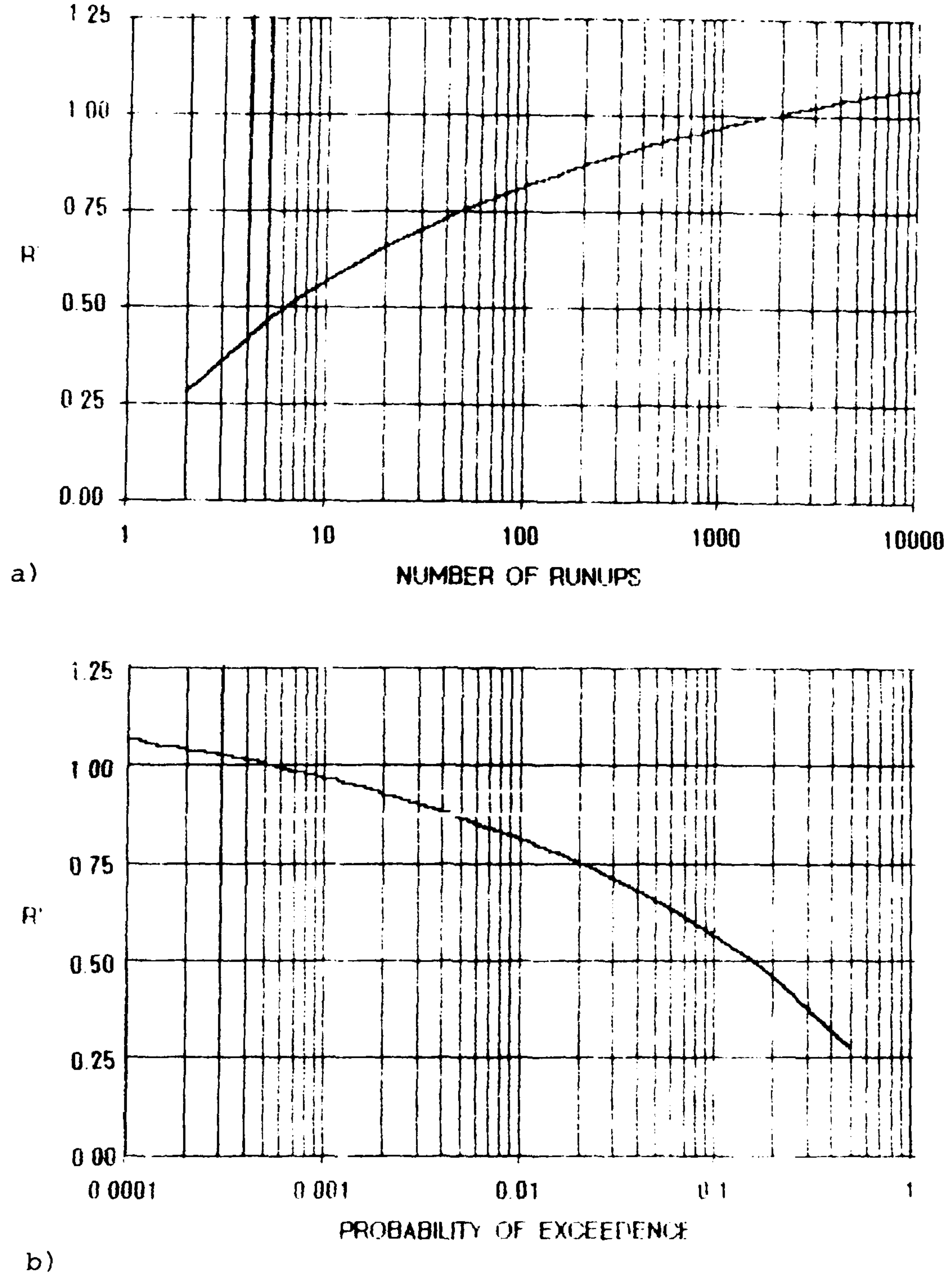



Figure 3. Resio's model for the extreme value distribution of runup on beaches, a) in terms of number of runups, b) in terms of probability of exceedance.

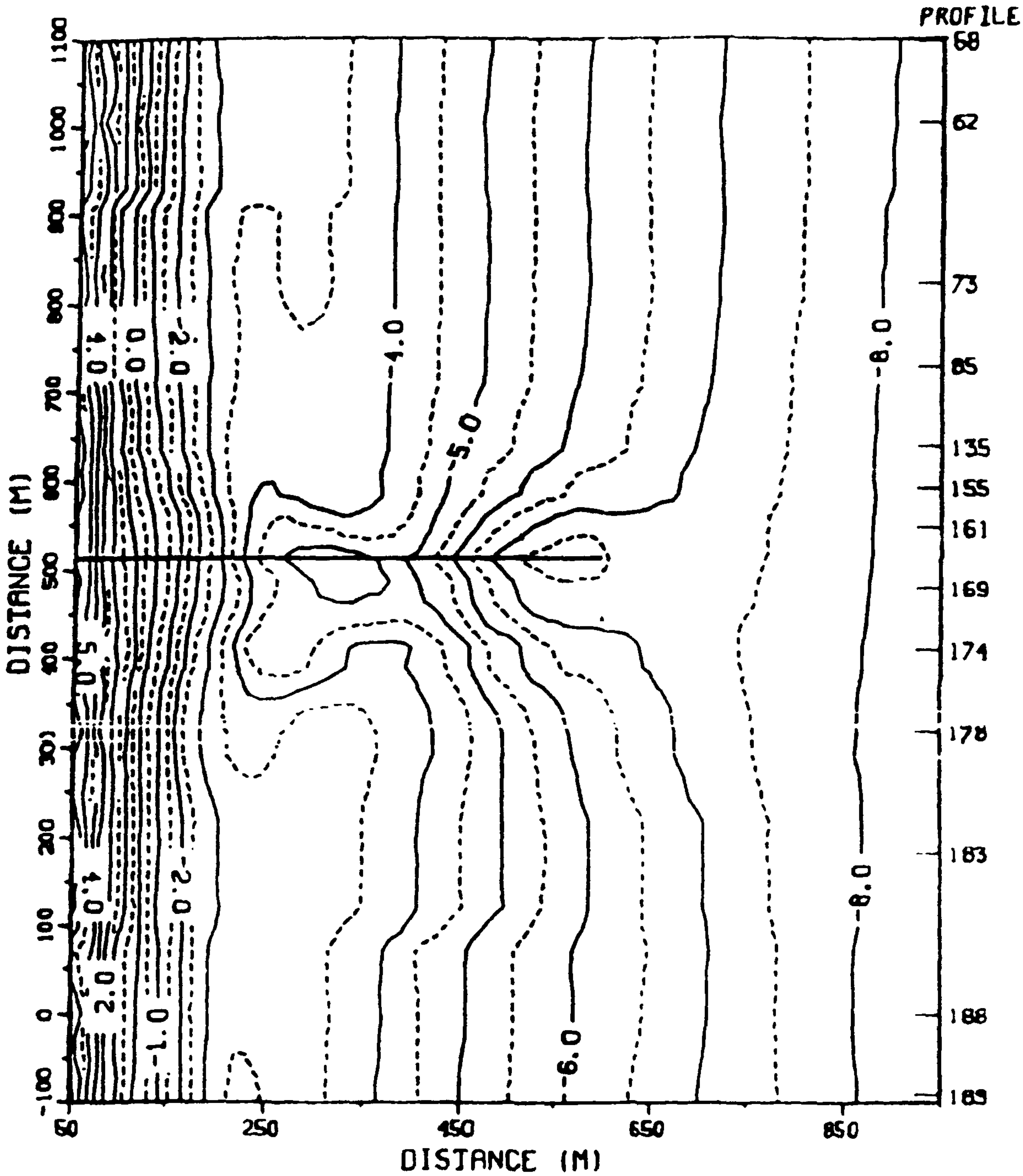



Figure 4. Bathymetry around FRF pier at Duck, North Carolina, 24 August 1982 (from Miller et al. 1986).

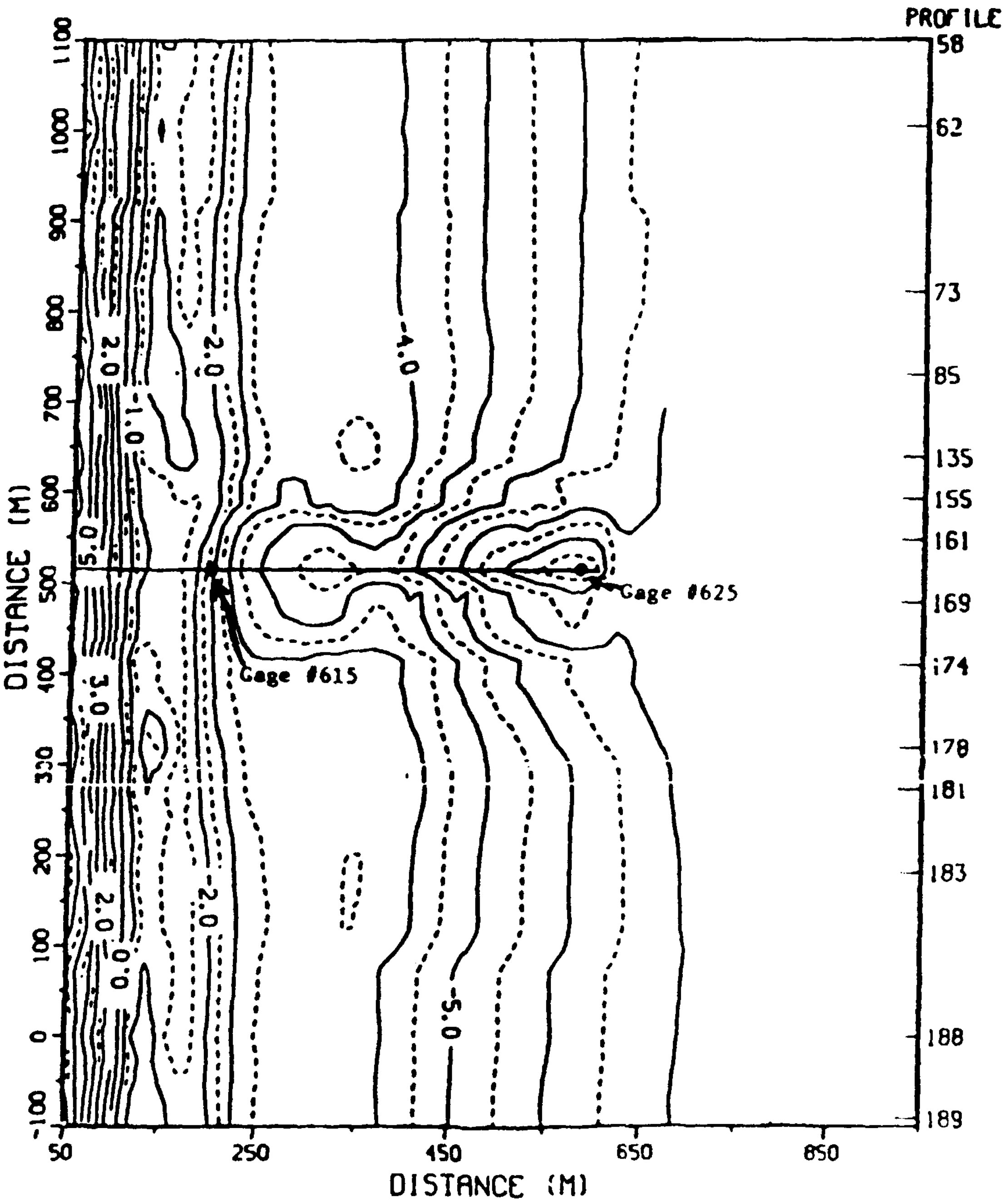



Figure 5. Bathymetry around FRF pier at Duck, North Carolina, 27 October 1982 (from Miller et al. 1986).

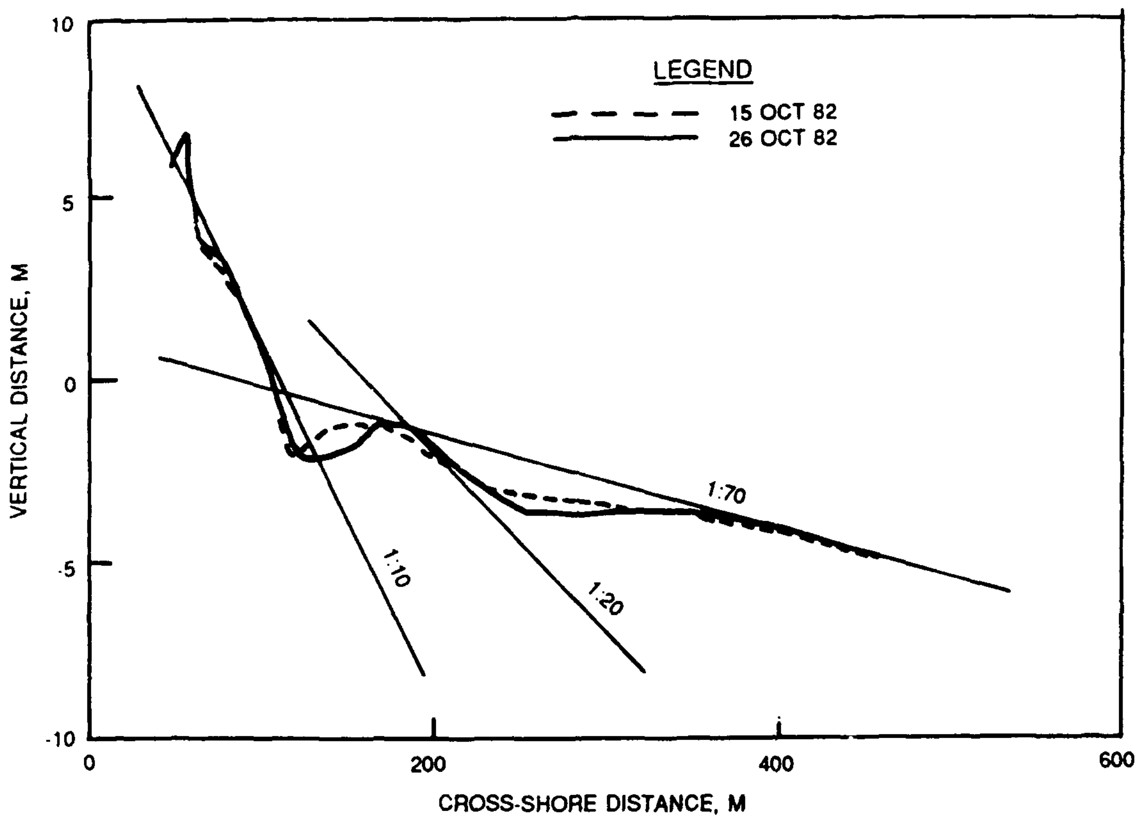



Figure 6. Beach profile at Duck, North Carolina, with flat slopes superimposed (modified from Holman and Sallenger 1985).

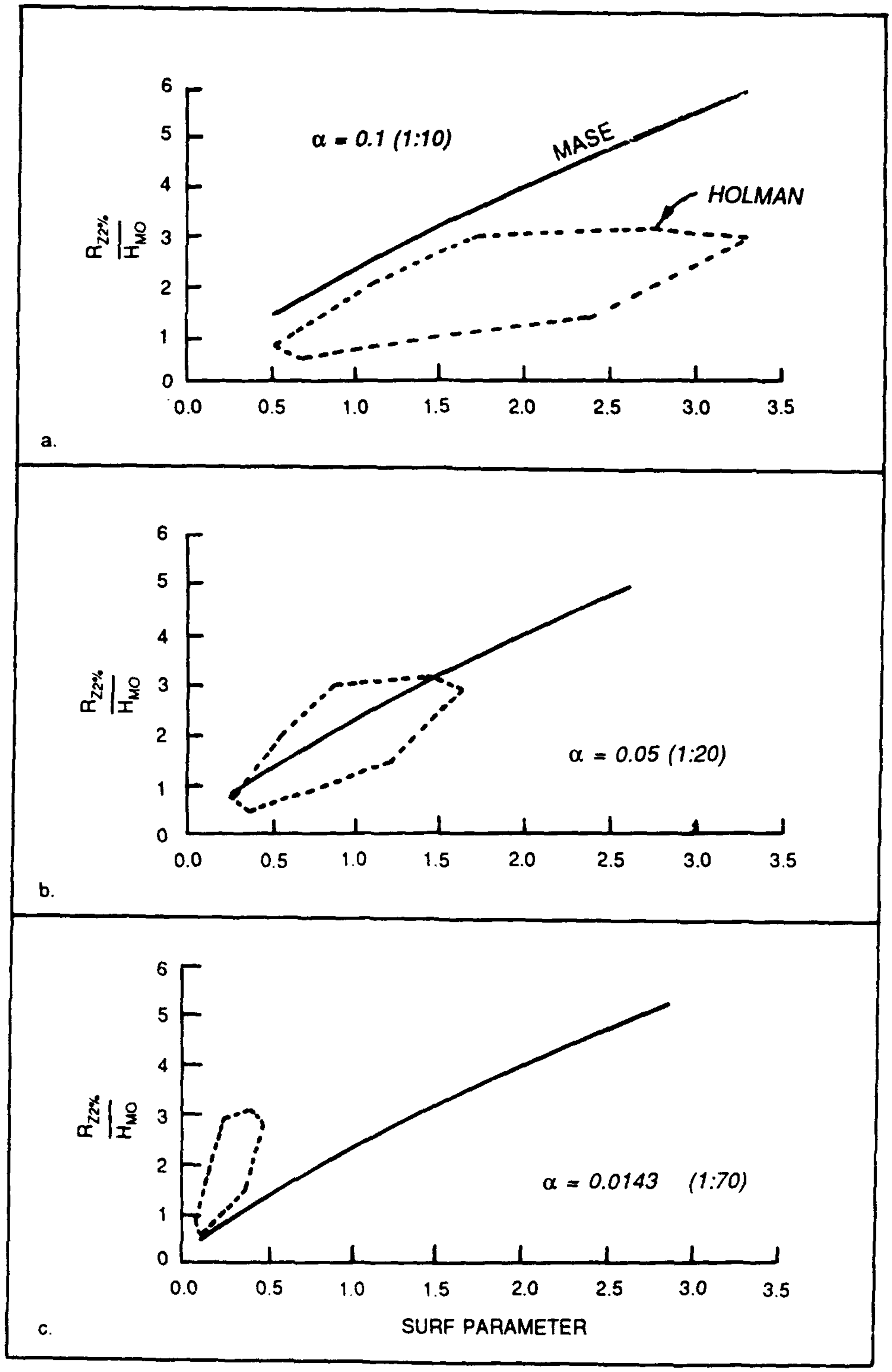



Figure 7. Comparison of Mase's (1984) equation and the envelope of Holman's (1986) data for different assumptions of beach slope, a) $\alpha = 0.1$, b) $\alpha = 0.05$, c) $\alpha = 0.0143$.

## APPENDIX A: NOTATION

| | |
|---|---|
| $a$ | Empirical coefficient in Equation 8 |
| $b$ | Empirical coefficient in Equation 8 |
| $c$ | Empirical coefficient in Equation 8 |
| $C$ | Coefficient in Equation 4 |
| $d$ | Water depth, m |
| $d$ | Empirical coefficient in Equation 9 |
| $e$ | Empirical coefficient in Equation 9 |
| $g$ | Acceleration due to gravity, m/sec$^2$ |
| $H$ | Wave height, m |
| $H_{mo}$ | Spectral significant wave height, m |
| $H_s$ | Significant wave height, m |
| $L$ | Local wavelength, m |
| $L_0$ | Deepwater wavelength, m |
| $L_p$ | Wavelength from linear theory corresponding with the peak frequency of the energy density spectrum, m |
| $N$ | Number of waves for Resio's model |
| $p$ | Subscript signifying local peak definition of individual runups |
| $P_e$ | Probability of exceedance in Resio's model |
| $R$ | Vertical runup distance due to monochromatic waves, m |
| $R_{max}$ | Maximum runup due to irregular waves, m |
| $R_p$ | Local peak definition of runup (see Figure 2), m |
| $R_{p\ mean}$ | Mean runup with local peak definition, m |
| $R_{ps}$ | Significant runup, average of the highest one-third runups as defined by the local peak method, m |
| $R_{p(1/10)}$ | Average of the highest one-tenth runups as defined by the local peak method, m |

| | |
|---|---|
| $R_{p2\%}$ | Runup level exceeded by the largest 2% of the runups as defined by the local peak method, m |
| $R_u$ | Upcrossing definition of runup (see Figure 2), m |
| $R_{u\ mean}$ | Mean runup with upcrossing definition, m |
| $R_{us}$ | Significant runup, average of the highest one-third runups, as defined by the upcrossing method, m |
| $R_{u2\%}$ | Runup level exceeded by the largest 2% of the runups as defined by the upcrossing method m |
| $R_z$ | Upcrossing definition of runup relative to SWL, m |
| $R_{z\ mean}$ | Mean runup with SWL upcrossing definition, m |
| $R_{zs}$ | Significant runup, average of the highest one-third runups, as defined by the SWL upcrossing method, m |
| $R_{z2\%}$ | Runup level exceeded by the largest 2% of the runups as defined by the SWL upcrossing method m |
| $R^*$ | Generic R in Equations 8 and 9 |
| $R'$ | Hunt's Equation coefficient in Resio's model (Equation 15) |
| S | Swash height (see Figure 2), m |
| $S_{2\%}$ | Swash height exceeded by the largest 2% of swashes, m |
| SWL | Still water level |
| t | Time, sec |
| tan | Tangent |
| $T_p$ | Wave period corresponding to the peak frequency of the energy density spectrum, sec |
| $T_r$ | Return period for Resio's model, units are number of waves |
| $\angle$ | Subscript signifying upcrossing definition of individual runups |
| $\alpha$ | Beach or structure slope in radians or as rise-over-run |
| $\eta$ | Vertical distance from the SWL to the intersection of the water surface and the beach, m |
| $\bar{\eta}$ | Average $\eta$ , m |

| | |
|---|---|
| $\eta_{max}$ | Maximum value of $\eta$ , m |
| $\eta_{2\%}$ | Level exceeded by the largest 2% of discrete $\eta(t)$ samples, m |
| $\eta(t)$ | Time history of $\eta$ |
| $\xi$ | Surf parameter |
| $\pi$ | Constant, 3.1416 |

## APPENDIX B: HOLMAN'S (1986) DATA

This appendix presents the summary data described by Holman (1986). This is the first time that this data has been published. This data was gathered from two unpublished sources. One, a summary table from the original letter report from Holman to CERC. Two, a set of two large binders that showed some of Holman's analysis results. The origin and a brief description of each column is:

1st column: Data number. Each refers to a movie film analyzed for a specific transect on the beach. From the summary table and correlated with the binders.

2nd column: Date. The day in October 1983 when the movie film was shot at Duck, NC. From the binders.

3rd column: Time. The time of the 17-minute filming (24-hour clock). From the binders.

4th column: Range. The distance from the pier of the runup analysis in meters. "n" and "s" refer to north and south of the pier. Note that many of Holman's 149 data points are from the same movie film at different locations along the beach. From the binders and the key at the beginning of the binders.

5th column: setup. This is actually not setup but $\bar{\eta}$. This column of data is from the summary table. Knowledge of the tide gage at the end of the pier must have been used to calculate this from the mean of the $\eta$ record which was referenced to an arbitrary datum.

6th column: Rs. This is the spectral significant runup from the summary table. From the summary table.

7th column: Hmo. Spectral significant wave height from the Baylor gage in d=8m at the end of the pier. From the summary table.

8th column: T. $T_p$ from the Baylor gage. From the summary table.

9th column: Tz. The mean zero-upcrossing period of the runups. From the summary table.

10th column: etamax. $\eta_{max}$ as defined in Appendix A. From the summary table.

11th column: eta2%. $\eta_{2\%}$ as defined in Appendix A. From the summary table and spot-checked with the binders.

12th column: Rp2%. $R_{u2\%}$ as defined in Appendix A. From the summary table.

13th column: S2%. $S_{2\%}$ as defined in Appendix A. From the summary table and spot-checked from the binders.

14th column: slope. Beachface slope. From the summary table.

15th column: SWL. Computed with the $\bar{\eta}$ from the summary table and the first moment of the $\eta$ record from the binders.

| Data # | date | time | range | setup (m) | Rs (m) | Hmo (m) | T (sec) | Tz (sec) | etamax (m) | eta2% (m) | Rp2% (m) | S2% (m) | slope | SWL (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 1555 | 100n | 0.22 | 1.36 | 0.90 | 9.5 | 12.3 | 1.26 | 0.89 | 1.03 | 1.44 | 0.14 | -0.30 |
| 2 | 4 | 1555 | 150s | 0.11 | 1.47 | 0.90 | 9.5 | 15.7 | 1.15 | 0.81 | 1.02 | 1.47 | 0.12 | -0.30 |
| 3 | 5 | 0836 | 100n | 0.51 | 2.10 | 0.80 | 11.0 | 13.4 | 2.08 | 1.72 | 1.94 | 2.40 | 0.14 | 0.83 |
| 4 | 5 | 1632 | 250n | 1.29 | 1.02 | 0.80 | 11.0 | 10.8 | 2.12 | 1.78 | 1.98 | 1.11 | 0.11 | -0.35 |
| 5 | 5 | 1632 | 200n | -0.77 | 2.94 | 0.80 | 11.0 | 14.0 | 1.21 | 0.66 | 1.04 | 3.18 | 0.16 | -0.35 |
| 6 | 5 | 1632 | 175n | -0.42 | 1.97 | 0.80 | 11.0 | 12.2 | 2.11 | 0.69 | 1.00 | 2.41 | 0.14 | -0.35 |
| 7 | 5 | 1632 | 150n | 0.15 | 1.47 | 0.80 | 11.0 | 13.9 | 1.40 | 1.02 | 1.24 | 1.72 | 0.12 | -0.35 |
| 8 | 5 | 1632 | 125n | 0.15 | 1.65 | 0.80 | 11.0 | 11.5 | 1.30 | 1.02 | 1.19 | 1.73 | 0.14 | -0.35 |
| 9 | 5 | 1632 | 100n | 0.11 | 1.56 | 0.80 | 11.0 | 13.0 | 1.21 | 0.93 | 1.12 | 1.58 | 0.16 | -0.35 |
| 10 | 5 | 1632 | 100n | 0.05 | 1.65 | 0.80 | 11.0 | 12.1 | 1.14 | 0.8[illegible] | 1.02 | 1.79 | 0.16 | -0.35 |
| 11 | 5 | 1632 | 75n | 0.74 | 1.08 | 0.80 | 11.0 | 11.8 | 1.57 | 1.33 | 1.41 | 1.08 | 0.15 | -0.35 |
| 12 | 6 | 1024 | 250n | 1.34 | 1.48 | 0.80 | 11.0 | 11.8 | 2.38 | 1.79 | 1.81 | 1.44 | 0.11 | 0.85 |
| 13 | 6 | 1024 | 200n | 1.02 | 1.93 | 0.80 | 11.0 | 11.5 | 1.70 | 1.87 | 1.89 | 1.95 | 0.16 | 0.85 |
| 14 | 6 | 1024 | 175n | 0.92 | 1.43 | 0.80 | 11.0 | 12.4 | 1.80 | 1.64 | 1.74 | 1.48 | 0.14 | 0.85 |
| 15 | 6 | 1024 | 150n | 0.98 | 1.41 | 0.80 | 11.0 | 12.9 | 1.86 | 1.60 | 1.71 | 1.31 | 0.12 | 0.85 |
| 16 | 6 | 1024 | 125n | 0.97 | 1.75 | 0.80 | 11.0 | 14.4 | 2.07 | 1.72 | 1.78 | 1.70 | 0.14 | 0.85 |
| 17 | 6 | 1024 | 100n | 0.81 | 2.33 | 0.80 | 11.0 | 12.8 | 2.19 | 1.94 | 2.06 | 2.12 | 0.16 | 0.85 |
| 18 | 6 | 1024 | 75n | 0.84 | 1.41 | 0.80 | 11.0 | 11.7 | 1.78 | 1.41 | 1.41 | 1.42 | 0.15 | 0.85 |
| 19 | 6 | 1024 | 50n | 0.62 | 1.36 | 0.80 | 11.0 | 11.8 | 1.60 | 1.39 | 1.54 | 1.40 | 0.13 | 0.85 |
| 20 | 8 | 1308 | 150n | 0.54 | 0.95 | 0.50 | 9.3 | 8.9 | 1.46 | 1.15 | 1.30 | 1.03 | 0.20 | 0.71 |
| 21 | 8 | 1308 | 100n | 0.23 | 1.17 | 0.50 | 9.3 | 9.6 | 1.34 | 0.95 | 1.13 | 1.29 | 0.14 | 0.71 |
| 22 | 8 | 1308 | 100s | 0.50 | 0.80 | 0.50 | 9.3 | 9.1 | 1.33 | 0.96 | 1.04 | 0.93 | 0.11 | 0.71 |
| 23 | 8 | 1508 | 150s | 0.47 | 1.03 | 0.50 | 9.3 | 8.8 | 1.38 | 1.01 | 1.21 | 1.06 | 0.13 | 0.71 |
| 24 | 9 | 1315 | 150n | 0.49 | 0.82 | 0.42 | 7.4 | 8.9 | 1.33 | 0.98 | 1.17 | 0.86 | 0.20 | 0.77 |
| 25 | 9 | 1315 | 100n | 0.07 | 1.00 | 0.42 | 7.4 | 9.7 | 1.14 | 0.65 | 0.85 | 1.04 | 0.14 | 0.77 |
| 26 | 10 | 0947 | 150n | 1.01 | 1.17 | 2.17 | 7.9 | 12.9 | 1.96 | 1.67 | 1.87 | 1.38 | 0.11 | 0.28 |
| 27 | 10 | 0947 | 100n | 0.98 | 1.48 | 2.17 | 7.9 | 11.5 | 2.60 | 1.81 | 2.00 | 1.69 | 0.16 | 0.28 |
| 28 | 10 | 0947 | 100s | 0.92 | 0.94 | 2.30 | 7.1 | 10.7 | 1.87 | 1.25 | 1.46 | 1.52 | 0.15 | 0.08 |
| 29 | 10 | 0947 | 150s | 0.90 | 1.30 | 2.30 | 7.1 | 10.6 | 2.03 | 1.51 | 1.66 | 1.68 | 0.14 | 0.29 |
| 30 | 10 | 1355 | 200n | 1.26 | 1.51 | 2.64 | 12.1 | 14.5 | 2.67 | 2.22 | 2.36 | 1.83 | 0.08 | 1.11 |
| 31 | 10 | 1355 | 175n | 1.15 | 1.35 | 2.64 | 12.1 | 14.0 | 2.37 | 1.98 | 2.10 | 1.84 | 0.09 | 1.11 |
| 32 | 10 | 1355 | 150n | 1.06 | 1.52 | 2.64 | 12.1 | 16.0 | 2.46 | 1.98 | 2.22 | 1.71 | 0.10 | 1.11 |
| 33 | 10 | 1355 | 125n | 1.45 | 1.50 | 2.64 | 12.1 | 13.2 | 2.65 | 2.29 | 2.42 | 1.80 | 0.11 | 1.11 |
| 34 | 10 | 1355 | 250s | 1.50 | 1.73 | 2.64 | 12.1 | 14.4 | 2.75 | 2.42 | 2.63 | 1.94 | 0.12 | 1.11 |
| 35 | 10 | 1355 | 75n | 1.05 | 1.35 | 2.64 | 12.1 | 16.4 | 2.10 | 1.84 | 2.02 | 1.56 | 0.10 | 1.11 |
| 36 | 10 | 1355 | 50n | 1.21 | 1.49 | 2.64 | 12.1 | 20.3 | 2.17 | 2.09 | 2.15 | 1.82 | 0.09 | 1.11 |
| 37 | 10 | 1355 | 100s | 0.78 | 2.22 | 2.64 | 12.0 | 26.3 | 1.92 | 1.69 | 1.83 | 1.69 | 0.08 | 1.22 |
| 36 | 10 | 1355 | 125s | 0.83 | 1.65 | 2.64 | 12.0 | 14.7 | 2.21 | 1.68 | 1.81 | 1.89 | 0.09 | 1.11 |
| 39 | 10 | 1355 | 150s | 0.56 | 2.21 | 2.64 | 12.0 | 16.0 | 2.26 | 1.94 | 2.22 | 2.35 | 0.10 | 1.35 |
| 40 | 10 | 1355 | 175s | 0.83 | 1.97 | 2.64 | 12.0 | 14.4 | 2.32 | 1.91 | 2.11 | 2.36 | 0.10 | 1.11 |
| 41 | 10 | 1355 | 200s | 0.80 | 1.88 | 2.64 | 12.0 | 14.1 | 2.18 | 1.83 | 2.07 | 2.19 | 0.09 | 1.11 |
| 42 | 10 | 1355 | 250s | 1.01 | 2.12 | 2.64 | 12.0 | 13.6 | 2.55 | 1.98 | 2.18 | 2.60 | 0.09 | 1.11 |
| 43 | 10 | 1550 | 150n | 1.06 | 1.68 | 2.64 | 11.6 | 16.4 | 2.62 | 2.09 | 2.43 | 1.88 | 0.10 | 1.02 |
| 44 | 10 | 1550 | 100n | 1.47 | 1.72 | 2.64 | 11.6 | 15.2 | 2.84 | 2.45 | 2.68 | 1.80 | 0.12 | 1.02 |
| 45 | 11 | 0925 | 150n | 0.91 | 1.75 | 2.39 | 13.8 | 15.2 | 2.64 | 1.87 | 2.16 | 1.90 | 0.10 | 0.06 |
| 46 | 11 | 0925 | 100n | 1.10 | 2.09 | 2.39 | 13.8 | 15.2 | 2.83 | 2.23 | 2.49 | 2.05 | 0.13 | 0.06 |
| 47 | 11 | 0925 | 100s | 0.78 | 1.15 | 2.39 | 13.8 | 18.4 | 1.93 | 1.53 | 1.65 | 1.32 | 0.08 | -0.44 |
| 48 | 11 | 0925 | 150s | 0.51 | 2.02 | 2.39 | 13.8 | 17.5 | 2.59 | 1.59 | 1.77 | 2.02 | 0.10 | 0.06 |

| Data # | date | time | range | setup (m) | Rs (m) | Hmo (m) | T (sec) | Tz (sec) | etamax (m) | eta2% (m) | Rp2% (m) | S2% (m) | slope | SWL (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 49 | 11 | 1326 | 100n | 1.21 | 2.43 | 2.53 | 14.2 | 16.0 | 2.92 | 2.43 | 2.66 | 2.83 | 0.13 | 0.80 |
| 50 | 11 | 1326 | 150n | 1.25 | 2.23 | 2.53 | 14.2 | 15.9 | 2.89 | 2.59 | 2.76 | 2.38 | 0.10 | 0.80 |
| 51 | 11 | 1513 | 150n | 1.45 | 2.31 | 2.60 | 13.8 | 16.0 | 3.06 | 2.62 | 2.90 | 2.55 | 0.11 | 0.96 |
| 52 | 11 | 1513 | 200n | 1.03 | 1.82 | 2.60 | 13.8 | 16.5 | 2.66 | 1.90 | 2.55 | 1.94 | 0.10 | 0.88 |
| 53 | 11 | 1513 | 100n | 1.14 | 2.94 | 2.60 | 13.8 | 17.3 | 3.36 | 2.75 | 3.11 | 3.28 | 0.12 | 0.96 |
| 54 | 11 | 1705 | 150n | 1.16 | 2.45 | 2.70 | 14.6 | 17.4 | 3.32 | 2.57 | 2.86 | 2.88 | 0.11 | 0.76 |
| 55 | 11 | 1705 | 100n | 0.98 | 2.41 | 2.70 | 14.6 | 17.6 | 3.17 | 2.39 | 2.80 | 3.01 | 0.12 | 0.76 |
| 56 | 11 | 1756 | 150n | 1.16 | 2.23 | 2.42 | 14.4 | 16.4 | 3.36 | 2.35 | 2.78 | 2.36 | 0.11 | 0.64 |
| 57 | 11 | 1756 | 100n | 0.87 | 2.46 | 2.42 | 14.4 | 18.1 | 3.32 | 2.40 | 2.80 | 2.94 | 0.12 | 0.64 |
| 58 | 12 | 0846 | 150n | 0.93 | 2.18 | 4.05 | 16.2 | 17.9 | 2.64 | 2.00 | 2.29 | 2.56 | 0.11 | -0.07 |
| 59 | 12 | 0846 | 100n | 0.72 | 2.10 | 4.05 | 15.3 | 20.2 | 2.58 | 1.82 | 2.18 | 2.55 | 0.12 | -0.07 |
| 60 | 12 | 0846 | 150s | 0.68 | 1.94 | 4.05 | 15.3 | 25.0 | 2.00 | 1.78 | 2.09 | 2.10 | 0.08 | -0.06 |
| 61 | 12 | 0846 | 100s | 0.69 | 1.81 | 4.05 | 15.3 | 30.9 | 2.15 | 1.77 | 1.94 | 2.06 | 0.08 | -0.07 |
| 62 | 12 | 1405 | 150n | 1.27 | 2.91 | 3.11 | 16.2 | 21.6 | 3.21 | 2.81 | 3.06 | 3.20 | 0.11 | 0.58 |
| 63 | 12 | 1405 | 100n | 1.08 | 2.85 | 3.11 | 16.2 | 18.8 | 3.45 | 2.78 | 3.18 | 3.08 | 0.12 | 0.58 |
| 64 | 12 | 1405 | 100s | 0.89 | 2.36 | 3.11 | 16.2 | 30.9 | 2.59 | 2.13 | 2.21 | 2.74 | 0.08 | 0.58 |
| 65 | 12 | 1405 | 150s | 1.05 | 2.36 | 3.11 | 16.2 | 28.8 | 3.16 | 2.34 | 2.63 | 2.80 | 0.08 | 0.58 |
| 66 | 12 | 1531 | 100n | 1.07 | 3.04 | 3.30 | 15.1 | 18.4 | 3.09 | 2.81 | 3.02 | 3.56 | 0.12 | 0.84 |
| 67 | 12 | 1531 | 100s | 1.04 | 2.41 | 3.30 | 15.1 | 25.3 | 2.74 | 2.33 | 2.57 | 2.60 | 0.08 | 0.84 |
| 68 | 12 | 1531 | 150s | 1.05 | 2.20 | 3.30 | 15.1 | 23.1 | 3.13 | 2.21 | 2.62 | 2.73 | 0.08 | 0.84 |
| 69 | 12 | 1722 | 150n | 1.35 | 2.52 | 2.76 | 16.5 | 18.8 | 3.25 | 2.62 | 2.98 | 2.58 | 0.11 | 0.80 |
| 70 | 12 | 1722 | 100n | 1.14 | 2.93 | 2.76 | 16.5 | 17.6 | 3.13 | 2.78 | 3.06 | 3.08 | 0.12 | 0.80 |
| 71 | 12 | 1722 | 100s | 1.00 | 2.32 | 2.76 | 16.5 | 25.3 | 2.87 | 2.41 | 2.77 | 2.42 | 0.08 | 0.80 |
| 72 | 12 | 1722 | 150s | 0.99 | 2.12 | 2.76 | 16.5 | 24.1 | 3.35 | 2.30 | 2.64 | 2.55 | 0.08 | 0.80 |
| 73 | 12 | 1815 | 150n | 1.45 | 2.70 | 2.88 | 16.3 | 21.0 | 3.52 | 2.92 | 3.22 | 2.99 | 0.11 | 0.70 |
| 74 | 12 | 1815 | 100n | 1.18 | 2.83 | 2.88 | 16.3 | 17.0 | 3.56 | 2.74 | 3.21 | 3.07 | 0.12 | 0.70 |
| 75 | 12 | 1815 | 100s | 0.93 | 1.94 | 2.88 | 16.3 | 22.1 | 2.54 | 1.95 | 2.37 | 2.43 | 0.08 | 0.70 |
| 76 | 13 | 0915 | 150n | 0.82 | 2.01 | 2.12 | 16.0 | 15.9 | 2.56 | 1.98 | 2.13 | 2.26 | 0.13 | -0.05 |
| 77 | 13 | 0915 | 100n | 0.83 | 2.02 | 2.12 | 16.0 | 18.6 | 2.62 | 1.96 | 2.31 | 2.06 | 0.12 | -0.05 |
| 78 | 13 | 0915 | 100s | 0.89 | 1.85 | 2.12 | 16.0 | 29.2 | 2.15 | 1.82 | 1.97 | 2.29 | 0.09 | -0.05 |
| 79 | 13 | 0915 | 150s | 0.72 | 2.41 | 2.12 | 16.0 | 24.7 | 2.51 | 1.98 | 2.15 | 2.98 | 0.12 | -0.05 |
| 80 | 13 | 1114 | 150n | 0.68 | 1.74 | 2.04 | 14.6 | 17.4 | 2.10 | 1.62 | 1.79 | 1.92 | 0.13 | -0.23 |
| 81 | 13 | 1114 | 100n | 0.69 | 1.87 | 2.04 | 14.6 | 20.0 | 2.67 | 1.67 | 1.92 | 1.98 | 0.12 | -0.23 |
| 82 | 13 | 1114 | 100s | 0.91 | 1.89 | 2.04 | 14.6 | 31.3 | 2.35 | 1.87 | 2.11 | 2.34 | 0.09 | -0.29 |
| 83 | 13 | 1114 | 150s | 0.63 | 2.18 | 2.04 | 14.6 | 24.4 | 2.27 | 1.80 | 1.87 | 2.15 | 0.12 | -0.23 |
| 84 | 13 | 1445 | 150n | 0.82 | 1.89 | 1.93 | 13.8 | 13.4 | 2.49 | 1.68 | 1.97 | 2.06 | 0.13 | 0.45 |
| 85 | 13 | 1445 | 100n | 0.90 | 1.75 | 1.93 | 13.8 | 14.8 | 2.68 | 1.76 | 2.15 | 1.98 | 0.12 | 0.45 |
| 86 | 13 | 1649 | 150n | 0.88 | 2.02 | 2.08 | 14.8 | 13.5 | 2.81 | 2.12 | 2.46 | 2.66 | 0.13 | 0.82 |
| 87 | 13 | 1649 | 100n | 0.88 | 1.91 | 2.08 | 14.8 | 14.7 | 2.25 | 1.95 | 2.19 | 2.16 | 0.12 | 0.82 |
| 88 | 14 | 0911 | 150n | 0.72 | 2.20 | 1.56 | 14.4 | 13.8 | 2.40 | 1.74 | 1.91 | 2.15 | 0.13 | 0.33 |
| 89 | 14 | 0911 | 100n | 0.57 | 1.64 | 1.56 | 14.4 | 14.4 | 1.88 | 1.38 | 1.58 | 1.61 | 0.12 | 0.33 |
| 90 | 14 | 0911 | 100s | 1.01 | 1.62 | 1.56 | 14.4 | 20.4 | 2.33 | 1.91 | 2.20 | 1.88 | 0.09 | 0.33 |
| 91 | 14 | 0911 | 150s | 1.27 | 1.74 | 1.56 | 14.4 | 16.0 | 2.56 | 2.16 | 2.35 | 1.80 | 0.12 | 0.33 |
| 92 | 14 | 1703 | 150n | 1.00 | 1.99 | 1.47 | 12.5 | 13.5 | 3.01 | 2.14 | 2.48 | 2.17 | 0.13 | 0.91 |
| 93 | 14 | 1703 | 100n | 0.86 | 1.43 | 1.47 | 12.5 | 13.8 | 2.02 | 1.67 | 1.85 | 1.36 | 0.11 | 0.91 |
| 94 | 14 | 1703 | 100s | 1.47 | 1.60 | 1.47 | 12.5 | 19.1 | 2.30 | 2.12 | 2.25 | 1.66 | 0.10 | 0.91 |
| 95 | 14 | 1703 | 150s | 1.63 | 1.96 | 1.47 | 12.5 | 17.8 | 2.86 | 2.49 | 2.66 | 2.22 | 0.11 | 0.91 |
| 96 | 15 | 0850 | 250n | 1.46 | [illegible] | [illegible] | 12.5 | 13.6 | 2.55 | 2.33 | 2.39 | 1.32 | 0.13 | [illegible] |

| Data # | date | time | range | setup (m) | Rs (m) | Hmo (m) | T (sec) | Tz (sec) | etamax (m) | eta2% (m) | Rp2% (m) | S2% (m) | slope | SWL (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 97 | 15 | 0850 | 200n | 0.84 | 1.29 | 0.97 | 12.5 | 12.7 | 1.84 | 1.52 | 1.64 | 1.29 | 0.11 | 0.60 |
| 98 | 15 | 0850 | 175n | 0.49 | 1.85 | 0.97 | 12.5 | 14.8 | 2.20 | 1.46 | 1.56 | 1.59 | 0.12 | 0.60 |
| 99 | 15 | 0850 | 150n | 0.64 | 1.53 | 0.97 | 12.5 | 13.2 | 1.87 | 1.55 | 1.72 | 1.68 | 0.13 | 0.60 |
| 100 | 15 | 0850 | 125n | 0.68 | 0.98 | 0.97 | 12.5 | 11.8 | 1.41 | 1.21 | 1.35 | 0.94 | 0.12 | 0.60 |
| 101 | 15 | 0850 | 100n | 0.66 | 1.17 | 0.97 | 12.5 | 12.9 | 1.81 | 1.27 | 1.42 | 1.14 | 0.11 | 0.60 |
| 102 | 15 | 0850 | 75n | 1.10 | 0.91 | 0.97 | 12.5 | 18.1 | 1.95 | 1.54 | 1.59 | 0.94 | 0.09 | 0.60 |
| 103 | 15 | 0850 | 50n | 1.22 | 0.80 | 0.97 | 12.5 | 24.7 | 1.90 | 1.62 | 1.70 | 0.87 | 0.07 | 0.60 |
| 104 | 15 | 0850 | 100s | 0.98 | 1.79 | 0.97 | 12.5 | 21.6 | 2.32 | 1.98 | 2.17 | 1.64 | 0.10 | 0.60 |
| 105 | 15 | 0850 | 125s | 1.30 | 1.84 | 0.97 | 12.5 | 17.6 | 2.61 | 2.09 | 2.21 | 1.78 | 0.10 | 0.60 |
| 106 | 15 | 0850 | 150s | 1.26 | 2.00 | 0.97 | 12.5 | 15.1 | 2.54 | 2.28 | 2.46 | 1.72 | 0.11 | 0.60 |
| 107 | 15 | 0850 | 175s | 1.16 | 2.10 | 0.97 | 12.5 | 15.6 | 2.49 | 2.21 | 2.38 | 1.94 | 0.10 | 0.60 |
| 108 | 15 | 0850 | 200s | 0.88 | 1.65 | 0.97 | 12.5 | 13.2 | 2.37 | 1.75 | 2.03 | 1.71 | 0.09 | 0.60 |
| 109 | 15 | 0850 | 250s | 0.65 | 1.49 | 0.97 | 12.5 | 12.5 | 1.74 | 1.34 | 1.49 | 1.47 | 0.11 | 0.60 |
| 110 | 15 | 0850 | 300s | 1.02 | 1.41 | 0.97 | 12.5 | 11.3 | 2.61 | 1.70 | 1.94 | 1.54 | 0.10 | 0.60 |
| 111 | 15 | 1535 | 150n | 0.31 | 1.07 | 0.89 | 11.8 | 12.1 | 1.21 | 0.87 | 1.04 | 1.01 | 0.13 | 0.10 |
| 112 | 15 | 1535 | 100n | 0.50 | 0.75 | 0.89 | 11.8 | 12.2 | 1.10 | 0.90 | 1.04 | 0.82 | 0.11 | 0.10 |
| 113 | 16 | 0847 | 150n | 0.49 | 1.14 | 0.66 | 11.1 | 12.4 | 1.44 | 1.12 | 1.23 | 1.19 | 0.13 | 0.73 |
| 114 | 16 | 0847 | 100n | 0.62 | 0.90 | 0.66 | 11.1 | 11.9 | 1.52 | 1.12 | 1.29 | 0.91 | 0.11 | 0.73 |
| 115 | 17 | 0929 | 150n | 0.58 | 0.89 | 1.37 | 6.3 | 11.6 | 1.52 | 1.14 | 1.30 | 1.00 | 0.11 | 0.76 |
| 116 | 17 | 0929 | 100n | 0.82 | 0.70 | 1.37 | 6.3 | 14.1 | 1.57 | 1.22 | 1.39 | 0.76 | 0.12 | 0.76 |
| 117 | 17 | 0929 | 100s | 0.82 | 0.84 | 1.37 | 6.3 | 12.1 | 1.60 | 1.32 | 1.41 | 0.94 | 0.14 | 0.76 |
| 118 | 17 | 0929 | 150s | 0.76 | 1.14 | 1.37 | 6.3 | 12.9 | 1.77 | 1.47 | 1.72 | 1.23 | 0.13 | 0.76 |
| 119 | 19 | 1300 | 150n | 0.40 | 0.94 | 0.77 | 12.3 | 11.8 | 1.27 | 0.97 | 1.06 | 1.04 | 0.12 | 0.02 |
| 120 | 19 | 1300 | 100n | 0.63 | 0.68 | 0.77 | 12.3 | 11.4 | 1.18 | 1.04 | 1.12 | 0.74 | 0.11 | 0.02 |
| 121 | 19 | 1300 | 100s | 0.52 | 0.78 | 0.77 | 12.3 | 12.1 | 1.09 | 0.98 | 1.06 | 0.79 | 0.10 | 0.02 |
| 122 | 19 | 1300 | 150s | 0.29 | 1.21 | 0.77 | 12.3 | 12.3 | 1.71 | 1.38 | 1.56 | 1.23 | 0.12 | 0.52 |
| 123 | 20 | 1128 | 150n | 0.40 | 0.90 | 1.02 | 6.8 | 10.3 | 1.27 | 0.93 | 1.11 | 1.04 | 0.12 | 0.56 |
| 124 | 20 | 1128 | 100n | 0.58 | 0.82 | 1.02 | 6.8 | 12.3 | 1.30 | 1.06 | 1.25 | 0.93 | 0.11 | 0.56 |
| 125 | 20 | 1303 | 150n | 0.36 | 0.86 | 1.02 | 6.8 | 11.3 | 1.41 | 0.85 | 0.93 | 0.88 | 0.12 | 0.24 |
| 126 | 20 | 1303 | 100n | 0.56 | 0.81 | 1.02 | 6.8 | 12.6 | 1.46 | 1.01 | 1.19 | 0.91 | 0.11 | 0.24 |
| 127 | 21 | 1045 | 150n | 0.71 | 1.05 | 1.07 | 8.7 | 10.9 | 1.59 | 1.27 | 1.40 | 1.21 | 0.12 | 0.60 |
| 128 | 21 | 1045 | 100n | 0.67 | 1.07 | 1.07 | 8.7 | 13.8 | 1.45 | 1.28 | 1.32 | 1.07 | 0.11 | 0.60 |
| 129 | 21 | 1350 | 150n | 0.51 | 1.25 | 1.15 | 8.1 | 11.9 | 1.61 | 1.21 | 1.45 | 1.34 | 0.12 | 0.22 |
| 130 | 21 | 1350 | 100n | 0.58 | 1.00 | 1.45 | 8.1 | 13.5 | 1.55 | 1.17 | 1.31 | 1.10 | 0.11 | 0.22 |
| 131 | 22 | 1145 | 150n | 0.94 | 0.81 | 1.45 | 9.5 | 12.7 | 1.76 | 1.42 | 1.65 | 0.96 | 0.09 | 0.70 |
| 132 | 22 | 1145 | 100n | 0.93 | 0.88 | 1.45 | 9.5 | 15.8 | 1.77 | 1.47 | 1.58 | 0.93 | 0.09 | 0.70 |
| 133 | 22 | 1145 | 100s | 0.99 | 1.01 | 1.45 | 9.5 | 15.9 | 1.83 | 1.59 | 1.78 | 1.18 | 0.10 | 0.70 |
| 134 | 22 | 1145 | 150s | 1.10 | 1.70 | 1.45 | 9.5 | 13.7 | 2.44 | 2.06 | 2.17 | 1.74 | 0.12 | 0.70 |
| 135 | 22 | 1516 | 150n | 0.92 | 0.88 | 1.45 | 9.5 | 12.4 | 1.81 | 1.45 | 1.52 | 0.92 | 0.09 | 0.20 |
| 136 | 22 | 1516 | 100n | 0.96 | 0.69 | 1.45 | 9.5 | 14.1 | 1.73 | 1.36 | 1.49 | 0.79 | 0.09 | 0.20 |
| 137 | 22 | 1516 | 100s | 0.84 | 1.04 | 1.45 | 9.5 | 13.9 | 1.77 | 1.45 | 1.67 | 1.10 | 0.10 | 0.20 |
| 138 | 22 | 1516 | 150s | 0.68 | 1.41 | 1.45 | 9.5 | 12.2 | 1.79 | 1.46 | 1.71 | 1.49 | 0.12 | 0.20 |
| 139 | 24 | 0846 | 150n | 0.95 | 1.18 | 3.09 | 8.2 | 12.4 | 2.01 | 1.55 | 1.71 | 1.28 | 0.09 | 0.33 |
| 140 | 24 | 0846 | 100n | 0.72 | 1.62 | 3.09 | 8.2 | 14.2 | 2.16 | 1.62 | 1.82 | 1.94 | 0.12 | 0.33 |
| 141 | 24 | 0846 | 100s | 0.46 | 1.28 | 3.09 | 8.2 | 18.4 | 2.07 | 1.33 | 1.48 | 1.69 | 0.10 | 0.33 |
| 142 | 24 | 0846 | 150s | 0.58 | 1.48 | 3.09 | 8.2 | 13.8 | 1.96 | 1.33 | 1.55 | 1.53 | 0.10 | 0.33 |
| 143 | 24 | 1247 | 100s | 0.97 | 1.96 | 3.52 | 8.1 | 21.4 | 2.44 | 2.06 | 2.17 | 2.18 | 0.10 | 1.00 |
| 144 | 24 | 1247 | 150s | 1.18 | 1.59 | 3.52 | 8.1 | 16.3 | 2.89 | 2.03 | 2.24 | 1.74 | 0.10 | 1.01 |

| Data # | date | time | range | setup (m) | Rs (m) | Hmo (m) | T (sec) | Tz (sec) | etamax (m) | eta2% (m) | Rp2% (m) | S2% (m) | slope | SWL (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 145 | 24 | 1516 | 100s | 1.17 | 2.11 | 3.55 | 9.6 | 22.9 | 2.92 | 2.20 | 2.48 | 2.12 | 0.10 | 0.92 |
| 146 | 25 | 0850 | 150n | 1.47 | 2.02 | 3.35 | 13.8 | 21.6 | 3.54 | 2.62 | 2.92 | 2.28 | 0.09 | 0.35 |
| 147 | 25 | 0850 | 100n | 1.32 | 2.49 | 3.35 | 13.8 | 21.9 | 3.88 | 2.60 | 2.92 | 2.74 | 0.12 | 0.36 |
| 148 | 25 | 1220 | 100n | 1.42 | 2.56 | 4.05 | 13.3 | 18.3 | 3.40 | 2.82 | 2.95 | 3.10 | 0.12 | 0.71 |
| 149 | 25 | 1220 | 150n | 2.62 | 1.70 | 4.05 | 13.3 | 18.6 | 2.83 | 2.23 | 2.46 | 1.92 | 0.09 | -0.65 |

# APPENDIX C: ANALYSIS OF HOLMAN'S DATA

This Appendix is a quick-and-dirty dimensional analysis of Holman's data which:

1. shows there is little influence of slope on runup.

2. shows a crude estimate of dimensionless depth across the bar explains the data as well as $\xi$ does.

3. presents an empirically modified Hunt's Equation model.

All of the following is based on Holman's $\eta_{2\%}$ statistic which is referenced to the SWL. Wave information appears to be from the Baylor gage at the end of the pier in 8m depth.

Figure C1 shows the dependence of runup on beachface slope is very weak. This implies that the wave steepness term is responsible for the ability of Hunt's Equation to explain runup. Figure C2 shows the influence of Hunt's wave steepness term on runup.

Depth across the bar was estimated by considering the bar to be 1.1m below the SWL for all cases and then adding the $\eta$ for that observation. The 1.1m is probably an underestimate of the depth of the bar but the addition of "setup" measured on the beachface is an overestimate. Figure C3 shows the dependence of runup on depth across the bar. The relationship looks as strong as that found by Holman for $\xi$ (Holman's Figure 6b).

Figure C4 combines the two dimensionless terms. The equation

$$\frac{\eta_{2\%}}{H_{mo}} = 2.5 \tanh \left\{ 0.3 \left[ \frac{(d/H_{mo})}{\sqrt{H_{mo}/L}} \right] \right\}$$

is fit to this data. Thus, a resulting model of runup is

$$\frac{\eta_{2\%}}{H_{mo}} \propto \frac{\tanh \, (d/3H_{mo})}{\sqrt{H_{mo}/L_o}}$$

This is plotted on Figure C5 and the following equation can be used to fit Holman's data,

$$\frac{\eta_{2\%}}{H_{mo}} = 0.4 + 0.11\xi_m \qquad \text{(Eq. 4)}$$

where a modified surf parameter is,

$$\xi_m = \frac{\tanh\ (d/3H_{mo})}{\sqrt{H_{mo}/L_o}}$$

The ability of the above equation to describe Holman's data is shown in Figure C6. Figure C7 shows how well Holman's model fits his own data. The present model fits better but has three fudge factors (empirical) instead of two, so it should.

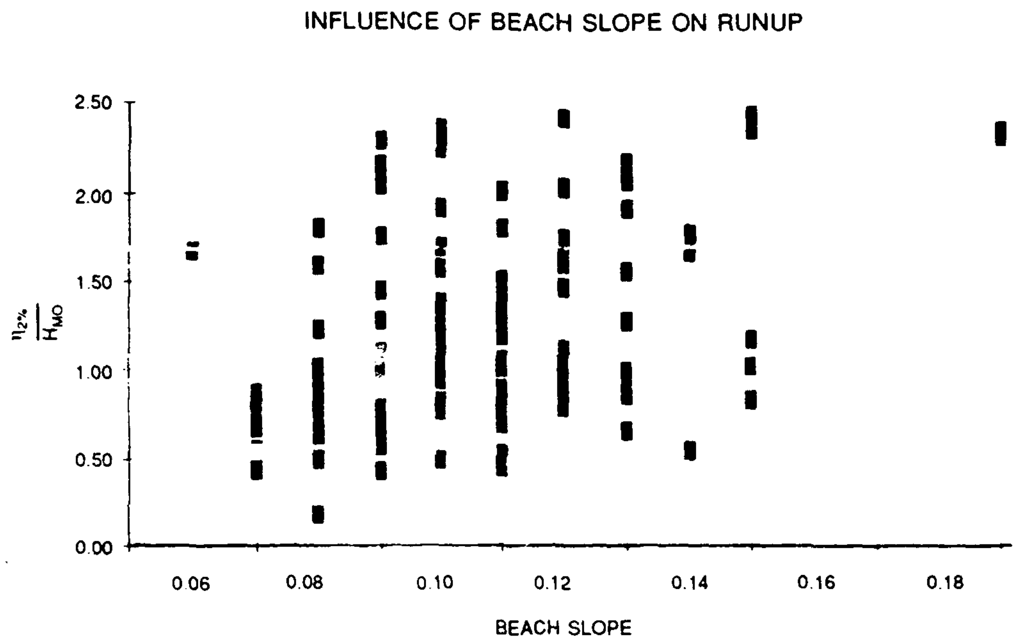



Figure C1.

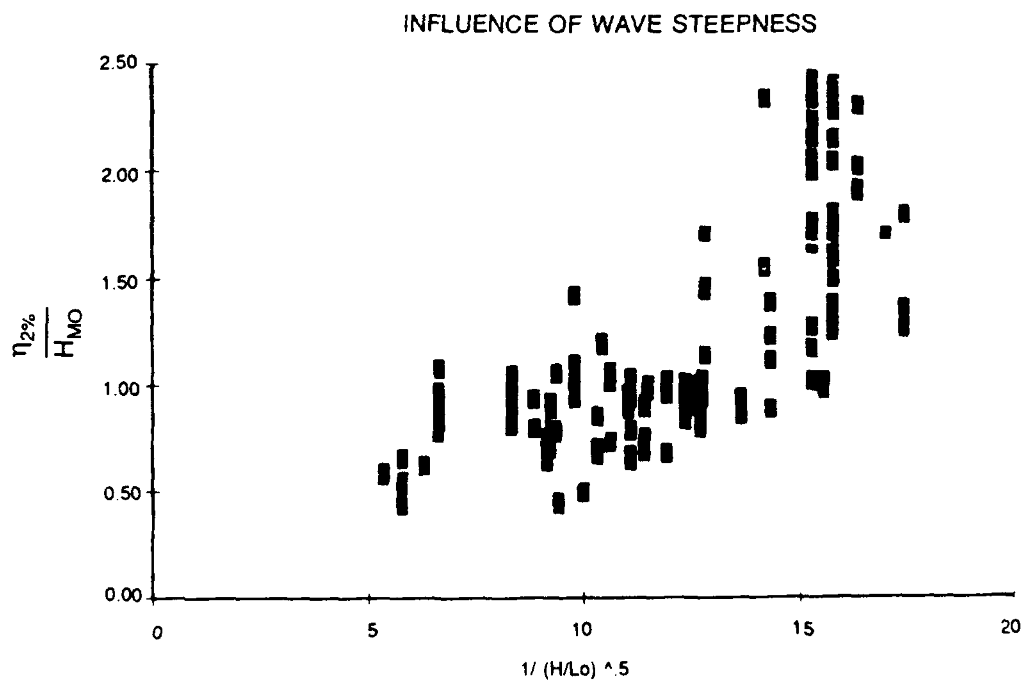



Figure C2.

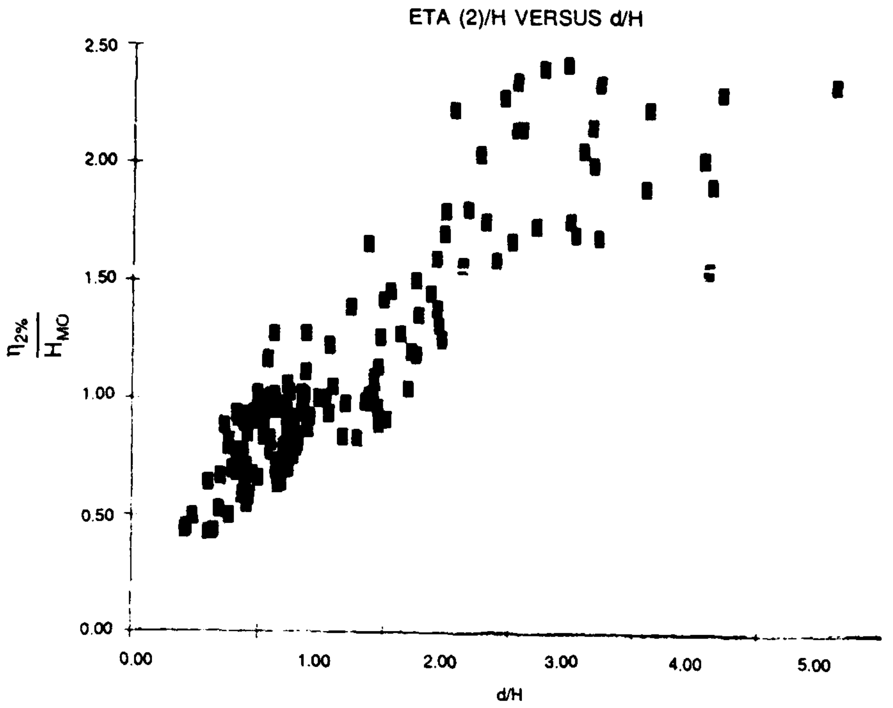



Figure C3.

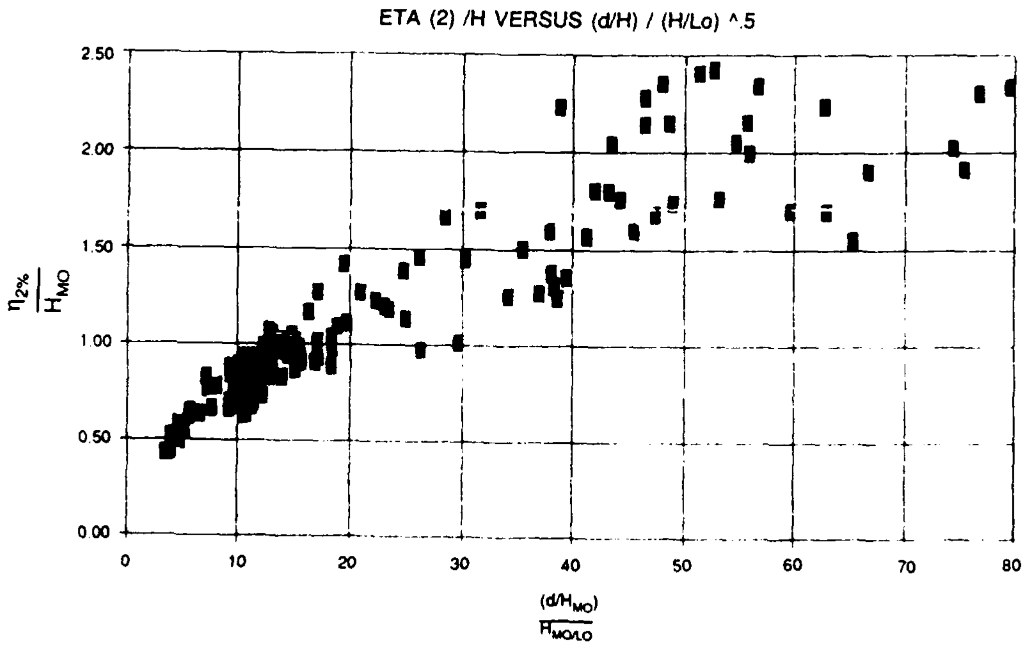



Figure C4.

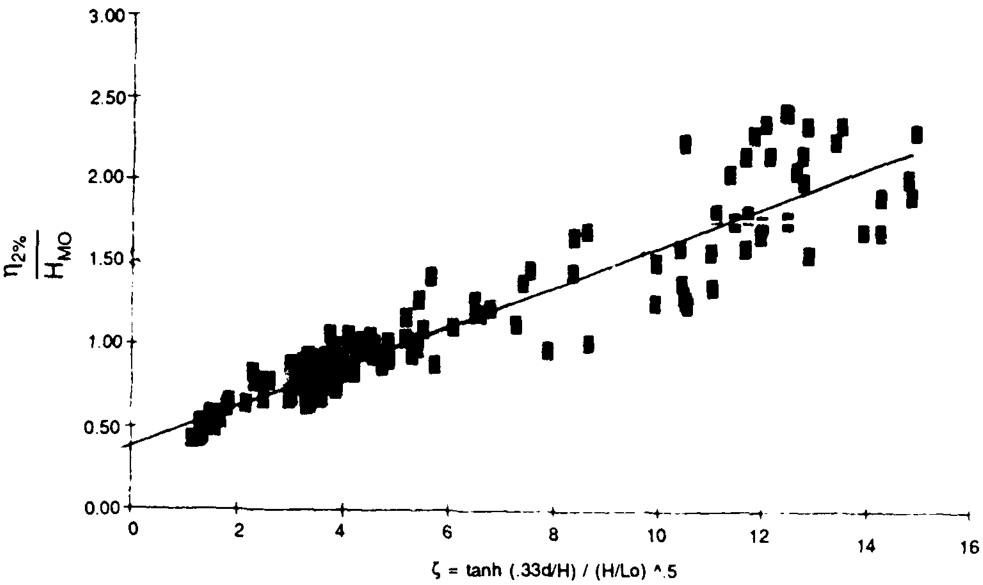



Figure C5.

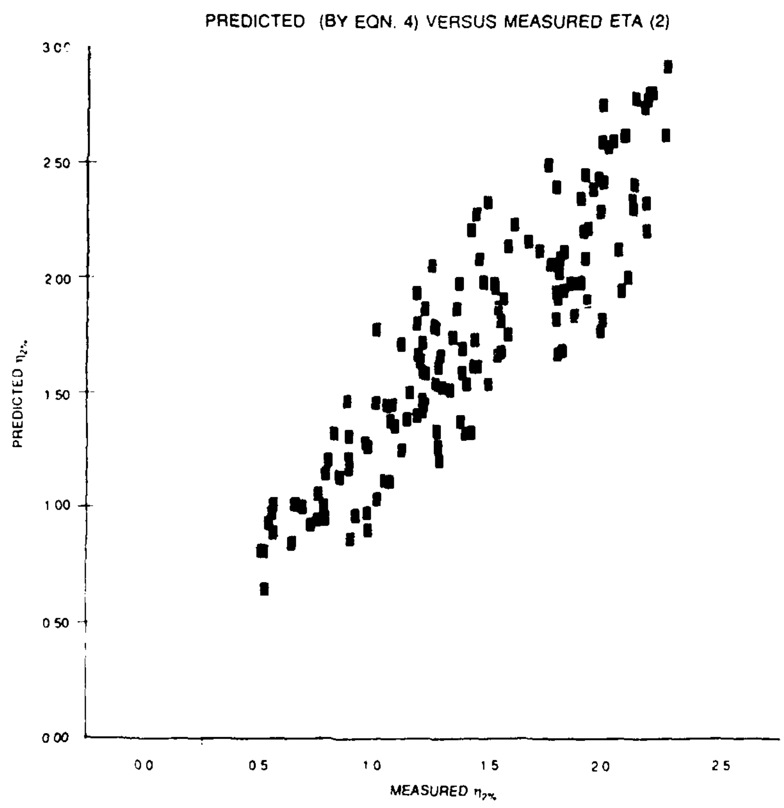
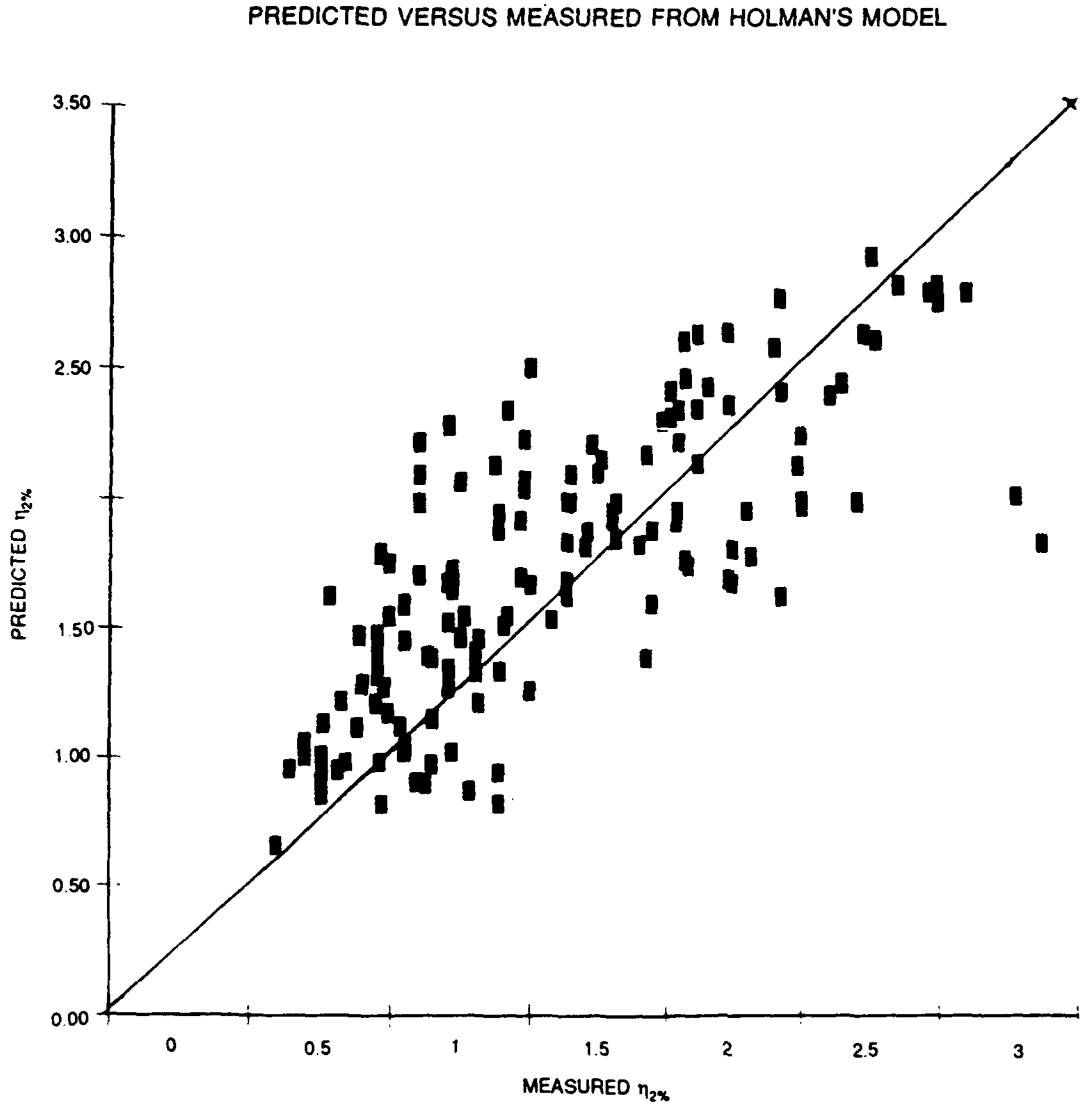



Figure C6.



PREDICTED VERSUS MEASURED FROM HOLMAN'S MODEL
3.50
3.00
2.50
1.50
1.00
0.50
0.00
PREDICTED $\eta_{2\%}$
0
0.5
1
1.5
2
2.5
3
MEASURED $\eta_{2\%}$


Figure C7.