INVESTIGATION AND IMPROVEMENT OF CAPABILITIES FOR THE FEMA WAVE RUNUP MODEL

(TECHNICAL DOCUMENTATION FOR RUNUP PROGRAM VERSION 2.0)

Report Prepared for
National Flood Insurance Program
Federal Emergency Management Agency
Washington, D.C. 20472

Dewberry & Davis
8401 Arlington Boulevard
Fairfax, Virginia 22031

April 1991

INVESTIGATION AND IMPROVEMENT OF CAPABILITIES FOR THE FEMA WAVE RUNUP MODEL

(TECHNICAL DOCUMENTATION FOR RUNUP PROGRAM VERSION 2.0)

Report Prepared for
National Flood Insurance Program
Federal Emergency Management Agency
Washington, DC 20472

By
Dewberry & Davis
Fairfax, Virginia 22031

April 1991

INVESTIGATION AND IMPROVEMENT OF CAPABILITIES
FOR THE FEMA WAVE RUNUP MODEL

EXECUTIVE SUMMARY

This investigation addresses the treatment of wave runup elevations within a computer program provided by Stone & Webster Engineering Corporation in 1981. Examination of the program documentation and review of the technical literature make apparent several shortcomings in that Wave Runup Model. Of primary importance, that 1981 Model does not consistently follow long-established empirical guidance on wave runup developed by the U.S. Army Corps of Engineers, particularly in publications by Saville and by Stoa. For this reason, the 1981 Model has now been upgraded in several appropriate ways.

The series of improvements has resulted in a modified Model with distinctly enhanced capabilities. These modifications increase the convenience and consistency of wave runup determinations, by including detailed consideration of shore geometry, and interpolation between runup guidance for situations bracketing the actual configuration. In addition, specific guidance on a meaningful runup statistic for coastal flooding now replaces the vaguely defined value termed "maximum wave runup" in the 1981 recommendations for treatment of storm conditions. The automated procedure yielding a runup elevation remains fundamentally simple and empirically based, as indicated by the following Figure 0 outlining operations within the modified Model.

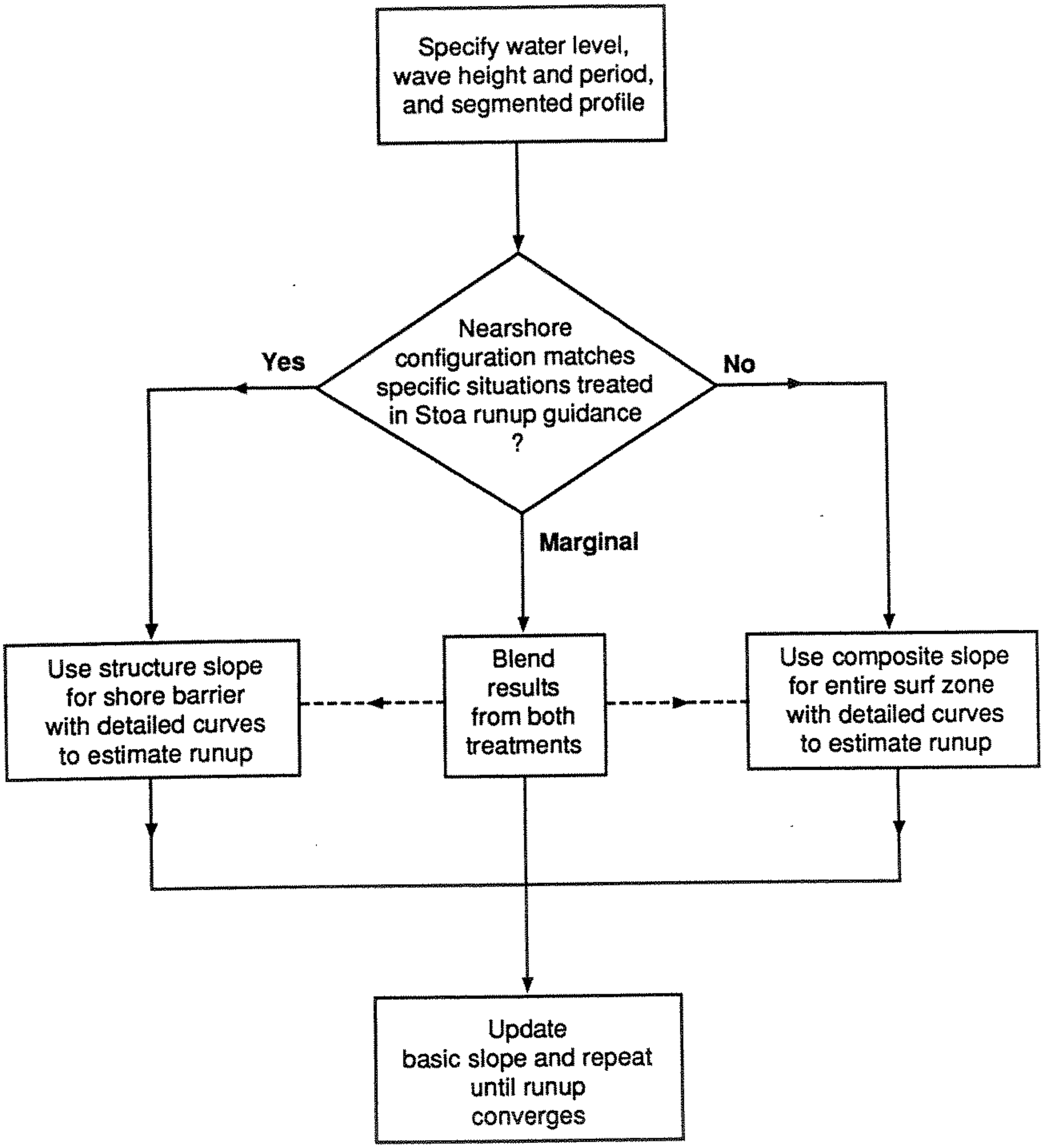


Figure 0. Overview of basic computation procedure implemented in modified FEMA Wave Runup Model.

Computations by the modified Model are verified to be accurate by comparison with over 650 measured runup elevations, the majority at least 3 feet above the static water level. Those measurements are primarily from large wave tanks, but some small tests of particular interest and a few sets of field data are considered. Definite agreement is demonstrated between measurements and computations for wide ranges of shore configurations and wave dimensions, with either uniform or irregular waves on various smooth or rough slopes.

These results in effect establish the functional utility of various Model elements: the objective analysis of basic geometry; the usage of roughness and scale effect coefficients as multipliers for estimated runup elevation; the implementation of a composite-slope treatment where specified geometry does not match that for available runup guidance; and the various interpolation procedures employed in runup determination. Of greatest importance for a coastal Flood Insurance Study, mean runup elevation is confirmed to be predictable from mean values of offshore wave height and wave period in storm wave action with various shore geometries, and that wave description can be conveniently estimated for the 100-year event at a given open-coast site.

CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

NOTE

Grateful acknowledgement is due to the following individuals for assistance in obtaining wave runup data utilized in the present investigation:

J. P. Ahrens, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

J. H. Balsillie, Division of Beaches and Shores, State of Florida Department of Natural Resources, Tallahassee, Florida

H.-H. Dette, Technical University of Braunschweig, Germany

S. Kielsgard, Dewberry & Davis, Fairfax, Virginia

M. Klein Breteler, Delft Hydraulics, Emmeloord, The Netherlands

C. B. Leidersdorf, Coastal Frontiers Corporation, Altadena, California

K. W. Pilarczyk, Road and Hydraulic Engineering Division, Rijkswaterstaat, Delft, The Netherlands

U. C. Sparboom, Grosser Wellenkanal, Hannover, Germany

O. Toyoshima, Tokai University, Orido, Japan

K. Uliczka, University of Hannover, Germany

SYMBOLS AND DEFINITIONS

d	water depth
d_a	depth at start of approach to shore barrier
d_b	depth at wave break point
d_s	depth at start of shore barrier
E_{top}	maximum elevation of shore barrier
g	acceleration due to gravity
H	wave height
H_b	wave height at break point
H_o	wave height referring to deep water
$\bar{H}$	mean wave height
H_s	significant wave height
I_2, I_3, I_4	interpolation weights in runup determination
i, j	numerical indices
k	horizontal extent of approach portion of profile
L	wavelength
L_a	wavelength at d_a
L_o	wavelength referring to deep water
m_a	cotangent of approach portion of profile
m_b	cotangent at d_b
m_c	cotangent of composite slope from d_b to R
m_s	cotangent of shore barrier
R	runup elevation above stillwater level
R_{max}	maximum runup elevation
R_s	significant runup elevation

SYMBOLS AND DEFINITIONS (continued)

$R_{.02}$	runup elevation having 2% exceedence
$\overline{R}$	mean runup elevation
R_b	runup estimate based on breaker-zone geometry
R_{sa}	runup estimate for shore barrier with sloped approach
R_{sf}	runup estimate for shore barrier with flat approach
RE	Reynolds number
RE*	approximate form for Reynolds number
r	roughness coefficient for runup reduction
S	surf similarity parameter
T	wave period
T_p	period of peak energy in wave spectrum
T_s	significant wave period
$\overline{T}$	mean wave period
X_a	horizontal station corresponding to d_a
X_b	horizontal station corresponding to d_b
v	kinematic fluid viscosity

INVESTIGATION AND IMPROVEMENT OF CAPABILITIES FOR THE FEMA WAVE RUNUP MODEL

INTRODUCTION

The focus of a Flood Insurance Study (FIS) is expected effects in the base flood having a one-percent chance of being equalled or exceeded in any year. In more common terms, the base flood is equivalent to the 100-year event, expected to recur once each 100 years on the average. Open-coast communities are subject to particularly extreme hazards due to storm surges and wave action from large water bodies; areas of special flood hazards in the 100-year event are designated as V zones or Coastal High Hazard Areas, having potential for inundation by water flows with significant velocity. Within the V zone, flood conditions permit a wave height of at least 3 feet. Proper delineation of the V zone requires consideration of likely effects associated with the base flood, including potential coastal erosion (FEMA, 1989), nearshore wave dimensions (FEMA, 1988), and wave runup at the ultimate shore barrier. Runup is a wave motion that can result in landward extension to the V zone defined by attenuating wave heights, wherever runup elevation is at least 3 feet.

Wave runup is measured as the vertical elevation reached by water waves incident on a barrier intersecting the stillwater flood level (SWFL). Taking into account this wave effect was determined to be necessary in view of flood damages recorded above SWFL in areas along the northern U.S. Atlantic coast, with relatively steep shores subject to "northeaster" storm conditions with large wavelengths or wave periods. In 1979, the Federal Emergency Management Agency (FEMA) contracted with Stone & Webster Engineering Corporation for the development of a consistent method to determine water elevations associated with wave breaking and runup. The result was a computer program providing runup elevation in specified flood situations, along with a manual documenting the program and the recommended wave runup analysis (Stone & Webster, 1981).

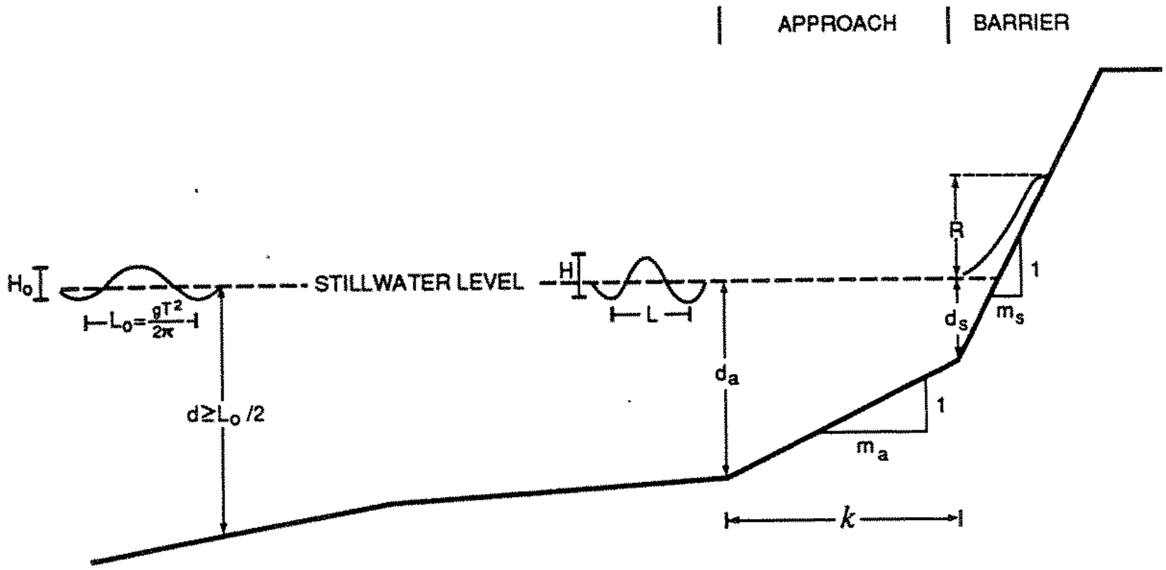
Wave runup analyses are increasingly common in coastal FISs because man-made shore structures are more prevalent, and steep profile segments can also result from expected dune erosion during the 100-year event. A wider range of applications and the long-term accumulation of experience led to an evaluation of the continued adequacy and advisable upgrades for the 1981 Wave Runup Model. This report describes investigations and documents a modified computer program providing improved capability and more convenient usage.

Four major sections follow in this report. First is a review of select technical literature, serving to introduce fundamental considerations and results. Second is a description of the 1981 Wave Runup Model and instructions for its FIS application, leading into an outline of notable weaknesses apparent in that runup treatment. Third is an account of improvements to the computer program or Model for runup elevations, along with the technical basis for these changes. Fourth is an evaluation of the accuracy of computed runup elevations, making up the majority of the report and mainly using newly available measurements from large wave tanks. This report closes with a summary of major conclusions from the present investigations, together with application guidance for a coastal FIS.

LITERATURE REVIEW

Wave runup is a topic of considerable importance in coastal engineering, since expected runup elevations for the design conditions determine an advisable vertical extent of a coastal structure meant to protect against wave action or flooding. Several hundred publications have addressed the processes and prediction of wave runup, implying that comprehensive literature survey would be an impractical task. Le Mehaute et al. (1968) concluded that theory will never provide accurate estimates for runup due to breaking waves, so any runup treatment must generally be based on measurements. This literature review focuses on empirical evidence, but aims only to summarize fundamental considerations and results. Figure 1 outlines the usual situation and variables in test programs investigating wave runup on engineered structures.

Two distinct contributions to wave runup elevation are a mean component, wave setup, and a fluctuating component, wave swash. Here setup measures the added water accruing to a steady state above the stillwater shoreline because of wave action, while swash indicates a representative extent of water oscillations at the limit to remnant waves. This distinction is necessary for theoretical treatment of wave runup, but engineering guidance generally includes setup and swash components in an inseparable way. That is due to the empirical basis being laboratory elevations relative to initial static water level in usually steady situations where both components automatically arise.



H_o = WAVE HEIGHT IN DEEP WATER

$L_o = gT^2/2\pi$ = WAVELENGTH IN DEEP WATER

g = ACCELERATION DUE TO GRAVITY

T = WAVE PERIOD

H, L = WAVE HEIGHT, WAVELENGTH IN ARBITRARY WATER DEPTH

d_a = WATER DEPTH AT SEAWARD END OF APPROACH SLOPE

m_a = COTANGENT OF APPROACH SLOPE

k = HORIZONTAL EXTENT OF APPROACH SLOPE

d_s = WATER DEPTH AT TOE OF SHORE STRUCTURE/BARRIER

m_s = COTANGENT OF STRUCTURE SLOPE

R = RUNUP ELEVATION ABOVE STILLWATER LEVEL

Figure 1. Definition sketch for notable variables in wave runup.

Simple formulas giving runup elevations for smooth slopes have been developed by several authors, for example, Wassing (1957), Hunt (1959), Chue (1980), Losada and Gimenez-Curto (1981), and Ahrens and Titus (1985). Such relationships demonstrate basic dependences of runup on incident wave conditions in a specified range of situations, and may provide an adequate elevation estimate for some purposes. An equation of well-established utility is that provided by Hunt (1959) for the normalized runup from breaking waves, R/H_o, in terms of shore slope and incident wave steepness:

$$R/H_o = 1.0\ m_s^{-1}\ (H_o/L_o)^{-0.5} = 1.0\ S_o \tag{1}$$

Here the combination of variables, $S_o = m_s^{-1}\ (H_o/L_o)^{-0.5}$, is called the surf similarity parameter since it categorizes many breaker phenomena (Battjes, 1974), although the deep-water value of wave height is not usually employed. Equation 1 has been adapted in the Netherlands to assess the adequacy of a sand-dune barrier eroded by extreme storm waves (Technical Advisory Committee, 1985).

Figure 2 displays several published equations summarizing measured wave runup on typical shore barriers in terms of the surf similarity parameter. This indicates the broad range and diverse variations of normalized runup possible with smooth or rough barriers. Wave runup clearly can reach higher elevations in irregular (natural) wave action than in repetitive or uniform waves.

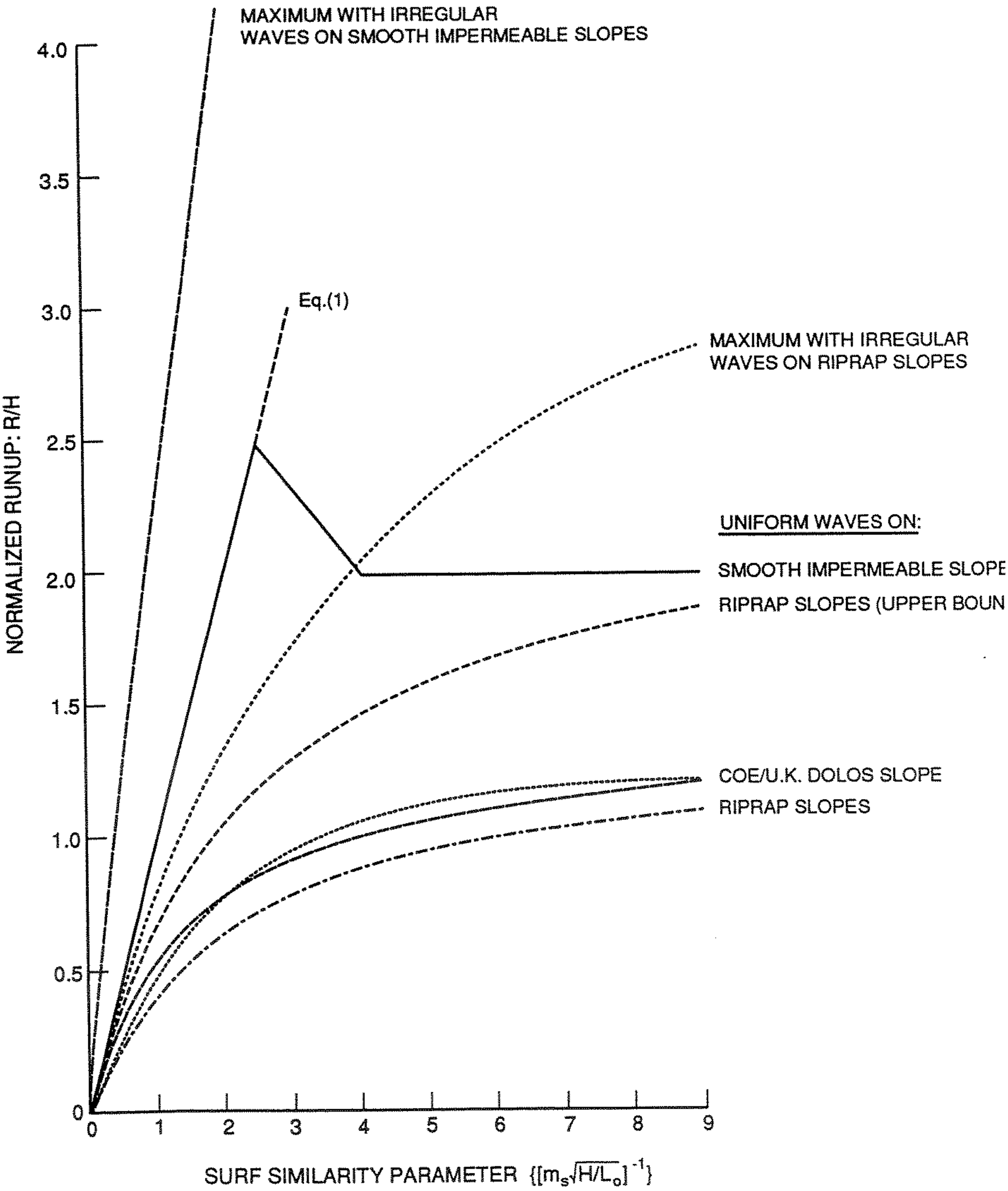


Figure 2. Some expressions for expected wave runup in various situations. Sources are Ahrens and McCartney(1975), Losada and Gimenez-Curto(1981), Ahrens and Heimbaugh(1988), and Mase(1989).

Battjes (1971) derived probability distributions for the range of runup elevations implied by Equation 1 in wave conditions of given statistical characteristics. With storm waves driven by wind, possible situations extend from a young sea, where wave heights and wavelengths are not correlated, to a fully developed sea, where that correlation is perfect. Examining an extreme runup with probability identical to the "controlling wave height" treated in an FIS (FEMA, 1988), this runup dimension is found to be a factor of 2.0 to 2.6 times the mean runup for wind-driven waves breaking on a barrier, according to the analysis by Battjes (1971). That mean runup due to irregular wave action is comparable to the runup elevation arising in uniform waves.

Simple empirical expressions ignore dependences of wave runup on geometrical details, such as water depth at the toe of the wave barrier. Also, actual measurements demonstrate marked complexities in runup variations even for the simplest situation of a single slope joining a horizontal bottom. Figure 3 presents a representative data summary (Stoa, 1978) as curves of normalized runup (R/H_o) versus the structure cotangent (m_s) for various values of incident wave steepness referred to deep water ($H_o/gT^2 = H_o/2\pi L_o$). Such empirical curves for a specific situation constitute the most detailed published runup guidance, although in structure design, they might be used only to outline required hydraulic model tests of promising configurations. Note that Equation 1 shows fair congruence with the right-hand limbs but not the remainder of detailed curves in Figure 3; for this situation, Equation 1 is approximately accurate only for S_o less than about 2 to 3.

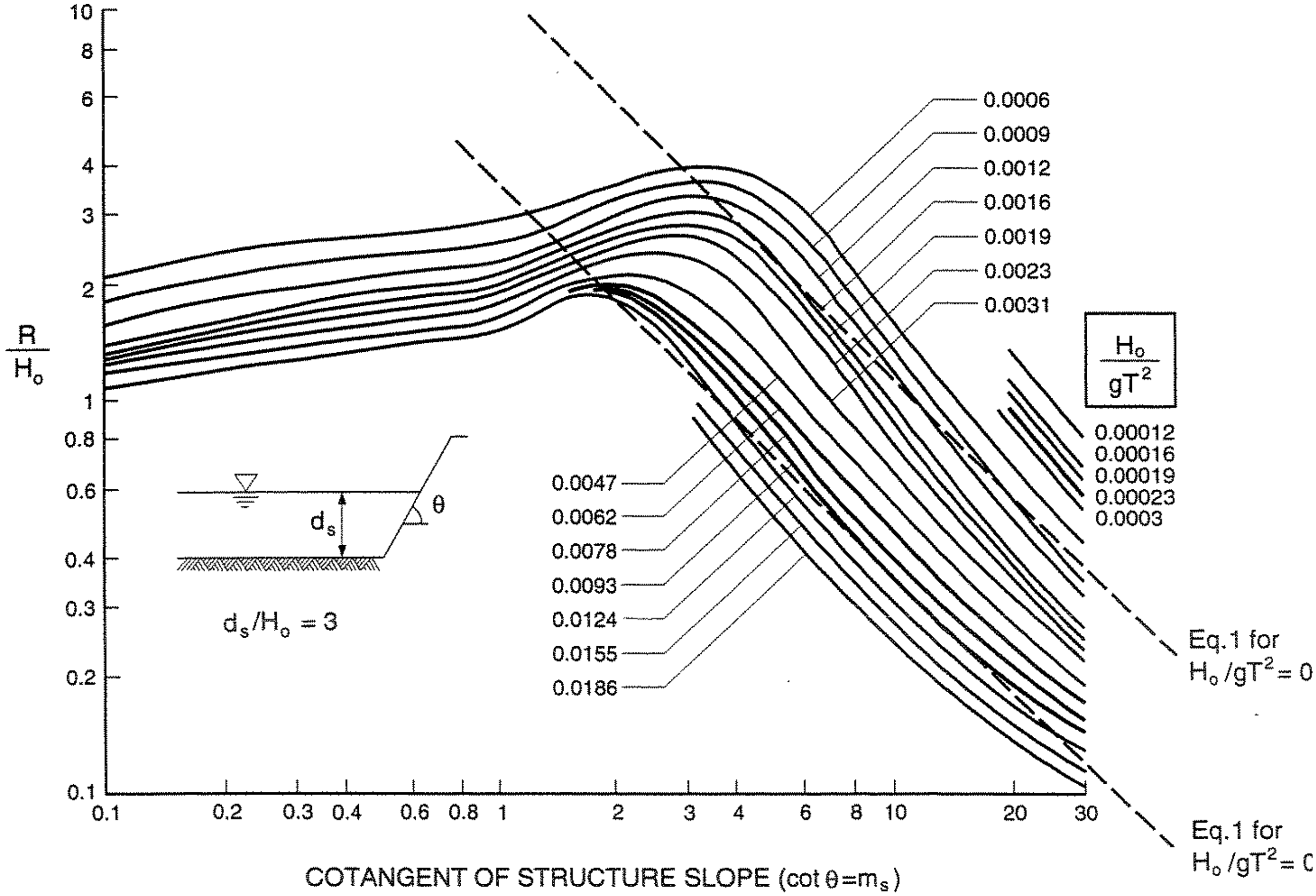


Figure 3. Representative set of empirical curves for wave runup (Stoa, 1978).

The maximum in R/H_o is associated with the gentlest shore slope resulting in wave reflection rather than breaking (Nagai and Takada, 1972). Conversely, a distinct maximum in R/H_o versus barrier slope does not occur for situations where wave breaking is initiated on the relatively gentle approach to a barrier. Savage (1958) summarized other tendencies of such empirical curves for structures extending into relatively deep water: normalized runup is maximum for about 1 on 2 slope with steep waves, but for about 1 on 5 slope with low waves. Savage also noted runup to be greatly affected by water depth at the structure toe; where that decreases below ($3 H_o$), runup elevation can be roughly doubled. In contrast, the Technical Advisory Committee (1974) emphasized that local wavelengths defined by approach water depths have no direct influence on runup and overtopping for waves breaking on a barrier.

Runup curves utilized here are those from a reanalysis (Stoa, 1978) of test data on mean elevations by the U.S. Army Corps of Engineers (USACE). Stoa's conclusions for uniform waves on simple structure geometries officially supersede design guidance presented in USACE manuals essentially unchanged since the 1960s (USACE, 1966, 1977, 1984). Note that the Stoa guidance was not incorporated in the 1984 edition of the USACE Shore Protection Manual.

Saville (1958) proposed a method for using laboratory results from relatively simple situations in the determination of wave runup with more complicated shore profiles. Termed the "composite-slope method," this considers a uniform hypothetical slope from breaker depth to runup limit. An iterative procedure arrives at a consistent estimate of runup elevation for specified geometry, based on empirical guidance for some idealized structure geometry. The fundamental presumption is that wave runup elevation may be defined using approximate surf-zone geometry, ignoring the detailed slope configuration. Overall breaking and runup processes are assumed similar on the hypothetical uniform and the actual composite slopes, without explicit analysis of the approximation involved.

Saville's method was developed primarily for application to levee profiles with a sizable horizontal shelf or berm near design water level. The empirical basis presented by Saville (1958) consists of many small tests covering wide ranges of slopes and wave conditions, but all configurations had either a berm or a slope break at stillwater level. The composite-slope method has since been widely recognized as useful despite certain limitations (Horikawa, 1978; USACE, 1984). It seems meant for application to situations with relatively low wave runup, since direct guidance is available for the more abrupt engineered barriers causing extreme runup elevations.

Some limitations were documented in early evaluations of the composite-slope method. Herbich et al. (1963) measured runup in a small wave tank with horizontal berms at or slightly above stillwater level, between higher and lower slopes of 1 on 4; wave heights were near 0.2 foot and wave periods about 1.3 seconds. The composite-slope method was determined to be appropriate for short berms, but actual runup was found to be less than predicted elevations when berm length exceeded (0.15 L), L being wavelength in the deepest portion of the tank. Wave processes with wider berms evidently become too complicated to relate to simple situations through overall surf-zone geometry.

Hosoi and Mitsui (1963) provided further conclusions regarding the composite-slope method, from tests in a fairly large tank with waves up to 2 feet high. These investigations addressed runup on a dike having front slope of 1 on 1.5, with various placements from the inner surf zone to above stillwater elevation in models of three separate sites. Geometries approaching the structure ranged from a simple 1 on 5 slope to a profile with 1 on 20, 1 on 6, and 1 on 70 segments. Hosoi and Mitsui (1963) concluded that the composite slope was applicable in explaining measured runup elevations for the two models with a relatively steep approach to the dike, where overall slopes were from 1 on 1.5 to 1 on 10; the method appeared inappropriate with a gentle approach where overall slope reached 1 on 45.

Taylor et al. (1980) described a runup computation procedure with some similarity to the composite-slope method. This procedure was developed for investigations of hurricane surge and wave runup on natural shore profiles in Volusia County, Florida. A parabolic approximation of the actual profile up to the dune peak provides an explicit expression for mean slope between the wave break point and the limit to wave uprush. Using Equation 1 and linear wave theory, the runup is determined iteratively from an arbitrary initial estimate. Example calculations show that a maximum occurs in runup elevation as wave height increases, due to reduced average slope as higher waves break further offshore. Taylor et al. (1980) provided no verification for their procedure, and noted that "the computed runup is quite sensitive to the manner in which the profile geometry is described." Approximating the shore profile by multiple linear segments, as in the FIS runup program (Stone & Webster, 1981), seems a more flexible and accurate procedure.

Based on small tests with steep armored slopes, Kobayashi and Jacobs (1985) proposed a modification of Saville's method to bring measured runups for profiles with berms into line with data for uniform slopes. The procedure adjusts actual wave height to an equivalent wave height controlling runup, by explicit consideration of the approximation to surf-zone cross section using the composite-slope method. Considering water volume inside the breaker point to cushion the ultimate result in wave breaking and runup, the adjustment gives actual and approximate situations the same average rate of wave energy supplied per unit surf-zone volume. However, the proposed adjustment has not yet been confirmed by extensive evaluation.

Runup guidance given by Stoa (1978) includes recommendations for extremely simplified treatment of scale and roughness effects. Scale effect between small tests and prototype situations is described for smooth barriers by a correction value depending only on structure slope; that multiplier increases normalized runups at small scale by a maximum of 14% for $m_s = 1.4$, and (for example) by 5% for $m_s = 0.2$ or 8, in order to obtain prototype elevations. Scale effects vanish for a vertical wall, or for gentle slopes with m_s greater than 15. For rough slopes, recommended corrections increase small-scale normalized runups by 6% at most, with variations identified for structure type but not slope. Those assessments were based on a limited number of large-tank tests, and recent results may support other conclusions. For example, Führböter (1986) reported negligible scale effect in runup on a smooth slope with $m_s = 4$, whereas Stoa's guidance would indicate a necessary correction of 10.4% to small-scale results. However, the actual data of Führböter (1986) reveal appreciable runup differences between similar situations tested at large and 1/10 sizes (Delft Hydraulics Laboratory, 1986).

In regard to slope roughness, guidance by Stoa (1978) takes into account that a much wider range of smooth than rough structure configurations has been tested. A multiplier less than unity is employed to reduce runup elevation determined for a certain hydraulically smooth geometry to an appropriate value for a geometrically similar configuration offering more flow resistance due to slope composition including roughness and permeability. However, the relation between runup on smooth and rough slopes has long been known to depend on wave steepness as well as slope material; Figure 4 from Saville (1959) demonstrates that basic curves have different shapes for smooth and rough slopes of the same inclination, so runup elevations cannot generally be related by a constant multiplier. The weakness involved in such roughness coefficients has been emphasized by Losada and Gimenez-Curto (1981), and by Allsop et al. (1985), among others. Of particular note, results in Merrifield and Zwamborn (1966) show that variations in runup reduction can depend on the exact type of roughness elements or slope armor units. Some guidance clearly specifies that runup estimates based on smooth-slope results and a roughness coefficient are only for applications involving relatively gentle slopes, where Equation 1 holds (Permanent International Association of Navigation Congresses, 1976); runup elevation on either smooth or rough slopes depends linearly on surf similarity parameter at low values.

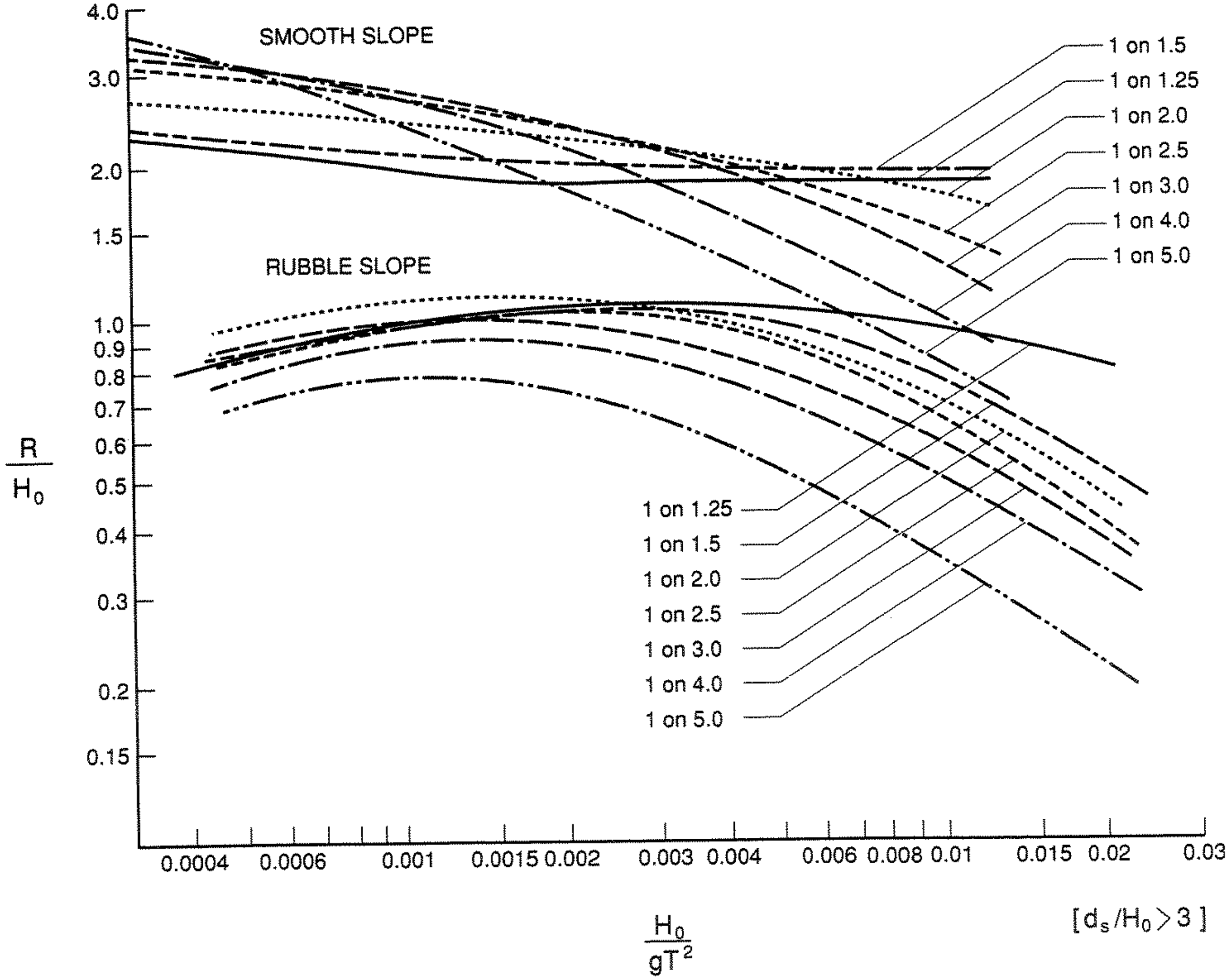


Figure 4. Runup curves in another format, showing different shapes for smooth and rough slopes (Saville, 1959).

Major advances relating to wave runup prediction after the Stoa (1978) guidance include the application of detailed models for breaker decay and transformation, and collection of field data sets establishing the importance of surf beat on natural sand beaches. There also have been many investigations with controlled irregular waves primarily in small situations, and several additional studies in large wave tanks. The focus in detailed considerations here will be on the latter type of evidence, to determine if older runup guidance provides an adequate explanation of newly available data for large situations. Such runup elevations typically at 3 to 10 feet above static water level provide crucial tests for predictive models.

However, a fundamental concern is the reproduction of typical runup processes in large tank tests. Prototype situations of primary interest have turbulent aerated flows, so that wave dimensions and surface roughness can affect the accuracy of reproduction. Scale and roughness effects are fundamentally interconnected through the flow character; for example, Führböter (1986) has pointed out that stronger or more complex scale effects are to be expected for rough surfaces due to greater aeration. Ideal formal guidance might be in the form of a design diagram identifying various flow regimes, such as that reported by Kamphuis (1975) for friction on impermeable beds under sinusoidal flows in a water tunnel. Any such guidance relating to wave runup would be very complex, with considerations including bed slope and composition, flow irregularity, and free-surface effects such as breaker type. A comprehensive direct investigation seems unlikely given the expense of large tank tests. In lieu of such generic tests, evidence might be pieced together by review of measured runup elevations for a wide range of test situations.

Available results from large tests do cover many barrier configurations, and the complexity of runup processes implies that simplified viewpoints generally remain useful in summarizing such evidence. Wave runup can be notably more complicated with irregular rather than uniform (repetitive) waves; in simple terms, more variable runup elevations arise with irregular waves than with uniform waves of generally comparable size, due to variant successions of wave characteristics. Early runup tests and empirical guidance addressed only uniform waves, but small tests have been conducted with irregular waves for about 25 years and similar large test results are now becoming available.

The simplest potential connection between uniform and irregular wave effects is based on an assumption of equivalence or linear superposition, where each element in the wave distribution is taken to correspond to a uniform wave train of similar height and period; expected results can be determined by appropriately weighted summation of the component effects. Such an assumption or procedure appears fundamentally questionable for wave runup, which arises from nonlinear wave transformations and can have a different frequency spectrum than the incident waves (Sutherland et al., 1976); runup of a particular wave depends on preceding effects, and not every incident wave results in a runup event. Authoritative guidance is not yet available on the distribution of runup elevations with specified irregular waves and nearshore profile. However, data from fairly large tests with a variety of irregular wavetrains and plane slopes showed that mean runup elevation correlates to mean wave height (Kaldenhoff and Gökcesu, 1978). A relation between those mean descriptions of cause and effect was also demonstrated with small wind waves (Webber and Bullock, 1968).

Aside from possible scale effect, there are significant differences between wave runup in controlled laboratory conditions and in field situations. Natural waves have a three-dimensional character and generally are obliquely incident on the beach or shore structure, so that runup processes can be more complicated than in laboratory channels. Also, incident waves could be affected by nearshore currents and other flows. In addition, strong winds during extreme storms can influence wave runup elevation (Sibul and Tichner, 1955), although wind effects are most clearly documented in spray overtopping for a barrier having top elevation just below maximum wave runup. These complications contribute to the scatter evident in field runup elevations.

The effect of oblique wave incidence on runup seems complex but might be described as of relatively minor magnitude. A fundamental consideration seems to be that oblique wave action reduces the effective slope of a shore barrier. That is contradicted by small laboratory tests with a smooth slope (Tautenhain et al., 1982) showing increased runup elevations for oblique waves in the regime where Equation 1 is appropriate. However, changes in runup elevations appear less than ±10% for wave directions within 45° of normal incidence.

Recent field investigations, such as Guza and Thornton (1982) and Holman (1986), have emphasized the importance of runup saturation with breaker zones of gentle slope, as runup energy density evidently reaches a limit at the incident wave frequencies and does not increase with wave height or energy there. Wave breaking and runup/rundown processes become physically separate with a wide surf zone and spilling breakers, so that individual runups cannot usually be attributed to particular incoming waves, which lose their identity before reaching the shore. Swash excursions and runup at the shore can generally be large but occur at frequencies markedly lower than incident waves, a type of motion termed surf beat since it is driven by the grouping of incident waves (Sonu et al., 1974; Kobayashi et al., 1988; Inman and Jenkins, 1989). That motion is largely determined by foreshore conditions including local slope, and arises with incident waves as low as 2 feet in height, for values of surf similarity parameter below about 1.5 to 2. Such low-frequency water motion is not predictable at present for specified incident waves and shore geometry (Kobayashi et al., 1989), but appears significant mainly for sand beaches of gentle slope. Surf beat and low-frequency swash processes seem unlikely to be important for most coastal conditions of interest during extreme storm surges, where greatly increased water level usually results in steep waves plunging against barriers.

For field data on sand beaches, Resio (1988) concluded that wave heights measured near the surf zone yield the most consistent runup correlations. Resio also recommended using local wavelength at the water depth of wave height determination, rather than deep-water wavelength. Requiring nearshore wave descriptions would introduce a significant complication into runup prediction: no simple relationship exists between offshore and nearshore wave characteristics (Mansard et al., 1988). Use of wave height and steepness referred to deep water seems an attractive feature of USACE runup guidance, since that wave description can be unequivocal.

Recent publications indicate that direct numerical solutions of equations describing the flows can provide an alternative to empirical methods for prediction of wave runup in specified conditions. Simplified treatment of shallow water equations with dissipation can provide simulations of the moving waterline for an arbitrary coastal profile (Kobayashi et al., 1987, 1989). Note that laboratory investigations with regular waves have documented basic empirical dependences of runup and rundown flows resulting from breaking (Roos and Battjes, 1976) and from reflection (Brandtzaeg et al., 1968). The approximate theoretical approach permits computation of wave transformation, reflection, runup, and rundown, but further development and verification seem required for convenient numerical models. Initial results show runup as strongly dependent on incident wave profile (Thompson, 1988), which is not easily predictable for extreme storm conditions.

In summary, fundamental uncertainties about runup prediction remain regarding scale effect, roughness effect, and application of laboratory results from idealized tests to complicated field configurations. Furthermore, the empirical basis for USACE guidance is repetitive runup effects with uniform waves, unlike the varying conditions arising in coastal storms. However, average field runups can exhibit scatter on the order of several feet in nominally unchanged conditions, so that confirmed runup dependences covering a wide range of situations appear more important than precise predictions for any particular circumstances. The empirical adequacy of a runup prediction procedure must of course be established using the many available measurements.

1981 WAVE RUNUP MODEL

Basic Content and Application Instructions

Figure 5 outlines the operation of the computer program by Stone & Webster (1981), incorporating a discretized form of runup curves from Stoa (1978). That guidance summarizes mean runup elevations measured over wide ranges of conditions with uniform laboratory waves, as curves of (R/H_o) versus m_s for various values of (H_o/L_o). A separate family of such curves pertains to each distinct geometrical situation investigated in USACE laboratory tests.

Figure 6 describes the gist of runup determination in the Stone & Webster Model. Program input includes SWFL and a segmented linear approximation to the nearshore profile. From those, the program assigns m_s as the slope of the first segment extending above SWFL (i.e., not inundated), and m_a as the slope of the profile segment immediately seaward. The elevation of SWFL above that slope break is taken as the water depth d_s, and for a first runup estimate d_s/H_o and m_a determine the family of curves to be utilized (Figure 6). R/H_o is estimated using m_s, H_o/L_o, and interpolation between the given curves of one family. If that runup elevation lies on the first profile segment extending above SWFL, the computation is complete, but otherwise an iteration procedure is used to get a self-consistent runup estimate.

If the initial estimate indicates runup overtops the first nonflooded profile segment, the program switches to an iterative treatment of the entire surf

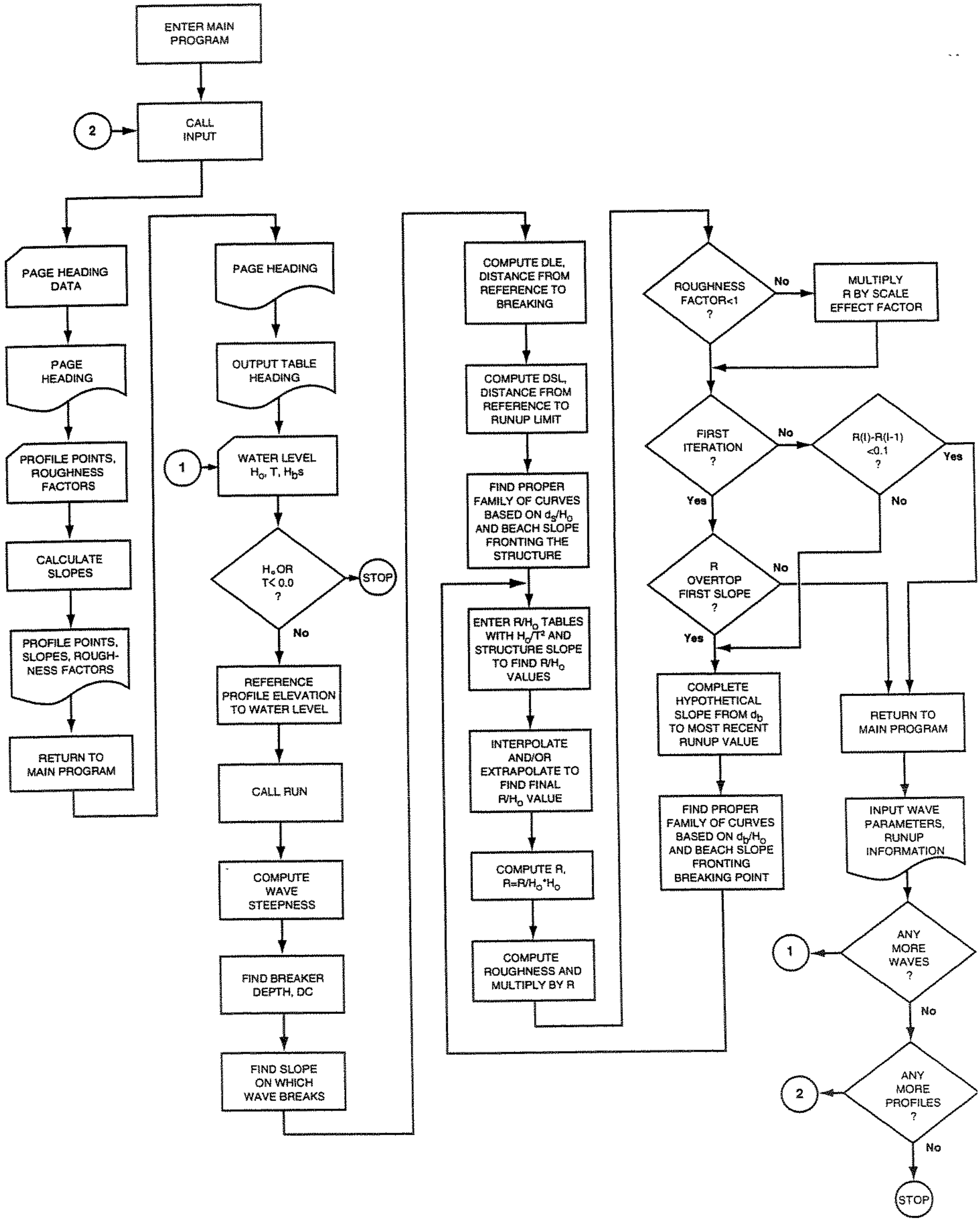
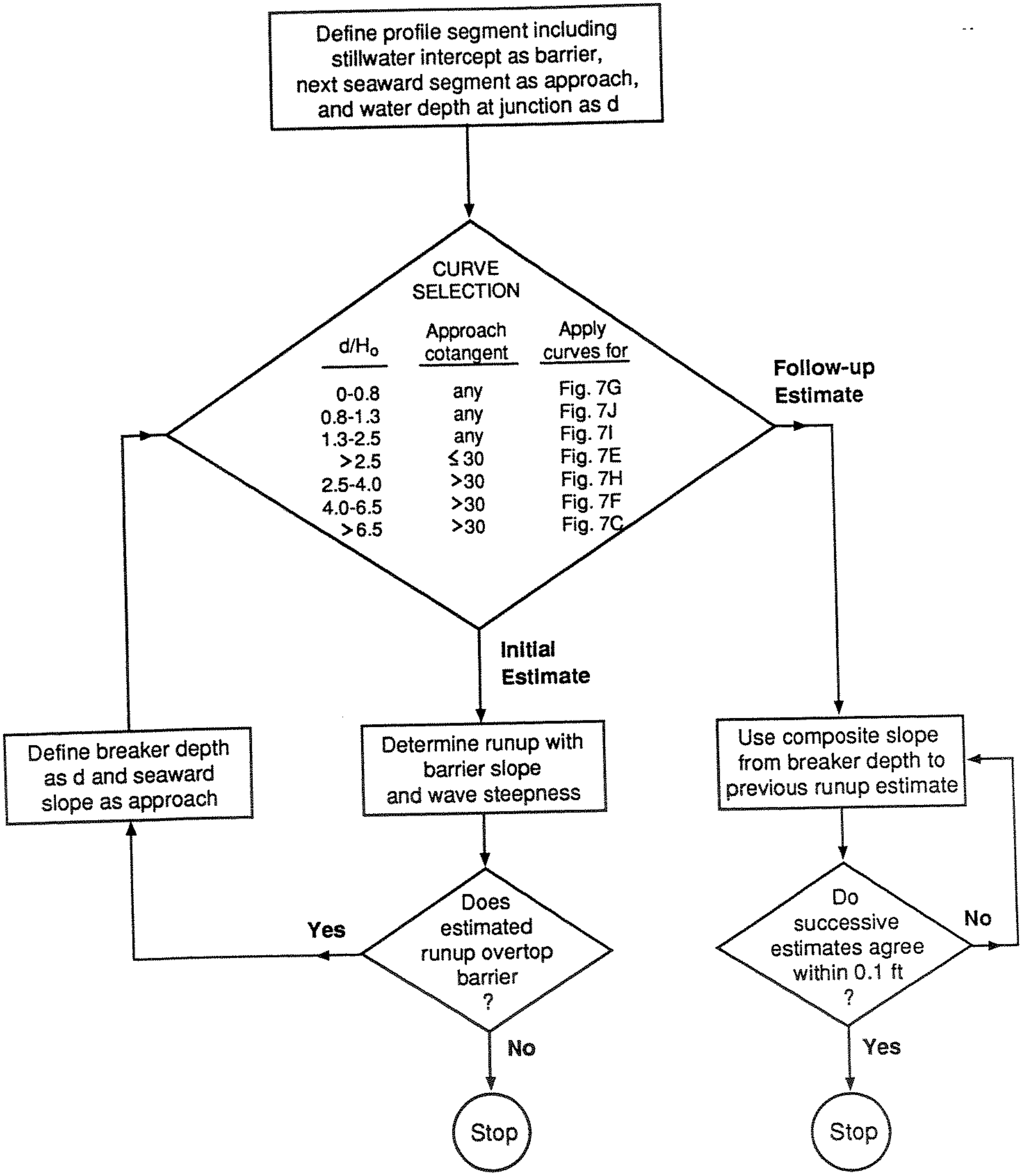


Figure 5. Block Diagram of Wave Runup Program (Stone & Webster, 1981)



d/H_o	Approach cotangent	Apply curves for
0-0.8	any	Fig. 7G
0.8-1.3	any	Fig. 7J
1.3-2.5	any	Fig. 7I
>2.5	≤ 30	Fig. 7E
2.5-4.0	>30	Fig. 7H
4.0-6.5	>30	Fig. 7F
>6.5	>30	Fig. 7C

Figure 6. Detailed description of runup determination in 1981 Model.

zone, using the Saville (1957) composite-slope method. Then the parameters considered are d_b, water depth at initial wave breaking, and m_b, slope exactly at (and used in determining) that break point, with d_b/H_o and m_b used to select the appropriate family of runup curves in place of d_s/H_o and m_a. Successive estimates of $(R/H_o)_i$ are based on $(m_c)_{i-1}$, the overall slope from d_b to the preceding estimate of runup elevation. This procedure continues with updated values of composite slope m_c until successive runup estimates agree to within 0.1 foot, when the last estimate is accepted.

Figure 7 shows the 10 separate geometries treated in runup guidance of Stoa (1978). Very wide ranges of structure slopes are covered, with the exception that for a sloped approach, empirical data do not extend to situations where the shore structure has a gentler slope than the 1 on 10 approach. The basic runup curves pertain to effects on smooth slopes at small scale. The program incorporates recommendations by Stoa, described previously, for simplified treatment of scale and roughness effects by means of multiplicative factors. A roughness coefficient for each profile segment is required program input, and automatically applied to runup elevation for segments above SWFL. The scale effect correction by Stoa (1978) is applied as documented, for smooth slopes; if roughness coefficient is lower than 0.99, that multiplier is applied directly with no correction to smooth-slope results for scale effect.

Other program inputs (Stone & Webster, 1981) are wave conditions to be considered, including the significant wave period typical of extreme storms at the study site, and a selection of deepwater wave heights, H_{oj}, from about 3 feet up to the significant height of the storm waves. For each wave

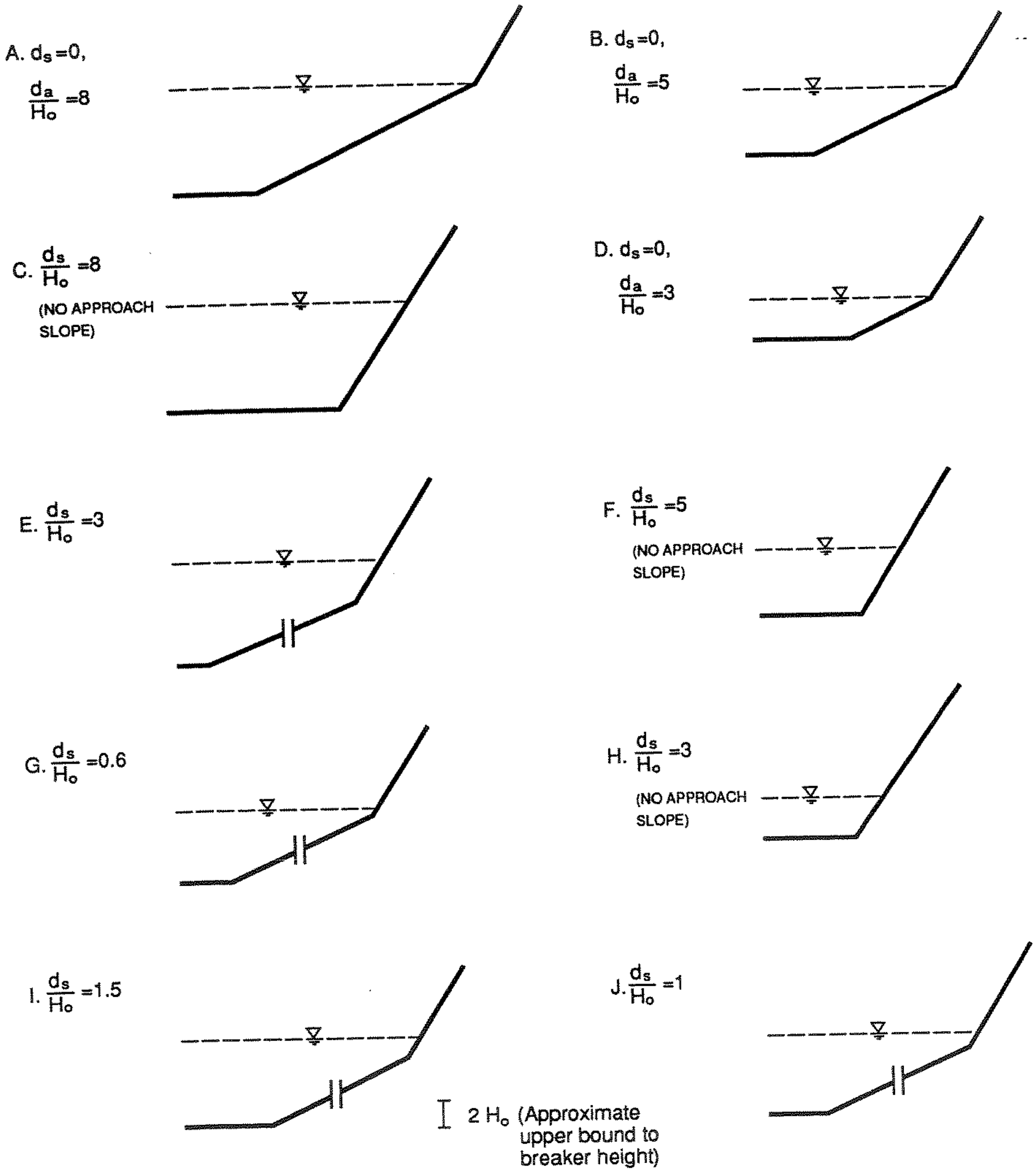


Figure 7. Ten configurations covered in guidance by Stoa(1978), arranged in approximate order of increasing runup elevations. For four cases with approach segment fronting steep shore structure, that slope is specified as 1 on 10 with horizontal extent of at least one-half the incident wavelength.

condition, a breaking wave height is also required for each slope segment below SWFL; that value is to be found manually using H_{oj}, T, and m_{bj}, following guidance in the USACE Shore Protection Manual (but the program automatically calculates breaker depth, d_{bj}).

From the input described, the program determines a runup elevation, R_j, for each condition in the specified spectrum of wave heights. Then the user is directed to select the highest value as "maximum wave runup," R_{max}, an elevation relative to SWFL for the situation. Computed runup will be too small if a beach berm is present on the profile, and the required correction must be manually applied following guidance in the USACE Shore Protection Manual.

Instructions for application include the judgment that a computed runup value of less than 2 feet is incapable of causing significant damage, if offshore slopes are mild. Larger values of R_{max} are used in defining an appropriate wave elevation associated with the base flood.

Apparent Weaknesses in Runup Treatment

The 1981 Wave Runup Model does not faithfully follow basic guidance provided by Stoa (1978); for instance, only seven of Stoa's ten curve families were incorporated within the Model code. The omitted results for $d_s = 0$ pertain to a notable class of coastal profiles having a slope break at SWFL (as with storm-induced dune erosion), but the Model might treat such situations using appreciably higher runup curves for $d_s/H_o = 0.6$. Another evident weakness is that the Model does not examine whether actual approach slope for low d_s/H_o conforms to the configuration specified by Stoa.

The 1981 Model includes very simplified treatment of specified profile geometry, with focus on the two slopes at and approaching SWFL. Neighboring profile segments of somewhat different slope cannot be considered to be part of the actual structure or its approach for the initial runup estimate. This makes special care advisable in preparing the input approximation of actual profile geometry, so that the computed runups are most meaningful.

Because the 1981 Model primarily analyzes the profile geometry using a simple assignment of d_s, an inappropriate family of runup curves can be utilized. As an example for one idealized situation, a structure rising from an approximately horizontal bottom for $d_s/H_o = 2.5$ will be treated using runup curves developed for a barrier sited in shallower water and a sloping approach with $m_a = 10$ (see Figures 6 and 7).

Another undesirable aspect of the 1981 Model is the use of discrete categories for d_s/H_o, so that profile configurations are considered exactly identical over some finite range of variation. This can lead to peculiar behavior of computed results, with appreciable jumps possible in runup elevation for small changes in conditions, through switches from one curve family to another. There is no provision for interpolation between runup elevations from curve families for idealized situations bracketing the actual case.

Implementation of the composite-slope method in the 1981 Model appears illogical. When the initial runup estimate corresponds to overtopping of the first nonflooded profile segment, extending to elevation E_{top}, consideration of d_b and m_c usually provides a much lower second runup estimate. The ultimate result will be incongruous if runup is determined not to reach E_{top}, since that elevation should be considered a lower bound on expected runup if assumptions for the first estimate were appropriate. Thus, the method of solving this computational problem involves an inconsistent treatment of wave runup. The composite-slope method appears suitable for assessing runup with nearshore profiles not matching simplified configurations covered by basic guidance, but the 1981 Model uses that calculation method if and only if the first shore segment is overtopped.

A final notable weakness is the treatment in the 1981 Model of the spectrum of storm wave conditions, where the maximum is selected from computed values of runup elevation for a range of fairly common wave heights. This may provide a reasonably large runup elevation likely to occur during the storm, but with an undefined frequency. Quantitative analysis of runup probabilities for the specified situation would be required to describe accurately the value termed "maximum wave runup" in documentation for the 1981 Model. That calculated value often does not approach the highest runup elevations actually occurring in irregular wave action.

MODIFICATIONS TO 1981 MODEL

The primary aim of these modifications to the existing wave runup Model (Stone & Webster, 1981) is to make its internal operation fully congruent with USACE runup guidance, as provided in Stoa (1978) and in the Shore Protection Manual (1984). This entails direct application of the Stoa runup curves for Figure 7 situations wherever basically appropriate, and reliance on the composite-slope method in other cases; those alternative treatments of wave runup may be identified as being based on d_s or d_b, the water depth used to initiate runup determination. The rationale for this procedure is that the laboratory data defining the Stoa runup curves generally cover structure situations of most engineering concern: cases with rather abrupt shore barriers and relatively large runup elevations. Aside from those directly investigated situations, the approximation involved in the composite-slope method appears necessary and appropriate for determining runup elevations likely to be relatively low according to available evidence.

This basic strategy for automatic runup estimation is made fully practicable by incorporating transitions between d_s and d_b results, to provide smooth variation in runup elevations with any slight change in wave conditions or nearshore profile. Each transition procedure makes use of a particular interpolation parameter I varying between 0 and 1, blending runups computed using d_s and d_b over some finite range of marginal situations.

The following material documents modifications to the 1981 Model under three separate categories: fundamental elements, detailed program analyses, and implementation of the composite-slope method. The present changes primarily affect the internal runup computations within the subroutine RUN and new subsidiary subroutines, with input and output of the computer program only changed to be somewhat more convenient. Appendix B provides operational flowcharts and source code for the upgraded FEMA Wave Runup Model. That listing includes all code of the original program (Stone & Webster, 1981); instructions no longer executed are now designated as comments.

Fundamental Elements

Three major additions have been made to the runup Model, namely: one set of Stoa curves omitted from the 1981 program; a tabulation defining local wavelength for specified water depth and wave period (fixing wavelength in deep water); and empirical results permitting the breaker point to be determined automatically for the input wave condition and profile. Adding these basic elements to the code corrects original weaknesses while improving the convenience and utility of the runup model.

The 1981 Model did not include runup guidance developed by Stoa for three configurations with $d_s = 0$ and a sloped approach extending to $d_a/H_o = 3$, 5, or 8. That class of situations apparently can be addressed adequately using curves for $d_a/H_o = 3$, since longer approaches (with horizontal extent much more than 30 times H_o) are expected to occur rarely and would yield slightly lower runups for storm waves. R/H_o curves from Stoa (1978) corresponding to Figure 7D have been added to the program in the same format as other guidance.

Length of an approach slope relative to local wavelength is required to judge the conformance of actual situations with those covered by Stoa's guidance. L_a, the wavelength at water depth d_a, is defined by linear wave theory through the relationship between d_a/L_a and d_a/L_o. Quantitative results in Table C-1 of the USACE <u>Shore Protection Manual</u> have been attached to the program, so that L_a may be determined for specified water depth and wave period.

The 1981 Model required manual determination of breaking wave heights in the preparation of input conditions. That procedure followed guidance from the <u>Shore Protection Manual</u>: empirical curves were used to define input H_b values but the code included explicit equations from another source for d_b. However, integrated guidance by Goda (1970) can provide the breaker index d_b/H_o directly from local slope and H_o/L_o (i.e., other input), as shown in Figure 8 from Horikawa (1978). This guidance has been incorporated within the program so that d_b is determined automatically from input profile and wave conditions. The new subroutine DBPLOT provides Figure 8 results as linear relationships between [log (log d_b/H_o)] and (log H_o/L_o), for H_o/L_o between 0.002 and 0.07 where the breaker index has approximately monotonic behavior. These imposed limits on wave steepness also roughly correspond to the common coverage in runup curves of Stoa (1978), and include pertinent storm waves.

Besides convenience, this modification offers increased consistency in breaker treatment, because the separate empirical results previously used show some disagreement. Those results can be compared utilizing the separate Goda results on H_b/H_o, which have relatively gentle variations; that yields d_b/H_b

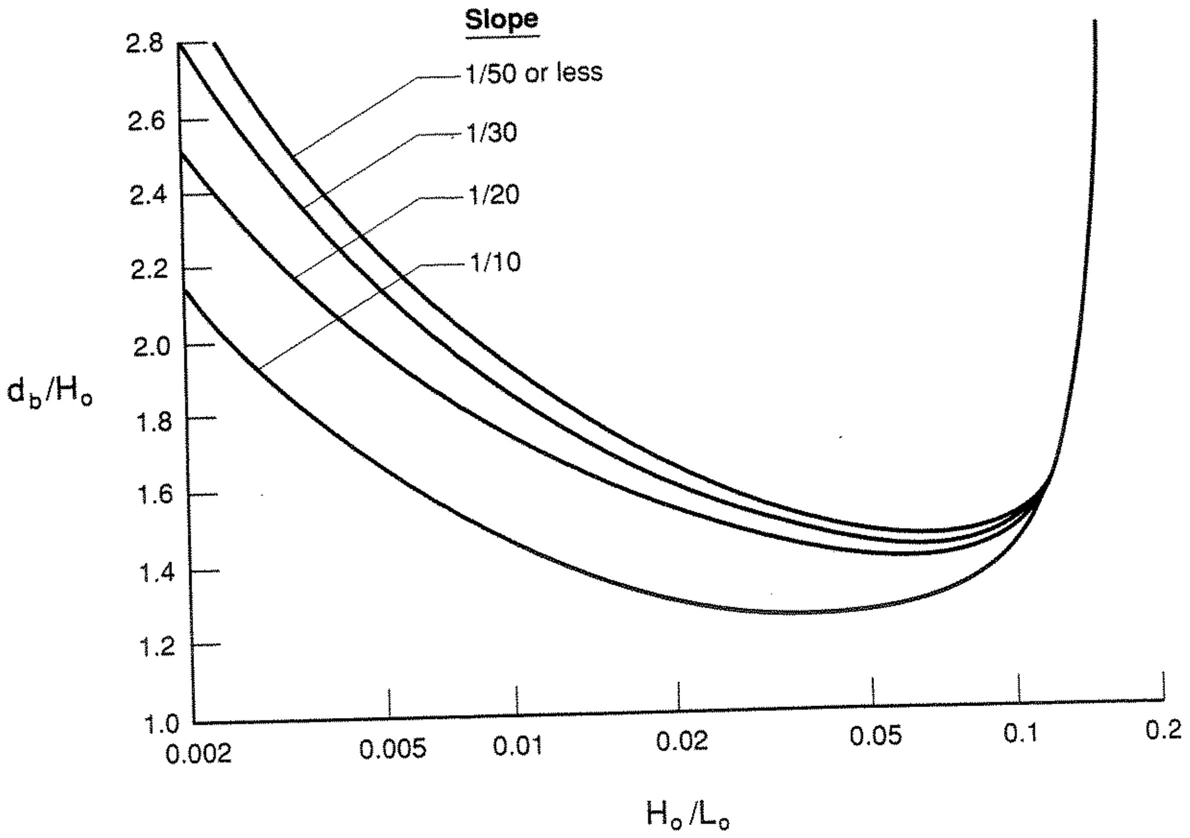
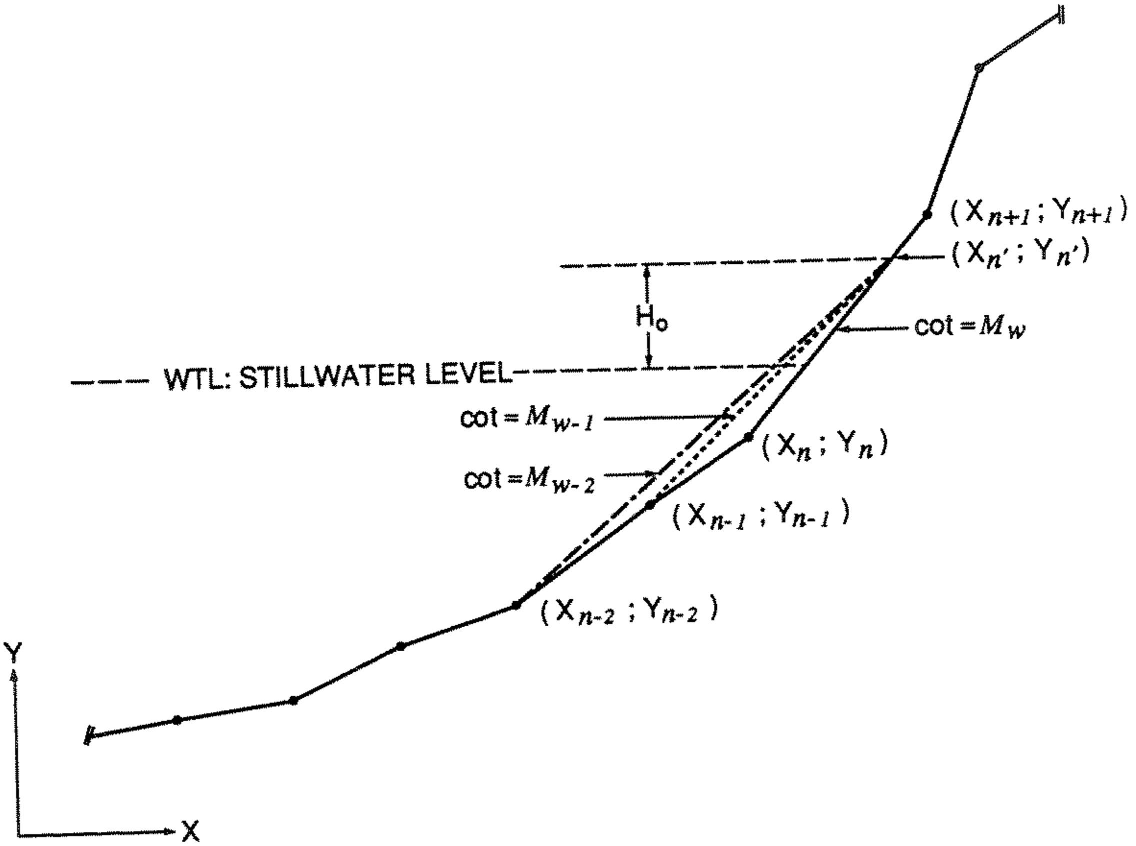


Figure 8. Results by Goda (1970) on water depth for initial wave breaking [from Horikawa, 1978].

versus H_b/L_o, which is the form of the other guidance. Disagreement between the two sets of conclusions diminishes appreciably as slope steepens from 1 on 50 to 1 on 10, so that additional results for slope of 1 on 5 or steeper could be used with some confidence to extend Goda's conclusions to slopes steeper than those treated in Figure 8. According to such a construction, the d_b/H_o index for a 1 on 10 slope in Figure 8 would be less than 10% above values appropriate to steeper slopes. Thus, the well-established Goda curve labeled "1/10" has been employed for slopes of 1 on 10 or steeper, giving complete coverage on d_b for all slopes. Some incident waves may reflect rather than break for slopes steeper than 1 on 10, but meaningless d_b values could only affect computations based on composite slope and giving low runup elevations. A cautionary notice is now provided in program output for this case, based on guidance for wave reflection versus breaking cited by Stoa (1978).

Detailed Program Analyses

The primary profile characteristic for runup estimation following Stoa (1978) is d_s, water depth at the toe of the relatively steep shore structure. That value expressed as d_s/H_o is the parameter used to select the appropriate family of empirical runup curves. The modified program examines the specified profile to determine the appropriate d_s, by means of the geometrical analysis outlined in Figure 9. This analysis effectively separates the steep shore barrier from the profile seaward, with the determination subject to the constraint that d_s cannot be less than zero, since a fully emerged structure is outside the range of Stoa's guidance.



Analysis for Seaward Extent of Shore "Structure"

1 - M_w = Cotangent of emergent profile segment (i.e., including stillwater intercept). If segment extends to elevation exceeding (WTL+H_o), determine coordinates at that elevation, $X_{n'}$; $Y_{n'}$, and use irplace of X_{n+1} ; Y_{n+1} in the following.

2 - Add first fully submerged profile segment to emergent one, and determine overall slope of combination, namely $M_{w-1} = (X_{n+1} - X_{n-1}) / (Y_{n+1} - Y_{n-1})$. If $M_{w-1} \leq 1.2\, M_w$, consider "Structure" to include present segment, and proceed to next step; otherwise, "Structure" extends seaward only to X_n ; Y_n .

3 - Add next seaward profile segment and determine new overall slope M_{w-2} . If $M_{w-2} \leq 1.2\, M_w$, admit this segment to "Structure" and repeat tentative extension; otherwise, do not.

Analysis for Seaward Extent of "Approach"

1 - M_{s-1} = contangent of profile segment immediately seaward of "Structure" limit. Add next seaward profile segment and determine overall slope M_{s-2} . If $M_{s-2} \leq 1.2\, M_{s-1}$ and $M_{s-2} \leq 15$, admit second segment to "Approach", and and proceed to next step; otherwise, "Approach" is limited to single segment.

2 - Add next seaward profile segment and determine overall slope M_{s-3} . If $M_{s-3} \leq 1.2\, M_{s-1}$ and $M_{s-3} \leq 15$, admit segment to "Approach" and repeat tentative extension; otherwise, do not.

Figure 9. Outline for new geometrical analysis of basic shore situation.

The other factor affecting the choice of runup guidance is the character of the approach to the barrier, in particular, its slope and extent. An objective analysis similar to that mentioned above is used to isolate the approach segment, with only the profile seaward of d_s being considered. These analyses separate the specified profile into structure, approach, and seaward segments, with an objective basis in overall slopes. This separation enables the input geometry to be matched properly with the two- or three-segment configurations shown in Figure 7, so that runup determination can proceed for either engineered structures or natural shore profiles.

Where Stoa's guidance considers an intermediate approach, the slope of that segment is specified to be 1 on 10. Consistent with that, an approach is here classified as horizontal unless its overall slope is 1 on 15 or steeper. This is judged an appropriate requirement for a geometrically distinct segment between the shore structure and an effectively horizontal profile seaward, because 1 on 15 is the criterion for appreciable slope where scale effects begin to arise in wave runup according to Stoa (1978). With gentler slopes, wave transformation is evidently gradual enough to be independent of the absolute energy or scale of waves. Sato and Kishi (1958) corroborated this demarcation, in tests of waves breaking on slopes of 1 on 9 and 1 on 17. Also, Van Dorn (1978) determined experimentally "that there exists a critical slope somewhere within the range 1 on 25 to 1 on 12 below which prebreaking behavior is largely independent of slope or frequency."

There is some direct evidence in available runup measurements on a suitable classification of shore approach as either effectively sloped or flat. Test results (Saville, 1955) for a curved seawall fronted either by 1 on 10 or 1 on 25 slope demonstrate that both wave runup elevations and water overtopping rates differ appreciably for the two situations. The 1 on 25 slope caused runup elevations consistent with guidance addressing a horizontal approach (Stoa, 1978), where that guidance is applicable, namely, for waves breaking on rather than offshore of the seawall. Additional evidence is from runup measurements for plane structures fronted either by a 1 on 20 or 1 on 30 approach slope (Tominaga, et al., 1966; Horikawa, 1978). Results differ appreciably with those two approaches only if the structure toe is in extremely shallow water, with that effect about the magnitude of the slope dependence in wave setup at the shoreline. Those tests, according to Stoa (1978), yielded lower runup elevations than similar structures with a 1 on 10 approach slope. Thus, a wide range of information points to a separation at about 1 on 15 between effectively sloped and flat approaches.

The profile extent identified as shore structure may include multiple segments of the input profile, with different slopes. Such a configuration has no effect on use of the composite-slope method in the modified Model, a distinct change from operation of the 1981 Model. Structures having compound slope now result in an iterative process yielding a consistent runup elevation: from d_s to the runup estimate defines overall structure slope for the succeeding runup evaluation, and this process is repeated until successive elevation estimates agree to within 0.15 foot. The last two estimates are then averaged. This is essentially the same convergence tolerance employed previously, but an additional decimal place is now used internally and in output, marking results as from the modified Model. The additional resolution also removes rounding errors arising in the 1981 Model, where, for example, input slope specifications could be slightly changed before runup computation.

Finally, the 1981 Model used runup guidance for the d_s/H_o value closest to that in the actual situation, but linear interpolation is now employed between runup elevations pertaining to the two d_s/H_o values having specific guidance and bracketing the actual geometry. This interpolation is omitted only for large d_s/H_o where no further guidance is available but runup should not vary much, and for small d_s/H_o with a flat approach where treatment by means of the composite-slope method becomes appropriate.

Implementation of Composite-Slope Method

Saville (1958) proposed that the composite-slope method might be universally applicable in treating wave runup, but the aim here is maximum usage of the specific runup guidance by Stoa (1978). An entirely consistent procedure is to apply the Stoa runup curves to all appropriate situations, and otherwise to employ the composite-slope method with the same curves but different entry values for runup estimates (i.e., d_b/H_o and m_c rather than d_s/H_o and m_s). The initial consideration is whether slope at the shoreline is comparable to or steeper than that just seaward. Stoa's guidance does not treat other situations, so the composite-slope method must be used.

The next step is to distinguish between flat and sloped approaches to the shore structure, because the Stoa guidance treats different ranges for those cases. All positive d_s values are covered for sloped approaches, but guidance for a flat approach only extends as low as $d_s/H_o = 3$ so that waves break on the structure rather than offshore. The latter guidance is recommended for usage down to $d_s/H_o = 2$, but cannot be pertinent below $d_s = d_b$ for flat approaches because that would constitute a fundamentally different situation.

For an approach classified as sloped, i.e., with overall inclination of 1 on 15 or steeper, Stoa's guidance includes a further requirement that a sloped approach must have a horizontal extent of at least 0.5 L_a (unless $m_s \geq 4$). Runup generally reaches a higher elevation for shorter approaches, as guidance for a flat approach and identical d_s/H_o becomes fully pertinent. A transitional region regarding the horizontal extent k of an approach categorized as sloped has been incorporated for

$$0.25\ L_a < k < 0.5\ L_a \tag{2a}$$

There the blend of computed runups is

$$R = I_2\ R_{sa} + (1 - I_2)R_{sf} \tag{2b}$$

and the interpolation parameter is

$$I_2 = (4k - L_a)/L_a \tag{2c}$$

Here R_{sa} denotes runup elevation estimated for a long approach slope, and R_{sf} is runup elevation estimated for a flat segment fronting the shore structure. Outside the range indicated in Equation 2a, R_{sa} is fully appropriate for larger k, and R_{sf} for smaller k. (The composite slope does not directly figure in this transition, but it might be used in determining R_{sa} or R_{sf}.)

A situation conforming to Stoa's cases with sloped approach implicitly requires that the incident wave breaks landward of d_a, rather than on the horizontal bottom seaward. Thus, transition between d_s and d_b basis has been specified for situations with

$$X_a - 0.1\ L_a < X_b < X_a + 0.1\ L_a, \tag{3a}$$

where X_a is the horizontal station corresponding to d_a and X_b corresponds to d_b. The transition employs this blend of computed runups:

$$R = I_3\ R_{sa} + (1 - I_3)\ R_b. \quad \text{(sloped approach)} \tag{3b}$$

Here the subscript b indicates a d_b basis, and the interpolation parameter is

$$I_3 = (X_b - X_a + 0.1\ L_a)/0.2\ L_a \tag{3c}$$

Runup computation entirely based on d_b or composite slope is appropriate for (lower) values of X_b further seaward than the range in Equation 3a, while for values further landward than given there, the d_s basis is fully suitable.

For an approach categorized as flat, the values of d_a and k cannot be too meaningful to the resultant runup; conformance to the Stoa guidance requires only that the situation have fairly large d_s/H_o. As mentioned, the incident wave breaking seaward of d_s certainly does not conform to configurations treated by runup guidance for flat approaches. Therefore, the transition between d_s and d_b basis has been included for situations with

$$d_b < d_s < 3\ H_o, \tag{4a}$$

by this blend of computed runups:

$$R = I_4\ R_{sf} + (1 - I_4)\ R_b \quad \text{(flat approach)} \tag{4b}$$

where the interpolation parameter is

$$I_4 = (d_s - d_b)/(3\ H_o - d_b) \tag{4c}$$

Runup computation entirely based on d_b is suitable for smaller d_s than in Equation 4a, and for larger values the d_s basis is fully appropriate.

These transitions between d_s and d_b computational bases provide finite ranges where runup will be partially determined using each viewpoint, namely, a simple shore structure configuration or an overall treatment of the breaker zone. Interpolations here treat the runup values denoted as R_s and R_b, rather than depth index and slope used to enter the basic runup curves, to be sure that the final runup estimate lies between appropriate limits. Transitional ranges consider horizontal geometry for a sloped approach but vertical geometry for a flat approach, consistent with underlying limits to the applicability of runup guidance in Stoa (1978).

Figure 10 provides a block diagram describing branching decisions arising in the modified Model. This analysis is much more detailed than in the 1981 Model, essentially replacing the procedure shown in Figure 6, and is designed to be in full agreement with specific USACE guidance. That USACE guidance is meant for manual execution accompanied by subjective judgments, but present branching and interpolation procedures permit fully automatic computations and yield smooth variations in results for most small changes of input conditions. Also, the program eliminates potential errors from manual interpolation within empirical results having logarithmic formats, such as Figures 3 and 8. The modified Model provides accurate runup elevations for a wide variety of situations, as demonstrated by the following results.

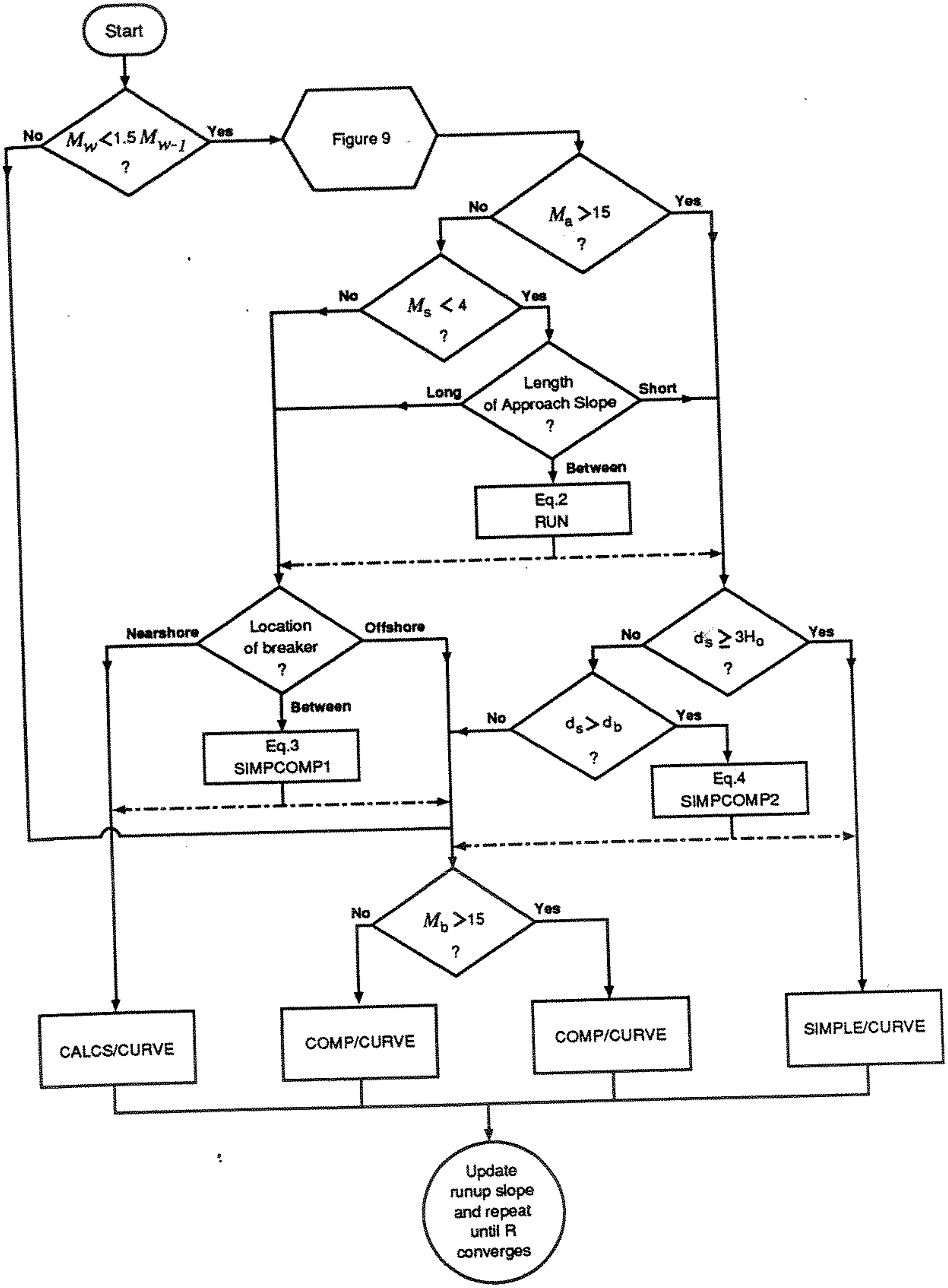


Figure 10. Flowchart of added branching decisions for computations in modified FEMA Wave Runup Model.

EVALUATION OF WAVE RUNUP COMPUTATIONS

This evaluation will focus on published measurements from the large tank studies outlined in Table 1. The newer data represent various shore geometries, test procedures, and measurement methods, permitting extensive checks of runup computations independent of the limited empirical basis in large-scale results for the Stoa (1978) guidance. The data sets described in Table 1 include about 450 runup measurements for 30 different configurations. Besides these results, several data sets are not yet fully documented in available publications, a prime example being runups measured in the Japanese large wave tank (Kajima et al., 1982; Shimada et al., 1986).

Data are considered in order of increasingly complex situations, within the two major categories of uniform or irregular incident waves. Not all Table 1 results are used here because some tests had wave steepness beyond the range accepted by the FEMA Model as appropriate to usual storm waves. The evaluation is summarized mainly by graphs of measured versus calculated runup elevations, along with a line given by linear regression. The regression results are summarized under the third subheading here, "Summary and Conclusions."

Computed results using both the 1981 Model and the modified Model will be presented for some data sets. This serves to demonstrate that Model modifications have little effect on computed runup elevations for simple configurations, including large USACE tests, but provide markedly better agreement with measurements for more complicated geometries.

Table 1a. Outline of Published Runup Data for Large Laboratory Waves: Smooth Slopes

Test Program	Basic Situation	Wave Conditions	Summary of Results
I. USACE Large Wave Tank, Washington, D.C. (Saville, 1987)	Uniform waves Plywood slope with approach Data after first few waves	H=0.9-6.0 ft T=2.61-16.01 sec d=10.0 ft m_s=3, 6	Mean runup of 1.6-17.1 ft in 35 tests; extremes 15-25% higher
II. USACE Large Wave Tank, Washington, D.C. (Saville, 1987; Kraus and Larson, 1988)	Uniform waves Sand slope Data for initial runups	H=1.6-6.0 ft T=3.75-16.0 sec d=12.5-15.0 ft m_s=15	Mean runup of 1.0-4.5 ft (for 3rd to 8th waves) in 12 tests; extremes roughly 30% higher
III. Deltaflume, The Netherlands (D.H.L., 1984a; Stive, 1985)	Uniform or irregular waves Sand slope Waterline variation given for long term (about 15 hr)	H=4 ft T=5.4 sec d=13.8 ft m_s=40	Runup elevations less than 1 ft in 2 tests
IV. Deltaflume, The Netherlands (Vellinga, 1986)	Irregular waves Eroding sand dune Data for 3 to 6 hr after test start	H_s=4.9 ft T=5.37 sec d=13.8 ft m_s=0.7	10% runup of 1.8 ft, 1% runup of 3.0 ft, 0.1% runup of 4.4 ft
V. Grosser Wellenkanal, Germany (Führböter, 1986; Sparboom et al., 1987)	Uniform waves Asphalt slopes Data over about 200 waves	H=1.5-6.9 ft T=2.4-5.8 sec d=15.1-17.1 ft m_s=4, 6	Median runup of 1.5-8.9 ft in 17 tests; extremes about 20% higher
VI. Grosser Wellenkanal, Germany (Uliczka & Dette, 1987)	Uniform or irregular waves Sand slope (with foreshore) Data over 20 waves at test restarts	H=4.8 ft T=6.0 sec d=13.1, 16.4 ft m_s=4	Mean runup from 2.0 ft to above 6.6 ft (overtopping) in 4 tests; extremes roughly 50% higher
VII. Deltaflume, The Netherlands (van der Meer, 1988)	Irregular waves Gravel slope "Runup Length" giving limit for 3,000 waves	H_s=2.0-5.5 ft T_p=2.6-5.9 sec d=14.8 ft m_s=5	Extreme runup elevations of about 3-8 ft in 9 tests
VIII. Grosser Wellenkanal, Germany (Führböter et al., 1989)	Uniform or irregular waves Asphalt slope Data over 100-400 waves	H=1.2-6.6 ft T=2.9-15.0 sec d=15.75 ft m_s=6	Median runup of 1.6-9.7 ft in 80 tests; extremes higher by 10% in uniform waves, 90% in irregular waves

Table 1b. Outline of Published Runup Data for Large Laboratory Waves: Rough Slopes

	Test Program	Basic Situation	Wave Conditions	Summary of Results
IX.	USACE Large Wave Tank, Washington, D.C. (Dai & Kamel, 1969)	Uniform waves Breakwater with quadripods or quarrystone Data for wave bursts	H=1.5-4.3 ft T=2.61-11.33 sec d=15.0 ft m_s=1.5	Mean runup of 1.0-5.8 ft in 27 tests
X.	USACE Large Wave Tank, Washington, D.C. (Ahrens, 1975)	Bursts of uniform waves Slopes armored with riprap Data for wave bursts	H=1.8-3.9 ft T=2.8-11.3 sec d=15.0 ft m_s=2.5, 3.5, 5	Mean runup of 1.8-5.9 ft in 49 tests
XI.	USACE Large Wave Tank, Washington, D.C. (McCartney & Ahrens, 1975)	Bursts of uniform waves Slope paved with Gobi blocks Data for wave bursts	H=1.5-2.9 ft T=2.8-8.5 sec d=15.0 ft m_s=3.5	Mean runup of 1.9-6.4 ft in 11 tests
XII.	Wave Research Facility, Corvallis, Oregon (DeBok & Sollitt, 1978)	Uniform waves Breakwater of fitted quarrystone with 2 approaches Data after 40 waves	H=1.3-4.4 ft T=2.85-5.06 sec d=8.8-10.8 ft m_s=2	Mean runup of 1.2-5.8 ft in 87 tests; also, mean runup of 0.9-2.8 ft in 25 half-size tests
XIII.	Wave Research Facility Corvallis, Oregon (Leidersdorf et al., 1984)	Irregular waves Compound slope with concrete block mattress Runup histograms given	$H_s \approx 3$ ft $T_s \approx 4.5$ sec d=11.0, 12.0 ft m_s=3	Mean runup of 1.8-2.4 ft in 3 tests; extremes 2.3 times higher
XIV.	Deltaflume, The Netherlands (van den Berg & Lindenberg, 1985)	Uniform waves Slope with Armorflex mat (linked concrete blocks) Data over 20-40 minutes	H=1.1-4.7 ft T=3.0-6.0 sec d=16.4 ft m_s=3	Mean runup of 2.3-10.8 ft in 8 tests
XV.	Grosser Wellenkanal, Germany (Bürger et al., 1988)	Irregular waves Breakwater with tetrapods Gage record for 6 minutes	H_s=2.4 ft T_p=4.5 sec d=14.8 ft m_s=1.5	Mean runup about 1.1 ft; maximum about 2.3 ft
XVI.	Grosser Wellenkanal, Germany (Führböter et al., 1989)	Uniform or irregular waves Slope with artificial grass or roughness cubes Data over 100-400 waves	H=1.2-6.6 ft T=3.0-15.0 sec d=15.75 ft m_s=6	Median runup of 1.8-9.5 ft in 78 tests; extremes higher by 10% in uniform waves, 70% in irregular waves

Uniform Waves

The first group of runup data to be considered pertains to hydraulically smooth slopes, including plywood, asphalt, and sand surfaces with the configurations shown in Figure 11. About half these tests are old and half new data, in regard to previous consideration by Stoa (1978). Figures 12 and 13 compare these runup measurements averaging over 5 feet to computations by the 1981 Model and by the modified Model, respectively. In each comparison, there is distinct agreement between measured and computed runups, firmly establishing the pertinence of the Stoa guidance to this wide range of conditions. This evidence indicates an error bar of approximately ±0.5 foot would be appropriate for computed results. There appears to be no dramatic difference in the predictability of runup elevations between old and new tests, and there is a slight improvement apparent in the accuracy of computations with the modified Model, indicating that the more exact conformance to detailed runup guidance is beneficial.

Besides that range of smooth geometries, an extensive recent data set (Führböter et al., 1989) permits evaluating runup computations for a 1 on 6 asphalt slope with a great variety of wave conditions. Figure 14 compares these data to computations with the modified Model. Six tests were repeated in this study, with measured runup elevations typically changing by about 0.2 foot or 5 percent. There are only a few comparable wave conditions between investigations of Führböter et al. (1989) and Saville (1987) for the same

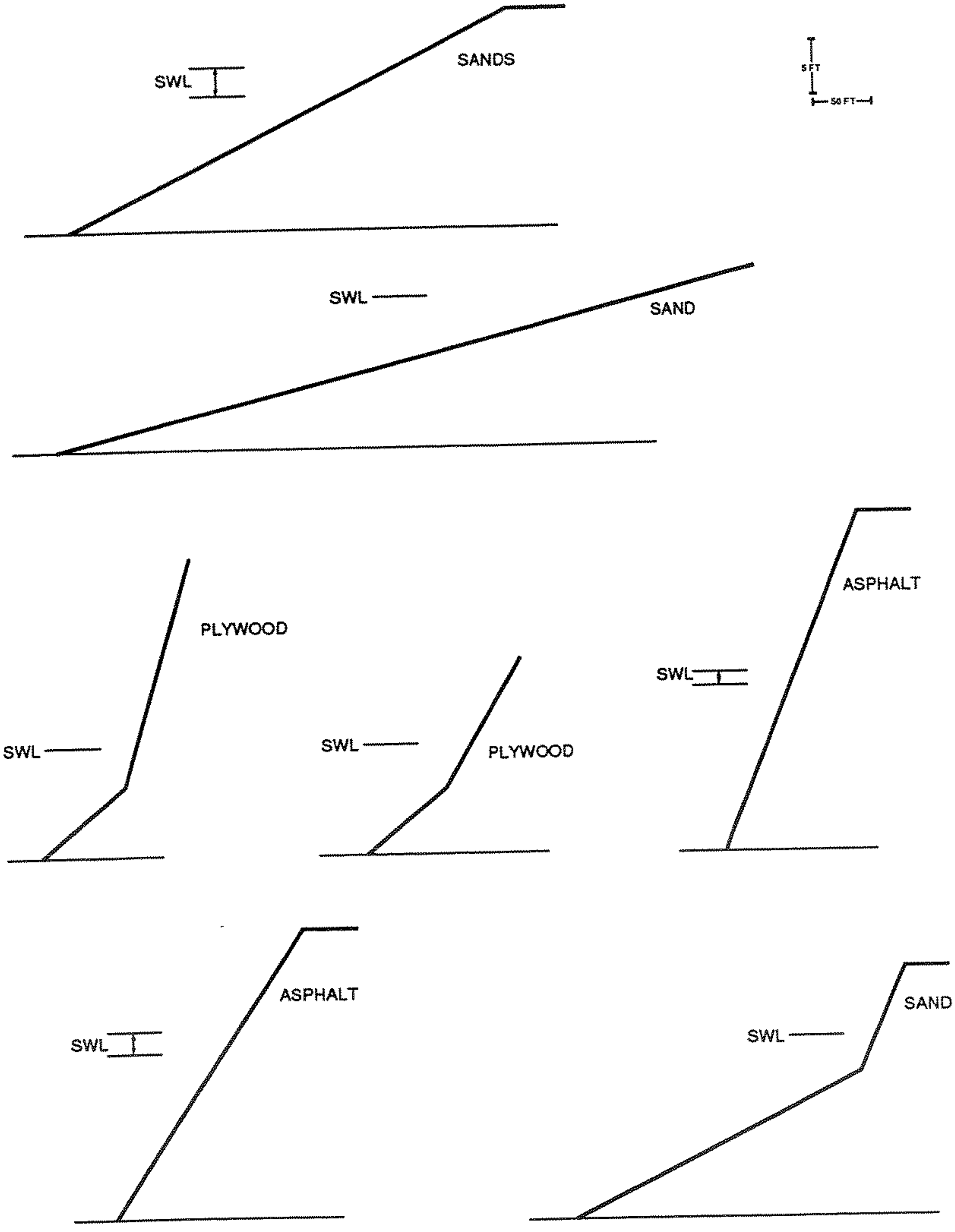


Figure11. Shore configurations in large tests with smooth slopes and uniform waves.

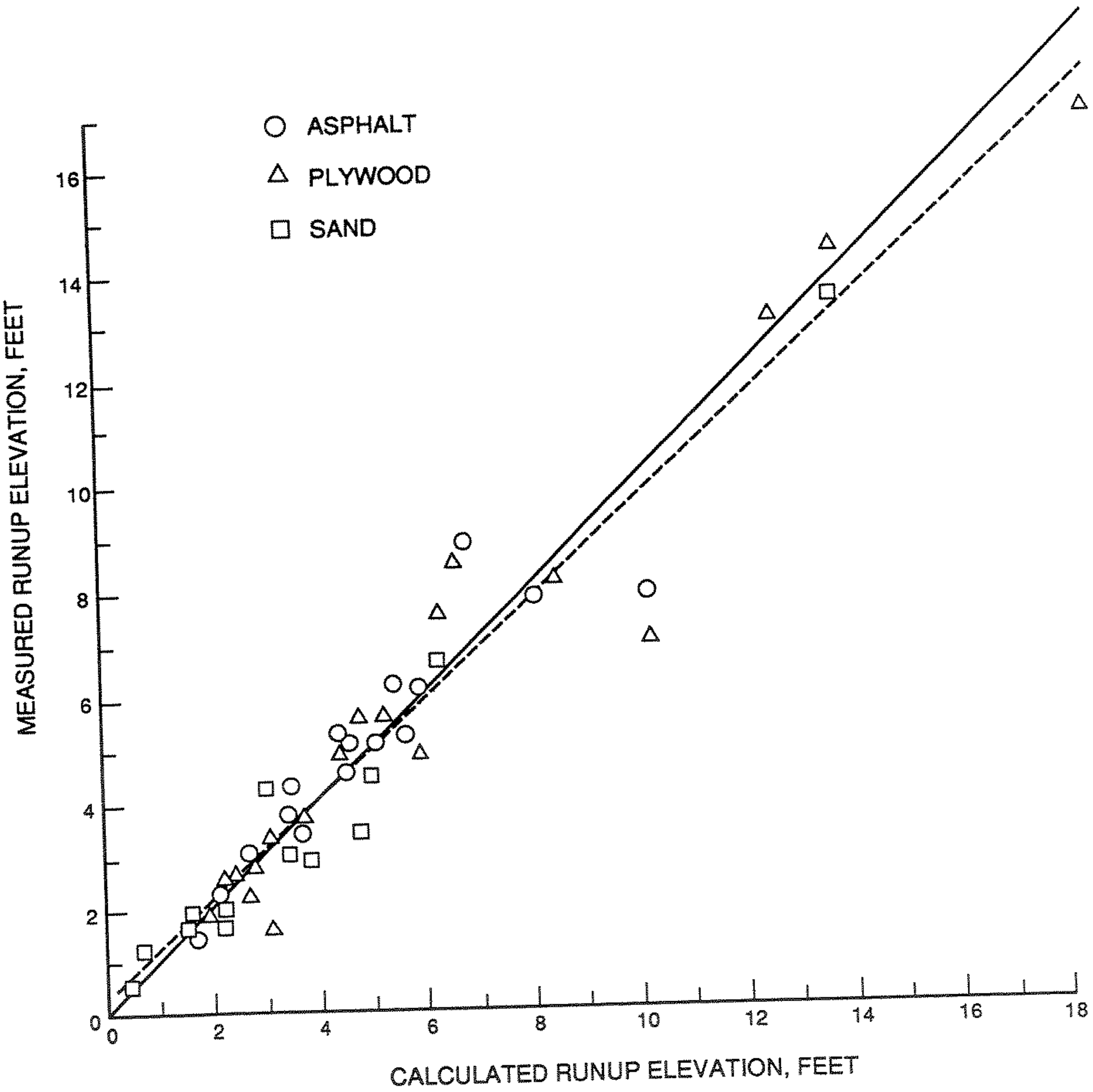


Figure 12. 1981 Model Results: Calculated and measured runup elevations in large tests with smooth slopes.

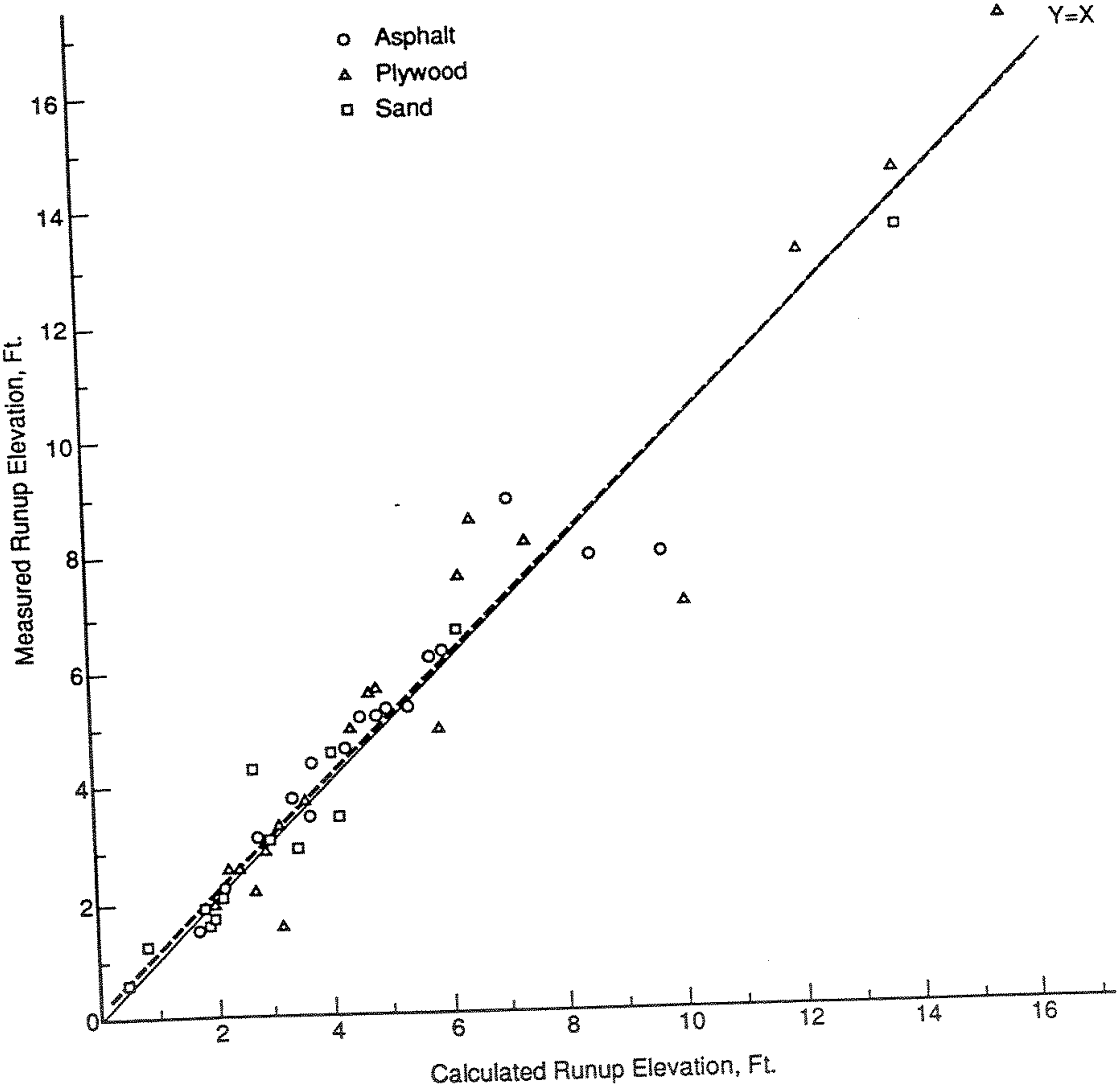


Figure 13. Modified Model Results: Calculated and Measured Runup Elevations in Large Tests with Smooth Slopes.

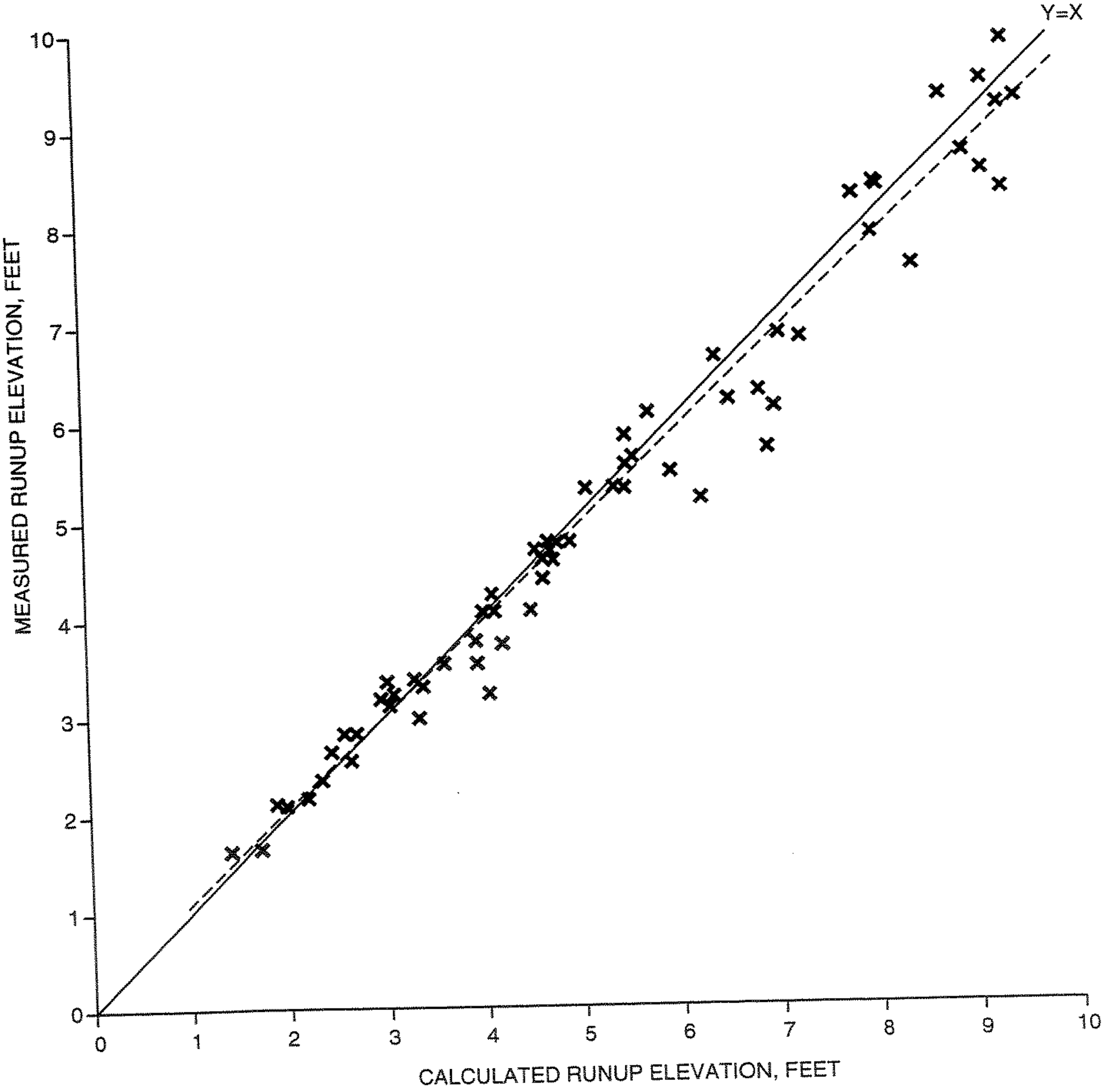


Figure 14. Modified Model Results: Calculated and Measured Runup Elevations in Large Tests with 1:6 Asphalt Slope.

barrier slope with submerged horizontal and 1 on 10 approaches, so that effects of this geometrical variation cannot be well defined directly from these data. However, indications are that the guidance of Stoa (1978) adequately treats this factor, with a slight increase usual in runup elevations for a horizontal approach, since each data set correlates well to appropriate runup computations by the modified Model. The scatter of these results is appreciably larger than the measurement repeatability, but overall agreement is again close to ideal. A slight tendency for runup overestimates here might be taken to suggest that the incorporated multiplier of 1.075 correcting for scale effect with this slope is somewhat too large. However, the maximum discrepancy in correlation is only about the magnitude of the 0.27-foot vertical resolution for the digital runup gage used in these tests, so any bias in calculations does not appear serious.

The results in Figures 13 and 14 for relatively simple geometries do not test all the detailed analyses potentially required in computing runup. More complicated geometries with smooth slopes were investigated by Saville (1955) and by Hosoi and Mitsui (1963), in tests with relatively small waves. Figure 15 shows profile configurations considered here, with 34 runup measurements given in Table 2. In view of the small test waves, no correction for scale effect has been applied in computing runup elevations; this is easily done in the Model by specifying a roughness coefficient equal to 0.50 and then doubling computed values to give runups on smooth slopes. There is a relatively narrow range of runup elevations, but the modified Model certainly yields more appropriate magnitudes than the 1981 Model and this improvement involves more than the additional decimal place in computations.

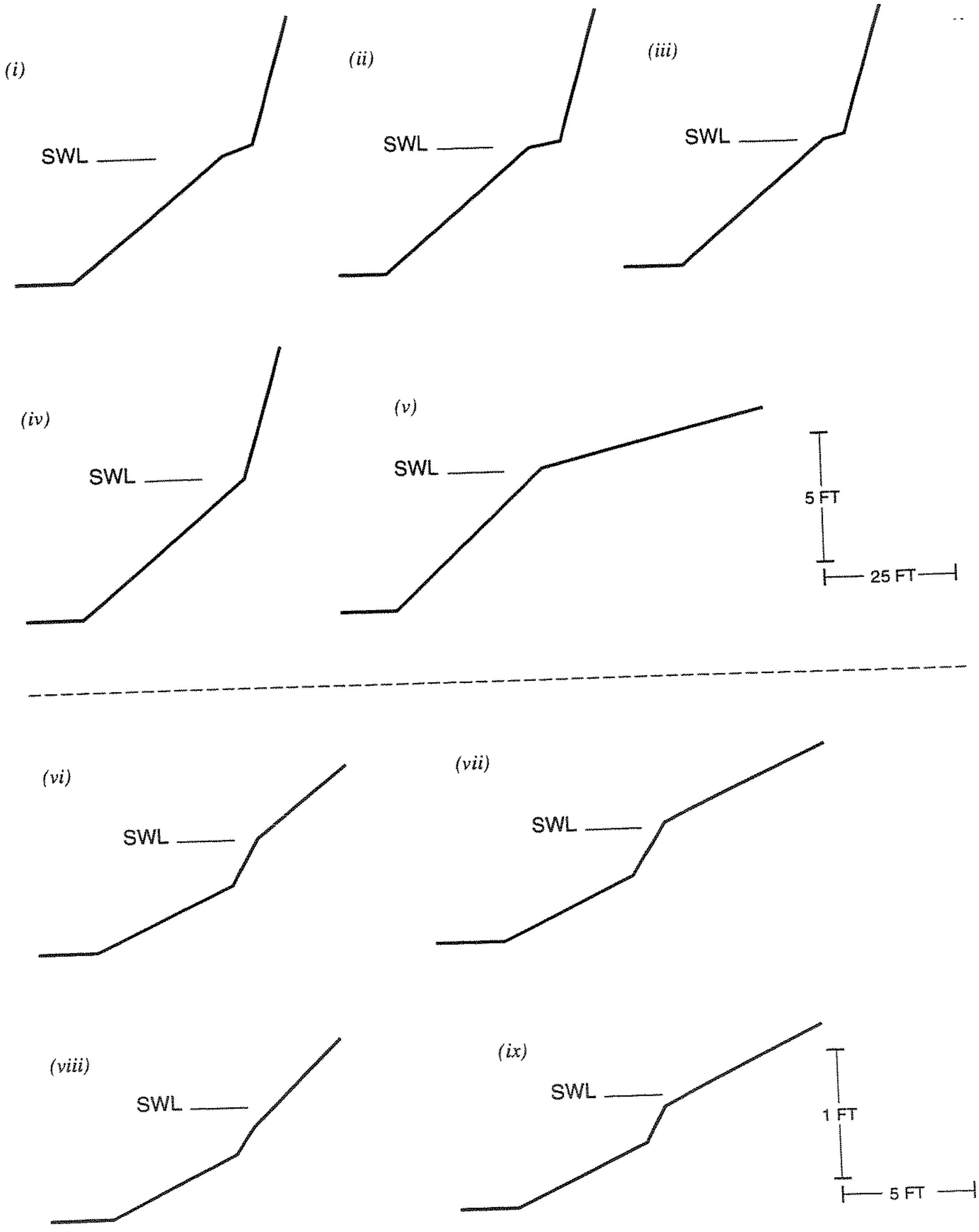


Figure 15. Complex profile configurations in small tests with smooth slopes. Profiles *i-v* tested by Hosui and Mitsui (1963), and profiles *vi-ix* by Saville (1955).

Table 2. Conditions and Results in Laboratory Tests with Small Waves on Smooth Compound Slopes (Hosoi and Mitsui, 1963; Saville, 1955)

Test Profile: Fig.	Water Depth, Ft	Wave Period, Sec	Wave Height, Ft	Measured Runup, Ft	Calculated Runup, Ft	
					1981 Model	Modified Model
15i	4.6	3.48	0.36	0.52	0.2	0.63
15ii	4.6	1.70	0.69	0.51	0.1	0.38
15iii	4.6	3.48	0.36	0.53	1.3	0.74
15iii	4.6	1.70	0.69	0.53	0.3	0.42
15iv	4.6	3.48	0.36	1.22	1.9	1.36
15v	4.6	3.48	0.36	0.20	0.2	0.37
15vi	0.83	1.00	0.20	0.25	0.2	0.24
15vii	0.83	1.00	0.20	0.19	0.1	0.18
15viii	0.83	1.00	0.20	0.20	0.2	0.21
15ix	0.83	1.00	0.20	0.14	0.1	0.14
15vi	0.83	1.10	0.27	0.31	0.2	0.29
15vii	0.83	1.10	0.27	0.23	0.1	0.21
15viii	0.83	1.10	0.27	0.25	0.2	0.25
15ix	0.83	1.10	0.27	0.17	0.1	0.18
15vi	0.83	1.19	0.33	0.35	0.2	0.29
15vii	0.83	1.19	0.33	0.26	0.1	0.23
15viii	0.83	1.19	0.33	0.29	0.2	0.27
15ix	0.83	1.19	0.33	0.21	0.1	0.19
15vi	0.83	0.82	0.20	0.20	-	0.20
15vii	0.83	0.82	0.20	0.16	-	0.15
15viii	0.83	0.82	0.20	0.15	-	0.17
15ix	0.83	0.82	0.20	0.11	-	0.11
15vi	0.83	0.91	0.27	0.28	-	0.24
15vii	0.83	0.91	0.27	0.21	-	0.18
15viii	0.83	0.91	0.27	0.20	-	0.21
15ix	0.83	0.91	0.27	0.15	-	0.15
15vi	0.83	1.28	0.40	0.40	-	0.31
15vii	0.83	1.28	0.40	0.30	-	0.25
15viii	0.83	1.28	0.40	0.34	-	0.29
15ix	0.83	1.28	0.40	0.24	-	0.21

Figure 16 shows profiles in large tests with rough slopes, including the relatively complicated breakwater configurations investigated by DeBok and Sollitt (1978). Besides the additional geometries, available runup data for rough slopes permit assessing the validity of computations using a constant roughness coefficient, r, as in the present Model.

Figure 17 compares runup computations by the modified Model to measured runups on permeable, very rough slopes with r = 0.50 or 0.60 in USACE tests (Dai and Kamel, 1969; Ahrens, 1975). Data scatter is more marked here than in Figure 13, but computed runups have an appropriate trend so that the constant roughness coefficient appears a useful approximation. Figure 17 suggests an error bar of approximately ±0.5 foot, but this is appreciable because runup elevations for smooth slopes with identical profiles have been about halved here. Increased error may be partially ascribed to greater uncertainty in runup measurements for rough permeable surfaces: in two repeat tests by Dai and Kamel (1969), runup differences were about 10 percent.

Further analysis demonstrates that use of a constant roughness coefficient leads to much of the Figure 17 scatter. The actual reduction factor of rough-slope compared to smooth-slope runup elevations is strongly dependent on the value of the surf similarity parameter, S_o. Figure 18 shows variations with S_o in the ratio of measured to predicted runup elevation for the tests by Ahrens (1975). Results in this format clearly demonstrate the varying accuracy of predictions, indicating that actual runup reduction changes over an appreciable range (at least from r of 0.55 to 0.65). A relative minimum in

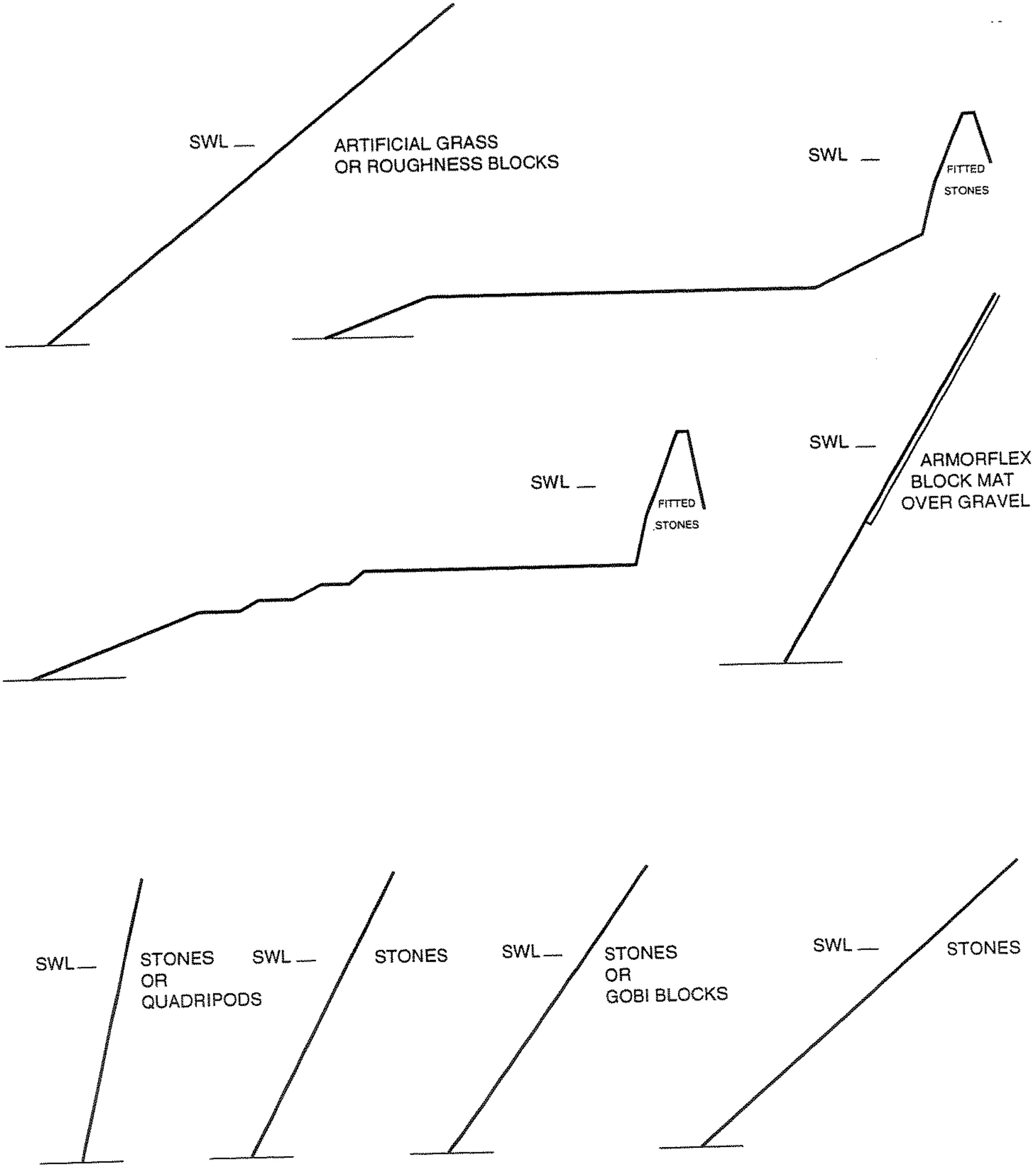


Figure 16. Shore configurations in large tests with rough slopes and uniform waves.

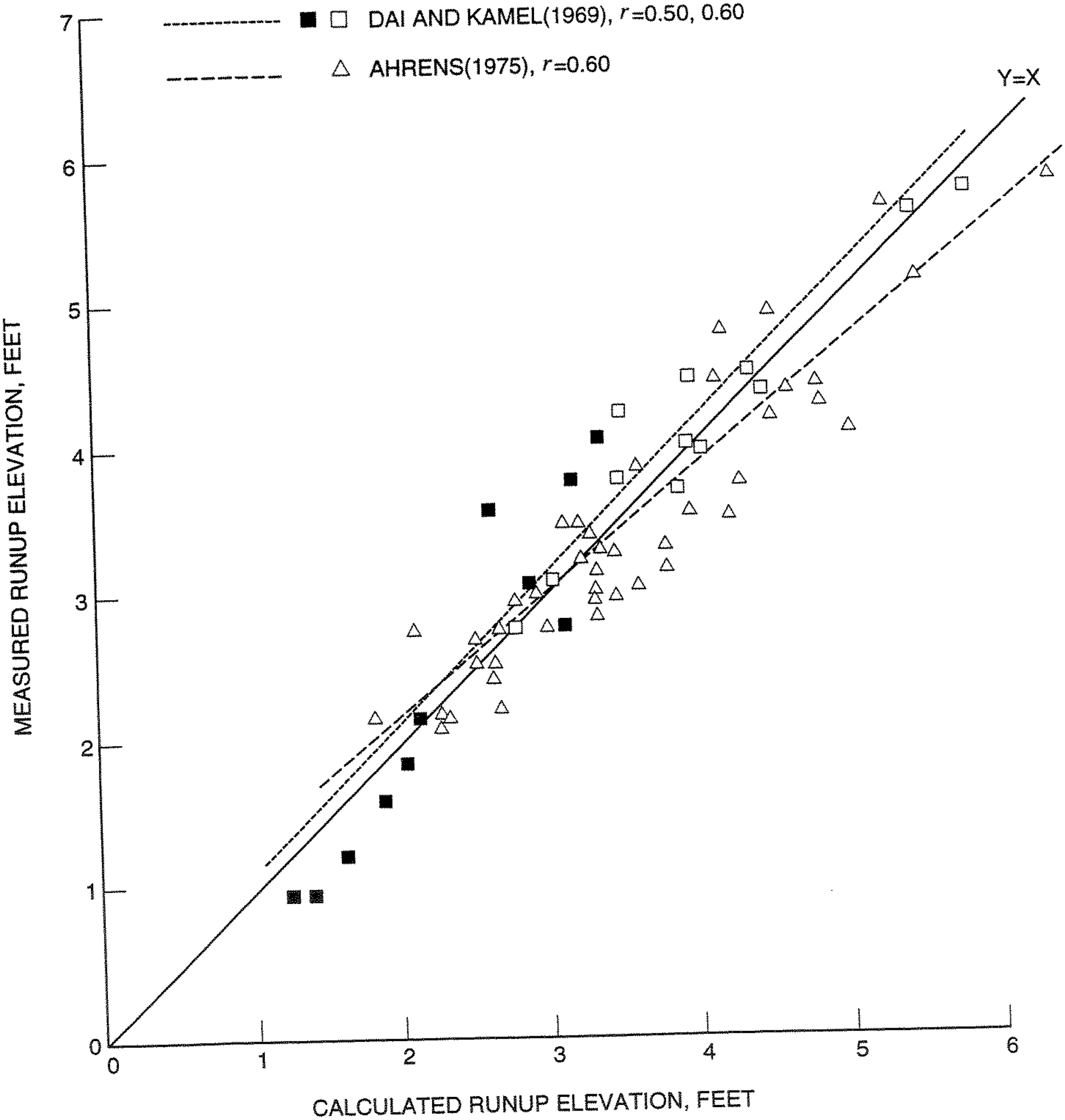


Figure 17. Modified Model Results: Calculated and Measured Runup Elevations for large USACE tests with very rough slopes.

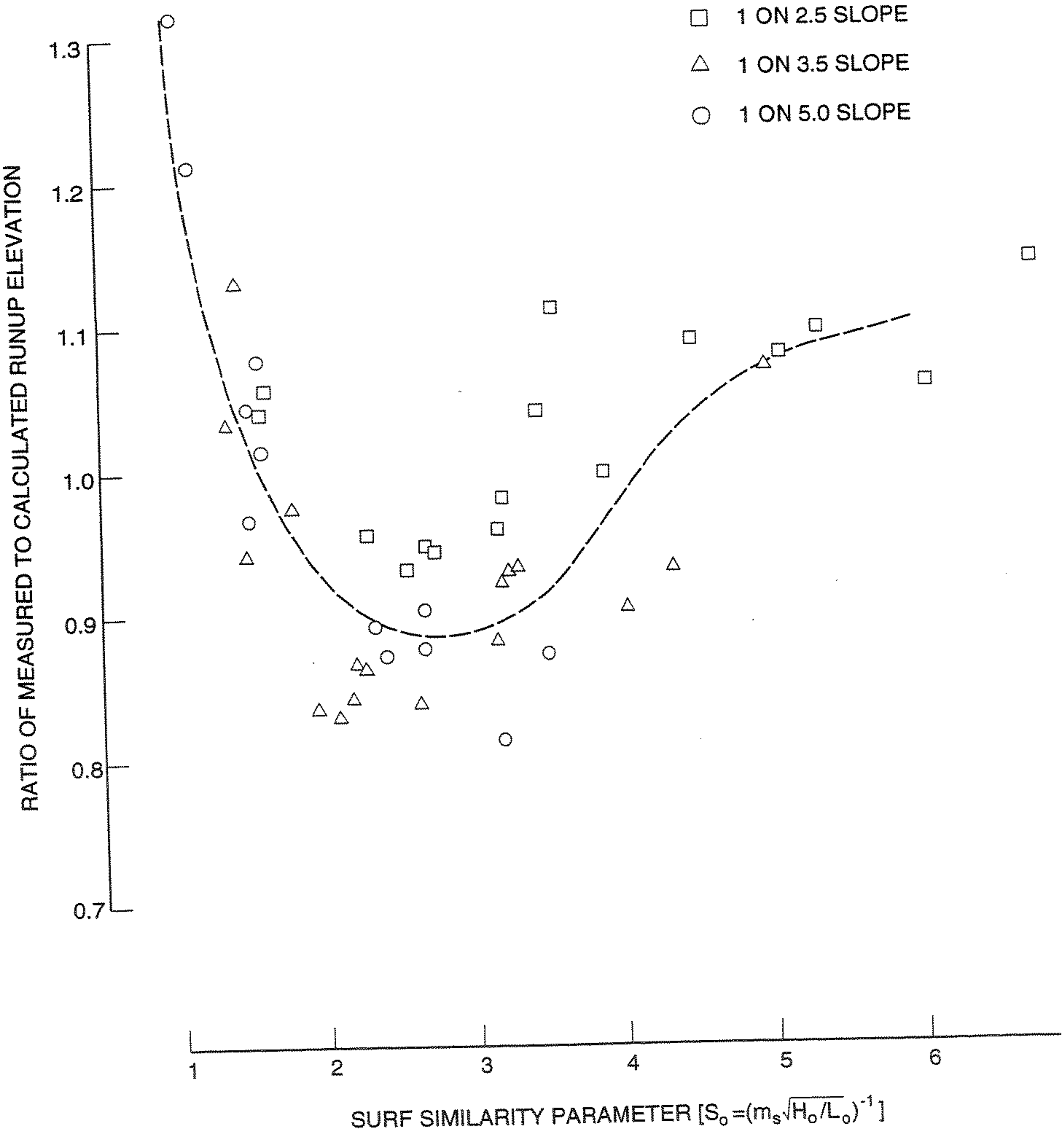


Figure 18. Apparent effect of surf similarity parameter in test results of Ahrens(1975) for very rough slopes.

measured runup elevations occurs near S_o=3, corresponding to collapsing breakers (Ahrens, 1975). That transitional surf condition occurs between the regimes of plunging breakers (lower S_o) and surging or reflecting waves (high S_o); collapsing breakers constitute the most damaging situation for deformable shore structures, giving minimum wave runup along with maximum wave impact (Bruun and Günbak, 1976). Transitional wave processes are evidently different on fixed smooth slopes (see Figure 2), so that use of constant r value in estimating runup might be a suitable approximation only in an overall sense for a wide range of S_o. However, other data sets for rough slopes do not show such marked weakness in the approximation of r as a constant. Test conditions by Ahrens (1975) correspond to "zero damage" of the shore structures, but with notable agitation of the angular armor stones. A minimum in runup elevations with collapsing breakers is likely to be less pronounced for more stable roughness elements or for varying storm wave characteristics.

Figure 19 compares measurements to calculations for two series of similar tests with moderately rough slopes, Gobi blocks treated as r=0.85 in the USACE large tank (McCartney and Ahrens, 1975), and smoother Armorflex blocks treated as r=0.95 in the large tank at Delft Hydraulics Laboratory (van den Berg and Lindenberg, 1985). The marked correlations here indicate an error bar of about ±0.3 foot for runup elevations, regardless of test details.

All data sets used in the development of conclusions by Stoa (1978) have now been examined. Additional measurements from large tests with controlled conditions permit further checks of Model computations that are fully independent of the original empirical basis for incorporated runup guidance.

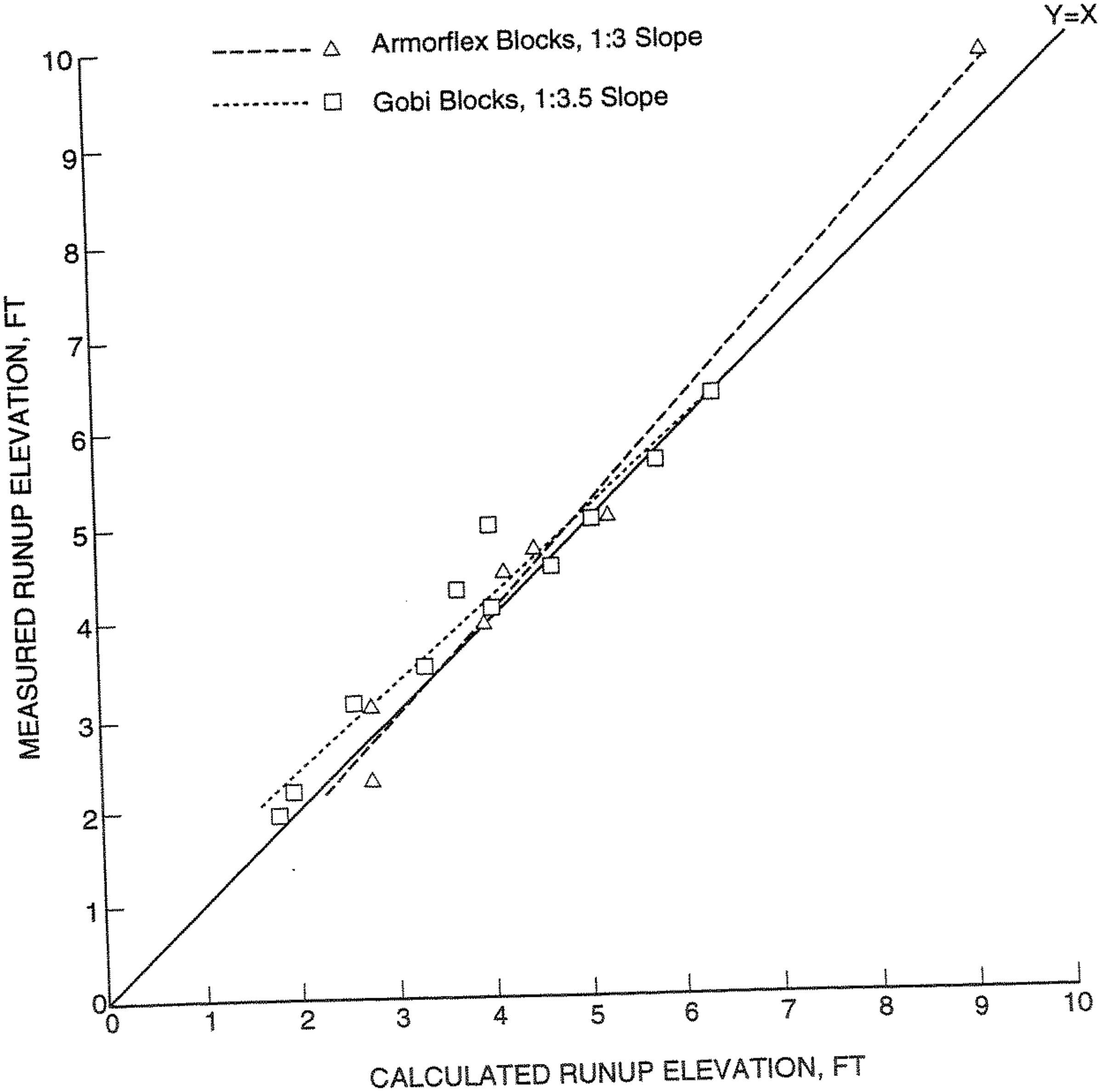


Figure 19. Modified Model Results: Calculated and Measured Runup Elevations in Large Tests with Gobi (r=0.85) and Armorflex (r=0.95) Blocks.

Führböter et al. (1989) provided a sizable runup data set for an impermeable 1 on 6 slope with moderate roughnesses: either artificial grass treated as r=0.95, or regularly spaced, nearly cubical blocks treated as r=0.90. Figure 20 compares these runup measurements to calculations by the modified Model. Results exhibit nearly ideal correlation and the indicated error bar is about ±0.3 ft as in Figure 19. Usual discrepancies between measurements and calculations are not much greater than in Figure 14 for the smooth slope, so only slight error appears introduced here by the approximations of constant r.

DeBok and Sollitt (1978) provided extensive data for a breakwater of fitted stone, with both horizontal and sloped approaches to the structure. Those different approaches and the composite structure, with 1 on 2 slope above 1 on 1.5, permit particularly valuable tests of computations. Figures 21 and 22 compare runup measurements to results from the 1981 Model and the modified Model, respectively, with each set of computations using r = 0.60. This evidence demonstrates the value of Model modifications, since the correlation is much more ideal in Figure 22 although calculated elevations generally exceed measurements. The same study also included half-size tests of identical configurations in the same large wave tank. Results pertain to the question of how large a test is required to provide essentially prototype runup processes and elevations. Figure 23 compares those runup measurements at half size to computations using the modified Model, showing somewhat better agreement than in Figure 22. This difference in behavior possibly demonstrates the occurrence of scale effects where the dissipation coefficient for smaller tests is notably different than with rough turbulent flow similar to

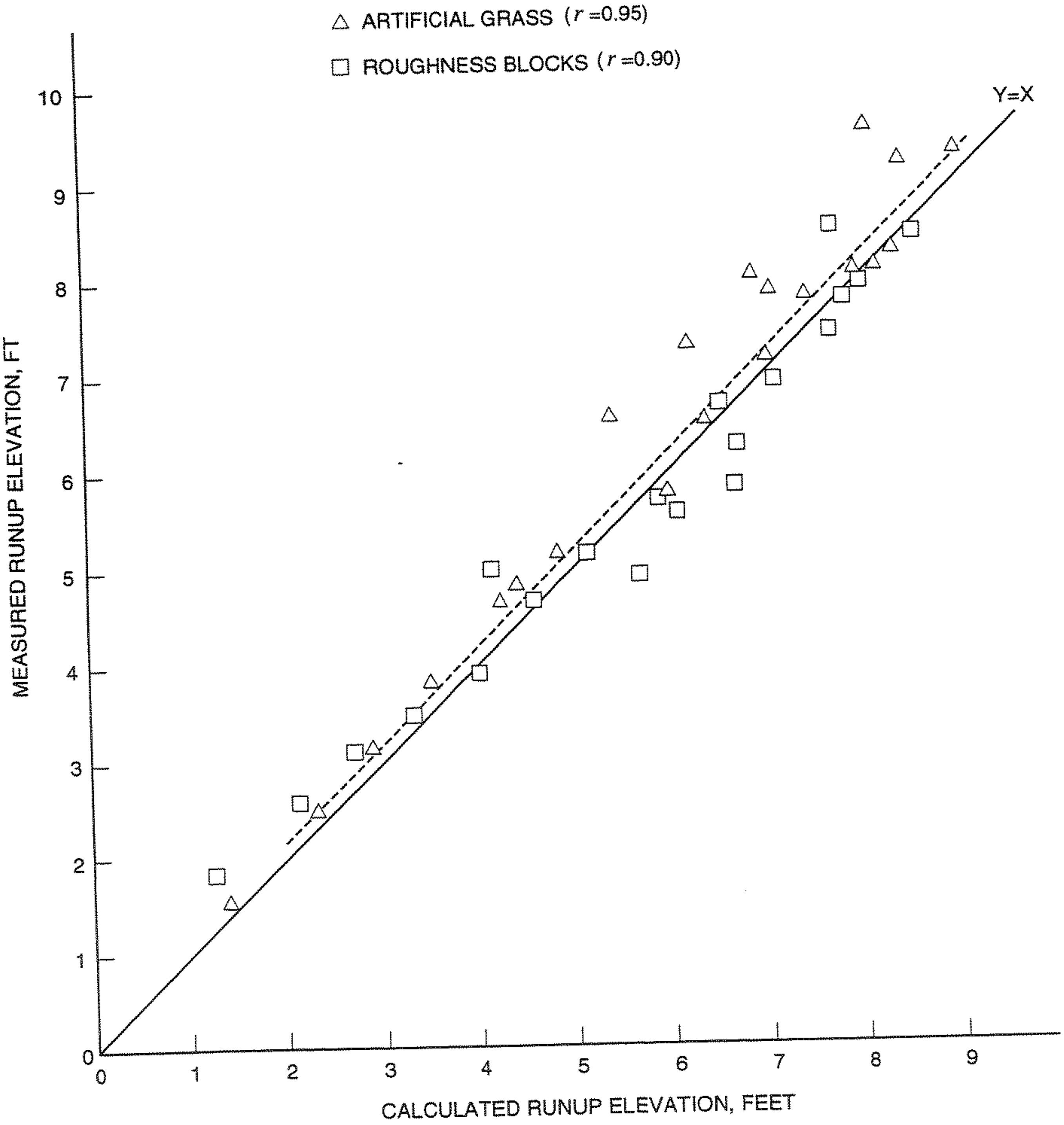


Figure 20. Modified Model Results: Calculated and Measured Runup Elevations in Large Tests with Rough 1:6 Slope.

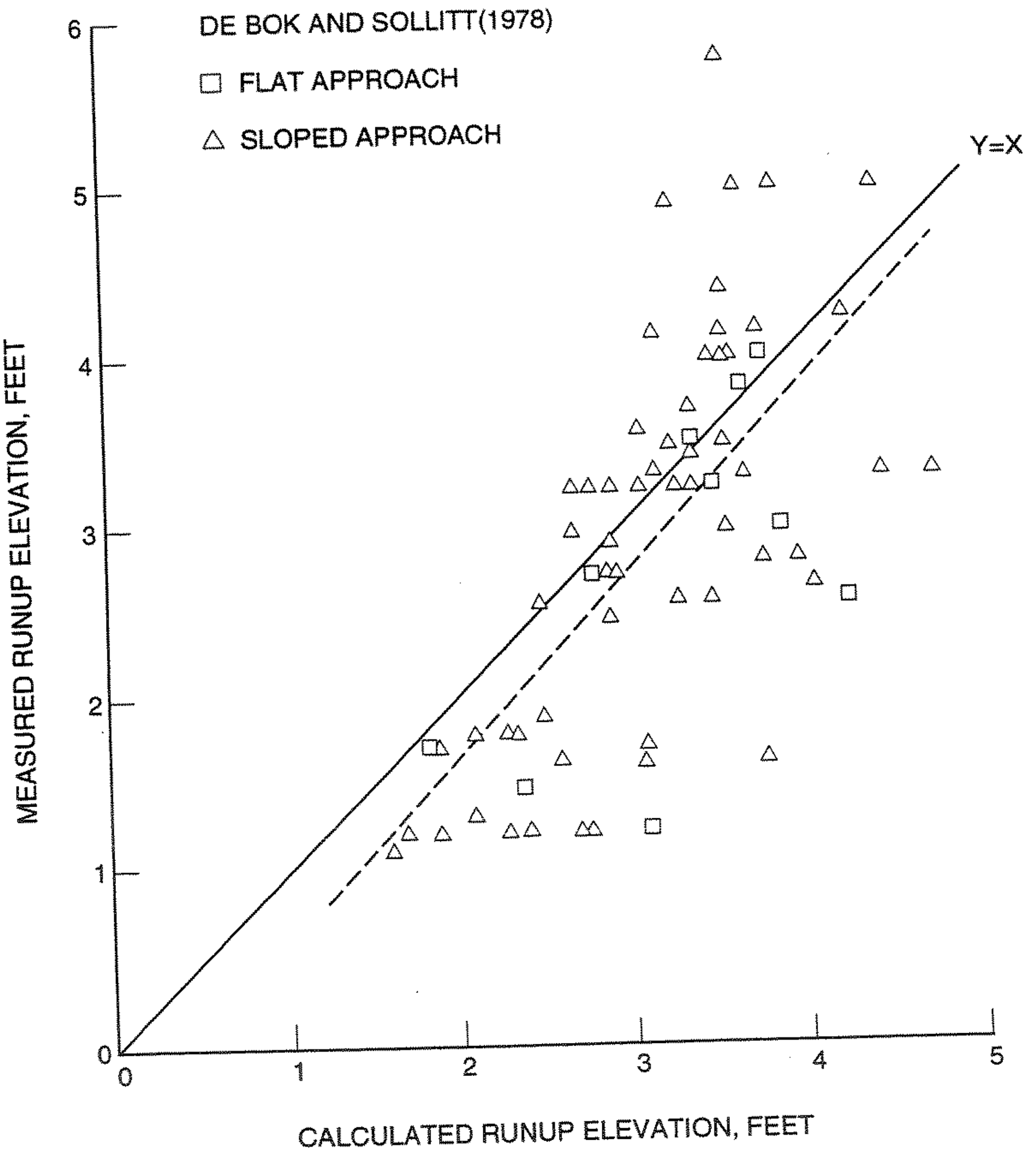


Figure 21. 1981 Model Results: Calculated and measured runup elevations for large tests with rough compound slope.

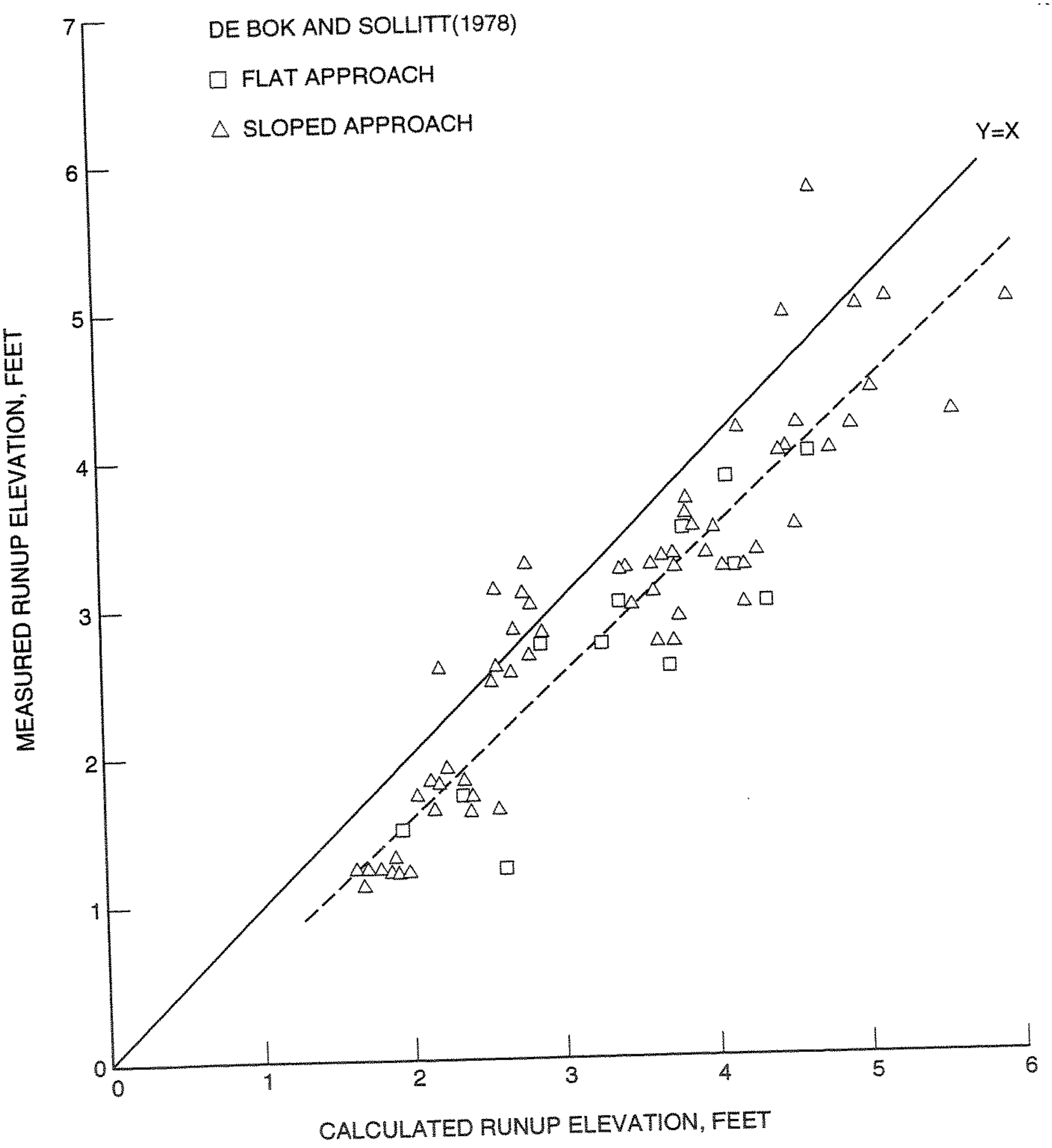


Figure 22. Modified Model Results: Calculated and measured runup elevations for large tests with rough compound slope.

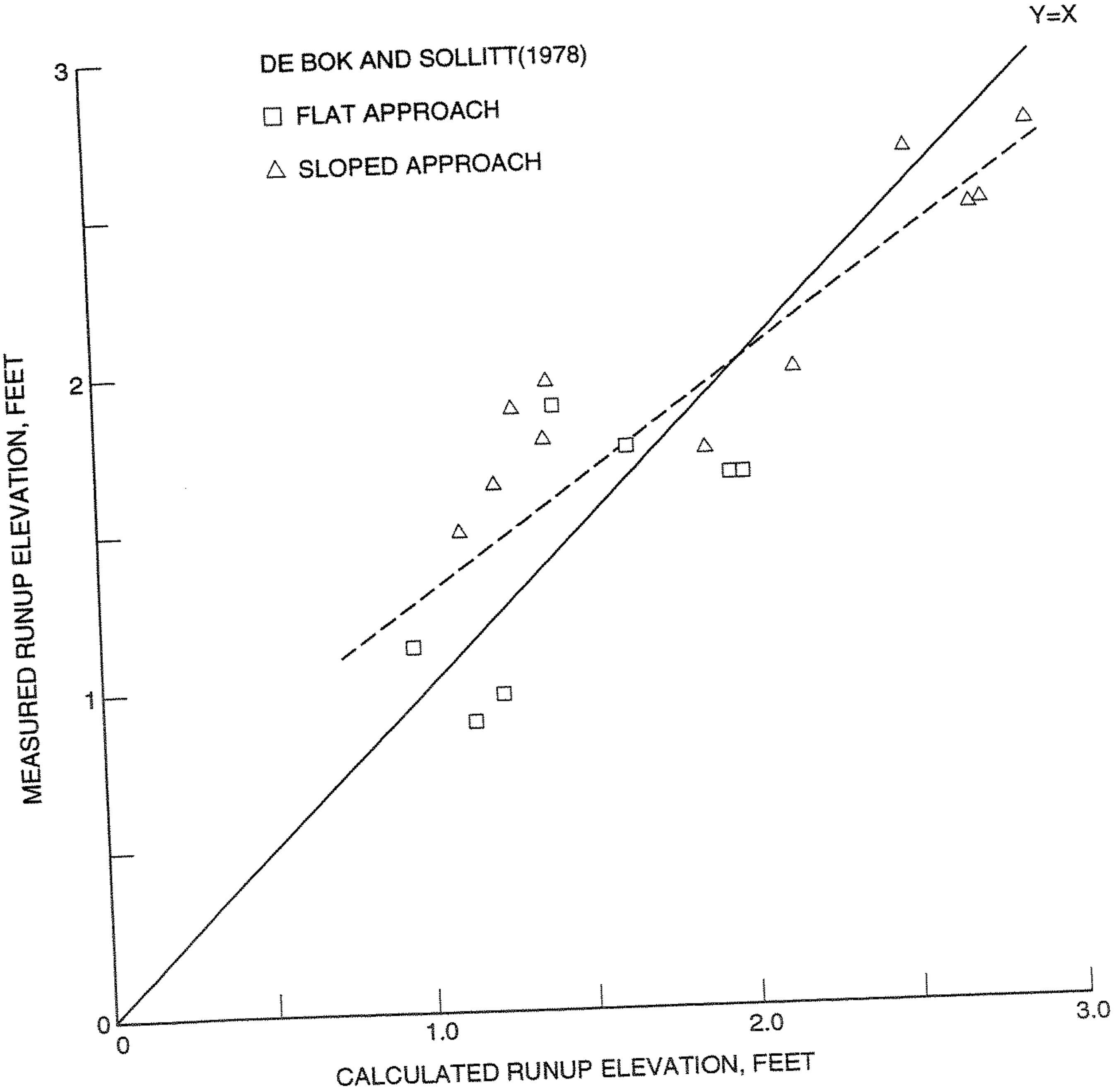


Figure 23. Modified Model Results: Calculated and measured runup elevations for "Half-Size" tests with rough compound slope.

the prototype. Of course, assessment of runup computations should focus on prototype situations, so this topic is important to the present evaluation.

There seem to be conflicting indications about the dynamic similarity of wave effects between these full- and half-size tests in the original reports (Sollitt and DeBok, 1976; DeBok and Sollitt, 1978). Results on structural stability and runup elevation were judged to be similar in the two test series, but scaled wave rundown was noted to be considerably different at half size and in clear accordance with very small tests. Since rundown must affect the succeeding wave runup, this points to a notable scale effect arising in half-size tests. Such a scale effect can be demonstrated by relating runup elevations to a Reynolds number measuring flow intensity for test conditions. Ideally, this flow parameter should refer directly to the runup geometry and processes, but they can be complex and hard to define; the more viable alternative is a parameter describing incident waves controlling runup.

The Reynolds number RE is defined as the product of characteristic flow velocity and length, divided by the kinematic fluid viscosity (v). Wave-induced flows near the bottom are characterized by peak horizontal water velocity and displacement, and linear wave theory permits convenient approximations of those characteristics for the moderate water depths usual in wave tanks (Nielsen, 1984). In terms of commonly specified test conditions, the Reynolds number may be expressed as

$$RE = [(H_o/g)^{0.5} T^2] \quad \frac{g^2 (H_o/d)^{1.5}}{32 \pi^2 v} \quad [1 - \frac{\pi d}{3L_o} - \frac{16\pi^2 d^2}{45 L_o^2}] \qquad (5)$$

The first bracketed term here expresses the primary variation of RE with test conditions, if d is treated as some reference water depth within the wave tank so that (H_o/d) remains about one. The second bracketed term also is approximately one, since H_o/L_o and thus d/L_o remain relatively small. Thus, it is appropriate to measure wave-induced flow intensity by the approximate form

$$RE^* = (H_o/g)^{0.5} \quad T^2 \tag{6}$$

Figure 24 displays results from tests of DeBok and Sollitt (1978) in another format, as the ratio of measured to calculated runup elevation versus the value of RE* for each wave condition, including the very small tests mentioned previously. There is a statistically definite correlation between runup ratios and RE* values over this broad range of conditions, indicating a notable scale effect in runup on this steep, rough structure. The Figure 24 variables show no appreciable correlation for RE* greater than 3 sec^3, consistent with that value as a threshold where scale effect becomes unimportant to wave runup on this structure. Scale effect may cause the basic difference in results between Figures 22 and 23, but does not explain the sizable scatter evident in Figure 24 between runup measurements and calculations for an individual test series. Much of this scatter is due to uncertainty in measurements, since 14 repeats in the smallest test series gave runup differences averaging 16.5 percent. The scatter may also be partially due to ignoring dependence of an appropriate r value on the surf similarity parameter, but that general dependence seems uncertain: the present data set shows a variation of runup ratios different from that in Figure 18, with decreasing values here as S_o becomes large. The constant r approximation certainly contribute to error in runup calculations for uniform wave action, but an adequate improvement does not appear straightforward. Also, as used in

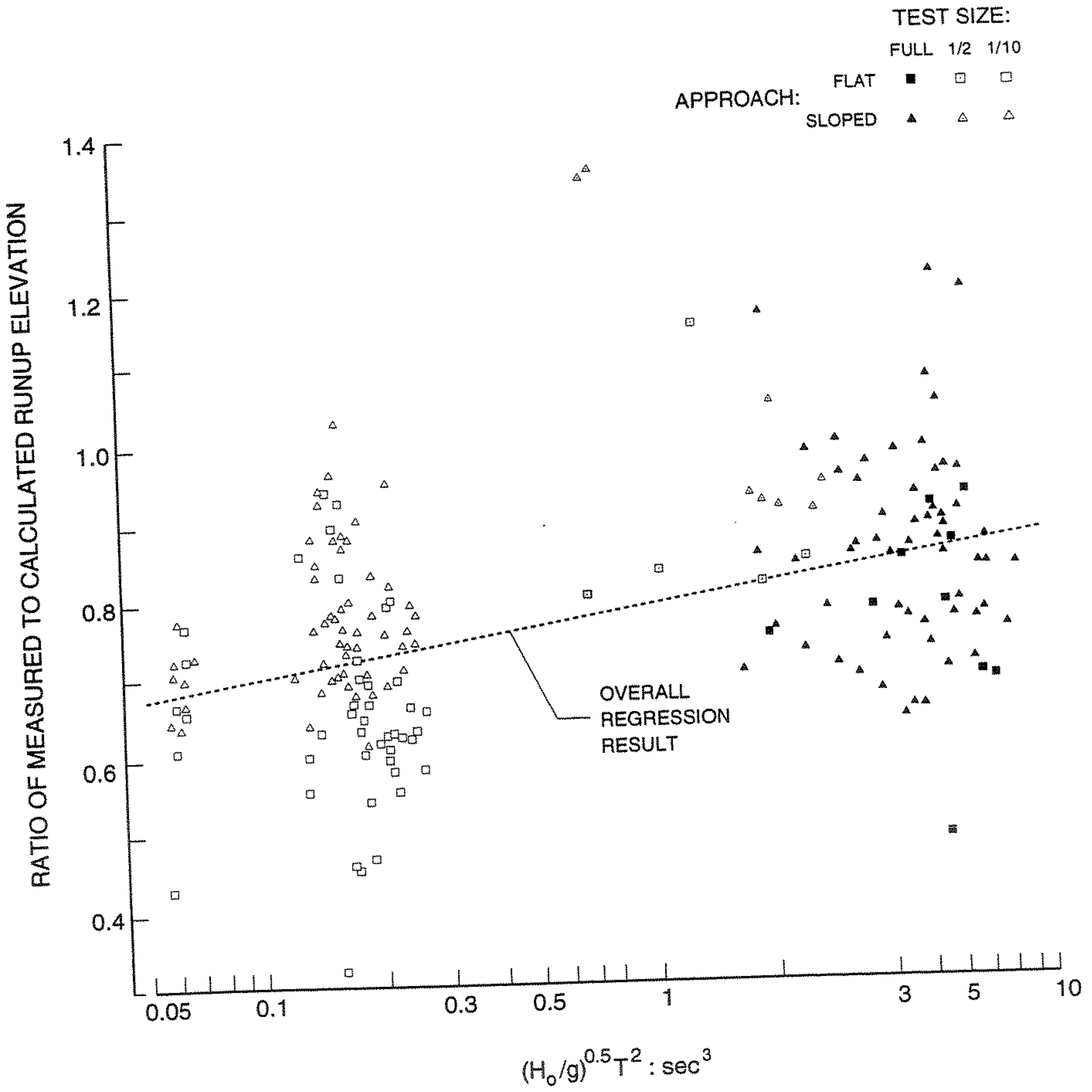


Figure 24. Apparent scale effect in results for rough compound slope (De Bok and Sollitt, 1978).

the Model with large waves, the appropriate r value reflects any scale effect in runups on rough slopes.

It should be noted that a threshold for prototype runup effects appears to be a simpler matter on smooth slopes, where available evidence suggests that scale effect perhaps ceases for RE* beyond about 10 sec^3. That transition to turbulent flow seems distinctly similar to Figure 24 results, with relatively high runup measurements occurring for slightly less intense flows on smooth slopes. Sizable wave dimensions are required for turbulent runup effects, since RE* = 10 sec^3 corresponds to H_o = 1 ft and T = 7.5 sec, or to H_o = 5 ft and T = 5 sec. Stated requirements have commonly been exceeded in large tanks, particularly for USACE tests.

Completing the Model evaluation for large uniform waves, Figure 25 compares runup computations and measurements for a proprietary test series at Delft Hydraulics Laboratory, made available through the cooperation of Rijkswaterstaat in the Netherlands. These tests had a horizontal approach to the 1 on 3 slope of concrete blocks, and the computations use a roughness coefficient of 0.95 regardless of the installation details. Among various test series in that large wave tank, this data set provides the sole instance where measured runup does not exhibit a simple relationship to the surf similarity parameter (Delft Hydraulics Laboratory, 1986). However, Figure 25 shows quantitative agreement between runup computations and measurements, supporting the application of detailed empirical guidance within the modified FEMA Model. Upon further examination of these results, some of the residual

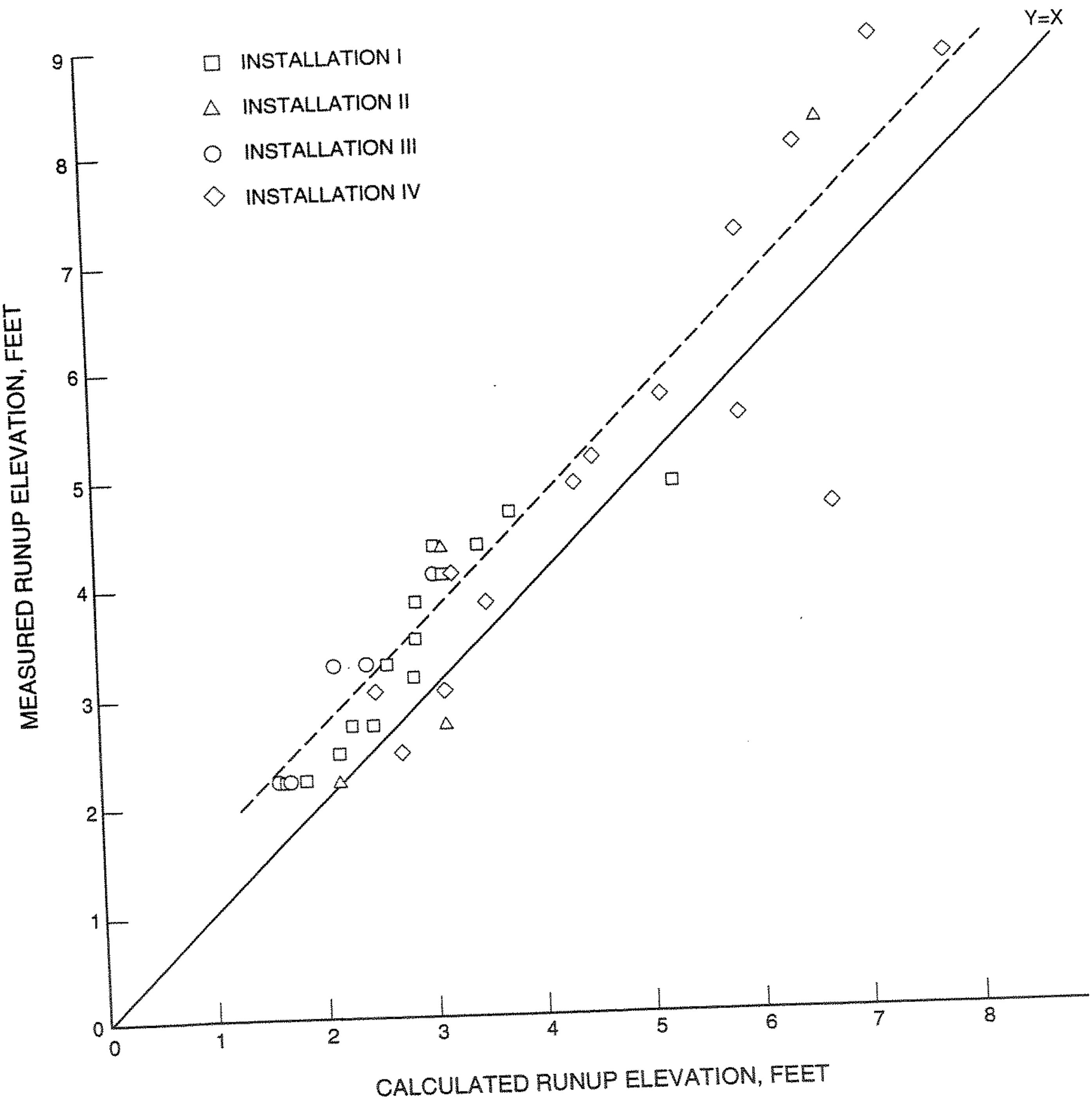


Figure 25. Modified Model Results: Calculated and measured runup elevations in Delft Hydraulics Laboratory tests with concrete blocks($r = 0.95$).

scatter and bias here can be ascribed to weaknesses in a constant r approximation and to scale effects in less intense flows, similar to variations displayed in Figures 18 and 24.

Overall, this extensive evaluation of computed runup elevations has demonstrated notable capabilities of the modified FEMA Model for treating effects with uniform wave action. Agreement of data and computations may be somewhat deteriorated due to scale effects or measurement errors or the approximate r values assigned for rough slopes. However, the Model clearly provides appropriate magnitudes and trends for available runup tests. The following material continues with evaluation of the FEMA Model for more complicated situations, directly relating to prototype runup elevations in extreme storms.

Irregular Waves

Two notable weaknesses in the empirical basis for the Stoa (1978) runup guidance are the exclusive treatment of simple geometries and uniform waves. Available evidence indicates the geometrical limitations in the data base may be diminished through supplementary considerations including the composite-slope method, but the significance of using only test results for idealized waves remains to be assessed. Prediction of runup elevations is appreciably more difficult with irregular incident waves, since dynamical processes are fundamentally different and the resultant wave runup shows much more variation. A nonlinear relationship is usual between the spectrums of waves and runups: wave energy can shift to different frequencies in runup, and elevation distributions can be transformed, with higher waves giving lower runups.

Boundary conditions controlling runup for a particular wave include the decay, runup, and return flow of the preceding wave, so that runup processes must be significantly more complex with irregular incident waves. Empirically, runup elevations are known to be affected by wave steepness, by wave breaking, and by normalized water depth at the toe of a shore structure (d_s/H_o). With irregular waves, the wave height most descriptive of a certain process might be the maximum, the significant, the root-mean-square, or the mean, in order of decreasing size for a specific condition. Also, different quantities can be used as a representative period for irregular waves, complicating any match with uniform wave action. Furthermore, the well-defined break point occurring with uniform waves has no clear analog for irregular wave action. Using an approximately parallel description (Goda, 1985), breaker-depth indices with irregular waves exhibit notable differences from the d_b/H_o curves for uniform waves in Figure 8. Such complications necessitate detailed experimental studies of runup due to irregular waves as a topic nearly independent of uniform-wave runups.

Carstens et al. (1966) measured runup elevations in fairly large tests with steep structures and demonstrated an influence of details in the wave description, but most published conclusions on irregular wave runup proceed from small-scale investigations. For steep slopes, Ahrens (1983) found that various Weibull distributions depending on test situation fit measured runup elevations with irregular waves. Reasoning based on superposition of uniform-wave components would suggest a simpler Rayleigh distribution of runup elevations, like that usual for individual wave heights (Shore Protection Manual, 1984). For gentle slopes, Mase and Iwagaki (1984) correlated runups to the surf similarity parameter by a weaker functional dependence than in Equation 1, and established notably different expressions for mean, significant, and maximum runup elevations. With complicated geometries, the transformations to be expected in runup of irregular waves have not been fully determined.

Ahrens and Titus (1978) suggested treating runup elevations for irregular waves by presuming the significant wave condition to be an appropriate measure of equivalence with a specific uniform wave condition. That choice appears questionable, since the mean description of irregular waves has been proposed as the proper measure in relation to runup elevations in uniform waves (Webber and Bullock, 1968; Kaldenhoff and Gökcesu, 1978). Investigations by Mimura et al. (1986) help to clarify the issue, by giving these conclusions: the representative description of irregular waves is the mean condition for macroscopic effects, but is the significant condition measuring the highest one-third of waves for microscopic processes (governed by energy density or wave height squared). In those terms, wave runup elevation is certainly a macroscopic phenomenon linearly related to incident wave dimension and properly described in terms of the mean wave condition for comparison to effects with uniform waves. Independent evidence for this will be presented after the range of runup elevations in irregular wave action has been described.

Several studies have provided probability distributions for runup elevations measured with large incident waves. Figure 26 presents some published data, in a log-probability format with R normalized by the mean measured runup elevation R. The results from Führböter (1986), for large uniform waves on a smooth slope, give runup elevations along a straight line in this format, corresponding to a narrow log-normal probability distribution. Other results in Figure 26 relate to irregular waves with basically similar dimensions and water depths for comparison with the displayed Rayleigh distribution thought to give a conservative approximation to natural runup (USACE Shore Protection Manual, 1984). The field data of Erchinger (1976) summarize runup elevations for a 1 on 6 upper dike slope of grass-covered clay, during the hour of maximum water level in a North Sea storm. The additional results from Leidersdorf et al. (1984) reflect reported runup histograms for three test situations with rough compound slopes under controlled irregular waves.

For uniform waves, the range of runup elevations only extends about ±20% from typical values, but the range is greatly enlarged with irregular wave action, extending nearly from 100% below to 150% above the most common or modal values

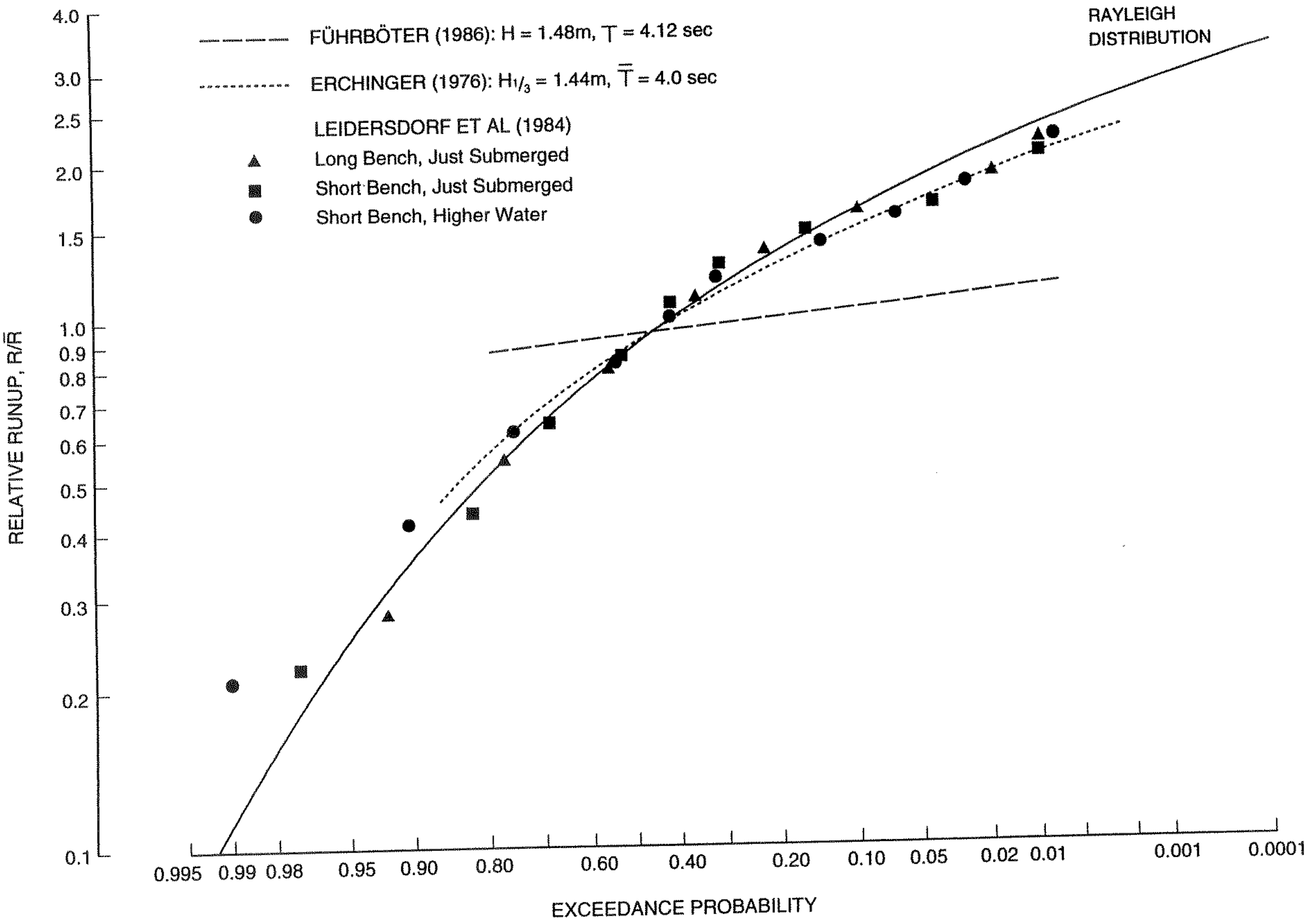


Figure 26. Probability distributions of measured wave runup elevations.

in these examples. Measured runup ranges here are all slightly narrower than implied by a Rayleigh distribution, so this appears to provide a convenient and conservative approximation in projecting relatively infrequent events. However, it seems clear that the Rayleigh distribution cannot give an entirely adequate account of extreme runup elevations.

Figure 27 presents three additional probability distributions as R/H_s, where documented local significant wave height has been used to normalize the runup elevations. Field data here (Grüne, 1982) pertain to a 1 on 4 asphalt dike during 15 minutes of a North Sea storm, with waves breaking over the tidal flat fronting the structure. One set of laboratory results (Führböter et al., 1989) refers to about 30 minutes of typical irregular wave action at a 1 on 6 asphalt slope. The final data set is from a proprietary test (Delft Hydraulics Laboratory, 1985) of waves with a particularly narrow frequency or period spectrum at a rough permeable slope of 1 on 3.5. Normalized runups are similar for these cases, but each set of results is appreciably narrower than a Rayleigh distribution and each exhibits some jointedness or multiple curvature. The upward curvature towards extreme elevations is least apparent in the shorter-term field results, but this is confirmed by reported ratios (Grüne, 1982) between runup elevations at various low exceedance probabilities. Extreme elvations depicted in Figure 27 reflect only a few runup episodes and may not conform to the probability distribution well defined by substantial samples of more common wave runups.

Battjes (1971) discussed runup elevations measured for a 1 on 3.6 dike slope of fitted blocks at lake sites with storm waves in the Netherlands. Runup clearly was well described by a Rayleigh distribution at least for 0.95 to

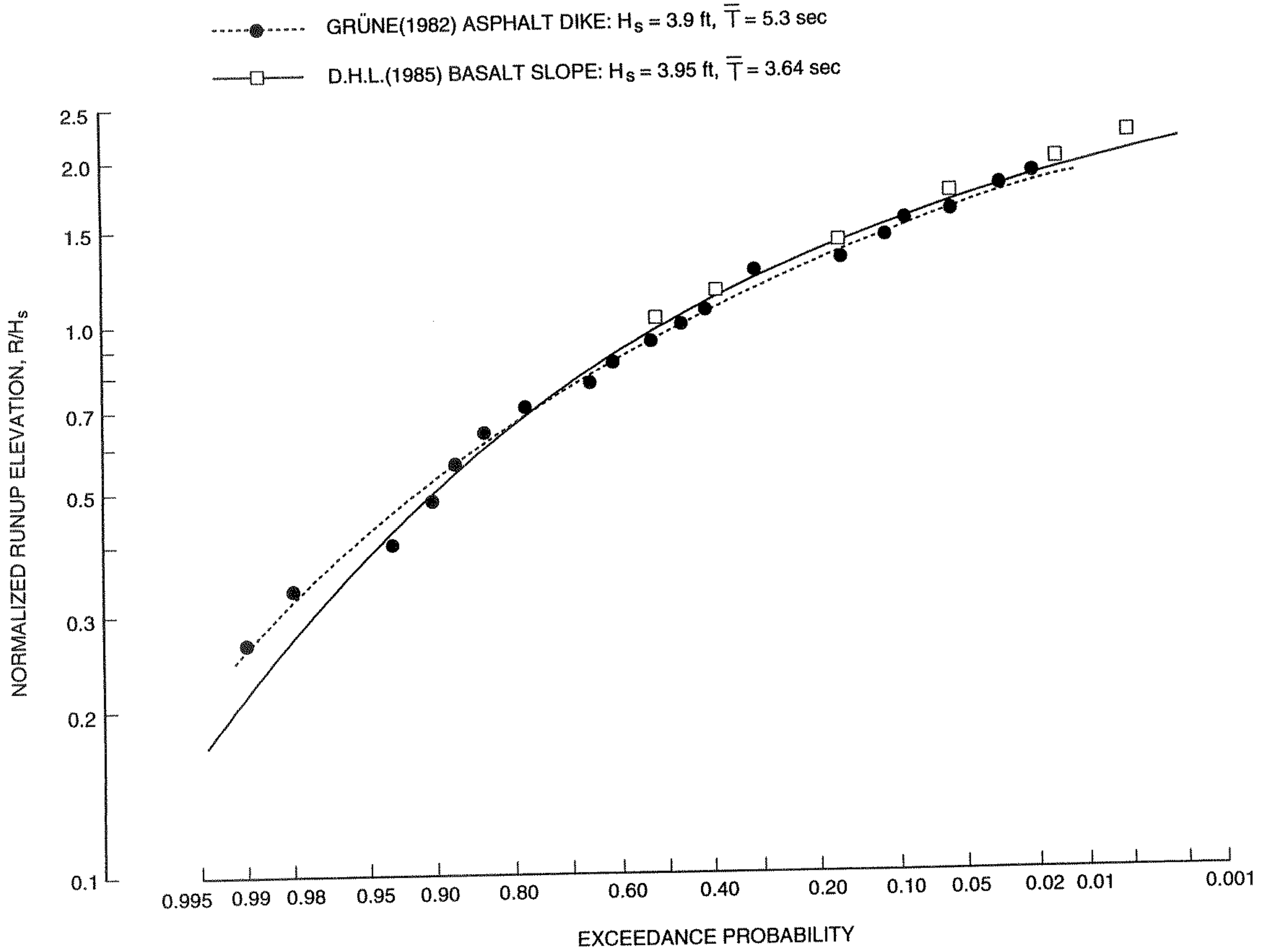


Figure 27. Additional probability distributions of elevations as R/H_s.

0.05 exceedance probabilities. Battjes (1971) surmised that one factor in this result was the dike berm near usual water level acting to increase the spread of runup elevations, and speculated that runup on plane slopes would generally extend over a narrower range than the Rayleigh distribution. Such an effect of barrier geometry is fully consistent with all results in Figures 26 and 27, although other factors may merit consideration with regard to conformance to the Rayleigh distribution. For example, an appreciable contribution from wave setup must tend to decrease the range of normalized runup elevations, when they are defined to include that component.

From available evidence, the Rayleigh distribution provides a usually meaningful approximation for a wide range of runup elevations with irregular wave action. Its exact usefulness remains to be defined for a fully representative range of structure and incident wave characteristics. However, residual uncertainty about exact shape of the probability distribution seems of lesser importance than the question of locating the basic curve in irregular wave action, that is, specifying one wave runup elevation having some certain exceedance percentage.

In regard to this question, wave runup measurements of Vellinga (1986) are of particular interest because the test profile closely corresponds to that recommended for FIS usage where simple duneface retreat is expected during the 100-year event (FEMA, 1989). Those runup elevations in a simulated extreme storm may help to clarify the correct interpretation of computed results in treatment of irregular wave action. Table 3 presents input and output of the modified FEMA Model for this case, with specified values of H_o covering a wide

```
CLIENT- FEMA                    ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY          JOB
PROJECT-DELTAGOOT TEST 1 OF ERODING SAND DUNE                                    RUN      PAGE  1
*****************************************************************************************************

                   CROSS SECTION PROFILE

                  LENGTH    ELEV.    SLOPE     ROUGHNESS

      1              0.0      0.0
                                     FLAT        1.00
      2             66.0      0.0
                                    56.97        1.00
      3            544.0      8.4
                                    14.62        1.00
      4            569.0     10.1
                                    23.03        1.00
      5            645.0     13.4
                                    10.91        1.00
      6            669.0     15.6
                                     0.73        1.00
      7            672.6     20.5

                      LAST SLOPE    1.00      LAST ROUGHNESS    1.00
```

```
CLIENT- FEMA                    ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY          JOB
PROJECT-DELTAGOOT TEST 1 OF ERODING SAND DUNE                                    RUN      PAGE  2
*****************************************************************************************************

                                         OUTPUT TABLE
                                         ------------

                     INPUT PARAMETERS                                  RUNUP RESULTS
                     ----------------                                  -------------

   WATER LEVEL     DEEP WATER                       BREAKING SLOPE    RUNUP SLOPE     RUNUP ABOVE      BREAK
   ABOVE DATUM     WAVE HEIGHT     WAVE PERIOD          NUMBER           NUMBER        WATER LEVEL      DEPTH
     (FT.)           (FT.)           (SEC.)                                              (FT.)          (FT.

     13.80            0.80            5.40                4                5              0.50            1
     13.80            1.20            5.40                4                5              0.60            2
     13.80            1.60            5.40                4                5              0.63            2
     13.80            2.00            5.40                4                5              0.71            3
     13.80            2.40            5.40                4                5              0.82            3
     13.80            2.80            5.40                3                5              0.91            4
     13.80            3.10            5.40                3                5              0.98            4
     13.80            3.50            5.40                2                5              1.07            5
     13.80            4.00            5.40                2                5              0.96            6
     13.80            4.50            5.40                2                5              0.88            7
     13.80            5.00            5.40                2                5              0.88            7
```

Table 3. Input and output of modified Model for runup at eroding sand dune in large test by Delft Hydraulics Laboratory (1983).

range up to the actual significant wave height of 5 feet, as originally recommended for FIS applications (Stone & Webster, 1981). Computed runup elevations in Table 3 do not approach the measured extreme of 4.4 feet above static water level. However, most results including that with the mean wave height of 3.1 feet are close to the actual mean runup elevation of about one foot.

With reference to Figure 26, probability distributions of actual runup elevations must intersect at some central point for comparable uniform and irregular wave action in a similar shore geometry. Associating mean runup elevation with the mean wave condition provides a simple and proper connection between the distributions, consistent with the empirical basis for runup guidance by Stoa (1978) and with other evidence mentioned previously. This viewpoint is supported by available data on runup elevations caused by irregular wave action in large tanks and in field situations. However, a clear demonstration of the empirical connection between the mean descriptions makes use of extensive laboratory measurements of small runups. (No adjustment for scale effect is applied in the following two sets of computations because of the small test waves.)

Kamphuis and Mohamed (1978) investigated situations with irregular waves on smooth slopes, documenting the mean runup elevation ($\overline{R}$) and the 2-percent-exceedance value ($R_{.02}$) commonly used as a representative extreme. With two types of generated spectra, measured wave characteristics were referred to deep water as the mean condition ($\overline{H}_o$, $\overline{T}$) and as a condition more pertinent to extreme waves, namely, the significant wave height and the period associated with peak energy in the spectrum (H_{os}, T_p). Figure 28a compares measurements to computations by the modified Model with $\overline{H}_o$ and $\overline{T}$ as input: $\overline{R}$ shows

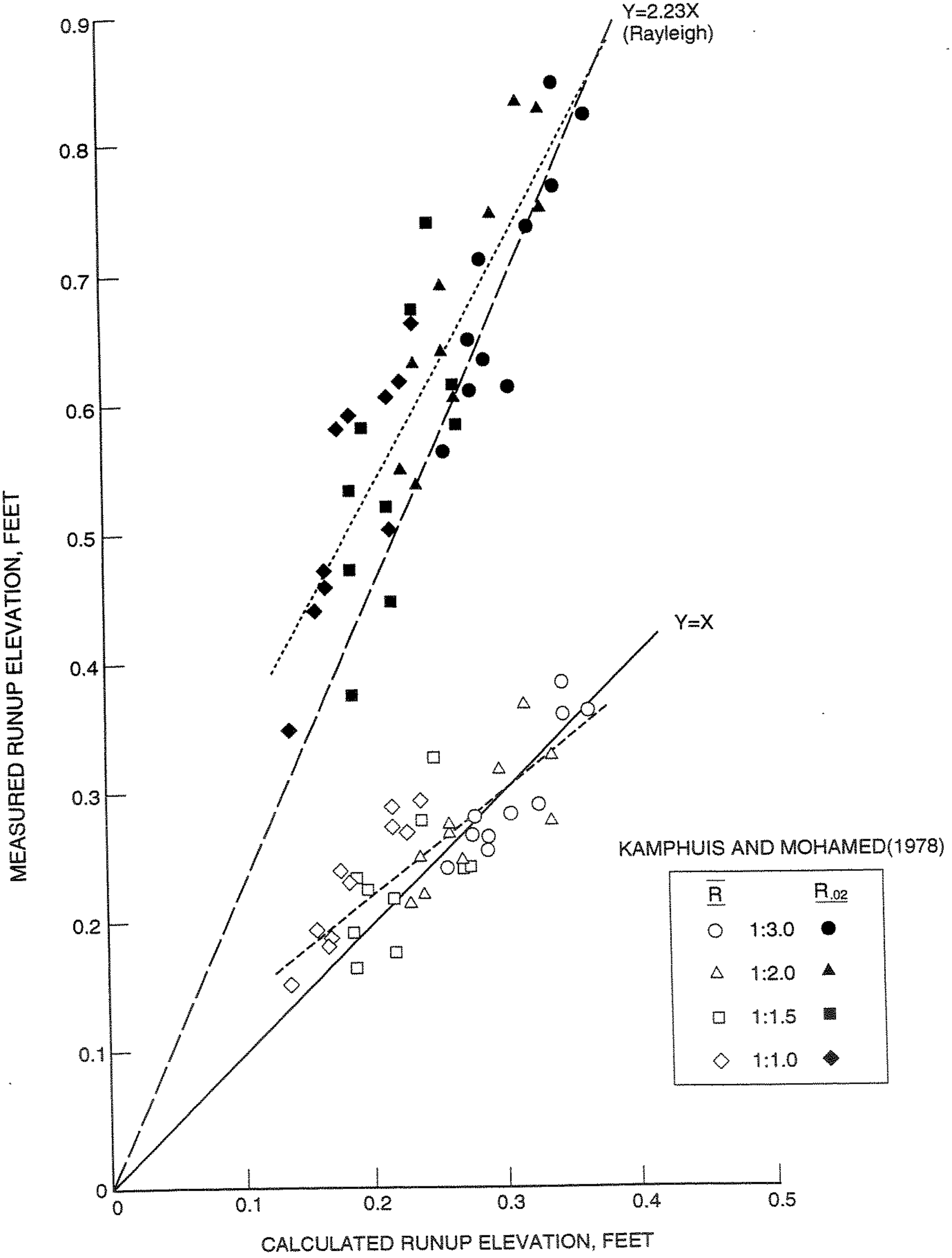


Figure 28a. Modified Model Results: Calculated and measured runup elevations with irregular waves reflecting from smooth slopes, described by the mean wave condition.

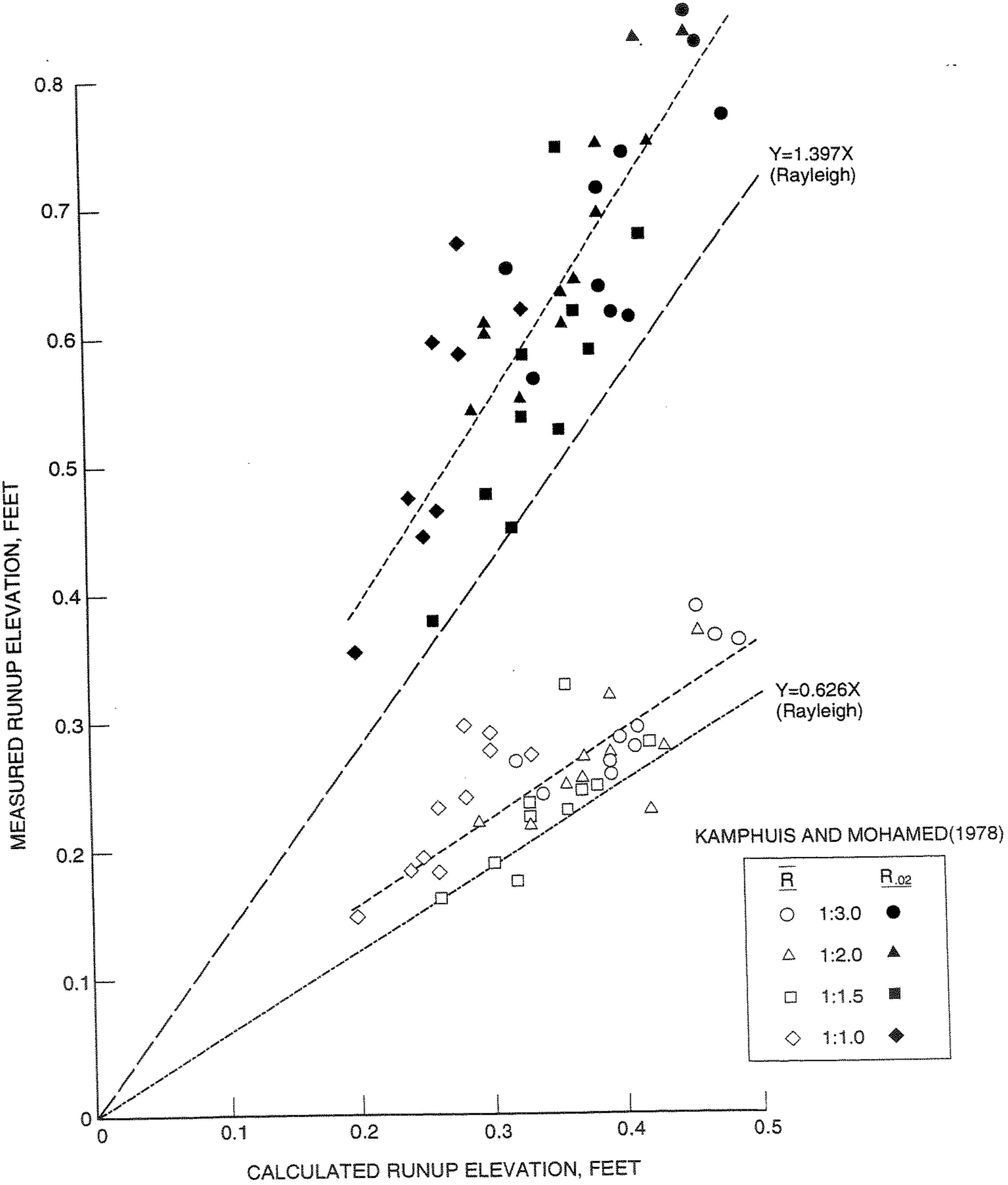


Figure 28b. Modified Model Results: Calculated and measured runup elevations with irregular waves reflecting from smooth slopes,described by the significant wave condition.

distinct quantitative agreement with computed values, and $R_{.02}$ is larger by nearly the factor that a Rayleigh distribution would indicate. More scatter is apparent in Figure 28b, where the same data are compared to alternative computations with H_{os} and T_p specified; in view of the theoretical relationships for a Rayleigh distribution, this display makes it clear that computed values are appreciably different from the significant runup elevations (i.e., the average of the highest one-third), contrary to guidance in the USACE Shore Protection Manual (1984). Measured runup elevations might be related in different ways to various chosen descriptions of irregular incident waves, but Figure 28 confirms that the mean wave condition is the proper specification in applying empirical results on runup elevation with uniform wave action. This evidence also indicates that the extreme $R_{.02}$ is more firmly related to computed runup elevation for the mean wave condition than for the significant wave condition in these simple situations. Runup computations here are rather sensitive to changed specification of waves because the steep test slopes imply near-maximum values of normalized runup, R/H. However, this demonstration is limited to irregular waves reflecting from plane slopes.

Supplementary results for breaking irregular waves on gentler smooth slopes have been published by Mase (1989). That study with overlapping wave and runup dimensions provided measured values of $\bar{R}$, R_s, and $R_{.02}$, from tests with a third type of generated wave spectrum and two selected degrees of wave grouping. Wave dimensions were described only by the significant condition, H_{os} and T_s, so runup computations for the mean wave condition proceed by assuming $\bar{H}_o = 0.626\ H_{os}$ (a Rayleigh distribution) and

$$\bar{T} / T_s = 1.173\ (H_{os}/L_{os})^{0.0762} \qquad (7)$$

as in related data for the Pierson-Moskowitz wave spectrum provided by Mase and Iwagaki (1984). Figure 29 presents comparisons of measurements and computations similar to those in Figure 28, and correlations are again notably less ideal with the significant wave rather than the mean condition as Model input. However, these new results differ to some extent: values of $\bar{R}$ measured by Mase (1989) are generally higher than computations, but values of $R_{.02}$ conform somewhat more closely to the expected multiple of computed mean elevations. Compared to the Rayleigh probability distribution, runup measurements of Kamphuis and Mohamed (1978) define a slightly wider range, whereas data of Mase (1989) define a somewhat narrower range. This discrepancy might be ascribed to different instrumentation or incident wave spectra; however, processes are also basically different, since waves break and runups occur at frequencies markedly lower than the incident conditions only in the tests by Mase (1989).

A recent USACE report (Walton et al., 1989) notes that the Shore Protection Manual provides "an untested methodology for using the results of the runup curves for computing irregular wave runup values." In the present examination, both sets of results indicate that the significant-wave treatment recommended in the USACE Shore Protection Manual yields an underestimate of intended runup elevations for smooth slopes. This is exactly opposite the conclusion by Gadd et al. (1988) based on large tests with rough slopes, where the recommended USACE treatment was reported to overestimate runup. The main point here is the firm relation between mean waves and runups, not the type of error arising with other assumptions. Effects with large irregular waves on various slopes remain of critical interest for further Model evaluations.

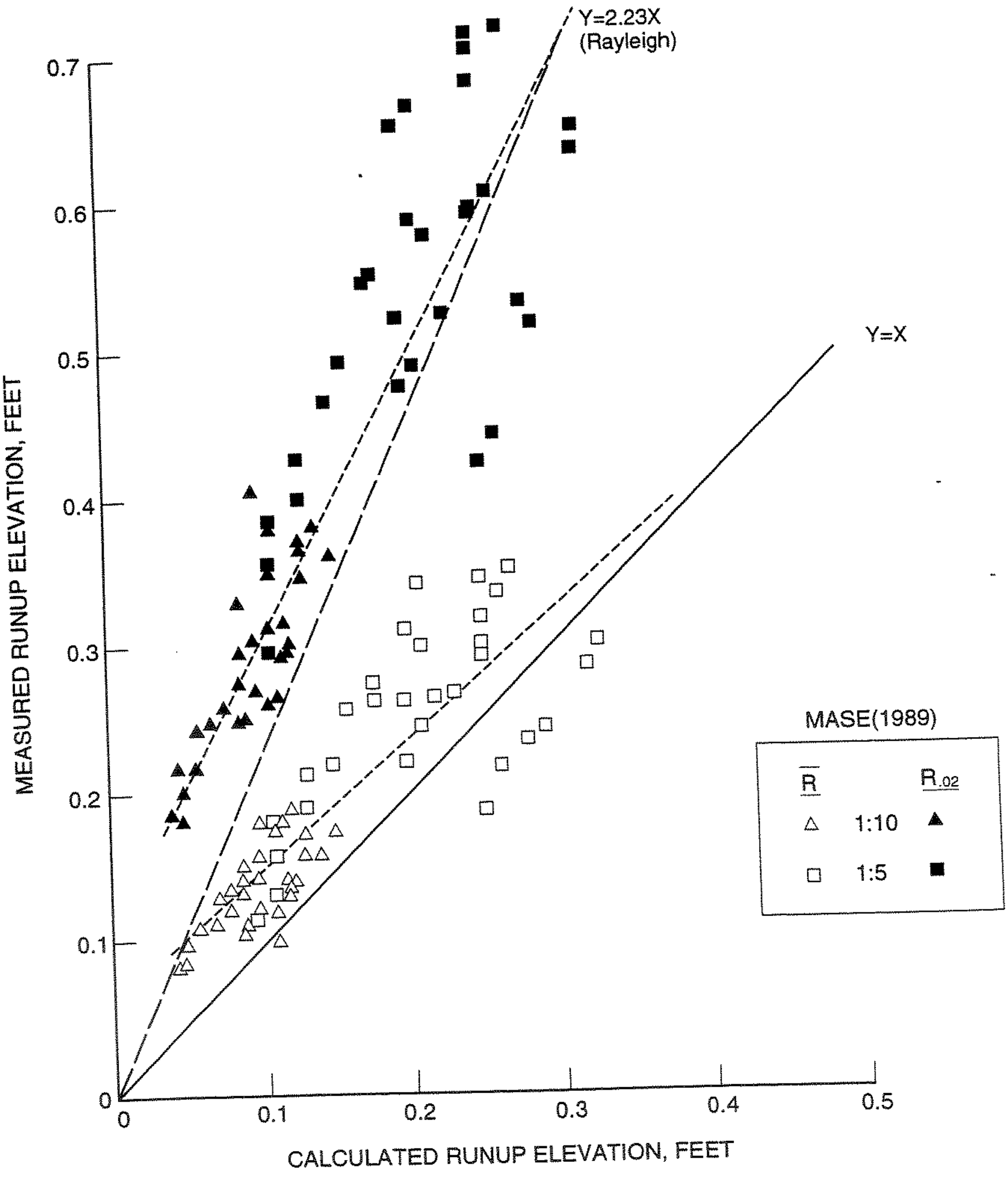


Figure 29a. Modified Model Results: Calculated and measured runup elevations with smooth slopes and irregular waves described by the mean condition.

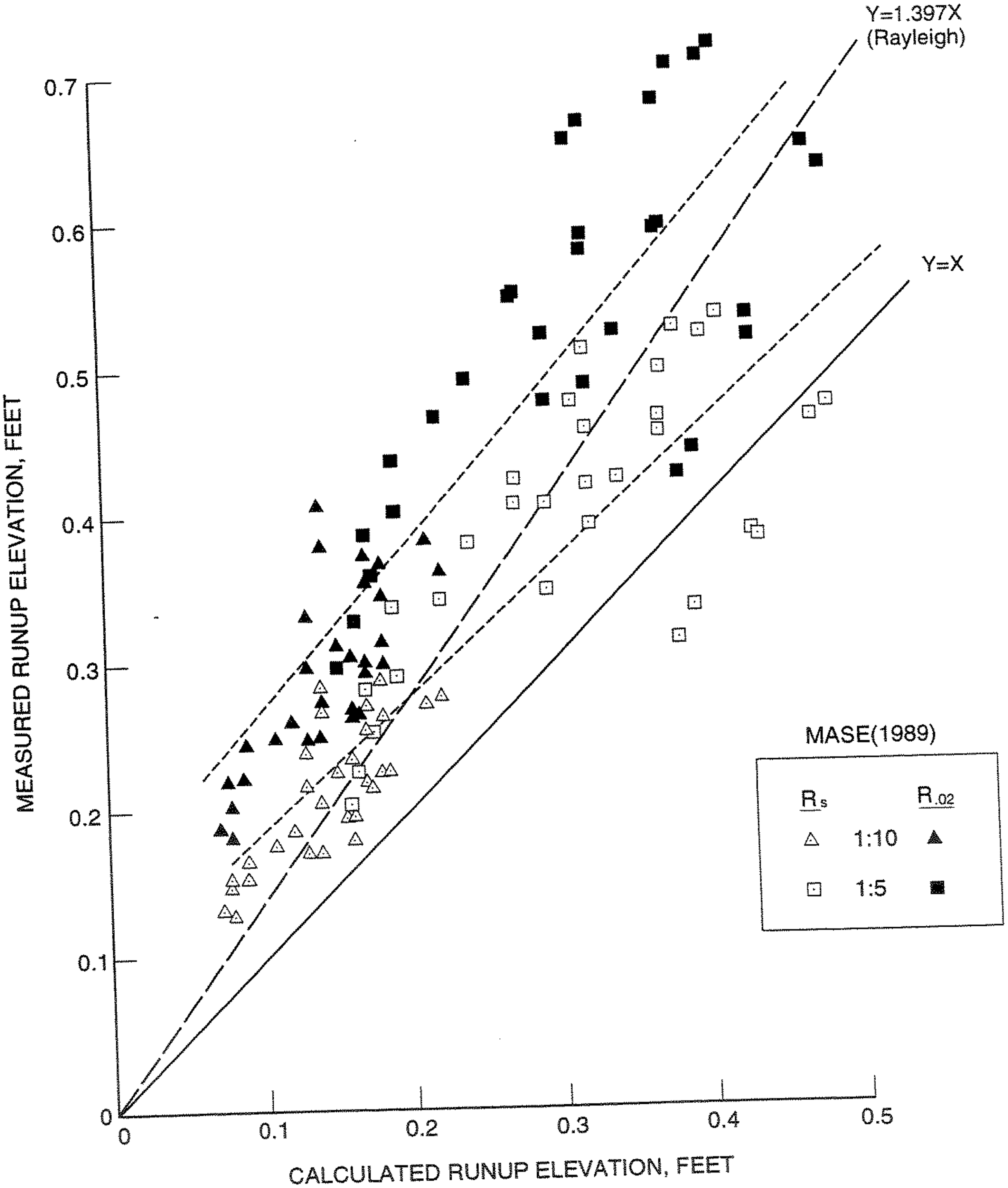


Figure 29b. Modified Model Results: Calculated and measured runup elevations with smooth slopes and irregular waves described by the significant condition.

Extensive runup measurements for irregular waves on protected slopes have been obtained in large tanks at Oregon State University, at Delft Hydraulics Laboratory and at the University of Hannover, but without full publication of exact conditions and results (e.g., Gadd et al., 1988; den Boer et al., 1983; Führböter and Sparboom, 1988). Figure 30 shows test configurations for some published data, and Figure 31 compares the mean runup elevations to computations using mean wave conditions with the modified Model. Those eight tests include rough structures and smooth slopes, but mean runup elevations are relatively small. Over the limited range represented, computations generally show quantitative agreement with the measured runup elevations; the notable exception is a measurement made while a relatively steep sand slope was adjusting to the start of erosive wave action.

Also, for the present investigation the Rijkswaterstaat of the Netherlands has granted access to several data sets covering a variety of configurations, and Figure 31 includes those results. Five additional configurations are represented here: a smooth concrete slope of 1 on 6, a grass-covered dike with slope primarily being 1 on 8, and three arrangements of fitted revetment having slope of 1 on 3.5. Roughness coefficients used in computations are 0.90 for the grass or revetment slopes. For the rough surfaces, distributions of runup elevations are available and the value corresponding to 46% exceedance has been used as a convenient estimate for mean runup, as implied by a Rayleigh distribution. The results for the grass dike correspond to peak and medium conditions during a storm simulation. For the smooth slope, available elevations are those exceeded by 2% and 13.5% of runups; the ratio there approximates that in a Rayleigh probability distribution, permitting a firm estimate of mean runup elevation from $R_{.135}$. This test situation included

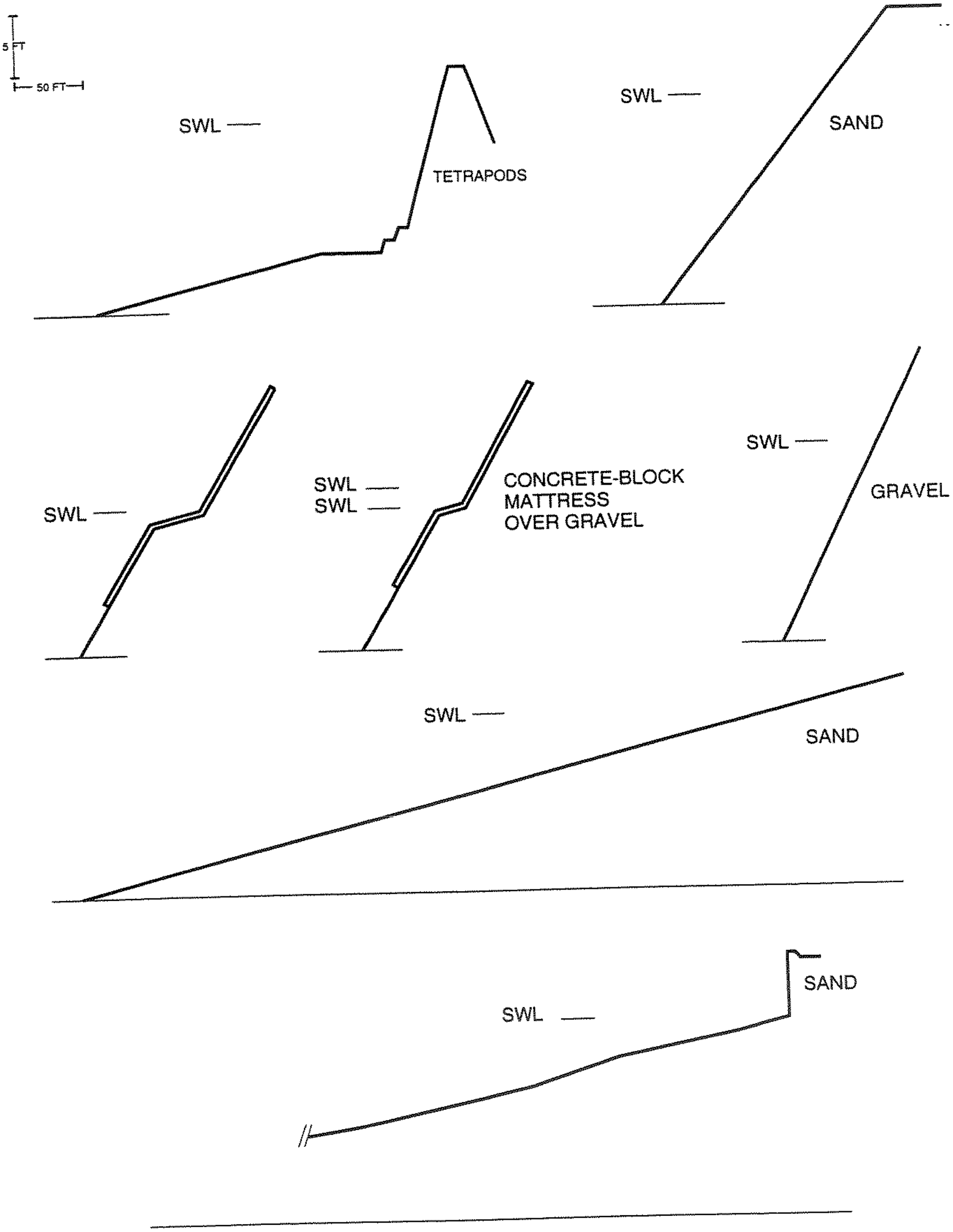


Figure 30. Test configurations with large irregular waves.

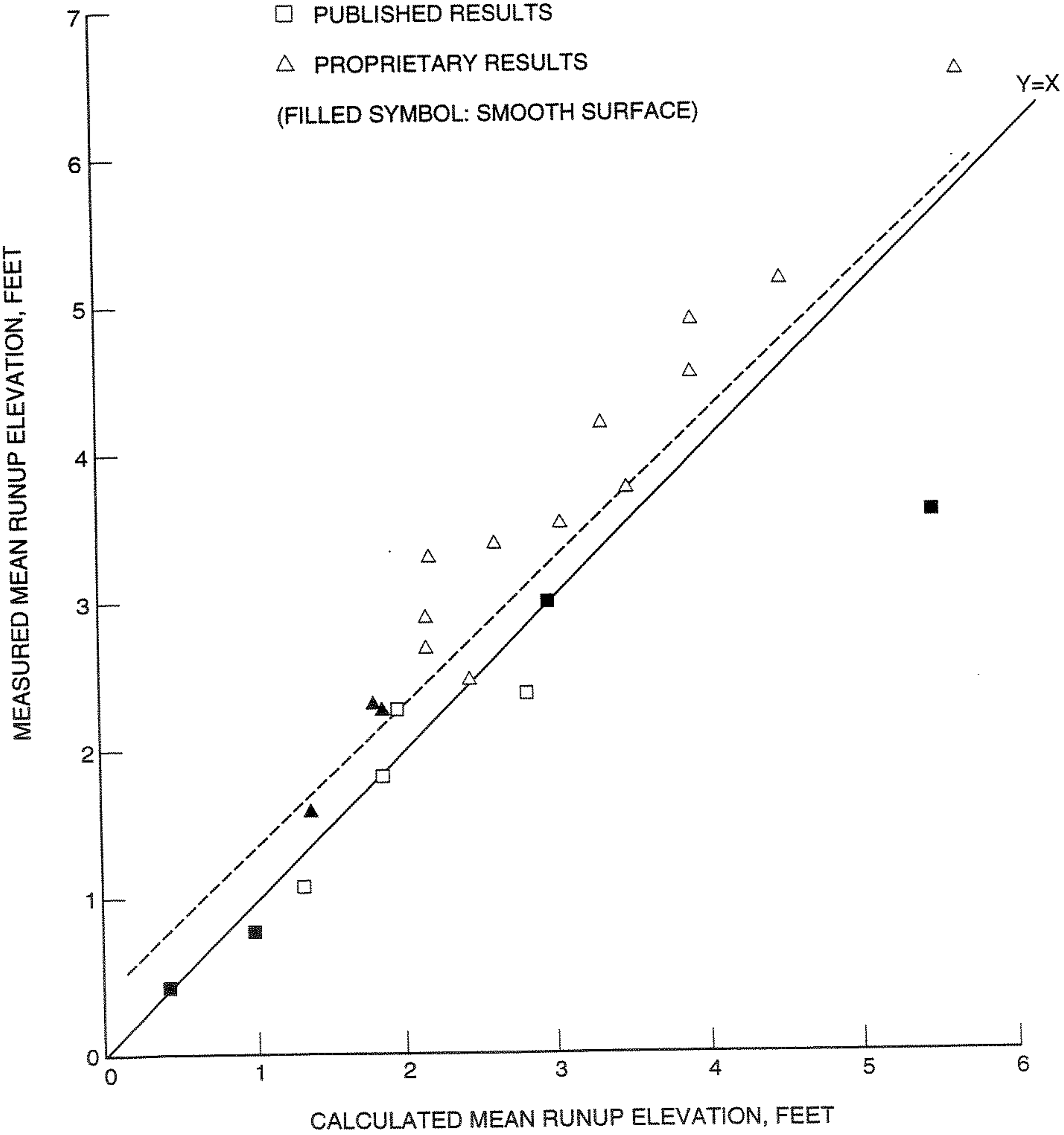


Figure 31. Modified Model Results: Calculated and measured mean runup elevations for large tests with irregular waves.

slight overtopping of the concrete barrier, usually by runups just exceeding $R_{.02}$; such effects should not have much influence on mean runup estimates. These additional results in Figure 31 provide extended confirmation of the predictable relationship between mean runup and mean wave conditions, although measurements are usually slightly higher than calculations. Overall, as previously, evidence indicates an error bar of less than ±0.5 ft in computing runup elevations for various large geometries, but Figure 31 results are all for relatively steep irregular waves.

The recent publication by Führböter et al. (1989) provides a sizable extension to available data on large runups in controlled irregular waves, for the Pierson-Moskowitz wave spectrum and a single barrier geometry. Median ($R_{.50}$) and extreme ($R_{.02}$) runup elevations are reported for smooth or slightly rough 1 on 6 slope, with incident waves documented by H_s and T_p. To calculate mean runup elevations using the modified Model, linear wave theory and T_p are used to define H_{os} and $\overline{H}_o = 0.626\ H_{os}$; with $T_p = T_s$, Equation 7 gives $\overline{T}$ by a form empirically valid for the wave spectrum and steepnesses tested. As previously for Figure 20, the artificial grass is treated by r=0.95, and the roughness blocks by r=0.90. Figure 32 compares measurements to calculations for these tests, showing definite agreement in trend but appreciable scatter for the wide range of wave steepness represented here. Values of $R_{.50}$ are generally somewhat higher than estimates for $\overline{R}$, but Figure 32 appears to reflect some remnant scale effect tending to inflate runup measurements: the more intense flows as measured by RE* yield the best agreement with runup estimates.

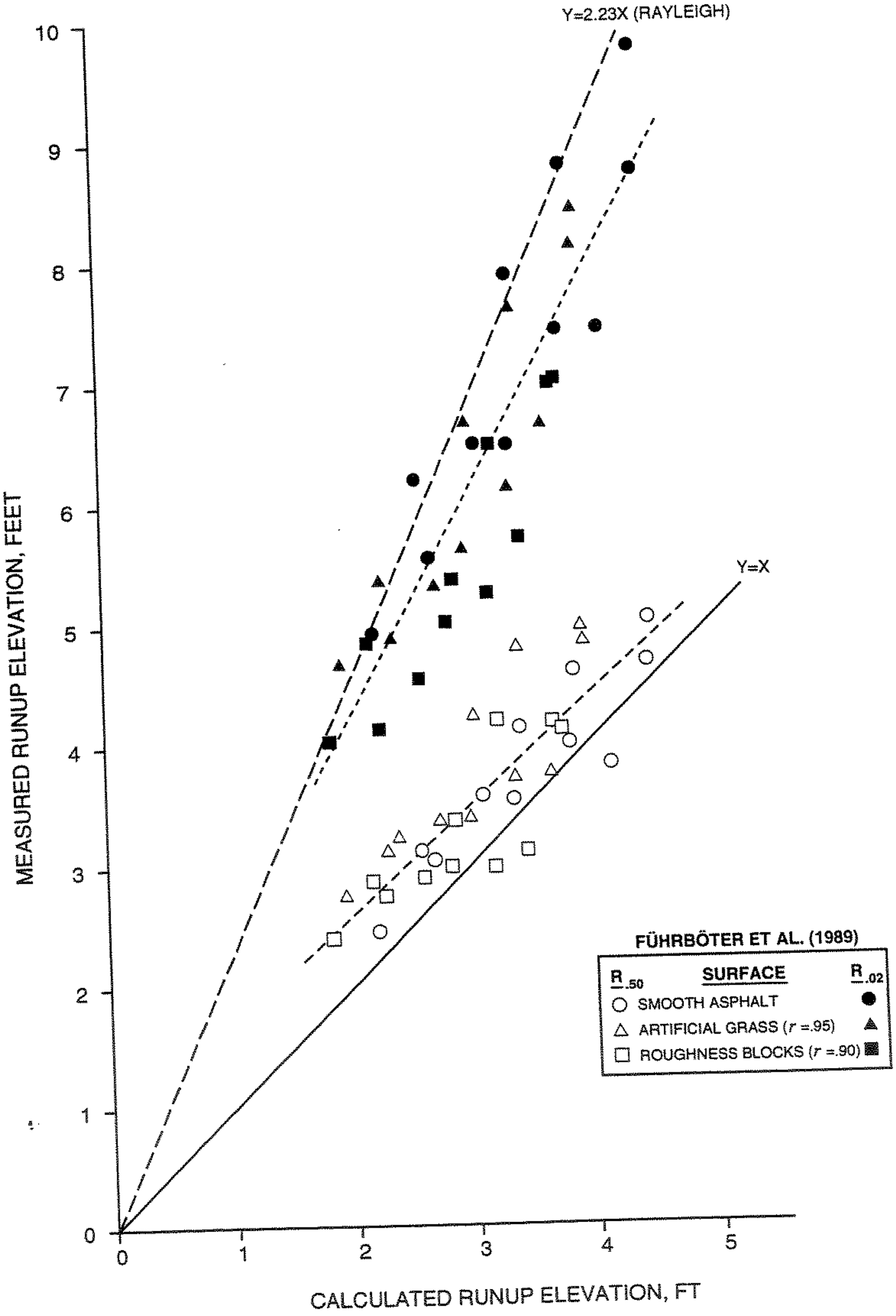


Figure 32. Modified Model Results: Calculated and Measured Runup Elevations with Large Irregular Waves on 1:6 Slope.

Another potential explanation for consistent underestimates of usual runup elevations in Figures 29a, 31, and 32, but not in Figure 28a, would be that the runup guidance for uniform waves does not fully manifest the wave setup component arising in irregular breaking wave conditions. The decay of wave height across the surf zone controls wave setup at the shore, and breaker dimensions and their variations are appreciably different between uniform and irregular waves. Wave setup might commonly be larger in irregular waves because the opposing wave setdown outside the well-defined surf zone with uniform waves may not occur. However, there appears to be no possibility at this time for an authoritative correction to present runup estimates, in the absence of empirical guidance for setup differences depending on wave character with fairly steep slopes.

In Figure 32, $R_{.02}$ values are seen to be markedly smaller multiples of $R_{.50}$ or $\overline{R}$ than a Rayleigh probability distribution would imply, particularly in data for the rough barriers. Runup distributions here are notably narrower than in the Figure 29a results from Mase (1989), for comparable smooth slopes and the same wave spectrum. The discrepancy may be attributed to test scale or to some effect on rough slopes narrowing the distribution of runup elevations. Another discrepancy in large irregular waves is evident between measured runup distributions for the two test series with 1 on 6 smooth slope. The present tests yield runup elevations conforming (Führböter et al., 1989) to a log-normal probability distribution notably narrower than the Rayleigh distribution. Proprietary Dutch tests, as previously discussed, support a Rayleigh distribution for wave runup elevations, even though incident waves had a relatively narrow (JONSWAP) spectrum. The difference in extreme runups might arise because slight overtopping occurred in the Dutch tests. However, usual wave runup elevations mesh well between these two data sets and show similar correlations with runup calculations. This behavior appears in agreement with the analysis of breaking-wave runups by Battjes (1971), concluding that only slight variations in mean runup result from extremely different incident spectra or stages in wave development.

Although fully documented data sets are scarce for field situations, wave runup elevations appear extremely variable. A field study by Terada (1976) on the Pacific coast of Japan includes measurements of wave height in deep water, wave period, and runup elevation on the coarse sand foreshore (1 mm grain diameter). The statistical measures for these variables are not specified, and reported values are used directly here. Typical values are wave height of 6 feet, wave period of 7 seconds, an essentially plane slope of 1 on 10, and runup of 5 feet above mean sea level, so conditions are comparable to some large tests. Figure 33 compares computed with measured runup elevations, demonstrating that the modified Model provides appropriate magnitudes for these cases. An error bar here would be about ±1.5 feet and the scatter is so large for this single data set that there is no appreciable correlation between calculations and measurements. The amount of scatter appears similar to that in field measurements of Holman (1986), and a much larger data set or wider elevation range is required to demonstrate predictability of the variations in field wave runups.

This is illustrated using other field results also displayed in Figure 33. Battjes (1971) and Technical Advisory Committee (1974) documented median runups of about 1 to 3 ft with a compound dike slope at two sites on the large IJssel Lake in the Netherlands. These runup elevations apparently refer to

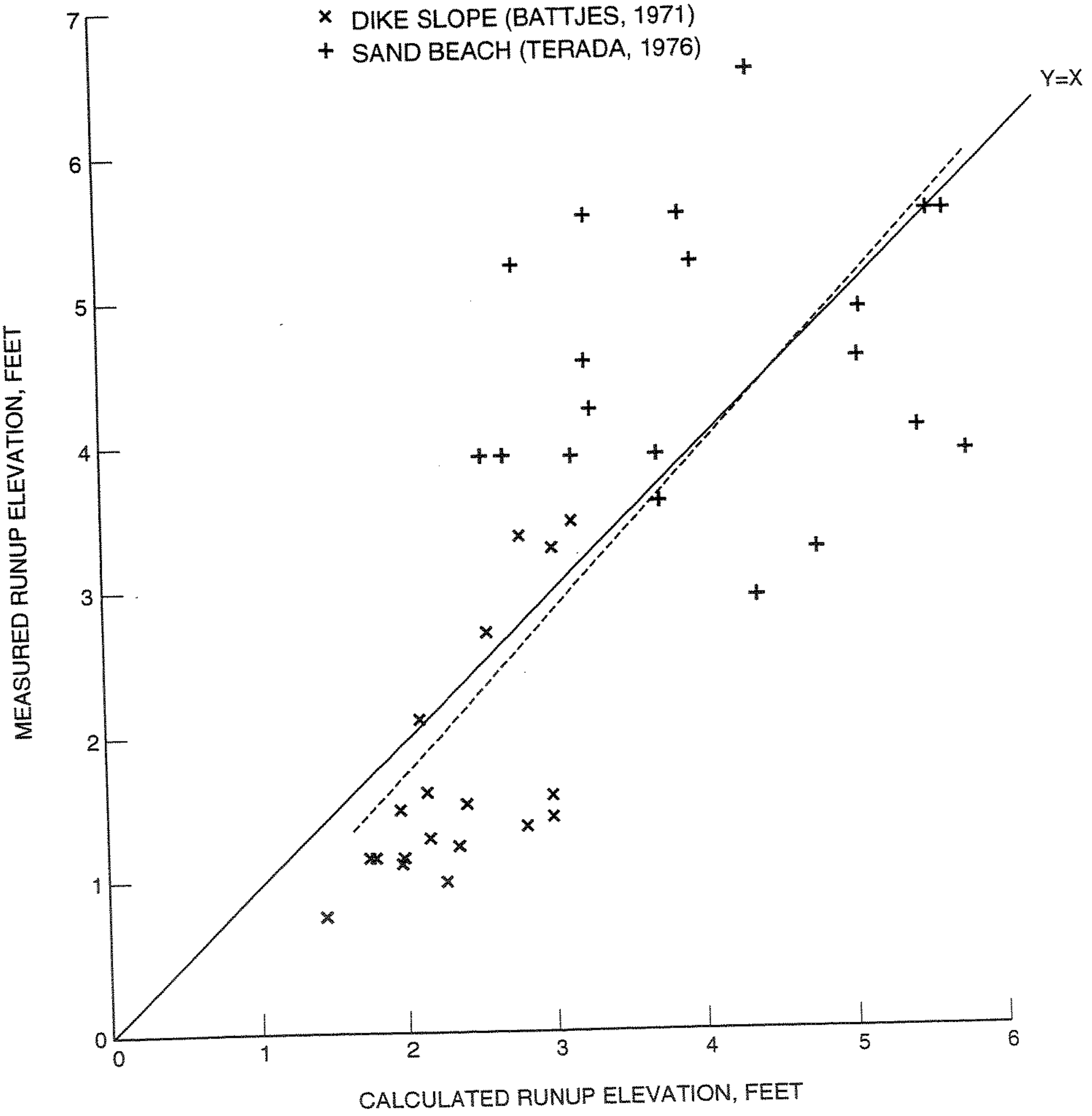


Figure 33. Modified Model Results: Calculated and measured runup elevations in two sets of field data.

measured mean water level, and thus exclude the wave setup component. Wave conditions were not recorded but may be deduced from the reported wind velocities, straight-line fetches, and approximate water depths; estimates following the Shore Protection Manual yield typical mean wave conditions of $\overline{H}_o$=2.6 ft and $\overline{T}$=3.6 sec, the latter value in agreement with other information provided by Battjes (1971). Figure 33 presents reported versus calculated runup elevations, with r=0.90 used in calculations for the dike surface of closely set blocks. There is a statistically significant correlation for this data set, although calculated runups are usually too large (probably due to the exclusion of wave setup from reported runup elevations). However, a much more ideal correlation between measurements and calculations arises over the broader elevation range in combined results from Battjes (1971) and Terada (1976).

The extensive field data set by Toyoshima (1988) gives large runup elevations observed at a seawall located on the Sea of Japan. That structure has 1 on 5 slope faced with fitted "Lotus-Uni" blocks, and the runup measurements pertain to 6 separate storms during four months. Documentation includes mean water level during each observation interval along with somewhat extreme values describing the deepwater wave height, the wave period, and the wave runup elevation. Documented wave and runup conditions are unusual statistical measures but appear to differ from customary significant descriptions only to a relatively minor extent; reported values are used directly here. A roughness coefficient of r = 0.90 was assumed for calculations, since a value intermediate between those for Gobi and Armorflex blocks would appear appropriate. Figure 34 compares computed results from the modified Model to the reported runup elevations ranging from 9 to 19 feet above mean water level.

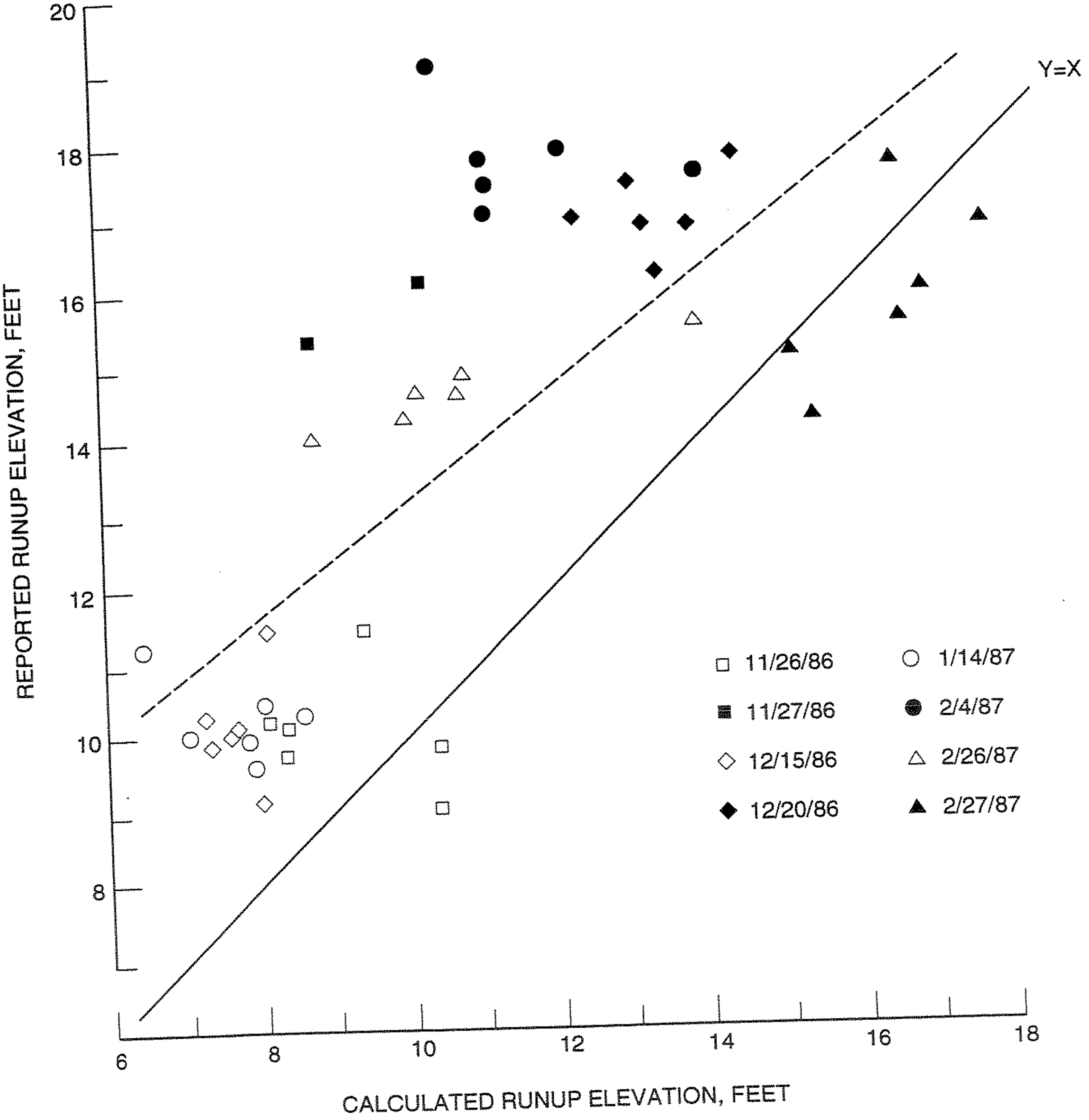


Figure 34. Modified Model Results: Calculated and measured runup elevations for storm waves on a sloping seawall (Toyoshima, 1988).

Measurements and computations exhibit a statistically definite relationship here, despite the troublesome aspects of reported values and the occasional wave overtopping. Actually, this set of field results shows behavior generally similar to laboratory results for a smooth 1 on 5 slope in Figure 29b, but magnitudes in Figure 34 are larger by a factor of about fifty and the correlation is somewhat closer to ideal here. The evident underprediction of these measurements might be ascribed to the use of (approximately) significant descriptions for waves and runups, as in Figure 29b; however, the possible underestimate of the wave setup contribution to storm wave runups could also be a factor in these results.

Figure 35 displays another analysis demonstrating that these runup measurements have a functional dependence on wave conditions in definite agreement with Equation 1 from Hunt (1959). The dashed regression line is given by

$$R/H_o = 0.236\ (H_o/L_o)^{-0.498} \tag{8}$$

with a coefficient of determination equal to 0.616. Measured runup again appears relatively high for a slope with tangent equal to 0.2, without considering the expected reduction attributable to slope roughness. The Model computations used for Figure 34 explain a lesser amount of total data variance than does Equation 8 in Figure 35, indicating that a simplified analysis may be all that is fully warranted for this data set where neither waves nor water levels were measured near the seawall.

Scattered and magnified runup elevations relative to laboratory results have commonly been noted in field investigations during storms (Erchinger, 1976; Grüne, 1982; Holman, 1986), and several complicating factors might contribute

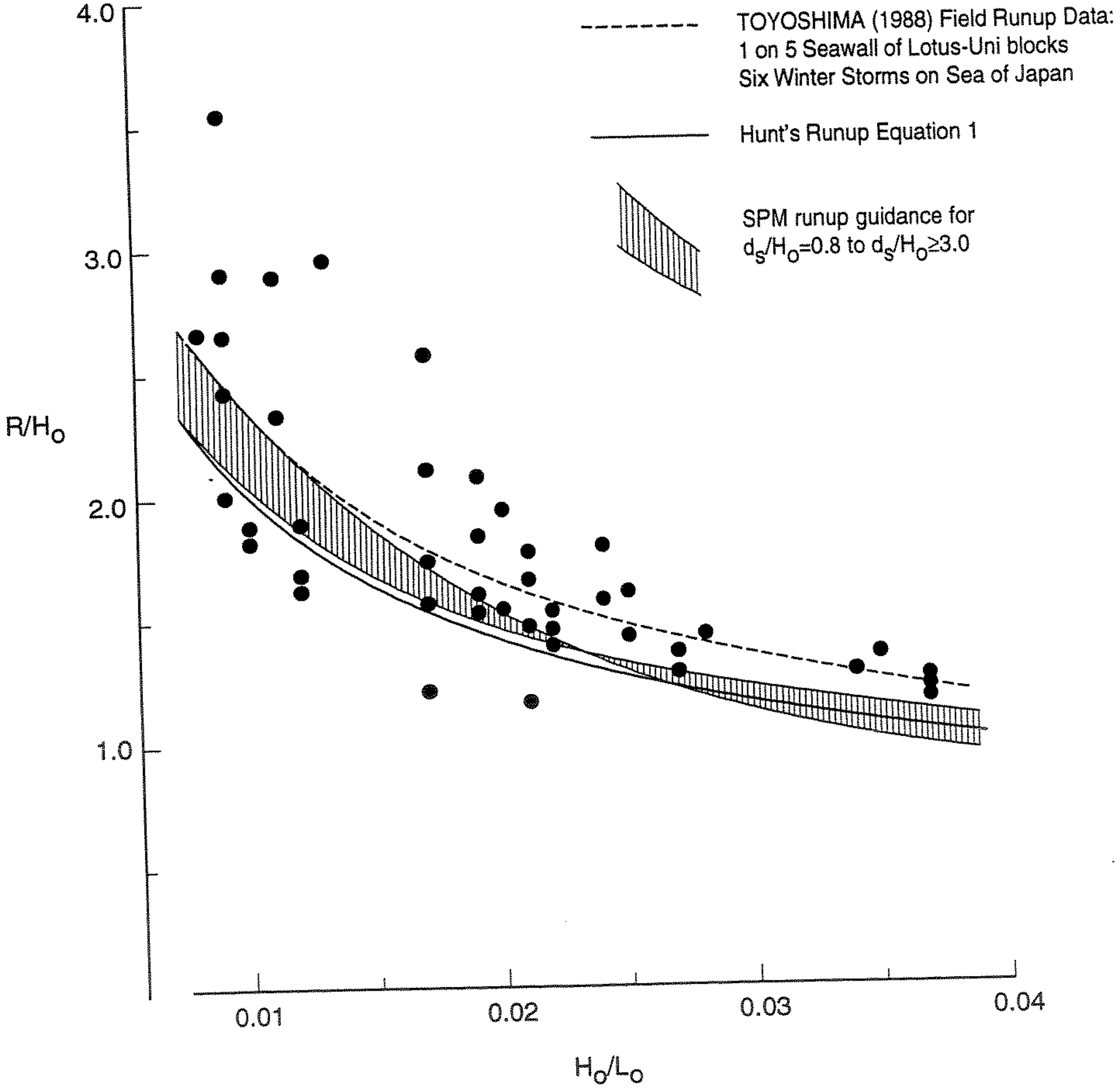


Figure 35. Another analysis of field runup data for a sloping seawall.

to this. Aside from extreme prototype flows, one factor of possible importance is the usual wave obliquity and another is onshore storm winds, which are thought to increase water overtopping rates where wave runup elevations exceed that of the barrier crest (USACE Shore Protection Manual, 1984). The potential effect with onshore winds in extreme storms may be an increase of about 25% in extreme runup elevations, according to the overall trend in field data of Grüne (1982) for windspeeds of up to 40 mph. However, that apparent effect might be due to other natural variables, and there is no authoritative guidance regarding runup elevation increases due to onshore wind. Also, the most definitive study (Jensen and Juhl, 1987) describes increased wave overtopping with wind as arising through effects on water spray, not on the uprushing water mass directly related to wave runup. It does not seem appropriate to attempt correction of runup estimates for the present application until typical field effects have been defined to the point of practical engineering guidance.

Summary and Conclusions

The major finding here is definite agreement in magnitude and trend between runup computations and measurements for a wide variety of shore geometries, slope characteristics, and wave conditions. Table 4 provides a summary of linear regression results for large wave runups in four distinct categories. Runup elevations are clearly predictable although there is generally increased scatter for rough slopes, for irregular waves, and for field situations, where processes are more complicated than allowed in the basic empirical guidance for smooth slopes of simple geometry, with uniform, normally incident waves, and no wind or currents. The measured runup elevations up to 19 feet above static water level cover most values to be expected at usual shore barriers during an extreme storm. Although the modified Model has been verified as accurate only for the specific ranges of conditions in present test cases, this evaluation of automated computation procedures points to the Model's usefulness over the full coverage of underlying USACE guidance.

Present procedures avoid direct comparison of various empirical results, where detailed consideration of exact conditions and measurement techniques would be advisable. Here computations are treated somewhat as a standard, and available measurements are shown to agree with computed results. Also, the measurements considered here reflect prototype runup magnitudes, except where investigations with large waves are scarce. In this way, validation of the runup elevations given by modified Model has been approached directly.

Table 4. Summary results from linear regression of large measured runups on Runup Model computations.

CLASSIFICATION	DATA POINTS	RANGE OF MEASURED RUNUP, FEET	INTERCEPT Yo (feet)	SLOPE m	COEFFICIENT OF DETERMINATION
Large uniform waves on smooth barriers	113	0.6-17.1	-0.051	1.022	0.934
Large uniform waves on rough barriers	261	0.9-10.0	-0.094	1.023	0.900
Irregular waves in large tanks	67	0.5-6.5	0.530	0.950	0.801
Natural waves in three field studies	82	0.8-19.1	0.312	1.120	0.865

Results for irregular waves are of particular interest, and these corroborate previous indications that mean runup elevation is determinable using the mean wave condition with standard guidance for uniform waves. This evaluation includes a variety of situations, but is restricted by the small number of large tank results published at present. Continued evaluation of Model computations seems advisable as additional data sets become available for large irregular waves and for field situations, since this topic is critical in application of runup estimates. From present evidence, however, no distinct empirical weakness is evident in the obvious procedure to estimate mean runup elevation for the mean wave condition likely to be associated with the 100-year event. This procedure simply avoids uncertainties involved in prediction of the spectrum of runup elevations for arbitrary shore geometry. In the present application, runup estimates based on laboratory measurements with uniform waves thus appear useful and trustworthy.

This extensive verification of computations using runup measurements provides distinct confirmation for details of the basic runup treatment. New features exercised in present evaluations of the modified Model include: geometrical analysis of the situation to isolate the effective shore structure and the approach segment of the profile; treatment by means of Saville's composite-slope method wherever direct runup guidance is not fully pertinent; and several interpolations incorporated within computations of runup elevation. These features provide consistent runup estimates by guaranteeing smooth variations in computed results for most small changes in basic conditions. Improved predictions of runup elevation are clearly evident for relatively complicated shore geometries, through closer conformance to USACE guidance.

From the present evidence, computations agree with total runup elevations as commonly measured, reflecting both wave setup and swash effects. This is most clearly demonstrated for a wide range of situations by results in Figure 13. Those runup measurements pertain to wave durations from about one minute to several hours, and thus include various portions of the wave setup expected to arise for a steady state. Computations appear to indicate accurately the combination of setup and swash contributing to wave runup elevations.

Also, runup measurements largely support usage of USACE guidance on scale and roughness factors as multipliers of runup estimates from curves for smooth slopes with small waves. There is no evidence of serious weakness in the scale-effect correction (Stoa, 1978) over the range of smooth slopes represented in the present data base. Although estimating runup by means of a roughness coefficient clearly provides a coarse approximation, the present evaluations generally confirm standard guidance on useful r values for various barrier-surface characteristics (Table 5). Since available results cover only a limited selection of common construction materials and slopes, continued usage of approximate roughness factors with smooth-slope results appears unavoidable in runup estimation at present. This approximation might introduce lesser errors for irregular storm waves, in that a wide range of breaker conditions then contributes to the mean runup elevation.

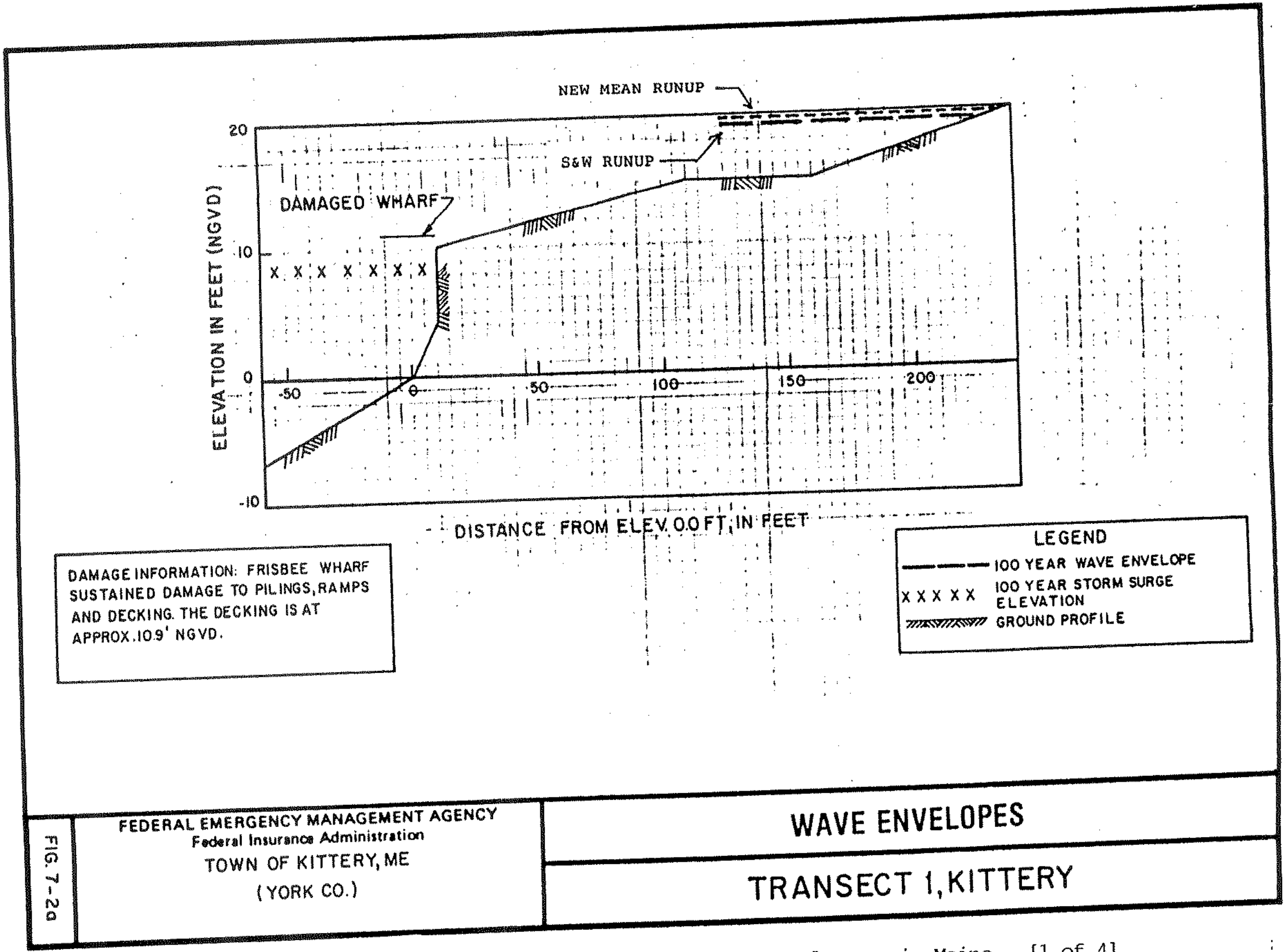
Table 5. Values of the roughness coefficient r for various slope characteristics, from USACOE Shore Protection Manual (1984).

Slope Surface Characteristics	Placement	r
Smooth, impermeable	------	1.00
Concrete blocks	Fitted	0.90
Basalt blocks	Fitted	0.85 to 0.90
Gobi blocks	Fitted	0.85 to 0.90
Grass	------	0.85 to 0.90
One layer of quarrystone (impermeable foundation)	Random	0.80
Quarrystone	Fitted	0.75 to 0.80
Rounded quarrystone	Random	0.60 to 0.65
Three layers of quarrystone (impermeable foundation)	Random	0.60 to 0.65
Quarrystone	Random	0.50 to 0.55
Concrete armor units (~ 50 percent void ratio)	Random	0.45 to 0.50

VERIFICATION WITH HISTORICAL DAMAGE INFORMATION

This verification addresses the four transects originally considered by Stone & Webster (1981) for York County, Maine. For each transect, wave damage was recorded at a site above peak stillwater elevation during an extratropical storm in February 1978. As noted by Stone & Webster (1981), "the February 1978 storm has the characteristics of the 100-year flood producing storm" for this vicinity. All information on the physical situations is extracted directly from the Stone & Webster report, with the reported significant wave condition simply converted to a mean wave description for the present runup calculations using $\overline{H}_o$=0.626 H_{os} = 19 ft and $\overline{T}$=0.85 T_s = 12 sec. The runup calculations are fully documented in Appendix B and results are displayed in Figure 36.

On each transect, the calculated mean elevation of wave runup is above the reported damage location, as was the case with the original Stone & Webster verification in terms of R_{max}. However, computations with the modified Model have a straightforward statistical interpretation and agree with extensive measurements of large runup elevations due to storm waves. In two of four cases here, calculated $\overline{R}$ exceeds the previous R_{max}, confirming that the Stone & Webster computations did not provide accurate estimates for maximum runup elevation in these storm situations. Both the present results and the previously discussed evaluations support application of computed mean runup as a well-defined elevation in FIS assessments of flood hazards for the 100-year event. Appropriate application must of course take into account that $\overline{R}$ indicates usual rather than extreme limits to uprush water.



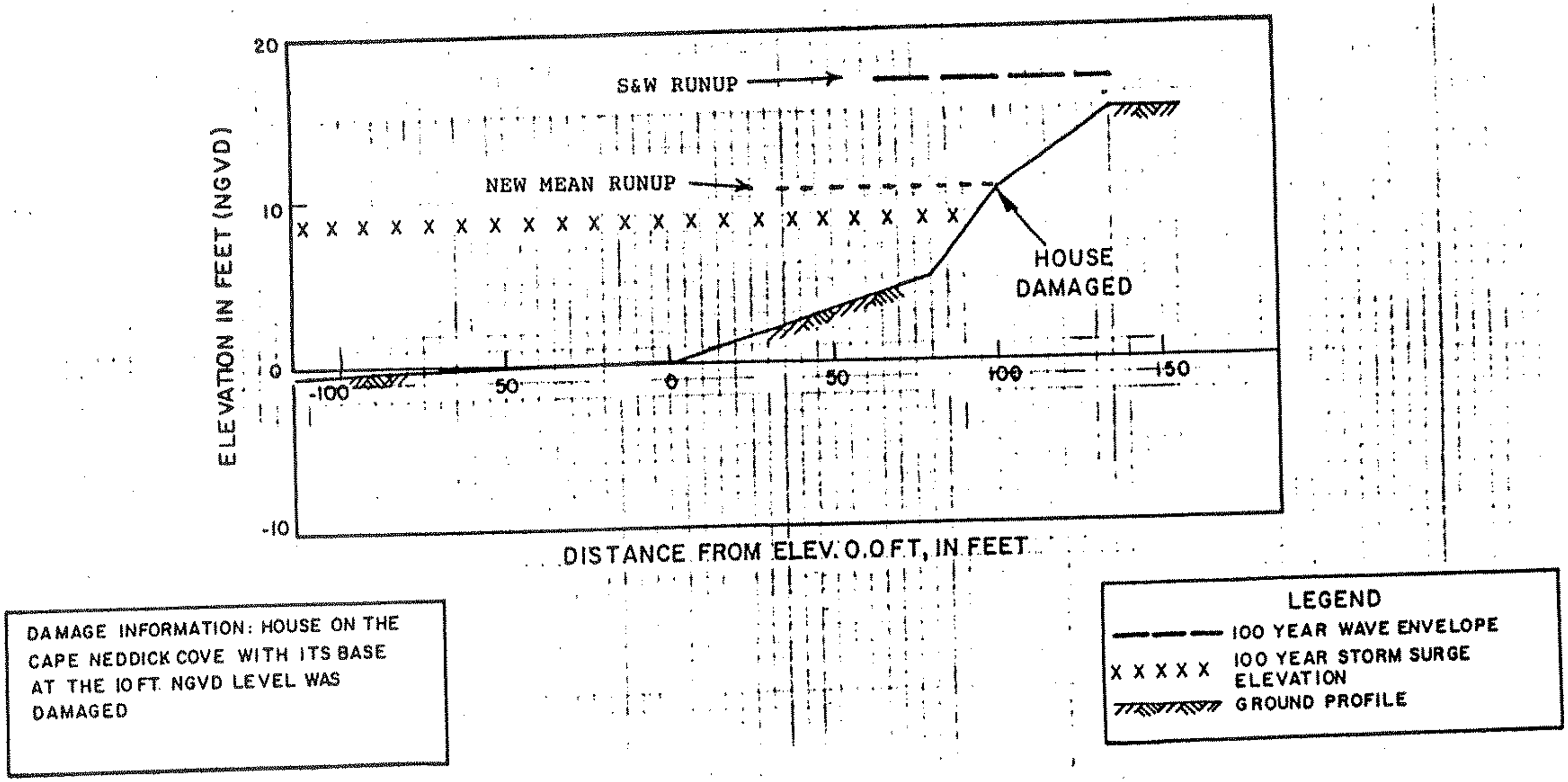
DAMAGE INFORMATION: FRISBEE WHARF SUSTAINED DAMAGE TO PILINGS, RAMPS AND DECKING. THE DECKING IS AT APPROX. 10.9' NGVD.

FEDERAL EMERGENCY MANAGEMENT AGENCY
Federal Insurance Administration
TOWN OF KITTERY, ME
(YORK CO.)

WAVE ENVELOPES

TRANSECT 1, KITTERY

Figure 36. Model verification for historical runup damages in Maine. [1 of 4]



DAMAGE INFORMATION: HOUSE ON THE CAPE NEDDICK COVE WITH ITS BASE AT THE 10 FT. NGVD LEVEL WAS DAMAGED

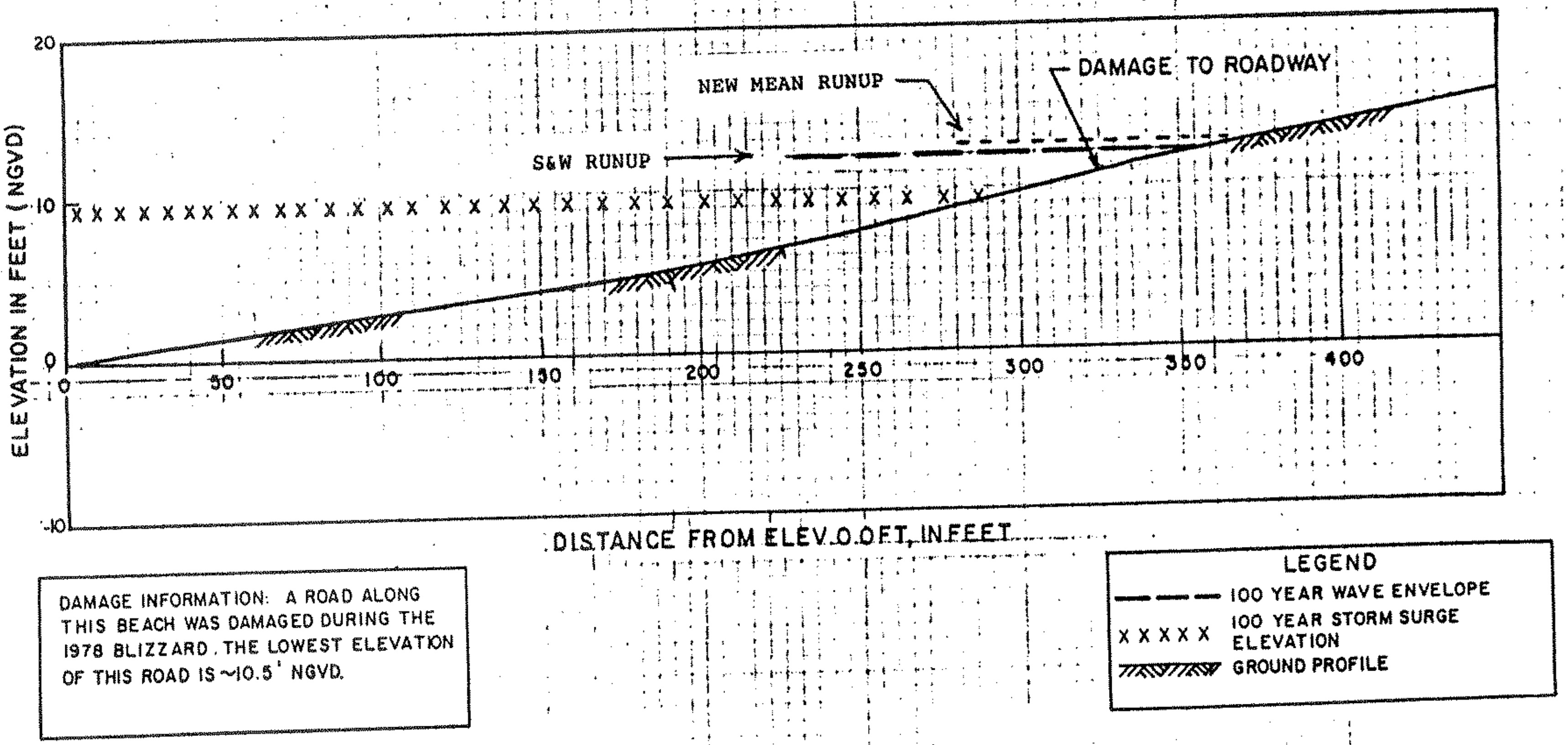
FEDERAL EMERGENCY MANAGEMENT AGENCY
Federal Insurance Administration
TOWN OF YORK, ME.
(YORK CO.)

WAVE ENVELOPES

TRANSECT 19-1, YORK

FIG. 7-2b

Figure 36. Model verification for historical runup damages in Maine. [2 of 4]



DAMAGE INFORMATION: A ROAD ALONG THIS BEACH WAS DAMAGED DURING THE 1978 BLIZZARD. THE LOWEST ELEVATION OF THIS ROAD IS ~10.5' NGVD.

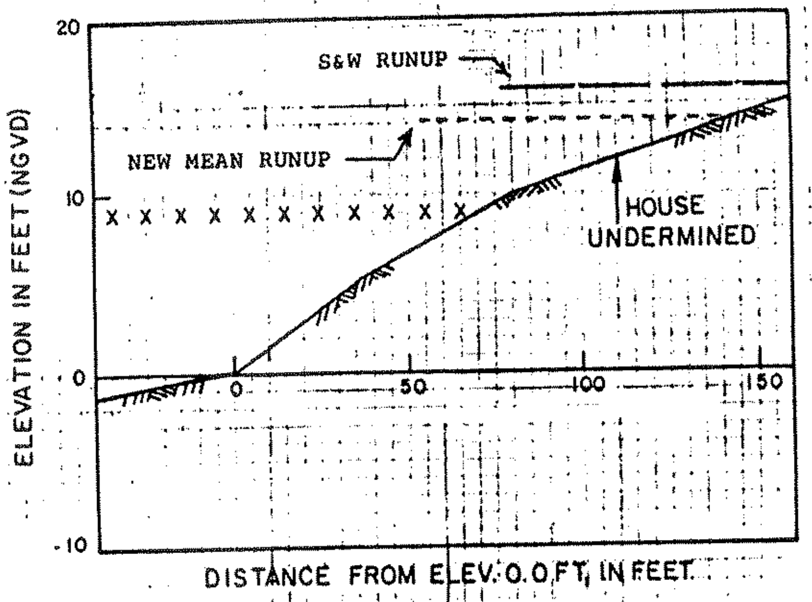
FIG. 7-2C

FEDERAL EMERGENCY MANAGEMENT AGENCY
Federal Insurance Administration
TOWN OF BIDDEFORD, ME
(YORK CO.)

WAVE ENVELOPES

TRANSECT 62, BIDDEFORD

Figure 36. Model verification for historical runup damages in Maine. [3 of 4]



DAMAGE INFORMATION: IN THE CAMP ELLIS AREA A HOUSE AT ~12' NGVD WAS UNDERMINED AND TIPPED DURING THE 1978 BLIZZARD.

FIG. 7-2d

FEDERAL EMERGENCY MANAGEMENT AGENCY
Federal Insurance Administration
TOWN OF SACO, ME
(YORK CO.)

WAVE ENVELOPES

TRANSECT 68-1, SACO

Figure 36. Model verification for historical runup damages in Maine. [4 of 4]

APPLICATION GUIDANCE

Wave runup remains a topic of intensive investigation, given the need for more accurate definition of the limit to expected wave effects and needed shore protection in extreme situations. Despite fundamental uncertainties regarding some aspects, present evidence indicates that mean runup elevation can be predicted from expected wave conditions in storm events for various shore geometries. Procedures executed in the modified FEMA Wave Runup Model blend direct empirical guidance from idealized situations with common approximate methods to treat complications, for example, in profile characteristics.

The procedure now specified for wave runup analysis in a coastal FIS is to employ the modified FEMA Wave Runup Model with the (single) wave condition expected to be associated with the local 100-year event. The wave condition related to mean wave runup consists of the mean wave height in deep water and the mean wave period. The estimated runup elevation provides a landward extension using standard procedures (Stone & Webster, 1981) to the extreme wave crest profile determined from FIS wave height analysis (WHAFIS: FEMA, 1988); WHAFIS treats an extreme "controlling wave height" limited by local conditions. Both wave analyses should pertain to coastal transects reflecting erosion effects expected to accompany the 100-year event (FEMA, 1989).

The specific focus on mean runup elevation and mean wave condition is the major change in FIS runup analysis. (Previous procedure was to perform runup computations for a range of wave heights from the significant down to a minimum at about 15% of the significant height; the largest computed value was then selected as an appropriate wave runup elevation.) The new procedure provides a well-defined statistical value summarizing the distribution of runup elevations. Mean runup elevation seems an entirely appropriate value for FIS application where the requirement is to treat expected base flood effects, in particular, to determine a limit of wave-augmented inundation with an equal chance of being too high or too low. This requirement is fortunate, since most engineering applications require an estimate near the upper bound to the probability distribution, where suitably accurate prediction might be more difficult given present knowledge of limitations in assuming a Rayleigh probability distribution for runup elevations.

Mean wave conditions associated with the 100-year event must depend on the actual storm climate at the study site. Convenient estimates may proceed from usual limiting conditions on open water in extreme events. Deep-water steepness of the significant or zero-moment wave condition in major hurricanes is typically H_{os}/L_{os} about 0.04 to 0.05, while for major extratropical storms with gale-force winds, typical values are H_{os}/L_{os} about 0.025 to 0.04. This deep-water wavelength customarily refers to the significant wave period or the period of peak energy in the wave spectrum; for common wave spectra in extreme storms, mean wave period is approximately 85% of those other period measures (Goda, 1985; Holthuijsen et al., 1989). For the Rayleigh probability distribution accurate in deep water, mean wave height is 62.6% of significant wave height. Thus, wave analysis for runup computation might only need to ascertain the type of 100-year event at the study site, along with the mean wave period likely to occur; the mean wave height is then determined using an appropriate wave steepness. Table 6 lists a series of period and height

Table 6. Some Appropriate Ocean Wave Conditions for Runup Computations Pertaining to 100-Year Event in Coastal Flood Insurance Studies

Mean Wave Period (sec)	Mean Deep-Water Wave Height (ft)
Hurricanes	
8	12
9	15½
10	19
11	23
12	27½
Extratropical Storms	
11	18
12	21½
13	25
14	29
15	33½

combinations usually suitable for wave runup computations addressing the 100-year event at seacoast sites. Variations of runup elevation will largely be determined by changes in transect geometry rather than in expected wave conditions along a fully exposed coast.

There likely will be some uncertainty about mean wave conditions to be expected in the 100-year event at a specific site. Given a tentative selection of wave condition, it seems appropriate to consider several additional conditions, e.g., wave periods along with wave heights about 5 percent higher and lower (or whatever band is a suitable estimate for the uncertainties). After executing runup computation for the nine combinations of those wave characteristics, a reasonable procedure in the present context is to apply the average of those elevations. A wide range in computed runup elevations signals the need for more detailed analysis of expected wave conditions or for reconsideration of the transect representation.

It should be noted that elevations given by the FEMA Wave Runup Model already contain the contribution from nearshore wave setup, in accordance with USACE guidance in the Shore Protection Manual. The empirical guidance refers runup to a static water elevation without waves and thus includes any change in mean water level associated with wave action near the shore barrier. Because wave setup is included and calculated elevation is the mean, runup magnitude should not be required to exceed 2 feet (as in previous guidance) for application in defining wave hazards associated with the base flood.

The mean runup estimate given by present procedures is suitable as an expected flood elevation for an FIS, but is not directly applicable for wave overtopping determinations or other assessments where extreme runup elevations are dominant. All available results provide support for this rule of thumb regarding extreme runups: if mean runup magnitude is doubled and the resultant elevation exceeds the crest of a structure intended for flood control, then wave overtopping likely will be considerable. Convenient guidance (e.g., Owen, 1980; Goda, 1985) then should be consulted regarding procedures for estimating wave overtopping rates. In cases with extensive shallow water fronting the shore barrier, a Rayleigh probability distribution is not appropriate and extreme runups can greatly exceed common elevations; one such case is a retreating sand dune, for which specific empirical guidance on expected wave overtopping is available (Delft Hydraulics Laboratory, 1983).

Verification of present procedures using historical damage information has been limited here to one extratropical storm on a few transects (Figure 36). Where possible, additional confirmation of computed runup elevations should be carried out using any available documentation of wave damages above stillwater flood level in extreme events at the specific FIS site.

REFERENCES

Ahrens, J. P., 1975: "Large Wave Tank Tests of Riprap Stability," Technical Memorandum No. 51, Coastal Engineering Research Center, Fort Belvoir, Virginia, 41 pp.

Ahrens, J. P., 1983: "Wave Runup on Idealized Structures," Proceedings of the Coastal Structures '83 Conference, pp. 925-938.

Ahrens, J. P., and Heimbaugh, M. S., 1988: "Irregular Wave Runup on Riprap Revetments," Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol. 114, pp. 524-530.

Ahrens, J. P., and McCartney, B. L., 1975: "Wave Period Effect on the Stability of Riprap," Proceedings of Civil Engineering in the Oceans III, pp. 1019-1034.

Ahrens, J. P., and Titus, M. F., 1978: "Irregular Wave Runup and Overtopping," Journal of the Waterway, Port, Coastal and Ocean Division, ASCE, Vol. 104, pp. 439-442.

Ahrens, J. P., and Titus, M. F., 1985: "Wave Runup Formulas for Smooth Slopes," Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol. 111, pp. 128-133.

Allsop, N. W. H., Franco, L., and Hawkes, P. J., 1985: "Wave Runup on Steep Slopes - A Literature Review," Report No. SR 1, Hydraulics Research Limited, Wallingford, England, 34 pp.

Battjes, J. A., 1971: "Runup Distributions of Waves Breaking on Slopes," Journal of the Waterways, Harbors and Coastal Engineering Division, ASCE, Vol. 97, No. WW1, pp. 91-114.

Battjes, J. A., 1974: "Surf Similarity," Proceedings of the 14th Coastal Engineering Conference, pp. 466-480.

van den Berg, C., and Lindenberg, J., 1985: "Stability of Armorflex Revetment System Under Wave Attack," in <u>Flexible Armoured Revetments Incorporating Geotextiles</u>, Thomas Telford, London, pp. 143-156.

den Boer, K., Kenter, C. J., and Pilarczyk, K. W., 1983: "Large Scale Model Tests on Placed Blocks Revetment," Proceedings of the Coastal Structures '83 Conference, pp. 307-319.

Brandtzaeg, A., Torum, A., and Ostby, O. R., 1968: "Velocities in Downrush on Rubble Mound Breakwaters," Proceedings of the 11th Coastal Engineering Conference, pp. 815-832.

Bruun, P., and Günbak, A. R., 1976: "New Design Principles for Rubble Mound Structures," Proceedings of the 15th Coastal Engineering Conference, pp. 2429-2473.

Bürger, W., Oumeraci, H., and Partenscky, H. W., 1988: "Geohydraulic Investigations of Rubble Mound Breakwaters," Proceedings of the 21st Coastal Engineering Conference, pp. 2242-2256.

Carstens, T., Torum, A., and Traetteberg, A., 1966: "The Stability of Rubble Mound Breakwaters Against Irregular Waves," Proceedings of the 10th Coastal Engineering Conference, pp. 958-971.

Chue, S. H., 1980: "Wave Runup Formula of Universal Applicability," Proceedings of the Institution of Civil Engineers (Great Britain), Vol. 69, Part 2, pp. 1035-1041.

Dai, Y. B., and Kamel, A. M., 1969: "Scale Effect Tests for Rubble-Mound Breakwaters," Research Report H-69-2, Waterways Experiment Station, Vicksburg, Mississippi, 51 pp.

DeBok, D. H., and Sollitt, C. K., 1978: "A Large Scale Model Study of Placed Stone Breakwaters," Ocean Engineering Report, Oregon State University, Corvallis, Oregon, 150 pp.

Delft Hydraulics Laboratory, 1983: "Wave Runup and Overtopping at Dunes During Extreme Storm Surge," Report M1819/Part II (in Dutch), Delft, The Netherlands, 35 pp.

Delft Hydraulics Laboratory, 1984a: "Scale Series on Dune Erosion; Large-Scale Tests in the Delta Flume," Report M1263 Part III (in Dutch), Delft, The Netherlands, Figures 213/14.

Delft Hydraulics Laboratory, 1984b: "Strength of the Outer Covering of a 'Green Dike' During Extreme Storm Surge," Report M1980/Volume A (in Dutch), Delft, The Netherlands, Table 6.

Delft Hydraulics Laboratory, 1985: "Strength of Oosterschelde Dikes Under Concentrated Wave Attack," Report M2036 (in Dutch), Delft, The Netherlands, Figure 5.3.

Delft Hydraulics Laboratory, 1986: "Slope Covering with Placed Stones; Large-Scale Wave Runup," Report M1881-02 (in Dutch), Delft, The Netherlands, 36 pp.

Erchinger, H. F., 1976: "Wave Runup in Field Measurements with Newly Developed Instrument," Proceedings of the 15th Coastal Engineering Conference, pp. 767-780.

Federal Emergency Management Agency, 1988: "Wave Height Analysis for Coastal Flood Insurance Studies (Technical Documentation for WHAFIS Program Version 3.0)," Washington, D.C., 199 pp.

Federal Emergency Management Agency, 1989: "Basis of Assessment Procedures for Dune Erosion in Coastal Flood Insurance Studies," Washington, D.C., 70 pp.

Führböter, A., 1986: "Model and Prototype Tests for Wave Impact and Runup on a Uniform 1:4 Slope," Coastal Engineering, Vol. 10, pp. 49-84.

Führböter, A., and Sparboom, U., 1988: "Full-Scale Wave Attack of Uniformly Sloping Sea Dikes," Paper No. 258 presented at 21st International Conference on Coastal Engineering, Torremolinos, Spain.

Führböter, A., Sparboom, U., and Witte, H. H., 1989: "Hannover Large Wave Flume: Experimental Results Regarding Wave Runup on Smooth and Rough Dike Banks with 1:6 Slope," Die Küste, Vol. 50, pp. 155-195 (in German).

Gadd, P. E., Manikian, V., and Machemehl, J. L., 1988: "Wave Runup Prediction vs. Model Test Results: A Comparison," Proceedings of the 21st Coastal Engineering Conference, pp 644-654.

Goda, Y., 1970: "A Synthesis of Breaker Indices," Transactions of the Japanese Society of Civil Engineers, Vol. 2, Part 2, pp. 227-230.

Goda, Y., 1985: <u>Random Seas and Design of Maritime Structures</u>, University of Tokyo Press, Tokyo, Japan, 323 pp.

Grüne, J., 1982: "Wave Runup Caused by Natural Storm Surge Waves," Proceedings of the 18th Coastal Engineering Conference, pp. 785-803.

Guza, R. T., and Thornton, E. B., 1982: "Swash Oscillations on a Natural Beach," Journal of Geophysical Research, Vol. 87, pp. 483-491.

Herbich, J. B., Sorensen, R. M., and Willenbrock, J. H., 1963: "Effect of Berm on Wave Runup on Composite Beaches," Journal of the Waterways and Harbors Division, ASCE, Vol. 89, No. WW2, pp. 55-72.

Holman, R. A., 1986: "Extreme Value Statistics for Wave Runup on a Natural Beach," Coastal Engineering, Vol. 9, pp. 527-544.

Holthuijsen, L. H., Booij, N., and Herbers, T. H. C., 1989: "A Prediction Model for Stationary, Short-Crested Waves in Shallow Water with Ambient Currents," Coastal Engineering, Vol. 13, pp. 23-54.

Horikawa, K., 1978: <u>Coastal Engineering, An Introduction to Ocean Engineering</u>, Wiley, New York, 402 pp.

Hosoi, M., and Mitsui, H., 1963: "Wave Runup on Sea Dikes Located in the Surf Zone or on the Shore," Coastal Engineering in Japan, Vol. 6, pp. 123-131.

Hunt, I. A., 1959: "Design of Seawalls and Breakwaters," Journal of the Waterways and Harbors Division, ASCE, Vol. 85, No. WW3, pp. 123-152.

Inman, D. L., and Jenkins, S. A., 1989: "Wave Overtopping at San Malo Seawall, Oceanside, California," Shore and Beach, Vol. 57, No. 3, pp. 19-25.

Jensen, O. J., and Juhl, J., 1987: "Wave Overtopping on Breakwaters and Sea Dikes," DHI Ref. 18/87, Danish Hydraulics Institute, Denmark, 15 pp.

Kajima, R., Shimizu, T., Maruyama, K., and Saito, S., 1982: "Experiments on Beach Profile Change with a Large Wave Flume," Proceedings of the 18th Coastal Engineering Conference, pp. 1385-1404.

Kaldenhoff, H., and Gökcesu, S. M., 1978: "New Dike Design Criteria Based on Wave Spectra," Proceedings of the 16th Coastal Engineering Conference, pp. 2500-2509.

Kamphuis, J. W., 1975: "Friction Factor Under Oscillatory Waves," Journal of the Waterways, Harbors, and Coastal Engineering Division, Vol. 101, No. WW2, pp. 135-144.

Kamphuis, J. W., and Mohamed, N., 1978: "Runup of Irregular Waves on Plane Smooth Slopes," Journal of the Waterway, Port, Coastal and Ocean Division, ASCE, Vol. 104, pp. 135-146.

Kobayashi, N., DeSilva, G. S., and Watson, K. D., 1989: "Wave Transformation and Swash Oscillation on Gentle and Steep Slopes," Journal of Geophysical Research, Vol. 94, pp. 951-966.

Kobayashi, N., and Jacobs, B. K., 1985: "Stability of Armor Units on Composite Slopes," Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol. 111, pp. 880-894.

Kobayashi, N., Otta, A. K., and Roy, I., 1987: "Wave Reflection and Runup on Rough Slopes," Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol. 113, pp. 282-298.

Kobayashi, N., Strzelecki, M. S., and Wurjanto, A., 1988: "Swash Oscillation and Resulting Sediment Movement," Proceedings of the 21st Coastal Engineering Conference, pp. 1167-1181.

Kraus, N. C., and Larson, M., 1988: "Beach Profile Change Measured in the Tank for Large Waves, 1956-1957 and 1962," Technical Report CERC-88-6, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, Mississippi, page A15.

Leidersdorf, C. B., Potter, R. E., and Sonu, C. J., 1984: "Study of Slope Protection Works for Arctic Ocean," Proceedings of the 31st Annual Conference, Japanese Society of Civil Engineers, pp. 552-556 (in Japanese).

LeMehaute, B., Koh, R. C. Y., and Hwang, L. S., 1968: "A Synthesis on Wave Runup," Journal of the Waterways and Harbors Division, ASCE, Vol. 94, No. WW1, pp. 77-92.

Losada, M. A., and Gimenez-Curto, L. A., 1981: "Flow Characteristics on Rough, Permeable Slopes Under Wave Action," Coastal Engineering, Vol. 4, pp. 187-206.

Mansard, E. P. D., Funke, E. R., Readshaw, J. S., and Girard, R. K., 1988: "On the Transformation of Wave Statistics Due to Shoaling," Proceedings of the 21st Coastal Engineering Conference, pp. 106-120.

Mase, H., 1989: "Random Wave Runup Height on Gentle Slope," Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol. 115, pp. 649-661.

Mase, H., and Iwagaki, Y., 1984: "Runup of Random Waves on Gentle Slopes," Proceedings of the 19th Coastal Engineering Conference, pp. 593-609.

McCartney, B. L., and Ahrens, J. P., 1975: "Stability of Gobi Block Revetment to Wave Attack," Technical Memorandum No. 55, Coastal Engineering Research Center, Fort Belvoir, Virginia, 22 pp.

van der Meer, J. W., 1988: "Rock Slopes and Gravel Beaches Under Wave Attack," Delft Hydraulics Communication No. 396, Delft, The Netherlands, 202 pp.

Merrifield, E. M., and Zwamborn, J. A., 1966: "The Economic Value of a New Breakwater Armour Unit 'Dolos'," Proceedings of the 10th Coastal Engineering Conference, pp. 885-912.

Mimura, N., Otsuka, Y., and Watanabe, A., 1986: "Laboratory Study on Two-Dimensional Beach Transformation Due to Irregular Waves," Proceedings of the 20th Coastal Engineering Conference, pp. 1393-1406.

Nagai, S., and Takada, A., 1972: "Relations Between Runup and Overtopping of Waves," Proceedings of the 13th Coastal Engineering Conference, pp. 1975-1992.

Nielsen, P., 1984: "Explicit Solutions to Practical Wave Problems," Proceedings of the 16th Coastal Engineering Conference, pp. 968-982.

Owen, M. W., 1980: "Design of Seawalls Allowing for Wave Overtopping," Report No. Ex 924, Hydraulics Research Station, Wallingford, England, 81 pp.

Permanent International Association of Navigation Congresses, 1976: "Final Report of the International Commission for the Study of Waves," Bulletin No. 25, Vol. III, Appendix No. 3B.

Resio, D. T., 1987: "Extreme Runup Statistics on Natural Beaches," Miscellaneous Paper CERC-87-11, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, Mississippi, 25 pp.

Roos, A., and Battjes, J. A., 1976: "Characteristics of Flow in Runup of Periodic Waves," Proceedings of the 15th Coastal Engineering Conference, pp. 781-795.

Sato, S., and Kishi, T., 1958: "Experimental Study of Wave Runup on Sea Wall and Shore Slope, Coastal Engineering in Japan, Vol. 1, pp. 39-43.

Savage, R. P., 1958: "Wave Runup on Roughened and Permeable Slopes," Journal of the Waterways and Harbors Division, ASCE, Vol. 84, No. WW3, Paper 1640, 38 pp.

Saville, T., Jr., 1955: "Laboratory Data on Wave Runup and Overtopping on Shore Structures," Technical Memorandum No. 64, Beach Erosion Board, Washington, D.C., 32 pp.

Saville, T., Jr., 1958: "Wave Runup on Composite Slopes," Proceedings of the 6th Coastal Engineering Conference, pp. 691-699.

Saville, T., Jr., 1959: Discussion of R. Y. Hudson, "Laboratory Investigation of Rubble-Mound Breakwaters," Journal of the Waterways and Harbors Division, ASCE, Vol. 85, No. WW3, Proc. Paper 2171, Figure 12.

Saville, T., Jr., 1987: "Early Large-Scale Experiments on Wave Runup," Shore and Beach, Vol. 55, No. 3-4, pp. 101-108.

Shimada, A., Fujimoto, T., Saito, S., Sakakiyama, T., and Hirakuchi, H., 1986: "Scale Effects on Stability and Wave Reflection Regarding Armor Units," Proceedings of the 20th Coastal Engineering Conference, pp. 2238-2252.

Sibul, O. J., and Tickner, E. G., 1955: "A Model Study on the Runup of Wind-Generated Waves on Levees with Slopes of 1:3 and 1:6," Technical Memorandum No. 67, Beach Erosion Board, Washington, D.C., 19 pp.

Sollitt, C. K., and DeBok, D. H., 1976: "Large Scale Model Tests of Placed Stone Breakwaters," Proceedings of the 15th Coastal Engineering Conference, pp. 2572-2588.

Sonu, C. J., Pettigrew, N., and Fredericks, R. G., 1974: "Measurement of Swash Profile and Orbital Motion on the Beach," WAVES '74 Conference Proceedings, pp. 621-638.

Sparboom, U., and Grosche, S., 1987: "Measurement of Wave Runup on a 1:6 Sloped Asphalt Dike in the Large Wave Channel," Technical Report (in German), University of Hannover, West Germany, 32 pp.

Stive, M. J. F., 1985: "A Scale Comparison of Waves Breaking on a Beach," Coastal Engineering, Vol. 9, pp. 151-158.

Stoa, P. N., 1978: "Reanalysis of Wave Runup on Structures and Beaches," Technical Paper No. 78-2, Coastal Engineering Research Center, Fort Belvoir, Virginia, 131 pp.

Stone & Webster Engineering Corporation, 1981: "Manual for Wave Runup Analysis, Coastal Flood Insurance Studies," Boston, Massachusetts, 96 pp.

Sutherland, A. M., Sharma, J. N., and Shemdin, O. H., 1976: "Wave Runup on a Simulated Beach," Proceedings of the 15th Coastal Engineering Conference, pp. 752-765.

Tautenhain, E., Kohlhase, S., and Partenscky, H. W., 1982: "Wave Runup at Sea Dikes Under Oblique Wave Approach," Proceedings of the 18th Coastal Engineering Conference, pp. 804-810.

Taylor, R. B., Özsoy, E., and Turco, T. J., 1980: "Wave Runup on Variable Beach Profiles," Journal of the Waterway, Port, Coastal, and Ocean Division, ASCE, Vol. 106, No. WW2, pp. 169-182.

Technical Advisory Committee on Protection Against Inundation (The Netherlands), 1974: "Wave Runup and Overtopping," Government Publishing Office, The Hague, The Netherlands, 176 pp.

Technical Advisory Committee on Sea-defenses (The Netherlands), 1985: "Guidelines for the Evaluation of Safety of Dunes as Coastal Defense," Government Printing Office, The Hague, The Netherlands, 24 pp.

Terada, M., 1976: "On the Wave Runup After Breaking on the Beach at Hiratsuka, Kanagawa Prefecture," Geographical Review of Japan, Vol. 49, pp. 550-561 (in Japanese).

Thompson, A. C., 1988: "Numerical Model of Breakwater Wave Flows," Proceedings of the 21st Coastal Engineering Conference, pp. 2013-2027.

Tominaga, Y., Hashimoto, H., and Sakuma, N., 1966: "Wave Runup and Overtopping on Coastal Dikes," Proceedings of the 10th Conference on Coastal Engineering, pp. 364-381.

Toyoshima, O., 1988: "Gentle Slope Seawalls Covered with Armour Units," Proceedings of the 21st Coastal Engineering Conference, pp. 1983-1996.

Uliczka, K., and Dette, H.-H., 1987: "Development of Wave Runup at Dune With and Without Foreshore - Prototype Scale," Mitteilungen Leichtweiss-Institute, Heft 94, 12 pp.

U.S. Army Corps of Engineers, Coastal Engineering Research Center, 1966: "Shore Protection, Planning and Design," Technical Report No. 4, Third Edition, Washington, D.C.

U.S. Army Corps of Engineers, Coastal Engineering Research Center, 1977: Shore Protection Manual, Third Edition, 3 volumes, Washington, D.C.

U.S. Army Corps of Engineers, Coastal Engineering Research Center, 1984: Shore Protection Manual, Fourth Edition, 2 volumes, Washington, D.C.

Van Dorn, W. G., 1978: "Breaking Invariants in Shoaling Waves," Journal of Geophysical Research, Vol. 83, pp. 2981-2988.

Vellinga, P., 1986: "Beach and Dune Erosion During Storm Surges," Delft Hydraulics Communications No. 372, Delft, The Netherlands, 169 pp.

Walton, T. L., Jr., Ahrens, J. P., Truitt, C. L., and Dean, R. G., 1989: "Criteria for Evaluating Coastal Flood-Protection Structures," Technical Report CERC 89-15, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, Mississippi, 160 pp.

Wassing, F., 1957: "Model Investigations on Wave Runup Carried Out in the Netherlands During the Past Twenty Years," Proceedings of the 6th Coastal Engineering Conference, pp. 700-714.

Webber, N. B., and Bullock, G. N., 1968: "A Model Study of the Distribution of Runup of Wind-Generated Waves on Sloping Sea Walls," Proceedings of the 11th Coastal Engineering Conference, pp. 870-887.

APPENDIX A

STORM SITUATIONS WITH DAMAGES DUE TO WAVE RUNUP

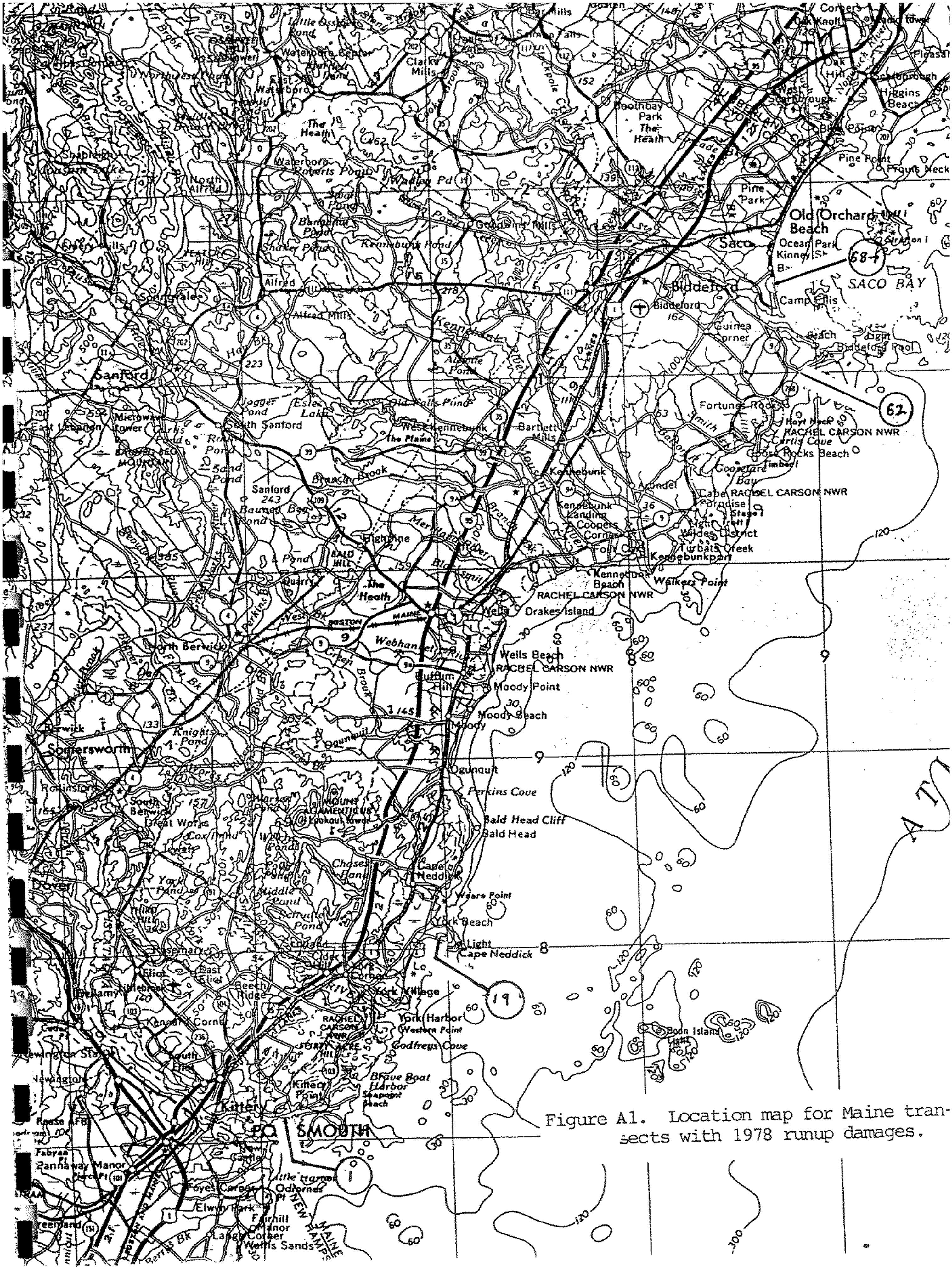


Figure A1. Location map for Maine transects with 1978 runup damages.

```
CLIENT- FEMA                     ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY        JOB
PROJECT-STONE & WEBSTER EXAMPLES (KITTERY)                                     RUN      PAGE  1
**********************************************************************************************

                     CROSS SECTION PROFILE

                   LENGTH   ELEV.    SLOPE     ROUGHNESS

       1           -500.0   -57.5
                                      8.70       1.00
       2            -60.0    -6.9
                                      8.67       1.00
       3              0.0     0.0
                                      2.50       1.00
       4             10.0     4.0
                                      0.02       1.00
       5             10.1    10.0
                                     19.98       1.00
       6            110.0    15.0
                                      FLAT       1.00
       7            160.0    15.0
                                     16.00       1.00
       8            240.0    20.0

                        LAST SLOPE  16.00     LAST ROUGHNESS    1.00
```

```
CLIENT- FEMA                   ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY          JOB

PROJECT-STONE & WEBSTER EXAMPLES (KITTERY)                                  RUN       PAGE  2

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

                                  OUTPUT TABLE
                                  ------------

                  INPUT PARAMETERS                              RUNUP RESULTS
                  ----------------                              -------------

       WATER LEVEL   DEEP WATER                   BREAKING SLOPE   RUNUP SLOPE   RUNUP ABOVE    BREAKER
       ABOVE DATUM   WAVE HEIGHT   WAVE PERIOD        NUMBER          NUMBER     WATER LEVEL    DEPTH
          (FT.)         (FT.)         (SEC.)                                        (FT.)        (FT.)

          8.68          17.84         11.30            1                7           10.10        22.66
          8.68          18.78         11.30            1                7           10.25        23.85
          8.68          19.72         11.30            1                7           10.56        25.04
          8.68          17.84         11.90            1                7           10.65        22.70
          8.68          18.78         11.90            1                7           11.02        23.85
          8.68          19.72         11.90            1                7           11.16        25.04
          8.68          17.84         12.50            1                7           11.19        22.95
          8.68          18.78         12.50            1                8           11.40        24.02
          8.68          19.72         12.50            1                8           11.76        25.09
```

Ave. 10.89

```
CLIENT- FEMA                       ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY          JOB
PROJECT-STONE & WEBSTER TESTS (YORK)                                              RUN       PAGE  3
*************************************************************************************************

                 CROSS SECTION PROFILE

                LENGTH    ELEV.    SLOPE     ROUGHNESS

   1            -660.0    -3.0
                                   220.00      1.00
   2            -110.0    -0.5
                                   211.54      1.00
   3               0.0     0.0
                                    16.00      1.00
   4              80.0     5.0
                                     3.85      1.00
   5             100.0    10.2
                                     7.29      1.00
   6             135.0    15.0
                                     FLAT      1.00
   7             150.0    15.0

                     LAST SLOPE 100.00    LAST ROUGHNESS   1.00
```

```
 CLIENT- FEMA                         ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY          JOB
PROJECT-STONE & WEBSTER TESTS (YORK)                                                 RUN      PAGE  4
**************************************************************************************************

                                         OUTPUT TABLE
                                         ------------

                    INPUT PARAMETERS                               RUNUP RESULTS
                    ----------------                               -------------

      WATER LEVEL  DEEP WATER                   BREAKING SLOPE  RUNUP SLOPE  RUNUP ABOVE   BREAKER
      ABOVE DATUM  WAVE HEIGHT    WAVE PERIOD       NUMBER        NUMBER     WATER LEVEL   DEPTH
         (FT. )      (FT. )         (SEC. )                                     (FT. )      (FT. )

         8. 65       17. 84         11. 30            1             5           1. 78       28. 27

         8. 65       18. 78         11. 30            1             5           1. 88       29. 53

         8. 65       19. 72         11. 30            1             5           1. 77       30. 78

         8. 65       17. 84         11. 90            1             5           1. 78       28. 72

         8. 65       18. 78         11. 90            1             5           1. 88       30. 00

         8. 65       19. 72         11. 90            1             5           1. 97       31. 26

         8. 65       17. 84         12. 50            1             5           1. 96       29. 18

         8. 65       18. 78         12. 50            1             5           2. 07       30. 47

         8. 65       19. 72         12. 50            1             5           1. 97       31. 74
```

Ave. 1.89

```
CLIENT- FEMA                  ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY        JOB
PROJECT-STONE & WEBSTER TESTS (BIDDEFORD)                                   RUN      PAGE  5
****************************************************************************************************

              CROSS SECTION PROFILE

            LENGTH   ELEV.    SLOPE     ROUGHNESS

 1          -500.0   -13.2
                               37.82       1.00
 2             0.0     0.0
                               38.00       1.00
 3           190.0     5.0
                               23.33       1.00
 4           225.0     6.5
                               23.33       1.00
 5           330.0    11.0
                               30.00       1.00
 6           450.0    15.0

               LAST SLOPE  30.00     LAST ROUGHNESS   1.00
```

```
CLIENT- FEMA                  ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY          JOB
                                                                          RUN      PAGE  6
PROJECT-STONE & WEBSTER TESTS (BIDDEFORD)
*******************************************************************************************

                                 OUTPUT TABLE
                                 ------------

              INPUT PARAMETERS                        RUNUP RESULTS
              ----------------                        -------------

   WATER LEVEL    DEEP WATER                    BREAKING SLOPE  RUNUP SLOPE   RUNUP ABOVE    BREAKER
   ABOVE DATUM    WAVE HEIGHT    WAVE PERIOD        NUMBER         NUMBER     WATER LEVEL    DEPTH
     (FT.)          (FT.)          (SEC.)                                        (FT.)       (FT.)

     9.50           17.84          11.30              1              5            2.85        28.04
     9.50           18.78          11.30              1              5            3.00        29.29
     9.50           19.72          11.30              1              5            2.96        30.54
     9.50           17.84          11.90              1              5            3.03        28.47
     9.50           18.78          11.90              1              5            3.19        29.74
     9.50           19.72          11.90              1              5            3.16        31.01
     9.50           17.84          12.50              1              5            3.21        28.91
     9.50           18.78          12.50              1              5            3.38        30.19
     9.50           19.72          12.50              1              5            3.35        31.47
```

Ave. 3.12

```
CLIENT- FEMA                       ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY          JOB
                                                                                RUN       PAGE  7
PROJECT-STONE & WEBSTER TESTS (SACCO)
***************************************************************************************************


                 CROSS SECTION PROFILE

                LENGTH   ELEV.     SLOPE      ROUGHNESS

     1          -500.0   -16.3
                                   30.69        1.00
     2           -40.0    -1.3
                                   30.30        1.00
     3             0 0     0.0
                                    7.00        1.00
     4            35.0     5.0
                                    9.00        1.00
     5            80.0    10.0
                                   16.00        1.00
     6         . 160.0    15.0

                     LAST SLOPE  16.00      LAST ROUGHNESS   1.00
```

```
                                 ** WAVE RUNUP COMPUTATIONS ** ENGINEERED BY          JOB
 CLIENT- FEMA
                                                                          RUN     PAGE  8
PROJECT-STONE & WEBSTER TESTS (SACCO)
*******************************************************************************************

                                       OUTPUT TABLE
                                       ------------

                 INPUT PARAMETERS                             RUNUP RESULTS
                 ----------------                             -------------

  WATER LEVEL   DEEP WATER                    BREAKING SLOPE  RUNUP SLOPE  RUNUP ABOVE   BREAKER
  ABOVE DATUM   WAVE HEIGHT    WAVE PERIOD        NUMBER         NUMBER    WATER LEVEL   DEPTH
     (FT.)         (FT.)         (SEC.)                                       (FT.)       (FT.)

     8.99          17.84         11.30              1               5          4.82        27.82
     8.99          18.78         11.30              1               5          4.88        29.07
     8.99          19.72         11.30              1               5          4.93        30.32
     8.99          17.84         11.90              1               5          5.00        28.24
     8.99          18.78         11.90              1               5          5.26        29.51
     8.99          19.72         11.90              1               5          5.32        30.77
     8.99          17.84         12.50              1               5          5.35        28.66
     8.99          18.78         12.50              1               5          5.45        29.94
     8.99          19.72         12.50              1               5          5.52        31.21
```

Ave. 5.17

APPENDIX B

SOURCE CODE FOR MODIFIED FEMA WAVE RUNUP MODEL (RUNUP PROGRAM VERSION 2.0)

As introduction to the source code listing, Figure A1 presents three flowcharts describing operations within the upgraded FEMA Wave Runup Model. The first flowchart is a more technically rigorous version of Figure 10, detailing the added branching decisions for runup computations. The second flowchart shows interrelations between the major program components; for clarity, several utility subroutines have been omitted from this display. The third flowchart provides an updated version of Figure 6 (Stone & Webster, 1981), summarizing major steps in the entire program.

PROGRAM RUNUP--VERSION 2.0 was developed on a DEC VAX 11/750 minicomputer in the FORTRAN-77 programming language. The VAX FORTRAN V5.0 compiler was selected for program development and for production runs. Compilation requires approximately 1 minute of computer time. Computer execution time is about 30 seconds for one profile, but varies according to the number of wave conditions input and the number of iterations required for convergence of a runup computation.

The FEMA Wave Runup Model consists of 1 main program and 17 subroutines. The following listing includes all codes of the original Stone & Webster (1981) program; instructions no longer executed are now designated as comments. This code is also available in a form enabling program execution on an IBM-compatible personal computer.

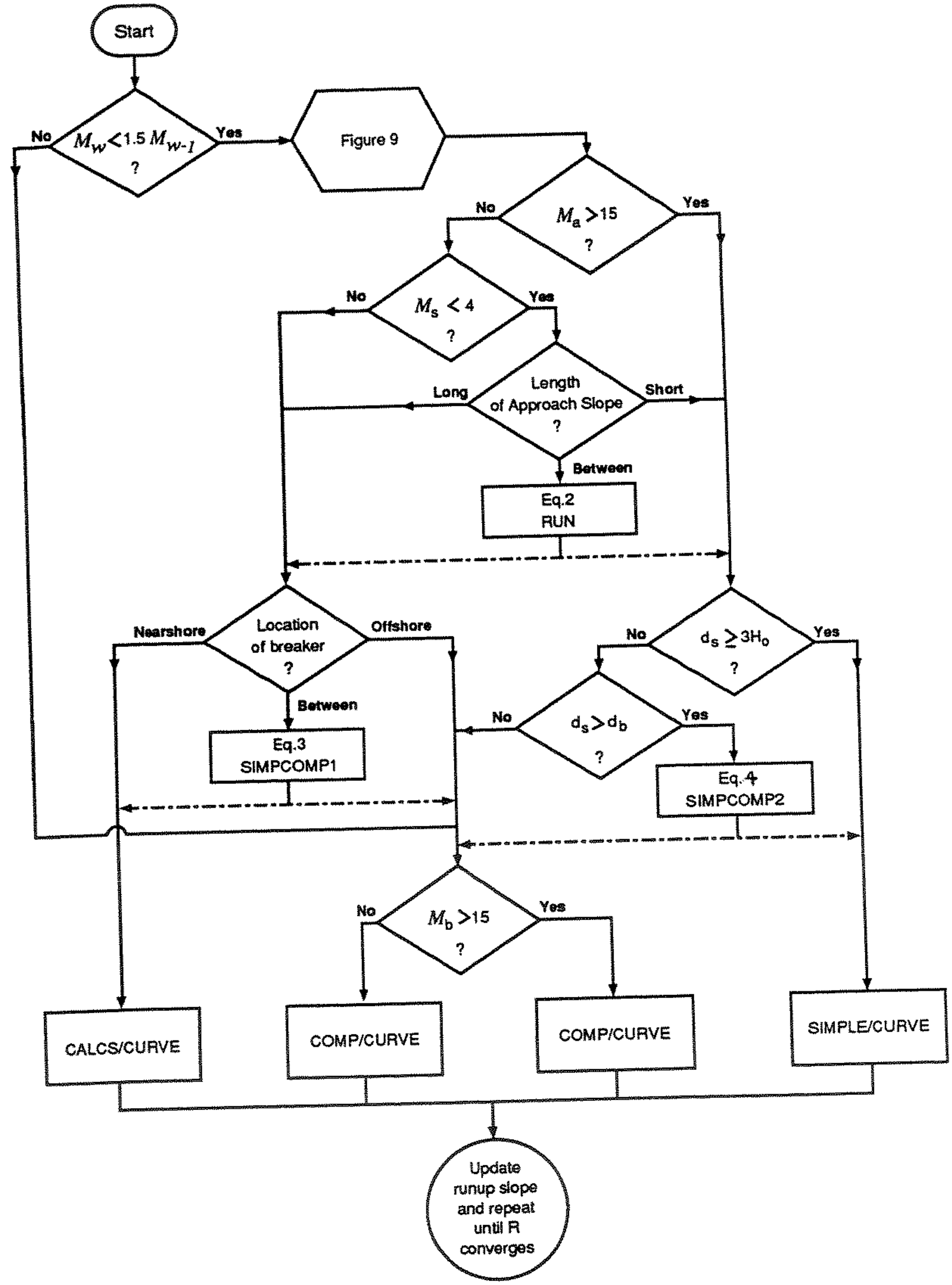


Figure B1. Additional flowcharts for upgraded Wave Runup Model:
a - Another version of Figure 10, referring to main report text and several program subroutines.

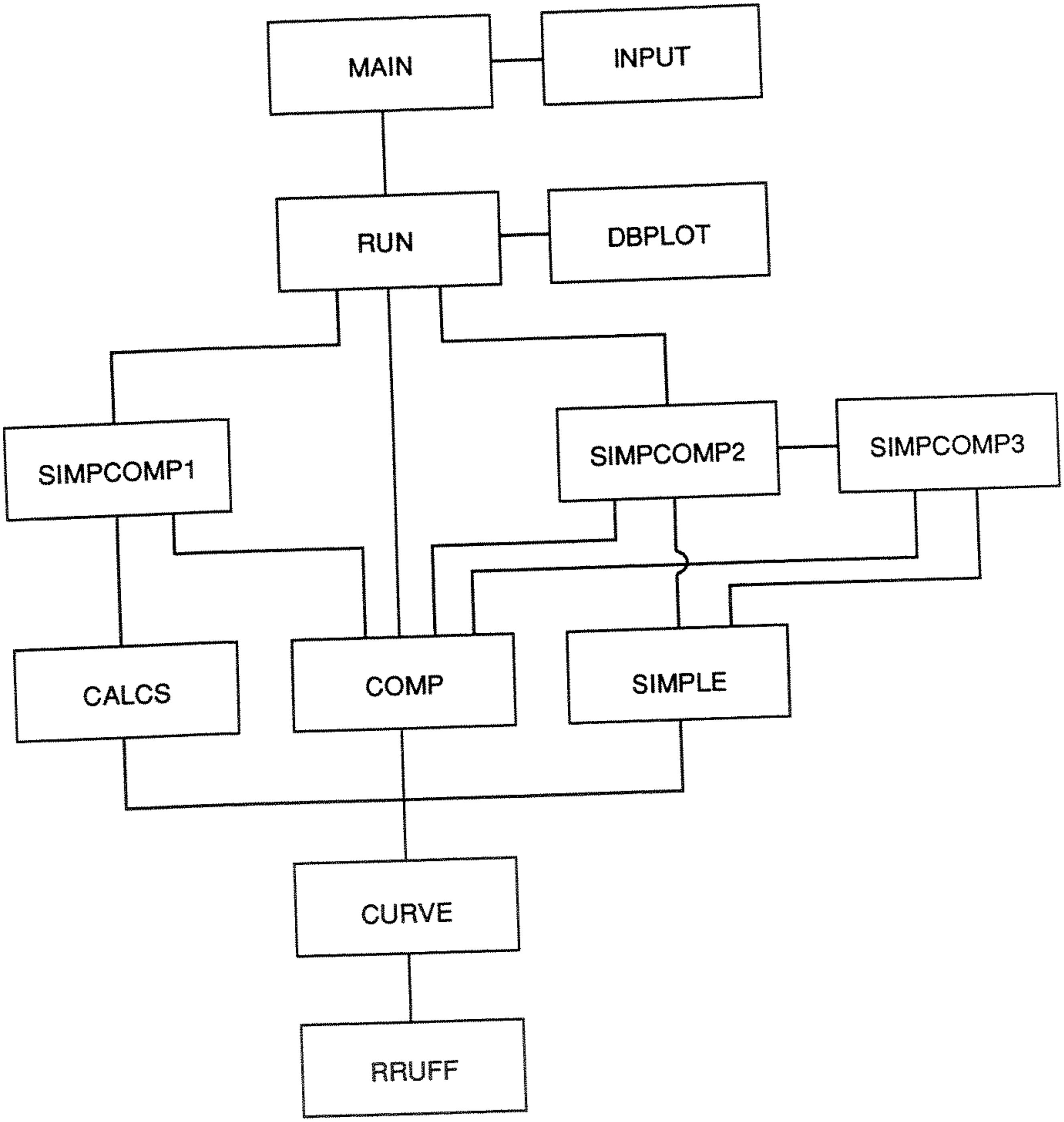


Figure B1. Additional flowcharts for upgraded Wave Runup Model:
b - Operation of nested computation subroutines by major subroutine RUN (general utility subroutines omitted).

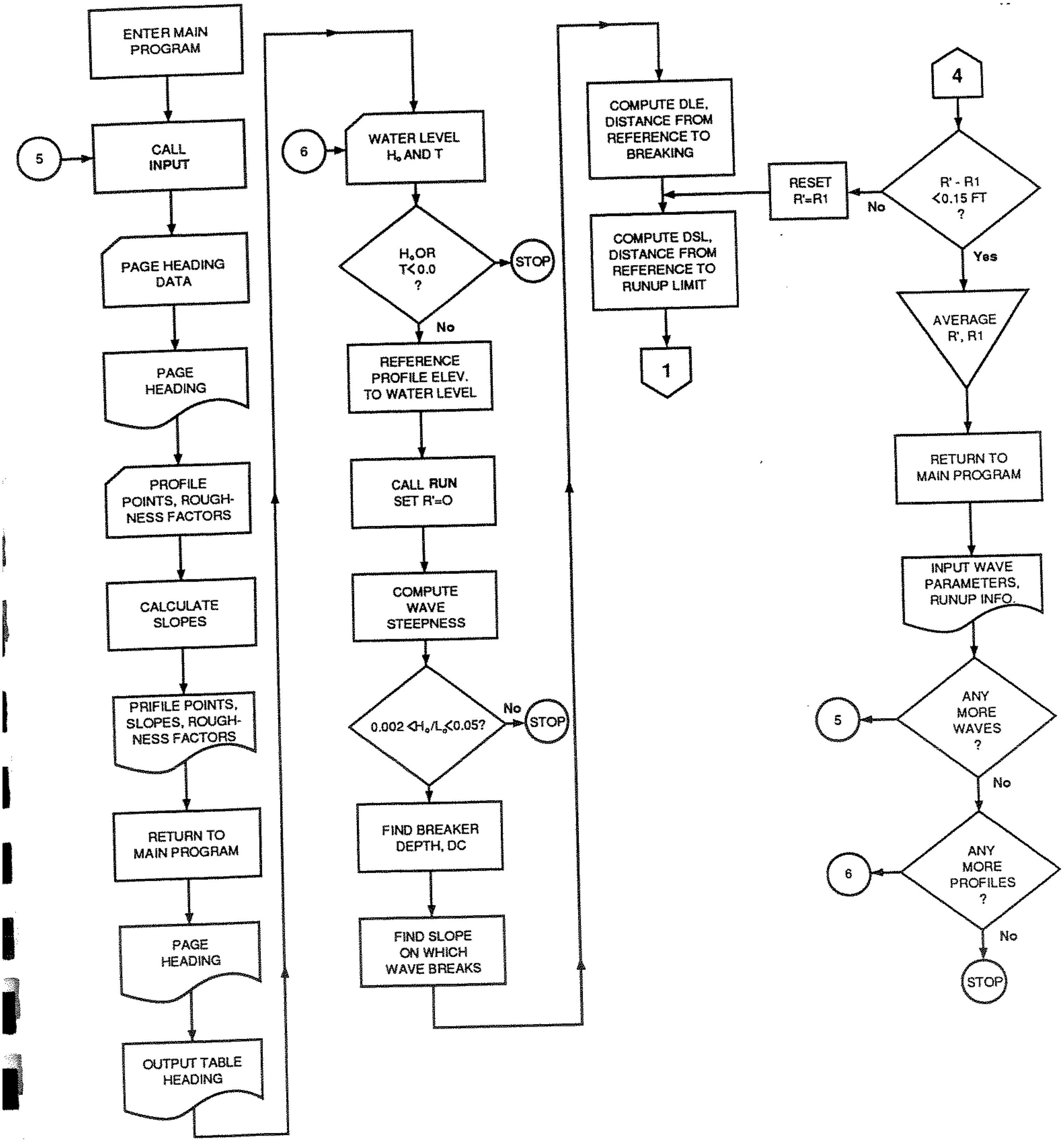
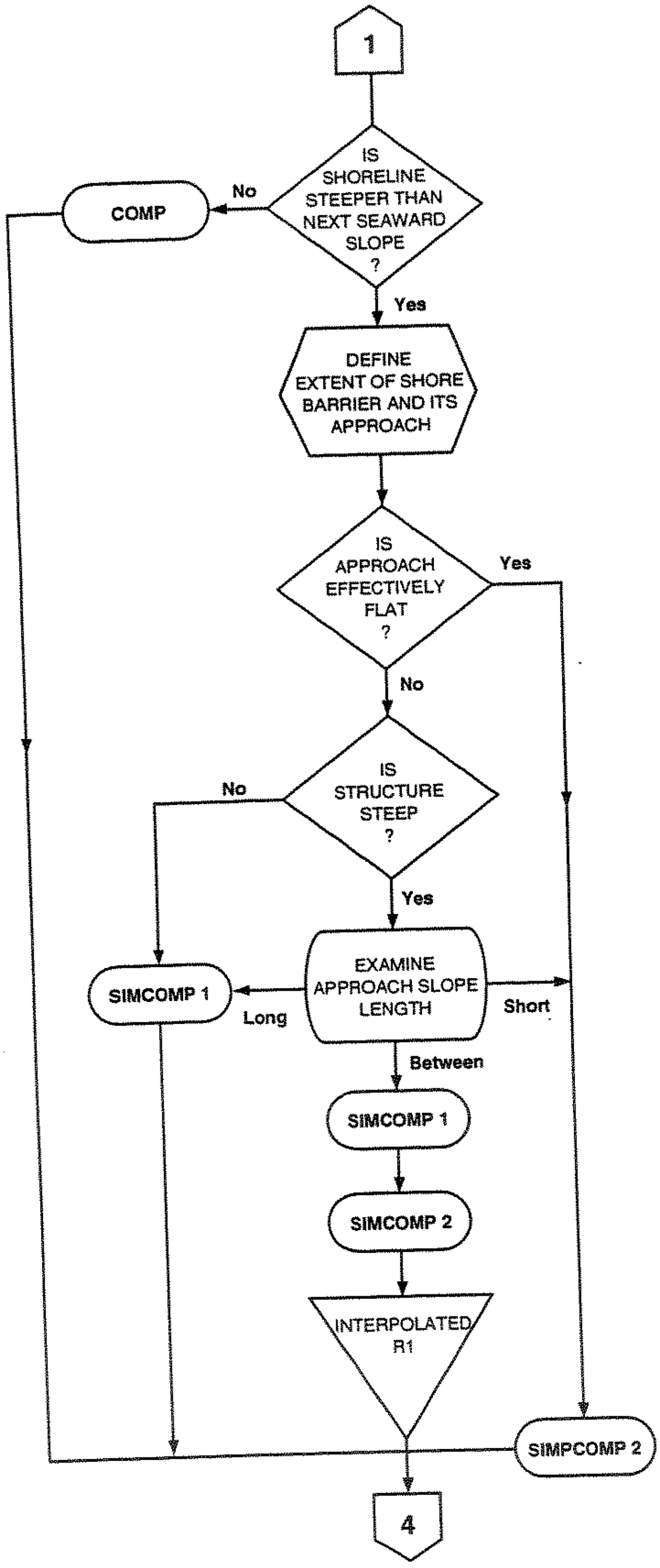
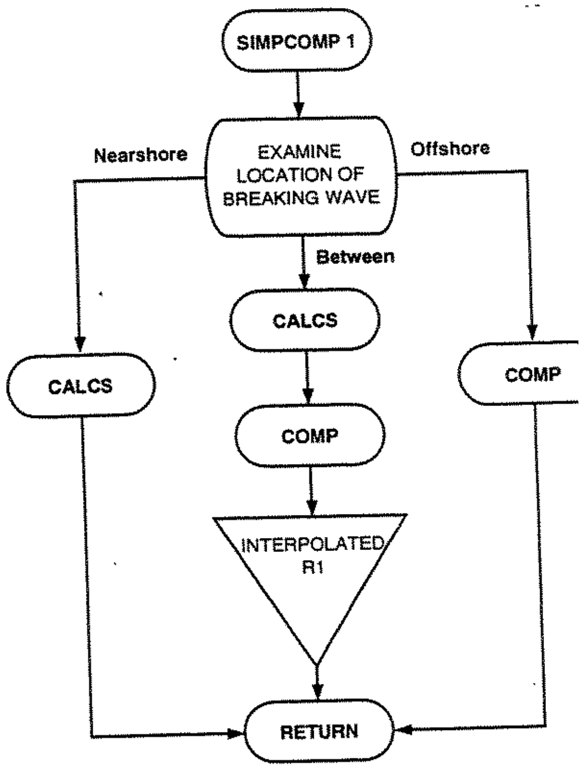
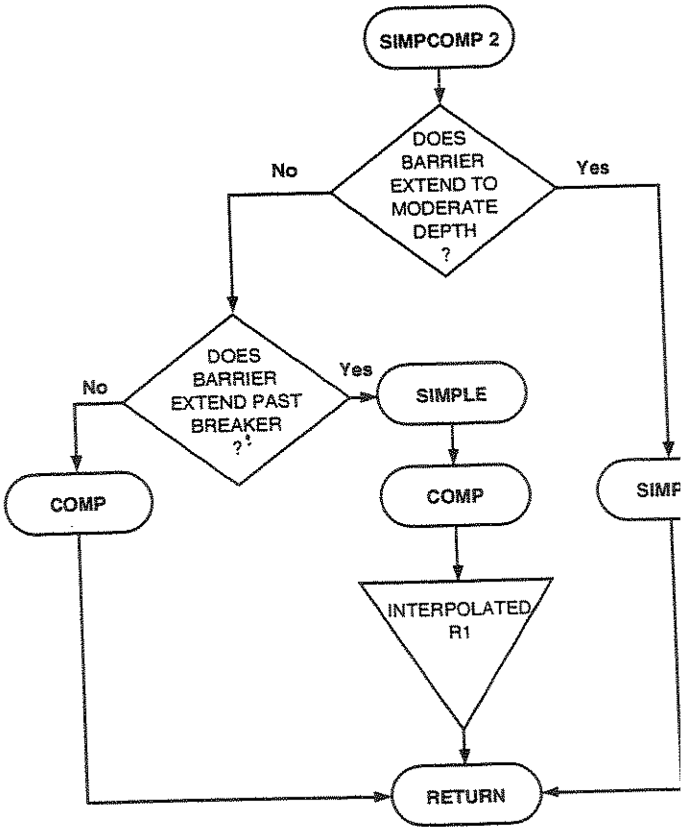


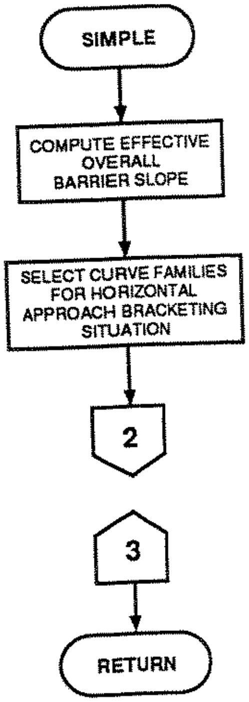
Figure B1. Additional flowcharts for upgraded Wave Runup Model: c-new version of Figure 6 showing the major steps in runup computation. [1 of 3]

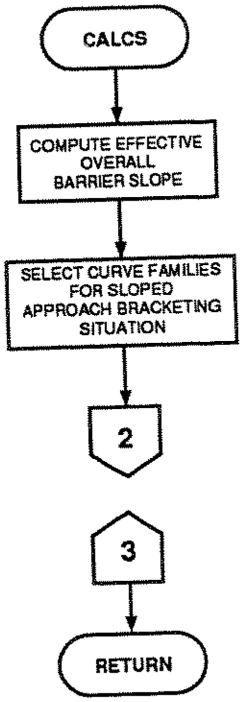

1
IS SHORELINE STEEPER THAN NEXT SEAWARD SLOPE ?
No
COMP
Yes
DEFINE EXTENT OF SHORE BARRIER AND ITS APPROACH
IS APPROACH EFFECTIVELY FLAT ?
Yes
No
IS STRUCTURE STEEP ?
No
Yes
EXAMINE APPROACH SLOPE LENGTH
Long
Short
Between
SIMCOMP 1
SIMCOMP 1
SIMCOMP 2
INTERPOLATED R1
SIMPCOMP 2
4

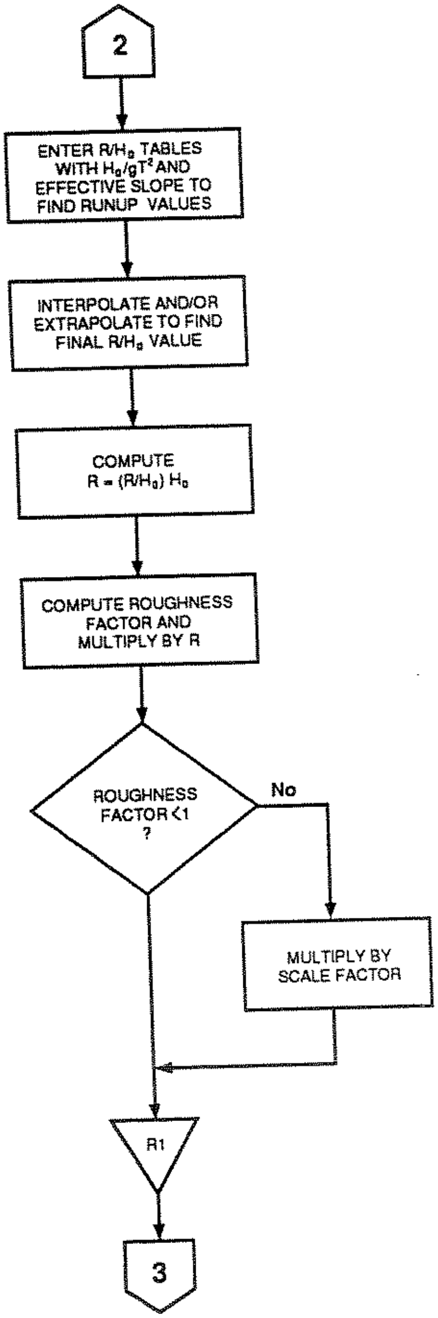

SIMPCOMP 1
EXAMINE LOCATION OF BREAKING WAVE
Nearshore
Offshore
Between
CALCS
CALCS
COMP
COMP
INTERPOLATED R1
RETURN

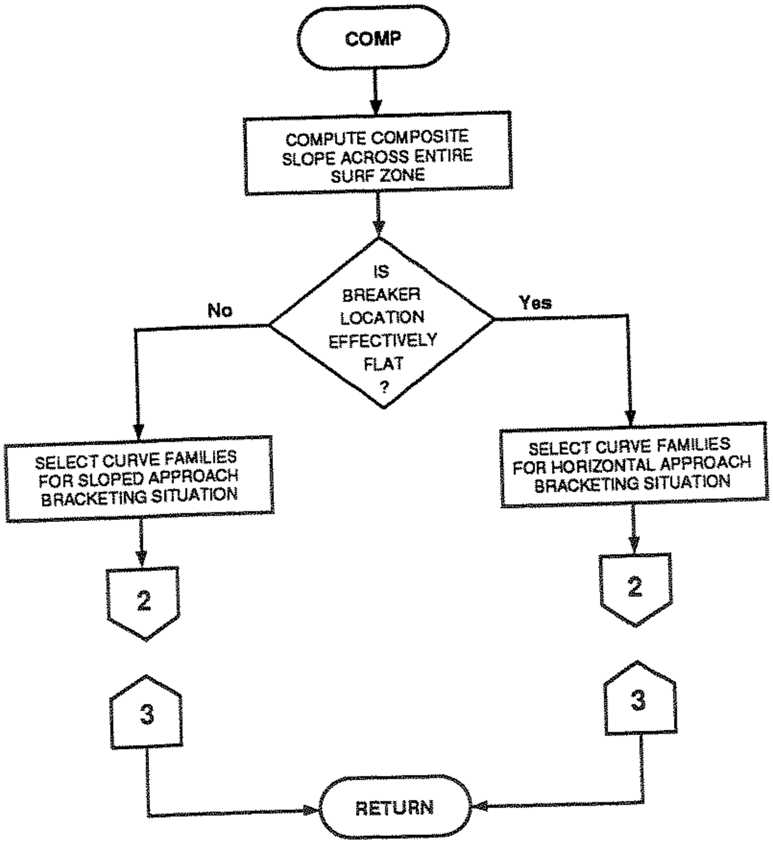

SIMPCOMP 2
DOES BARRIER EXTEND TO MODERATE DEPTH ?
No
Yes
DOES BARRIER EXTEND PAST BREAKER ?
No
Yes
SIMPLE
COMP
COMP
INTERPOLATED R1
RETURN

[2 of 3]


SIMPLE
COMPUTE EFFECTIVE OVERALL BARRIER SLOPE
SELECT CURVE FAMILIES FOR HORIZONTAL APPROACH BRACKETING SITUATION
2
3
RETURN


CALCS
COMPUTE EFFECTIVE OVERALL BARRIER SLOPE
SELECT CURVE FAMILIES FOR SLOPED APPROACH BRACKETING SITUATION
2
3
RETURN


2
ENTER R/H$_0$ TABLES WITH H$_0$/gT^2 AND EFFECTIVE SLOPE TO FIND RUNUP VALUES
INTERPOLATE AND/OR EXTRAPOLATE TO FIND FINAL R/H$_0$ VALUE
COMPUTE R = (R/H$_0$) H$_0$
COMPUTE ROUGHNESS FACTOR AND MULTIPLY BY R
ROUGHNESS FACTOR <1 ?
No
MULTIPLY BY SCALE FACTOR
R1
3


COMP
COMPUTE COMPOSITE SLOPE ACROSS ENTIRE SURF ZONE
IS BREAKER LOCATION EFFECTIVELY FLAT ?
No
Yes
SELECT CURVE FAMILIES FOR SLOPED APPROACH BRACKETING SITUATION
SELECT CURVE FAMILIES FOR HORIZONTAL APPROACH BRACKETING SITUATION
2
2
3
3
RETURN

[3 OF 3]

```
      PROGRAM RUNUP--VERSION 2.0--MARCH 1990                            MAIN0010
C     THIS PROGRAM CALCULATES THE RUNUP OF WAVES ON SEGMENTED PROFILES  MAIN0020
C                                                                       MAIN0030
C                                                                       MAIN0040
C*****VARIABLE DICTIONARY                                               MAIN0050
C                                                                 UNITS MAIN0060
C     NAME MODE SIZE   DESCRIPTION                                      MAIN0070
C                                                                       MAIN0080
C     DEP   I*4 16     VERT DIMENSION OF PROFILE,SEA TO LAND     FT*100 MAIN0090
C     DL    I*4 16     HORIZ DIMENSION OF PROFILE,SEA TO LAND    FT     MAIN0100
C     S     R*4 16     SLOPES OF PROFILE                                MAIN0110
C     NP    I*4 1      NUMBER OF POINTS IN PROFILE                      MAIN0120
C     IPAGE I*4 1      CURRENT PAGE NUMBER                              MAIN0130
C     DT    I*4 118    PAGE HEADING                                     MAIN0140
C     H     R*4 1      HEIGHT OF DEEP-WATER WAVE                 FEET   MAIN0150
C     T     R*4 1      PERIOD OF DEEP-WATER WAVE                 SEC    MAIN0160
C     R     R*4 1      CALCULATED RUNUP                          FEET   MAIN0170
C     II    I*4 1      NO. OF SLOPE ON WHICH WAVE BREAKS                MAIN0180
C     ISL   I*4 1      NO. OF SLOPE ON WHICH RUNUP LIMIT FALLS          MAIN0190
C     IFC   I*4 16     CONVERGENCE FLAGS                                MAIN0200
C     IFG   I*4 16     EXCEED TABLE FLAG                                MAIN0210
C     IFD   I*4 1      DUMMY                                            MAIN0220
C     LISL  I*4 16     TABLE OF STARTING SLOPES                         MAIN0230
C     LII   I*4 16     TABLE OF ENDING SLOPES                           MAIN0240
C     RAS   R*4 16     TABLE OF CALCULATED RUNUPS                FEET   MAIN0250
C     WTB   R*4 1      INPUT WATER LEVEL                                MAIN0260
C     WTL   I*4 1      WATER LEVEL MULTIPLIED BY 100             FT*100 MAIN0270
C     WTTL  I*4 1      VALUE OF WTL AT PREVIOUS STEP             FT*100 MAIN0280
C     IZ    I*4 1      POINTER INTO ARRAYS OF ANSWERS AND FLAGS         MAIN0290
C     IM    I*4 1      POINTER TO MAXIMUM RUNUP                         MAIN0300
C     DA    I*4 25     ARRAY OF ERROR CODES                             MAIN0310
C     MD               FLAG FOR VIOLATION OF WAVE STEEPNESS LIMITS
C                                                                       MAIN0320
C*****START OF PROGRAM                                                  MAIN0330
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H                                            MAIN0340
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
      DIMENSION DA(25)                                                  MAIN0380
      DATA DA/'  ','SO','LU','TI','ON',' D','OE','S ','NO','T ','CO',   MAIN0390
     1'NV','ER','GE','  ','DA','TA',' E','XC','EE','DE','D ','TA','BL', MAIN0400
     2'E '/                                                             MAIN0410
C
C_____OPEN INPUT FILES
C
C     CALL FILES
C                                                                       MAIN0420
C_____READ IN PROFILE
C                                                                       MAIN0430
   10 CALL INPUT
```

```
      IJK=0
      WTTL=0
      KJ=0
      IPAGE =IPAGE+1
      WRITE(6,1100) DT,IPAGE
C
C_____OUTPUT TABLE
C
      WRITE(6,1300)
   20 IF(KJ.EQ.1)GO TO 10
      IF(IJK.GT.0) WTTL=WTB*100
      READ(5,1000,END=70)KJ,WTB,HO,T
      MD=0
C
C_____BRANCH ON NEGATIVE RUN PARAMETERS
C
      IF(HO.LE.0.OR.T.LE.0) GOTO 80
      WTL=WTB*100.
      IQ=1
C
C_____REFERENCE PROFILE TO STILL WATER LEVEL
C
      DO 30 I=1,NP
      DEP(I)=DEP(I)-WTL+WTTL
   30 CONTINUE
      IJK=IJK+1
      WTL=0
      CS=0
C  40 CALL RUN(HO,T,R,II,IQ,ADC)
   40 CALL RUN(IQ,ADC)
      IF (MD .EQ. 25) GOTO 20
C
      IM=IQ-1
      IF (CS.EQ.1) WRITE (6,1700)
      IF(IFG(IQ).EQ.1) GO TO 60
      IF(IFC(IQ).EQ.1) GO TO 50
      WRITE (6,1400) WTB,HO,T,LII(IQ),LISL(IQ),RAS(IQ),ADC
      GO TO 20
   50 WRITE (6,1500) WTB,HO,T,LII(IQ),LISL(IQ),RAS(IM),RAS(IQ),ADC,
     1  (DA(J),J=1,14)
      GO TO 20
   60 WRITE (6,1600) WTB,HO,T,(DA(J),J=1,25)
      GOTO 20
   70 STOP
   80 WRITE (6,1200)
      STOP
 1000 FORMAT(I1,F5.2,12(1X,F5.2))
 1100 FORMAT('1 ',59A2/'0',59A2,T119,I2//,60('**')///)
 1200 FORMAT(' NEGATIVE RUN PARAMETER, PROGRAM STOPS')
 1300 FORMAT(T45,'OUTPUT TABLE'/T45,6('--')////T20,'INPUT PARAMETERS',
     1T69,'RUNUP RESULTS',/T20,8('--'),T69,13('-')//T9,'WATER LEVEL',
     2T24,'DEEP WATER',T58,'BREAKING SLOPE',T76,'RUNUP SLOPE',T91,
     3'RUNUP ABOVE',T110,'BREAKER'/T9,'ABOVE DATUM',T24,'WAVE HEIGHT',
     4T39,'WAVE PERIOD',T62,'NUMBER',T79,'NUMBER',T91,'WATER LEVEL',
     5 T110,'DEPTH'/T12,
     6'(FT.)',T27,'(FT.)',T42,'(SEC.)',T94,'(FT.)',T111,'(FT.)'/)
 1400 FORMAT(/T10,F6.2,T25,F6.2,T40,F6.2,T64,I2,T81,I2,T95,F6.2,T112,
     1 F6.2)
```

```
1500 FORMAT(1X,T10,F6.2,T25,F6.2,T40,F6.2,T64,I2,T81,I2,T89,F6.2,        MAIN0880
    1T95,F6.2,T112,F6.2/T90,14A2///)                                     MAIN0890
1600 FORMAT(1X,T10,F6.2,T25,F6.2,T40,F6.2,T55,25A2///)                   MAIN0900
1700 FORMAT(/1X,'COMPOSITE SLOPE USED BUT WAVE MAY REFLECT, NOT BREAK')
     END                                                                 MAIN0910
```

```
      SUBROUTINE INPUT                                                   INPU0010
C     THIS ROUTINE INPUTS HEADING DATA, LAST SLOPE, AND PROFILE          INPU0020
C     AND PRINTS INPUT                                                   INPU0030
C                                                                        INPU0040
C*****VARIABLE DICTIONARY                                                INPU0050
C                                                                        INPU0060
C     NAME MODE SIZE   DESCRIPTION                             UNITS     INPU0070
C                                                                        INPU0080
C     DEP   I*4 16     VERT DIMENSION OF PROFILE               FT*100    INPU0090
C     DL    I*4 16     HORIZONTAL DIMENSION OF PROFILE         FT        INPU0100
C     S     R*4 16     PROFILE SLOPE VALUES                              INPU0110
C     NP    I*4 1      NUMBER OF POINTS IN PROFILE                       INPU0120
C     WTL   I*4 1      WATER LEVEL x100                        FT*100    INPU0130
C     IPAGE I*4 1      CURRENT PAGE NUMBER                               INPU0140
C     DT    I*4 118    PAGE HEADING                                      INPU0150
C     RDEP  R*4 16     DEPTH INPUT BUFFER,SEA TO LAND          FT        INPU0160
C     RDL   R*4 16     LENGTH INPUT BUFFER,SEA TO LAND         FT        INPU0170
C     FLAT  A*4 1      ALPHANUMERIC CONSTANT  'FLAT'                     INPU0180
C     BLANK A*4 1      ALPHANUMERIC CONSTANT  '    '                     INPU0190
C     SL    R*4 1      SLOPE OF LAST LANDWARD SECTION                    INPU0200
C     IC    I*4 1      FLAG TO DETECT END OF PROFILE DATA                INPU0210
C     GA    R*4 1      USED IN SLOPE CALCULATIONS                        INPU0220
C     RDD   R*4 1      OUTPUT BUFFER OF LENGTHS                FT        INPU0230
C     RDP   R*4 1      OUTPUT BUFFER OF DEPTHS                 FT        INPU0240
C     S1    R*4 1      OUTPUT BUFFER OF SLOPES                           INPU0250
C     ROUGH R*4 16     ARRAY OF ROUGHNESS VALUES                         INPU0270
C                                                                        INPU0280
C*****START OF SUBROUTINE                                                INPU0290
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
      DATA FLAT,BLANK/'FLAT','    '/                                     INPU0350
      EQUIVALENCE (RDEP(1),S(1))                                         INPU0360
C
C-----READ PAGE HEADING DATA                                             INPU0370
```

```
C
      READ(5,1000)  (DT(I),I=5,17),(DT(I),I=47,51),(DT(I),I=55,59),     INPU0380
     1  (DT(I),I=64,100),DT(112),DT(113)                                 INPU0390
C
C-----WRITE HEADING DATA                                                 INPU0400
C
      IPAGE =IPAGE+1                                                     INPU0410
      WRITE(6,1100)DT,IPAGE                                              INPU0420
C
C-----READ SLOPE, DEFAULT=0 IF SLOPE .LT. 0                              INPU0430
C
   10 READ (5,1200) SL                                                   INPU0440
      IF(SL.LT.0) SL=0.                                                  INPU0450
C
C-----READ IN PROFILE ALL DIMENSIONS ARE IN FEET                          INPU0460
C
      DO 20 NP=1,20                                                      INPU0470
      READ (5,1300) IC,RDEP(NP),RDL(NP),ROUGH(NP)                        INPU0480
      IF(IC.EQ.1) GOTO 30                                                INPU0490
   20 CONTINUE                                                           INPU0500
C
C-----TOO MANY SLOPES IN INPUT                                            INPU0510
C
      WRITE (6,1400)                                                     INPU0520
      STOP                                                               INPU0530
C
C-----FILL UP DEP,DL,ROUGH ARRAYS                                         INPU0540
C
   30 II=NP                                                              INPU0550
      MAXPTS = NP
      NP=NP+1                                                            INPU0560
      DO 40 J=1,II                                                       INPU0570
      DEP(J)=NINT(RDEP(J)*100.)+ SIGN(1.0,RDEP(J))                       INPU0590
      VERT(J)=DEP(J)
      HORIZ(J)=RDL(J)*100.
   40 DL(J)=RDL(J)                                                       INPU0600
      S(II)=SL                                                           INPU0610
C
C-----CALCULATE SLOPES                                                    INPU0620
C
      NA=NP-2                                                            INPU0630
      DO 50 I=1,NA                                                       INPU0640
      GA=(DEP(I+1)-DEP(I))/100.                                          INPU0650
      IF(ABS(GA).LT.0.0001)GA=0.0001                                     INPU0660
   50 S(I)=(RDL(I+1)-RDL(I))/GA                                          INPU0670
      DEP(NP)=DEP(II)+10000                                              INPU0680
      DL(NP)=DL(II)+(S(II)*(DEP(NP)-DEP(II))/100)                        INPU0690
C
C-----PRINT OUT PROFILE                                                   INPU0700
C
      WRITE (6,1500)                                                     INPU0710
      DO 80 I=1,II                                                       INPU0720
      RDD=DL(I)                                                          INPU0730
      RDP=DEP(I)/100.                                                    INPU0740
      S1=S(I)                                                            INPU0750
      RR1=ROUGH(I)                                                       INPU0760
      IF(S1.GT.1000) S1=FLAT                                             INPU0770
      IF(I.EQ.II) S1=BLANK                                               INPU0780
```

```
      IF(I.EQ.II) RR1=BLANK
C      WRITE (6,1900) I,RDD,RDF
      WRITE (6,1900) I,RDL(I),RDF
      IF(S1.NE.S(I)) GOTO 60
      WRITE (6,1600) S1,RR1
      GOTO 80
   60 IF(RR1.NE.ROUGH(I)) GO TO 70
      WRITE (6,1700) S1,RR1
      GO TO 80
   70 WRITE(6,1800) S1,RR1
   80 CONTINUE
      WRITE (6,2000) S(II),ROUGH(II)
      RETURN
 1000 FORMAT(2X,13A2,32X,10A2/2X,39A2)
 1100 FORMAT('1 ',59A2/'0 ',59A2,T119,I2//,60('**')///)
 1200 FORMAT (F4.1)
 1300 FORMAT(I1,1X,F5.1,1X,F6.1,1X,F5.3)
 1400 FORMAT(' MORE THAN 20 POINTS IN PROFILE, PROGRAM STOPS')
 1500 FORMAT(T23,'CROSS SECTION PROFILE'
     1 //T21,'LENGTH   ELEV.    SLOPE     ROUGHNESS'/)
 1600 FORMAT(T38,F7.2,T51,F5.2)
 1700 FORMAT(T41,A4,T51,F5.2)
 1800 FORMAT(T41,A4,T51,A4)
 1900 FORMAT(1X,T10,I2,T20,F7.1,T30,F5.1)
 2000 FORMAT('0',T26,'LAST SLOPE',F7.2,'     LAST ROUGHNESS'F7.2)
      END
```

```
      SUBROUTINE LOOK(X,N,IV,L,M,IFG)
C      LOOK --  DIGITIZE ANALOG INPUT VALUE BY MODIFIED BINARY SEARCH
C     OUTPUT POINTERS TO VALUES IMMEDIATELY BEFORE AND AFTER INPUT VALUE
C
C*****VARIABLE DICTIONARY
C
C     NAME MODE SIZE   DESCRIPTION
C
C     X      I*4       TABLE TO BE LOOKED INTO (ASCENDING ORDER )
C     N      I*4 1     NUMBER OF ELEMENTS IN TABLE
C     IV     I*4 1     ANALOG INPUT VALUE
C     L      I*4 1     POINTER TO ENTRY IN X BEFORE IV
C     M      I*4 1     POINTER TO ENTRY IN X AFTER IV
C     IFG    I*4 1     TABLE EXCEEDED FLAG
C
C*****START OF SUBROUTINE
      INTEGER*4 IV,X(1)
      L=1
      M=N
C
C-----CHECK TO SEE IF DATA EXCEEDS TABLE
C
```

```
      IF(X(L).GT.IV) GOTO 30
      IF(X(M)-IV)40,20,20
C
C-----PERFORM LOOKUP
C
   10 IF(X(M).GT.IV) GOTO 20
C
C-----MOVE LOW POINTER UP
C
      L=M
      M=MO
C
C-----MOVE HI POINTER DOWN
C
   20 MO=M
      M=(M-L)/2+L
C
C-----CHECK TO SEE IF DONE
C
      IF(M.NE.L) GOTO 10
      IF(N.NE.M) M=L+1
      RETURN
C
C-----DATA LESS THAN 1ST ENTRY IN TABLE
C
   30 M=1
      IFG=1
      RETURN
C
C----- DATA GREATER THAN LAST ENTRY IN TABLE
C
   40 L=N
      IFG=1
      RETURN
      END
```

```
      SUBROUTINE LOGLOG(X1,X2,Y1,Y2,X,Y)
C
C     THIS SUBROUTINE PERFORMS A LOGLOG INTERPOLATION FOR COMPUTED
C     VALUE X CONTAINED BETWEEN KNOWN VALUES X1 AND X2.  THE OUTPUT IS
C     THE REAL VALUE Y, WHICH IS CONTAINED BETWEEN KNOWN VALUES Y1 AND
C     Y2.  INPUT VARIABLES TO THE SUBROUTINE ARE REAL.  THE LOGARITHM
C     OF EACH VARIABLE IS TAKEN IN THE SUBROUTINE.
C
      IMPLICIT INTEGER*4(X,Y)
      RX1=X1
      RX2=X2
      RY1=Y1
      RY2=Y2
      RX=X
      RX1=ALOG10(RX1)
```

```
      RX2=ALOG10(RX2)
      RY1=ALOG10(RY1)
      RY2=ALOG10(RY2)
      RX=ALOG10(RX)
      SLOPE=(RY1-RY2)/(RX1-RX2)
      Y=10**(RY1+SLOPE*(RX-RX1))
      RETURN
      END
```

```
      SUBROUTINE LOGLIN(X1,X2,Y1,Y2,X,Y)
C     THIS SUBROUTINE PERFORMS A LOG-LINEAR INTERPOLATION BETWEEN TWO
C     KNOWN POINTS (X1,Y1) AND (X2,Y2).  THE VALUE OF X IS CONTAINED
C     BETWEEN X1 AND X2 ON THE LOGARITHMIC SCALE.  THE OUTPUT VALUE,
C     Y IS CONTAINED BETWEEN Y1 AND Y2 ON THE LINEAR SCALE.  REAL
C     NUMBERS ENTER THE SUBROUTINE AND THE NECESSARY LOGARITHMS ARE
C     DONE IN THE SUBROUTINE.
      IMPLICIT INTEGER*4(X,Y)
      RX1=X1
      RX2=X2
      RX=X
      RX1=ALOG10(RX1)
      RX2=ALOG10(RX2)
      RX=ALOG10(RX)
      SLOPE=(Y1-Y2)/(RX1-RX2)
      Y=Y1+SLOPE*(RX-RX1)
      RETURN
      END
```

```
C *    SUBROUTINE RUN(H0,T,R,II,IQ,ADC)
      SUBROUTINE RUN(IQ,ADC)
C     THIS SUBROUTINE ORGANIZES ALL RUNUP CALCULATIONS
C     BASED UPON THE PROFILE AND WAVE PARAMETERS
C
C*****VARIABLE DICTIONARY
C
C     NAME MODE SIZE   DESCRIPTION                                UNITS
C
C     R      R*4 1      CALCULATED RUNUP                          FEET
C     S      R*4 15     PROFILE SLOPES
C     T      R*4 1      PERIOD OF DEEP WATER WAVE                 SEC
C     DB     I*4 27,13,7 VALUES OF R/H0 FUNCTION OF PDB,PDB1,PCH  *100
```

```
C     DL    I*4 15   HORIZONTAL DISTANCE FROM ORIGIN,          FEET    RUN00130
C                    INCREASING FROM SEA TO LAND                       RUN00140
C     HO    R*4 1    HEIGHT OF DEEP WATER WAVE                 FEET    RUN00180
C     II    I*4 1    NO. OF SLOPE ON WHICH WAVE BREAKS                 RUN00190
C     IQ    I*4 1    POINTER INTO ARRAYS OF ANSWERS AND FLAGS          RUN00200
C     ADC            WAVE BREAKING DEPTH
C     NP    I*4 1    NUMBER OF POINTS IN PROFILE                       RUN00210
C     DCS   I*4 1    EFFECTIVE SLOPE                           *100    RUN00220
C     DEP   I*4 20   PROFILE HEIGHT ASCENDING ORDER            FT*10   RUN00230
C     IFC   I*4 16   CONVERGENCE FLAGS                                 RUN00240
C     IFD   I*4 1    DUMMY FLAG                                        RUN00250
C     IFG   I*4 16   EXCEED TABLE FLAG                                 RUN00260
C     ISL   I*4 1    NO. OF SLOPE ON WHICH RUNUP LIMIT LIES            RUN00270
C     LII   I*4 16   TABLE OF ENDING SLOPES                            RUN00280
C     PCH   I*4 7    VALUES OF  D/HO  FOR ENTRY INTO DB         *10    RUN00290
C     PDB   I*4 27   VALUES OF SLOPE FOR ENTRY INTO DB*100             RUN00300
C     RAS   R*4 16   TABLE OF CALCULATED RUNUPS                FEET    RUN00310
C     SCC   I*4 12   SCALING FACTORS AS A FUNCTION OF SLOPE            RUN00320
C     SLO   I*4 12   SLOPE(TAN*10) FOR USE IN SCALING                  RUN00330
C     WTL   I*4 1    WATER LEVEL X100                          FT*100  RUN00340
C     DCHB  I*4 1    BREAKER DEPTH BY BREAKER HEIGHT RATIO             RUN00350
C     HOT2  I*4 1    HO/T**2                                   *10000  RUN00360
C     LISL  I*4 16   TABLE OF STARTING SLOPES                          RUN00370
C     PDB1  I*4 13   VALUES OF HO/T**2 FOR ENTRY INTO DB        *1000  RUN00380
C     DTT            GROUND ELEVATION WHERE WAVE BREAKS
C     DLE            STATION OF BREAKING WAVE (SEA TO LAND)
C     DC             BREAKER DEPTH *100
C     R10            RUNUP *100
C     DTR            WATERLEVEL + RUNUP *100
C     MWST           SLOPE (COT)OF STRUCTURE
C     DS1            DEPTH OF STRUCTURE TOE *100
C     SA             SLOPE (COT)OF APPROACH
C     K1             HORIZONTAL LENGTH OF APPROACH SLOPE
C     DSA            DEPTH OF SEAWARD END OF APPROACH SLOPE
C     HST            HORIZONTAL STATION OF STRUCTURE TOE
C     MW             SLOPE (COT) OF SEGMENT ON WHICH THE
C                    SWL INTERSECTS THE PROFILE ELEVATION.
C     MWA            ARRAY OF CALCULATED SLOPES (COT)
C     MS1            SLOPE OF FIRST SEGMENT SEAWARD OF STRUCTURE
C                    TOE.
C     MS1H           HORIZONTAL STATION OF SEAWARD POINT OF MS1 SLOPE
C     MWSE           NEXT SEAWARD SLOPE (COT) FROM MW.
C     HSA            HORIZONTAL STATION OF MOST SEAWARD POINT OF
C                    APPROACH SLOPE.
C     SA1            ARRAY OF CALCULATED APPROACH SLOPES (COT).
C     MAXPTS         MAXIMUM NO. OF PROFILE POINTS ORIGINALLY READ
C     SWL            WTB *100 (ORGINAL SWL SCALED BY 100)
C     HORIZ          HORIZONTAL DIMENSION *100 (CORRESPONDS TO RDL)
C     VERT           VERTICAL DIMENSION *100 (CORRESPONDS TO RDEP)
C     REFSWL         DISTANCE FROM REF. PT. TO POINT WHERE VERT=SWL
C     HOSCALE        HO*100 ( DEEP WATER WAVE HEIGHT SCALED BY 100)
C     MD             FLAG FOR VIOLATION OF WAVE STEEPNESS LIMITS
C     DXLA           WAVELENGTH AT SEAWARD END OF APPROACH
C
C
C                                                                      RUN00400
C*****START OF SUBROUTINE*******                                       RUN00410
C
```

```
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3,K1
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
      COMMON /SY/ PDB(27),PDB1(13),PCH(9)
      COMMON /SZ/ DB(27,13,8)
      COMMON /SDL/ DLL(730)
      DIMENSION SLB1(14),SLB2(14),SLT1(14),SLT2(14),DELS1(14),
     1          DELS2(14)
C
      DATA SLO/   10,   20,   40,   60,   80,  100,  140,  200,  300,
     1           500,  800, 1500/
      DATA SCC/ 1000, 1049, 1097, 1119, 1131, 1136, 1140, 1136, 1120,
     1          1089, 1052, 1000/
C
C
C         COMPUTATION COMMENTED OUT FOR DIRECT DETERMINATION
C         OF BREAKER DEPTH FROM DEEPWATER WAVE CONDITIONS,
C         USING SUBROUTINE DBPLOT INCORPORATING GODA'S RESULTS
C
C
C     SLOPE FUNCTIONS TO CALCULATE BREAKING DEPTH AS A FUNCTION OF
C     BOTTOM SLOPE AND WAVE STEEPNESS (WEGGEL'S ANALYSIS,1972)
C     B(SLOPE)=1.0/(0.64*(1.0+EXP(-19.5/SLOPE)))
C     A(SLOPE)=1.36*(1.0-EXP(-19.0/SLOPE))
C
      IFG(IQ)=0
      IFC(IQ)=0
C
C_____WAVE STEEPNESS
C
      HOT2=HO*10000/(T*T)+.5
C
C_____COMPUTATION TO FIND BREAKING DEPTH AND SLOPE ON WHICH WAVE BREAKS
C
      DO 10 IX=1,10
C**** IF(HB(IX).EQ.0.0) GO TO 10
      SLP=S(IX)
C**** DCHB=10./(B(SLP)-A(SLP)*HB(IX)/(T*T))
C**** DC=DCHB*HB(IX)
C**** ADC=DC/10.
C
C
C------------------------------------------------------------------
C SUBROUTINE DBPLOT: COMPUTE WAVE BREAKING HEIGHT AT A SLOPE FOR
C                    KNOWN DEEP WATER WAVE USING GRAPHICAL RESULTS
C        INPUT  HO: DEEP WATER WAVE HEIGHT
C                T: WAVE PERIOD
C              SLP: SEGMENT SLOPE (COTANGENT)
```

```
C
C        OUTPUT  ADC:WAVE BREAKING DEPTH
C-----------------------------------------------------------------
C
C
      CALL DBPLOT(SLP,ADC)
      IF (MD .EQ. 25) RETURN
      DC=ADC*100.
C
C
C
      DTT=WTL-DC                                                        RUN00730
      IF(DTT.LT.DEP(IX+1)) GO TO 20                                     RUN00740
      IF(DTT.GT.DEP(NP-1)) GO TO 40                                     RUN00750
   10 CONTINUE                                                          RUN00760
C
C_____WAVE CANNOT BREAK ON SLOPE BEFORE SLOPE IX                        RUN00770
C
   20 IF(DTT.GE.DEP(IX)) GO TO 30                                       RUN00780
      DC=WTL-DEP(IX)                                                    RUN00790
      DTT=WTL-DC                                                        RUN00800
   30 II=IX                                                             RUN00810
      JJ=IX+1                                                           RUN00820
C
C_____COMPUTE DISTANCE FROM REFERENCE TO BREAKING POINT                 RUN00830
C
      CALL RINT(DEP(II),DEP(JJ),DL(II),DL(JJ),DTT,DLE)                  RUN00840
      IFD=0                                                             RUN00850
      GO TO 50                                                          RUN00860
   40 II=NP-1                                                           RUN00870
      DLE=DL(II)+((WTL-DC-DEP(II))*S(II))/100.+.5                       RUN00880
C
C_____FIND FAMILY OF CURVES                                             RUN00890
C
   50 R=0.                                                              RUN00900
      IF (H0.EQ.0.) GO TO 220                                           RUN00910
C     DH = DC/H0                                                        RUN00920
C
C_____LOOP UNTIL R SAME AS R1                                           RUN00930
C
C
      CALL LOOK(PDB1,13,H0T2,KK,LL,IFG(IQ))                             RUN00940
      IFD=0                                                             RUN00950
      DO 210 N=1,10                                                     RUN00960
      IFD=0                                                             RUN00970
      R10=R*100.                                                        RUN00980
      DTR=WTL+R10                                                       RUN00990
      NPP=NP-1                                                          RUN01000
C
C_____FIND SLOPE THAT RUNUP LIMIT INTERSECTS                            RUN01010
C
      DO 60 IT=1,NPP                                                    RUN01020
      IF(DTR.LT. DEP(IT)) GO TO 70                                      RUN01030
   60 CONTINUE                                                          RUN01040
      GO TO 80                                                          RUN01050
   70 IAL=IT-1                                                          RUN01060
      ISL1=IT                                                           RUN01070
```

```
C
C_____COMPUTE DSL, DISTANCE FROM SEAWARD REFERENCE TO THE RUNUP LIMIT   RUN01080
C
      CALL RINT(DEP(IAL),DEP(ISL1),DL(IAL),DL(ISL1),DTR,DSL)            RUN01090
C                                                                       RUN01100
C
C            DETERMINATION COMMENTED OUT FOR MORE APPROPRIATE
C            IMPLEMENTATION OF COMPOSITE SLOPE METHOD
C            FARTHER DOWN IN PROGRAM.
C
C_____DETERMINE IF WAVE OVERTOPS SLOPE THAT WATER LEVEL INTERSECTS      RUN01110
C_____IF NOT, THE COMPOSITE SLOPE METHOD IS NOT REQUIRED AND A ONE-     RUN01120
C_____STEP WAVE RUNUP CALCULATION IS PERFORMED.                         RUN01130
C
C     IF(R.EQ.0) GO TO 100                                              RUN01140
      GO TO 90                                                          RUN01150
   80 IAL=NP-1                                                          RUN01160
C
C
C
C************************************************************************
C
C----- FIND DISTANCE FROM REFERENCE POINT TO POINT WHERE GROUND
C----- ELEVATION IS SAME AS SWL.(REFERENCE POINT IS THE MOST SEAWARD
C----- PROFILE POINT)
C
C
90    HOSCALE = HO*100.
      SWL = WTB*100.
      DO 5 I=1,MAXPTS-1
        IF (SWL .LE. VERT(I+1)) THEN
           CALL SWLINT(VERT(I),VERT(I+1),HORIZ(I),HORIZ(I+1),SWL,REFSWL)
           GO TO 6
         ENDIF
5     CONTINUE
6     CONTINUE
      IF (R .EQ. 0) GOTO 100
C
C_____COMPUTE DSL, THIS EQUATION COMPUTES DSL WHEN  THE RUNUP LIMIT     RUN01170
C_____IS ON THE LAST LANDWARD SLOPE                                     RUN01180
C
      DSL=DL(IAL)+((R10+WTL-DEP(IAL))*S(IAL))/100.+.5                   RUN01190
C  90 DCS=1000*(DSL-DLE)/DC+R10                                         RUN01200
C     GO TO 120                                                         RUN01210
C  100 DS = -DEP(IAL)/HO                                                RUN01220
C     IF (DS.LE.25) GO TO 110                                           RUN01230
C     IF (S(IAL-1).GT.30) DS=DS*100                                     RUN01240
  100 CONTINUE
C 110 CALL LOOK(PCH,8,DS,IZ,K,IFD)                                      RUN01250
C     DCS=S(IAL)*100                                                    RUN01260
C                                                                       RUN01270
C
C  110 CONTINUE
C
C************************************************************************
C    FIND THE POINT WHERE THE STILLWATER INTERSECTS THE GROUND PROFILE.
C************************************************************************
C
```

```
    J=I+1
      IF((SWL+1).EQ.VERT(J))THEN
          IF((VERT(J+1)-VERT(J)).GT.0)THEN
              MW=(HORIZ(J+1)-HORIZ(J))/(VERT(J+1)-VERT(J))
          ELSE
              MW=10000
          ENDIF
          IF((VERT(J)-VERT(I)).GT.0)THEN
            MWSE=(HORIZ(J)-HORIZ(I))/(VERT(J)-VERT(I))
          ELSE
            MWSE=10000
          ENDIF
         IF(MW.GE.(1.5*MWSE)) GOTO 919
         IF(VERT(J+1).GT.(SWL+HOSCALE))THEN
            YN1=SWL+HOSCALE
            CALL SWLINT(VERT(J),VERT(J+1),HORIZ(J),HORIZ(J+1),YN1,XN1)
         ELSE
            YN1=VERT(J+1)
            XN1=HORIZ(J+1)
         ENDIF
               GO TO 112
       ELSE
               GO TO 111
       ENDIF
 111 IF ((VERT(J)-VERT(I)) .GT. 0) THEN
       MW=(HORIZ(J)-HORIZ(I))/(VERT(J)-VERT(I))
     ELSE
       MW=10000
     ENDIF
     IF ((VERT(I)-VERT(I-1)) .GT. 0 .AND. I .GT. 1) THEN
       MWSE=(HORIZ(I)-HORIZ(I-1))/(VERT(I)-VERT(I-1))
     ELSE
       MWSE = 10000
     ENDIF
      IF (MW .GE. (1.5*MWSE)) GOTO 919
      IF (VERT(I+1).GT.(SWL+HOSCALE)) THEN
        YN1=SWL+HOSCALE
        CALL SWLINT(VERT(I),VERT(J),HORIZ(I),HORIZ(J),YN1,XN1)
      ELSE
        YN1=VERT(J)
        XN1=HORIZ(J)
      ENDIF
      GO TO 203
C
C*********************************************************************
C GEOMETRICAL ANALYSIS TO ISOLATE EFFECTIVE STRUCTURE & APPROACH:
C FIND THE STRUCTURE SLOPE AND SLOPE OF THE APPROACH IF THE STILLWATER
C INTERSECTS THE PROFILE AT AN INPUT POINT.
C*********************************************************************
C
  112 IF ((SWL+1) .EQ. VERT(J)) THEN
        MW1=(XN1-HORIZ(J))/(YN1-VERT(J))
        DO 101 L=1,J
          MWA(J+1-L)=(XN1-HORIZ(J+1-L))/(YN1-VERT(J+1-L))
          IF (MWA(J+1-L) .GT. 1.2*MW1) GOTO 102
C
C
C   CHECK TO SEE IF THE NEXT SEAWARD SLOPE SHOULD BE ADDED TO CALCULATE
```

```
C   THE STRUCTURE SLOPE.
C
C
101     CONTINUE
102         IF (L .EQ. 2) THEN
              MWST=(XN1-HORIZ(J))/(YN1-VERT(J))
              HST=HORIZ(J)/100.
              DS1=0
              MS1=MWSE
              MS1H=HORIZ(I)/100.
              M=J
              GO TO 303
            ELSE IF (L.EQ.(J+1)) THEN

                 MWST=MWA(1)
                 HST=HORIZ(1)
                 DS1=SWL-VERT(1)
                 SA=10000
                 K1=1.0
                 DSA=DS1
                 HSA=HST
                 GO TO 910
            ELSE
              MWST=MWA(J+2-L)
              HST=(HORIZ(J+2-L)/100.)
              DS1=SWL-VERT(J+2-L)
              IF ((VERT(J+2-L)-VERT(J+1-L)) .GT. 0) THEN
                MS1=(HORIZ(J+2-L)-HORIZ(J+1-L))/
     1            (VERT(J+2-L)-VERT(J+1-L))
                MS1H=HORIZ(J+1-L)/100.
              ELSE
                MS1=10000
                MS1H=HORIZ(J+1-L)/100.
              ENDIF
              M=J+2-L
            ENDIF
               IF(I.EQ.1)THEN
                IF((VERT(J)-VERT(I)).GT.0)THEN
                 SA=(HORIZ(J)-HORIZ(I))/(VERT(J)-VERT(I))
                 K1=(HORIZ(J)-HORIZ(I))/100.
                 DSA=SWL-VERT(I)
                 HSA=HORIZ(I)/100.
                 GO TO 910
                ELSE
                 SA=10000
                 DSA=SWL-VERT(I)
                 K1=1.0
                 HSA=HORIZ(I)/100.
                 GO TO 910
                ENDIF
               ENDIF
C
C   EXAMINE APPROACH SEAWARD OF THE STRUCTURE
C
 303   DO 103 B=1,(I-L+1)
         IF ((VERT(M)-VERT(M-B-1)) .GT. 0) THEN
           SA1(B)=(HORIZ(M)-HORIZ(M-B-1))/(VERT(M)-VERT(M-B-1))
         ELSE
```

```
          SA1(B)=10000
        ENDIF
C
C
C   CHECK TO SEE IF NEXT SEAWARD SLOPE SHOULD BE ADDED TO CALCULATE
C   THE APPROACH SLOPE.
C
C
        IF ((SA1(B).GT.(1.2*MS1)).OR.(SA1(B).GT.15)) THEN
          IF (B .EQ. 1) THEN
            DSA=SWL-VERT(M-1)
            SA=MS1
            HSA=MS1H
            K1=(HORIZ(M)-HORIZ(M-1))/100.
            GOTO 910
          ELSE
            SA=SA1(B-1)
            K1= (HORIZ(M)-HORIZ(M-B+1))/100.
            DSA=SWL-VERT(M-B+1)
            HSA=HORIZ(M-B+1)/100.
            GOTO 910
          ENDIF
        ENDIF
 103   CONTINUE
       IF((VERT(M)-VERT(1)).GT.0)THEN
            SA=(HORIZ(M)-HORIZ(1))/(VERT(M)-VERT(1))
       ELSE
            SA=10000
       ENDIF
       GOTO 810
     ENDIF
C
C
C        CALCULATE THE (COT) STRUCTURE SLOPE AND (COT) SLOPE OF APPROACH
C        IF THE STILLWATER INTERSECTS THE GROUND PROFILE BETWEEN INPUT
C        POINTS.
C
  203 DO 204 A=1,I
        MWA(J-A)=(XN1-HORIZ(J-A))/(YN1-VERT(J-A))
C
C           CHECK TO SEE IF NEXT SEAWARD SLOPE SHOULD BE ADDED TO
C           CALCULATE THE (COT) STRUCTURE SLOPE.
C
C
        IF (MWA(J-A).GT.(1.2*MW)) THEN
          IF (A.EQ.1) THEN
            MWST=MW
            HST=(HORIZ(I)/100.)
            DS1=SWL-VERT(I)
            IF (VERT(I)-VERT(I-1).GT. 0) THEN
              MS1=(HORIZ(I)-HORIZ(I-1))/(VERT(I)-VERT(I-1))
            ELSE
              MS1=10000
            ENDIF
            MS1H=HORIZ(I-1)/100.
            GOTO 504
          ELSE
            MWST=MWA(J-A+1)
```

```
            HST=(HORIZ(J-A+1)/100.)
            DS1=SWL-VERT(J-A+1)
            IF  (VERT(J-A+1)-VERT(J-A).GT.0) THEN
              MS1=(HORIZ(J-A+1)-HORIZ(J-A))/(VERT(J-A+1)-VERT(J-A))
            ELSE
              MS1=10000
            ENDIF
            MS1H=HORIZ(J-A)/100.
            GOTO 503
          ENDIF
        ENDIF
204   CONTINUE
      MWST=MWA(J-A+1)
      HST=(HORIZ(J-A+1)/100.)
      DS1=SWL-VERT(J-A+1)
      K1=1.0
      SA=10000
      GOTO 911
503      IF(A.EQ.I)THEN
         K1=(HORIZ(2)-HORIZ(1))/100.
         DSA=SWL-VERT(1)
         HSA=HORIZ(1)/100.
           IF((VERT(2)-VERT(1)).GT.0)THEN
              SA=(HORIZ(2)-HORIZ(1))/(VERT(2)-VERT(1))
           ELSE
              SA=10000
           ENDIF
         GO TO 910
         ENDIF
504   DO 104 B=1,(I-A+1)
         M=J-A+1
         IF ((VERT(M)-VERT(M-B)) .GT. 0) THEN
           SA1(B)=(HORIZ(M)-HORIZ(M-B))/(VERT(M)-VERT(M-B))
         ELSE
           SA1(B)=10000
         ENDIF
C
C
C    CHECK TO SEE IF THE NEXT SEAWARD SLOPE SHOULD BE ADDED TO CALCULATE
C    THE (COT) OF THE APPROACH SLOPE.
C
C
         IF (SA1(B) .GT. (1.2*MS1) .OR. ((SA1(B) .GT. 15) .AND.
        1 (B.NE.1))) THEN
           SA=SA1(B-1)
           K1=(HORIZ(M)-HORIZ(M-B+1))/100
           DSA=SWL-VERT(M-B+1)
           HSA=HORIZ(M-B+1)/100.
           GO TO 910
         ENDIF
104   CONTINUE
          IF(VERT(M)-VERT(1).GT.0)THEN
             SA=(HORIZ(M)-HORIZ(1))/(VERT(M)-VERT(1))
          ELSE
             SA=10000
          ENDIF
810   K1=(HORIZ(M)-HORIZ(1))/100
      DSA=SWL-VERT(1)
```

```
      HSA=HORIZ(1)/100.
910   CONTINUE
C
C
C    CALCULATE THE DEEPWATER WAVELENGTH TRANSFORMED AT APPROACH (DLO)
C
C
         DLO=(100.*DSA)/(5.12*T*T)
           IF (DLO.LE.100.) THEN
              ID1=DLO
              DLO1=DLO
              DLO2=DLO1+1.
           ELSE
              IF (DLO.LE.6000.) THEN
                 ID1=90.+(DLO/10.)
                 DLO1=(DLO/10.)*10.
                 DLO2=DLO1+10.
              ELSE
                 IF (DLO.LE.10000.) THEN
                    ID1=630.+(DLO/100.)
                    DLO1=(DLO1/100.)*100.
                    DLO2=DLO1+100.
                 ENDIF
              ENDIF
           ENDIF
           CALL RINT(DLO1,DLO2,DLL(ID1),DLL(ID1+1),DLO,DLA)
C
C
C       CALCULATE WAVELENGTH (DXLA) AND DETERMINE PARAMETERS OF 1/10,
C       1/2,1/4 OF THE WAVELENGTH TO BE USED TO DETERMINE THE METHOD USED
C       TO CALCULATE THE RUNUP ELEVATION.
C
C
           DXLA=100*DSA/DLA
           DXLA1=DXLA/10
           DXLA2=DXLA/2
           DXLA4=DXLA/4
C
C
C_____ CHECK FOR FLAT OR SLOPED APPROACH
C
C
911      IF (SA .LT. 15) THEN
C
C_____ CHECK FOR STEEP STRUCTURE
C
            IF (MWST.GE.4) THEN
              CALL SIMPCOMP1
            ELSE
C
C******************CHECK HORIZONTAL APPROACH LENGTH FOR BRANCHING****
C
               IF (K1 .GE. DXLA2) CALL SIMPCOMP1
               IF (K1 .LE. DXLA4) CALL SIMPCOMP2
               IF (K1 .GT. DXLA4 .AND. K1 .LT. DXLA2) THEN
                  I2=(K1-DXLA4)/DXLA4
                  CALL SIMPCOMP1
                  RL=R1
```

```
                CALL SIMPCOMP2
                RF=R1
                R1=I2*RL+(1-I2)*RF
             ENDIF
           ENDIF
      ELSE
199        CALL SIMPCOMP2
        ENDIF
        GOTO 200
919      CALL COMP
 180   IF(R.NE.0) THEN
         GO TO 200
       ELSE
         GO TO 205
       ENDIF
C      IF((R1*10).LT.DEP(ISL1)) GO TO 200
C      IF(DH.LE.25) GO TO 190
C      IF(S(II).GT.30) DH=DH*100
C      CALL LOOK(PCH,8,DH,IZ,K,IFD)
C
C_____CHECK FOR CONVERGENCE OF RUNUP
C
   200 CONTINUE
       IF(ABS(R-R1).LT.0.15)THEN
          R2=(R+R1)/2.
          GOTO 220
       ENDIF
  205  LISL(IQ)=IAL
       LII(IQ)=II
       R=R1
       RAS(IQ)=R
       IQ=IQ+1
   210 CONTINUE
       IQ=IQ-1
       IFC(IQ)=1
       GOTO 230
   220 LISL(IQ)=IAL
       LII(IQ)=II
       RAS(IQ)=R2
       RETURN
   230 LISL(IQ)=IAL
       LII(IQ)=II
       RAS(IQ)=R1
       RETURN
       END
```

```
C     SUBROUTINE RRUFF(R1,FROUGH,N)
      SUBROUTINE RRUFF(FROUGH,N)
C
C     COMPUTATION OF WEIGHTED ROUGHNESS FACTOR FROM
C     WTL TO WAVE RUNUP LIMIT
```

```
                                                                        RUFF0050
C                                                                       RUFF0060
C***** VARIABLE DICTIONARY ****                                         RUFF0070
C                                                                       RUFF0080
C     NAME   MODE SIZE                                                  RUFF0090
C                                                                       RUFF0100
C     SLPLEN R*4   1    DISTANCE ALONG ONE SLOPE                        RUFF0110
C     ROUGH  R*4   16   ROUGHNESS FACTOR ON ONE SLOPE                   RUFF0120
C     FROUGH R*4   1    FINAL ROUGHNESS FACTOR FOR THE TOTAL SLOPE      RUFF0130
C                       LENGTH FROM WTL TO RAS(IM)                      RUFF0140
C     NM1    I*4   1    NO. OF POINTS IN THE PROFILE                    RUFF0150
C     TOTLEN R*4   1    TOTAL SLOPE LENGTH FROM WTL TO RAS(IM)          RUFF0160
C     RL     R*4   1    ROUGHNESS FACTOR TIMES SLOPE LENGTH             RUFF0170
C
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD

      NM1=NP-1                                                          RUFF0210
      TOTLEN=0.0                                                        RUFF0220
      TOTRL=0.0                                                         RUFF0230
C
C_____FIND SLOPE THAT STILLWATER LEVEL INTERSECTS, LI                    RUFF0240
C
      IF(N.GT.1) GO TO 30                                               RUFF0250
      DO 10 J1=1,NM1                                                    RUFF0260
      IF(WTL.LT.DEP(J1+1)) GO TO 20                                     RUFF0270
   10 CONTINUE                                                          RUFF0280
   20 LI=J1                                                             RUFF0290
   30 DDTR=WTL+R1*100                                                   RUFF0300
C
C_____FIND SLOPE THAT RUNUP INTERSECTS, LIS                              RUFF0310
C
      DO 40 J2=1,NM1                                                    RUFF0320
      IF(DDTR.LT.DEP(J2+1)) GO TO 50                                    RUFF0330
   40 CONTINUE                                                          RUFF0340
   50 LIS=J2                                                            RUFF0350
      DO 60 K=LI,LIS                                                    RUFF0360
C
C_____FIND LENGTH OF INDIVIDUAL SLOPE SECTION                            RUFF0370
C
      SLPLEN=(((DEP(K+1)-DEP(K))/100.)**2+(DL(K+1)-DL(K))**2)**0.5      RUFF0380
C
C_____MULTIPLY SLOPE SECTION LENGTH BY ROUGHNESS FACTOR                  RUFF0390
C
      RL=SLPLEN*ROUGH(K)                                                RUFF0400
      IF(K.EQ.LI)SLPLEN=((((DEP(LI+1)-WTL)*S(LI))/100.)**2+((DEP(LI+1)- RUFF0410
     1  WTL)/100.)**2)**0.5                                             RUFF0420
      IF(K.EQ.LI) RL=SLPLEN*ROUGH(LI)                                   RUFF0430
```

```
      IF(K.EQ.LIS)SLPLEN=(((R1-(DEP(LIS)/100.))*S(LIS))**2+(R1-(DEP(LIS)RUFF0440
     1  /100.))**2)**0.5                                                RUFF0450
      IF(K.EQ.LIS) RL=SLPLEN*ROUGH(LIS)                                 RUFF0460
C
C_____ADD UP SLOPE SECTION LENGTHS                                      RUFF0470
C
      TOTLEN=TOTLEN+SLPLEN                                              RUFF0480
C
C_____ADD UP (SLOPE LENGTH *ROUGHNESS FACTOR) VALUES                    RUFF0490
C
   60 TOTRL=TOTRL+RL                                                    RUFF0500
C
C_____COMPUTE FINAL ROUGHNESS FACTOR                                    RUFF0510
C
   70 FROUGH=TOTRL/TOTLEN                                               RUFF0520
      RETURN                                                            RUFF0530
      END                                                               RUFF0540
```

```
      SUBROUTINE RINT(X1,X2,Y1,Y2,X,Y)                                  RINT0010
C
C              SUBROUTINE  RINT PERFORMS A SINGLE LINEAR
C                  INTERPOLATION BY METHOD Y=MX+B
C
C     INPUT KNOWN DATA POINTS  (X1,Y1),(X2,Y2)                          RINT0030
C     GIVEN X FIND Y=F(X)=MX+B   M=SLOPE  B=START VALUE                 RINT0040
C     OUTPUT  (X,Y)                                                     RINT0050
C                                                                       RINT0060
C*****VARIABLE DICTIONARY                                               RINT0070
C                                                                       RINT0080
C     ALL INPUT AND OUTPUT IS  I*4                                      RINT0090
C                                                                       RINT0100
C*****START OF SUBROUTINE                                               RINT0110
      IMPLICIT INTEGER*4(X,Y)                                           RINT0120
      G=X2-X1                                                           RINT0130
C
C-----DIVISION BY ZERO CHECK                                            RINT0140
C
      IF(G.NE.0.) GOTO 10                                               RINT0150
      Y=Y1                                                              RINT0160
      RETURN                                                            RINT0170
   10 RAT=(X-X1)/G                                                      RINT0180
      Y=(Y2-Y1)*RAT+Y1                                                  RINT0190
      RETURN                                                            RINT0200
      END                                                               RINT0210
```

```
      SUBROUTINE SWLINT(X1,X2,Y1,Y2,X,Y)
C
C              SUBROUTINE  SWLINT, CORROSPONDING TO RINT BUT FOR
C              REAL VARIABLES, PERFORMS A SINGLE LINEAR
C              INTERPOLATION BY METHOD Y=MX+B
C
C     INPUT KNOWN DATA POINTS  (X1,Y1),(X2,Y2)
C     GIVEN X FIND Y=F(X)=MX+B   M=SLOPE  B=START VALUE
C     OUTPUT  (X,Y)
C
C*****VARIABLE DICTIONARY
C
C         ALL INPUT AND OUTPUT IS  R*4
C
C
C*****START OF SUBROUTINE
      G=X2-X1
C
C-----DIVISION BY ZERO CHECK
C
      IF(G.NE.0.) GOTO 10
      Y=Y1
      RETURN
   10 RAT=(X-X1)/G
      Y=(Y2-Y1)*RAT+Y1
      RETURN
      END
```

```
      BLOCK DATA                                                        BLOC0010
C                                                                       BLOC0020
C     THIS SUBROUTINE INITIALIZES MEMORY                                BLOC0030
C                                                                       BLOC0040
C*****VARIABLE DICTIONARY                                               BLOC0050
C                                                                       BLOC0060
C     NAME MODE SIZE   DESCRIPTION                              UNITS   BLOC0070
C                                                                       BLOC0080
C     PDB   I*4 27     VALUES OF SLOPE FOR ENTRY INTO DB        *100    BLOC0090
C     PDB1  I*4 13     VALUES OF H/T**2 FOR ENTRY INTO DB       *1000   BLOC0100
C     PCH   I*4 9      VALUES OF  D/HO  FOR ENTRY INTO DB       *10     BLOC0110
C     DB    I*4 2457   VALUES OF R/HO AS FUNCT. OF PDB,PDB1,PCH *100    BLOC0120
C     DB  CONSISTS OF THE DUMMY ARRAYS  D101-D807, DL1-DL3              BLOC0130
C     IPAGE I*4 1      CURRENT PAGE NUMBER                              BLOC0140
C     DT    I*4 118    PAGE HEADING                                     BLOC0150
C                                                                       BLOC0160
C*****START OF SUBROUTINE                                               BLOC0170
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
```

```
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEF(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
      COMMON /SY/ PDB(27),PDB1(13),PCH(9)                              BLOC0200
      COMMON /SZ/ D101(180),D107(171),D201(180),D207(171),D301(180),   BLOC0210
     1  D307(171),D401(180),D407(171),D501(180),D507(171),D601(180),   BLOC0220
     2  D607(171),D701(180),D707(171),D801(180),D807(171)
      COMMON /SDL/ DL1(198),DL2(198),DL3(198),DL4(136)
      DATA DT/'CL','IE','NT','- ',16*0,'**',' W','AV','E ','RU','NU',  BLOC0240
     1 'P ','CO','MP','UT','AT','IO','NS',' *','* ',4*0,'EN','GI','NE', BLOC0250
     2 'ER','ED',' B','Y ',6*0,'JO','B ',5*0,'PR','OJ','EC','T-',46*0,  BLOC0260
     3 'RU','N ',3*0,' P','AG','E ',0/,IPAGE/0/                        BLOC0270
      DATA PDB1/   97,  193,  290,  386,  515,  611,  740,  997, 1512,  BLOC0280
     1           1995, 2509, 2992, 3989/                                BLOC0290
      DATA  PCH/    0,   60,  100,  150,  300, 4000, 6000, 9000, 31000/ BLOC0300
C                                                                       BLOC0310
      DATA PDB/    10,   15,   20,   30,   40,   50,   60,   80,  100,  BLOC0320
     1            112,  130,  150,  170,  200,  250,  300,  350,  400,  BLOC0330
     2            450,  500,  600,  700,  800, 1000, 1500, 2000, 3000/  BLOC0340
C  FIGURE 5
      DATA D101/  600,  600,  600,  600,  600,  600,  590,  575,  560,
     2            550,  540,  540,  540,  540,  530,  520,  500,  490,
     3            480,  460,  410,  370,  330,  260, -999, -999, -999,
     1            540,  540,  540,  540,  540,  540,  520,  505,  495,
     2            490,  480,  475,  470,  460,  445,  430,  420,  410,
     3            400,  390,  350,  290,  245,  180, -999, -999, -999,
     1            400,  400,  400,  400,  400,  400,  400,  400,  398,
     2            388,  385,  380,  378,  369,  357,  348,  335,  320,
     3            301,  280,  235,  200,  170,  130, -999, -999, -999,
     1            320,  320,  320,  320,  320,  320,  320,  318,  316,
     2            313,  311,  308,  307,  306,  300,  290,  280,  265,
     3            248,  230,  196,  170,  150,  120, -999, -999, -999,
     1            233,  233,  233,  233,  233,  233,  238,  240,  244,
     2            248,  249,  250,  250,  248,  241,  235,  220,  207,
     3            192,  178,  155,  136,  120,   97, -999, -999, -999,
     1            200,  200,  200,  200,  200,  200,  203,  210,  211,
     2            212,  213,  214,  214,  215,  211,  207,  194,  181,
     3            170,  158,  137,  119,  107,   89, -999, -999, -999,
     1            178,  178,  178,  178,  178,  178,  180,  181,  182,
     2            183,  184,  183,  182,  180,  178,  171,  165,  155/
      DATA D107/  147,  137,  119,  104,   94,   78, -999, -999, -999,
     1            150,  150,  150,  150,  150,  150,  150,  150,  150,
     2            151,  149,  148,  147,  143,  140,  136,  129,  122,
     3            115,  108,   96,   86,   78,   66, -999, -999, -999,
     1            108,  108,  108,  108,  108,  108,  110,  113,  115,
     2            115,  115,  114,  112,  110,  108,  103,   99,   95,
     3             89,   84,   74,   67,   61,   52, -999, -999, -999,
     1             90,   90,   90,   90,   90,   90,   92,   95,   98,
     2             98,   98,   97,   96,   94,   91,   88,   84,   80,
     3             75,   72,   64,   58,   52,   44, -999, -999, -999,
     1             76,   76,   76,   76,   76,   76,   80,   83,   85,
     2             86,   86,   85,   84,   83,   79,   75,   71,   67,
     3             64,   60,   55,   50,   46,   39, -999, -999, -999,
     1             68,   68,   68,   68,   68,   68,   72,   75,   77,
```

```
      2          78,  78,  78,  76,  74,  70,  66,  62,  59,
      3          56,  53,  48,  44,  41,  35,-999,-999,-999,
      1          58,  58,  58,  58,  58,  58,  61,  64,  66,
      2          67,  67,  66,  64,  62,  58,  54,  51,  48,
      3          46,  43,  39,  36,  34,  30,-999,-999,-999/
C  FIGURE 8                                                     BLOC0350
       DATA D201/ 600, 600, 600, 600, 600, 600, 590, 575, 560,  BLOC0360
      2          550, 540, 540, 540, 540, 530, 520, 500, 490,   BLOC0370
      3          480, 460, 410, 370, 330, 260,-999,-999,-999,   BLOC0380
      1          540, 540, 540, 540, 540, 540, 520, 505, 495,   BLOC0390
      2          490, 480, 475, 470, 460, 445, 430, 420, 410,   BLOC0400
      3          400, 390, 350, 290, 245, 180,-999,-999,-999,   BLOC0410
      1          460, 460, 460, 460, 460, 460, 460, 460, 460,   BLOC0420
      2          460, 460, 450, 445, 435, 420, 400, 380, 360,   BLOC0430
      3          340, 320, 275, 225, 190, 140,-999,-999,-999,   BLOC0440
      1          415, 415, 415, 415, 415, 415, 420, 430, 440,   BLOC0450
      2          440, 435, 430, 425, 415, 395, 375, 350, 325,   BLOC0460
      3          300, 270, 220, 185, 160, 120,-999,-999,-999,   BLOC0470
      1          365, 365, 365, 365, 365, 365, 375, 390, 395,   BLOC0480
      2          400, 400, 395, 390, 380, 360, 340, 310, 280,   BLOC0490
      3          250, 230, 190, 160, 140, 105,-999,-999,-999,   BLOC0500
      1          320, 320, 320, 320, 320, 320, 330, 345, 350,   BLOC0510
      2          355, 355, 350, 340, 330, 315, 300, 275, 245,   BLOC0520
      3          220, 195, 160, 140, 120,  94,-999,-999,-999,   BLOC0530
      1          285, 285, 285, 285, 285, 285, 295, 305, 320,   BLOC0540
      2          320, 320, 315, 310, 300, 280, 255, 235, 210/   BLOC0550
       DATA D207/ 185, 165, 140, 120, 105,  82,-999,-999,-999,  BLOC0560
      1          250, 250, 250, 250, 250, 250, 250, 255, 260,   BLOC0570
      2          265, 265, 260, 260, 245, 230, 210, 185, 165,   BLOC0580
      3          145, 135, 112,  97,  86,  69,-999,-999,-999,   BLOC0590
      1          195, 195, 195, 195, 195, 195, 200, 210, 220,   BLOC0600
      2          220, 220, 220, 215, 205, 185, 160, 140, 125,   BLOC0610
      3          110, 103,  88,  76,  68,  54,-999,-999,-999,   BLOC0620
      1          170, 170, 170, 170, 170, 170, 180, 190, 195,   BLOC0630
      2          198, 200, 198, 192, 182, 165, 145, 125, 110,   BLOC0640
      3           98,  88,  75,  65,  57,  47,-999,-999,-999,   BLOC0650
      1          155, 155, 155, 155, 155, 155, 165, 175, 180,   BLOC0660
      2          185, 185, 180, 175, 160, 140, 120, 105,  95,   BLOC0670
      3           84,  76,  65,  56,  49,  40,-999,-999,-999,   BLOC0680
      1          142, 142, 142, 142, 142, 142, 150, 158, 165,   BLOC0690
      2          168, 170, 165, 155, 142, 125, 110,  96,  85,   BLOC0700
      3           75,  69,  58,  50,  43,  35,-999,-999,-999,   BLOC0710
      1          120, 120, 120, 120, 120, 120, 130, 140, 145,   BLOC0720
      2          150, 150, 145, 140, 130, 112,  96,  85,  75,   BLOC0730
      3           67,  60,  51,  44,  37,  32,-999,-999,-999/   BLOC0740
C   FIGURE 9                                                    BLOC0750
       DATA D301/ 700, 700, 700, 700, 700, 700, 670, 640, 620,  BLOC0760
      2          600, 600, 600, 600, 600, 590, 570, 550, 520,   BLOC0770
      3          500, 470, 420, 370, 320, 250,-999,-999,-999,   BLOC0780
      1          660, 660, 660, 660, 660, 660, 630, 580, 550,   BLOC0790
      2          540, 520, 520, 520, 510, 500, 470, 440, 420,   BLOC0800
      3          390, 370, 330, 270, 230, 170,-999,-999,-999,   BLOC0810
      1          620, 620, 620, 620, 620, 620, 600, 540, 510,   BLOC0820
      2          500, 480, 460, 460, 460, 440, 410, 380, 360,   BLOC0830
      3          330, 310, 260, 215, 185, 140,-999,-999,-999,   BLOC0840
      1          570, 570, 570, 570, 570, 570, 540, 500, 470,   BLOC0850
      2          460, 440, 440, 440, 430, 400, 370, 340, 310,   BLOC0860
      3          285, 260, 215, 185, 160, 120,-999,-999,-999,   BLOC0870
```

```
     1          520,  520,  520,  520,  520,  520,  500,  470,  450,  BLOC0880
     2          440,  430,  420,  410,  390,  360,  340,  310,  280,  BLOC0890
     3          250,  220,  180,  155,  135,  105, -999, -999, -999,  BLOC0900
     1          480,  480,  480,  480,  480,  480,  470,  450,  430,  BLOC0910
     2          420,  420,  410,  400,  375,  340,  310,  285,  260,  BLOC0920
     3          235,  200,  170,  140,  120,   95, -999, -999, -999,  BLOC0930
     1          450,  450,  450,  450,  450,  450,  440,  430,  420,  BLOC0940
     2          410,  400,  390,  380,  360,  325,  290,  255,  225/  BLOC0950
      DATA D307/ 200,  180,  150,  125,  110,   84, -999, -999, -999,  BLOC0960
     1          405,  405,  405,  405,  405,  405,  400,  395,  390,  BLOC0970
     2          385,  375,  365,  345,  320,  280,  250,  215,  185,  BLOC0980
     3          165,  145,  120,  100,   88,   70, -999, -999, -999,  BLOC0990
     1          345,  345,  345,  345,  345,  345,  340,  330,  325,  BLOC1000
     2          320,  310,  300,  290,  275,  240,  205,  175,  150,  BLOC1010
     3          130,  120,   96,   80,   70,   55, -999, -999, -999,  BLOC1020
     1          300,  300,  300,  300,  300,  300,  295,  285,  280,  BLOC1030
     2          278,  270,  260,  255,  235,  205,  170,  145,  125,  BLOC1040
     3          115,  100,   82,   70,   60,   48, -999, -999, -999,  BLOC1050
     1          265,  265,  265,  265,  265,  265,  260,  260,  255,  BLOC1060
     2          252,  248,  240,  230,  210,  182,  155,  130,  115,  BLOC1070
     3          100,   89,   72,   60,   52,   41, -999, -999, -999,  BLOC1080
     1          233,  233,  233,  233,  233,  233,  233,  233,  233,  BLOC1090
     2          233,  230,  225,  218,  195,  165,  135,  115,  100,  BLOC1100
     3           88,   78,   64,   53,   46,   36, -999, -999, -999,  BLOC1110
     1          203,  203,  203,  203,  203,  203,  203,  205,  206,  BLOC1120
     2          208,  205,  200,  190,  173,  146,  122,  102,   88,  BLOC1130
     3           76,   68,   56,   46,   40,   32, -999, -999, -999/  BLOC1140
                                                                     BLOC1150
C         FIGURE 10
      DATA D401/ 460,  460,  460,  460,  460,  460,  460,  460,  465,  BLOC1160
     2          465,  470,  480,  490,  495,  500,  505,  505,  495,  BLOC1170
     3          480,  470,  430,  370,  315,  235, -999, -999, -999,  BLOC1180
     1          395,  395,  400,  400,  400,  400,  395,  390,  395,  BLOC1190
     2          395,  400,  410,  420,  420,  415,  400,  390,  375,  BLOC1200
     3          365,  345,  315,  270,  230,  170, -999, -999, -999,  BLOC1210
     1          330,  330,  340,  340,  340,  350,  355,  370,  370,  BLOC1220
     2          380,  390,  400,  405,  400,  390,  370,  350,  330,  BLOC1230
     3          310,  290,  250,  220,  185,  140, -999, -999, -999,  BLOC1240
     1          310,  315,  320,  330,  330,  335,  340,  360,  365,  BLOC1250
     2          370,  400,  400,  400,  390,  380,  360,  335,  310,  BLOC1260
     3          285,  260,  220,  185,  160,  120, -999, -999, -999,  BLOC1270
     1          295,  300,  305,  310,  320,  325,  330,  350,  370,  BLOC1280
     2          390,  400,  400,  390,  380,  360,  345,  320,  295,  BLOC1290
     3          265,  240,  195,  160,  140,  105, -999, -999, -999,  BLOC1300
     1          270,  285,  295,  300,  305,  310,  320,  340,  360,  BLOC1310
     2          375,  390,  395,  395,  380,  355,  325,  295,  265,  BLOC1320
     3          240,  215,  175,  145,  125,   95, -999, -999, -999,  BLOC1330
     1          260,  265,  275,  290,  295,  305,  315,  335,  360,  BLOC1340
     2          375,  385,  390,  385,  365,  330,  295,  265,  235/  BLOC1350
      DATA D407/ 205,  190,  155,  130,  110,   86, -999, -999, -999,  BLOC1360
     1          240,  240,  245,  245,  250,  260,  275,  300,  325,  BLOC1370
     2          340,  350,  350,  345,  330,  295,  255,  225,  200,  BLOC1380
     3          175,  160,  130,  110,   95,   74, -999, -999, -999,  BLOC1390
     1          210,  210,  210,  215,  220,  225,  235,  255,  270,  BLOC1400
     2          280,  280,  280,  275,  265,  235,  200,  175,  155,  BLOC1410
     3          135,  120,  100,   85,   73,   57, -999, -999, -999,  BLOC1420
     1          190,  190,  190,  190,  195,  200,  205,  220,  240,  BLOC1430
     2          245,  245,  245,  240,  230,  205,  175,  150,  135,  BLOC1440
     3          115,  105,   85,   70,   60,   46, -999, -999, -999,  BLOC1450
```

```
     1          175,  175,  175,  180,  180,  185,  190,  205,  220,  BLOC1460
     2          225,  225,  220,  215,  205,  180,  155,  135,  115,  BLOC1470
     3          105,   92,   74,   62,   53,   40, -999, -999, -999,  BLOC1480
     1          165,  165,  165,  165,  168,  170,  172,  185,  190,  BLOC1490
     2          195,  198,  195,  195,  180,  160,  135,  120,  105,  BLOC1500
     3           94,   82,   66,   56,   47,   36, -999, -999, -999,  BLOC1510
     1          145,  145,  145,  145,  145,  145,  148,  155,  165,  BLOC1520
     2          170,  175,  170,  165,  155,  140,  120,  105,   94,  BLOC1530
     3           84,   74,   60,   49,   42,   34, -999, -999, -999/ BLOC1540
C        FIGURE 11                                                  BLOC1550
      DATA D501/195,  210,  225,  240,  250,  255,  265,  280,  285,  BLOC1560
     2          290,  290,  300,  310,  320,  330,  340,  350,  355,  BLOC1570
     3          360,  360,  340,  310,  275,  225, -999, -999, -999,  BLOC1580
     1          195,  210,  225,  240,  250,  255,  265,  280,  285,  BLOC1590
     2          290,  290,  300,  310,  320,  330,  340,  350,  355,  BLOC1600
     3          335,  320,  280,  245,  215,  170, -999, -999, -999,  BLOC1610
     1          190,  200,  210,  230,  240,  250,  250,  260,  260,  BLOC1620
     2          270,  280,  280,  300,  310,  320,  325,  330,  325,  BLOC1630
     3          300,  275,  235,  200,  175,  140, -999, -999, -999,  BLOC1640
     1          190,  200,  210,  230,  240,  250,  250,  260,  260,  BLOC1650
     2          270,  280,  280,  290,  300,  310,  310,  315,  300,  BLOC1660
     3          265,  245,  200,  175,  150,  120, -999, -999, -999,  BLOC1670
     1          180,  190,  200,  220,  230,  235,  240,  255,  265,  BLOC1680
     2          270,  275,  280,  280,  285,  295,  300,  285,  265,  BLOC1690
     3          230,  205,  170,  145,  125,  100, -999, -999, -999,  BLOC1700
     1          170,  180,  185,  190,  205,  220,  230,  235,  250,  BLOC1710
     2          255,  258,  260,  262,  270,  280,  285,  270,  240,  BLOC1720
     3          215,  190,  155,  135,  115,   90, -999, -999, -999,  BLOC1730
     1          155,  165,  175,  180,  185,  195,  200,  210,  220,  BLOC1740
     2          225,  235,  240,  245,  250,  260,  265,  240,  210/  BLOC1750
      DATA D507/185,  165,  140,  120,  103,   80, -999, -999, -999,  BLOC1760
     1          145,  150,  155,  165,  170,  180,  185,  192,  200,  BLOC1770
     2          205,  210,  215,  220,  230,  235,  225,  200,  175,  BLOC1780
     3          155,  140,  115,   98,   84,   66, -999, -999, -999,  BLOC1790
     1          120,  127,  132,  140,  148,  152,  160,  167,  177,  BLOC1800
     2          180,  190,  200,  205,  210,  200,  175,  155,  135,  BLOC1810
     3          125,  110,   90,   77,   67,   53, -999, -999, -999,  BLOC1820
     1          115,  120,  125,  135,  140,  145,  150,  160,  172,  BLOC1830
     2          175,  177,  190,  195,  195,  180,  155,  135,  120,  BLOC1840
     3          108,   97,   80,   67,   58,   44, -999, -999, -999,  BLOC1850
     1          110,  115,  120,  130,  135,  140,  145,  155,  170,  BLOC1860
     2          172,  180,  185,  187,  185,  168,  140,  120,  106,  BLOC1870
     3           93,   84,   69,   58,   50,   39, -999, -999, -999,  BLOC1880
     1          105,  110,  115,  120,  128,  132,  138,  147,  160,  BLOC1890
     2          165,  172,  180,  180,  177,  155,  130,  110,   96,  BLOC1900
     3           85,   75,   62,   52,   45,   35, -999, -999, -999,  BLOC1910
     1           92,   98,  102,  108,  115,  122,  128,  138,  150,  BLOC1920
     2          155,  165,  168,  165,  158,  135,  115,   97,   84,  BLOC1930
     3           75,   65,   53,   44,   37,   29, -999, -999, -999/ BLOC1940
                                                                    BLOC1950
C        FIGURE 2
      DATA D601/240,  270,  280,  290,  290,  295,  305,  315,  325,  BLOC1960
     2          335,  345,  360,  375,  400,  420,  430,  430,  430,  BLOC1970
     3          425,  415,  375,  325,  280,  215,  130,   90,   55,  BLOC1980
     1          210,  230,  240,  255,  265,  270,  275,  280,  290,  BLOC1990
     2          300,  310,  320,  340,  355,  380,  400,  402,  395,  BLOC2000
     3          385,  365,  315,  265,  220,  170,  100,   72,   45,  BLOC2010
     1          185,  200,  210,  225,  235,  240,  243,  247,  253,  BLOC2020
     2          265,  280,  295,  310,  325,  350,  360,  360,  350,  BLOC2030
```

```
     3           340,  315,  270,  225,  185,  140,   84,   60,   37,  BLOC2040
     1           160,  175,  185,  200,  208,  212,  218,  222,  230,  BLOC2050
     2           240,  250,  270,  280,  300,  325,  335,  330,  315,  BLOC2060
     3           300,  275,  230,  195,  160,  120,   73,   53,   33,  BLOC2070
     1           140,  152,  162,  175,  185,  192,  200,  208,  215,  BLOC2080
     2           230,  240,  255,  265,  280,  295,  305,  300,  285,  BLOC2090
     3           270,  245,  200,  165,  135,  100,   62,   43,   27,  BLOC2100
     1           130,  145,  155,  168,  175,  182,  188,  198,  205,  BLOC2110
     2           215,  230,  240,  250,  260,  280,  288,  280,  265,  BLOC2120
     3           245,  220,  180,  145,  120,   92,   56,   40,   26,  BLOC2130
     1           130,  140,  148,  158,  165,  170,  175,  182,  190,  BLOC2140
     2           205,  215,  230,  240,  250,  265,  270,  260,  240/  BLOC2150
      DATA D607/ 215,  190,  160,  130,  110,   82,   50,   37,   24,  BLOC2160
     1           125,  132,  140,  150,  155,  160,  165,  170,  180,  BLOC2170
     2           190,  203,  215,  225,  235,  242,  240,  225,  200,  BLOC2180
     3           180,  155,  125,  105,   90,   68,   44,   36,   23,  BLOC2190
     1           120,  127,  132,  140,  145,  150,  152,  160,  168,  BLOC2200
     2           178,  190,  200,  207,  213,  207,  190,  170,  150,  BLOC2210
     3           135,  120,  100,   85,   72,   56,   37,   28,   19,  BLOC2220
     1           115,  122,  125,  135,  140,  145,  147,  152,  160,  BLOC2230
     2           170,  180,  192,  200,  203,  190,  165,  145,  125,  BLOC2240
     3           112,  100,   84,   72,   62,   48,   32,   24,   17,  BLOC2250
     1           115,  122,  125,  135,  140,  145,  147,  152,  160,  BLOC2260
     2           170,  180,  190,  195,  195,  180,  150,  130,  115,  BLOC2270
     3           100,   90,   72,   62,   53,   40,   28,   22,   16,  BLOC2280
     1           115,  122,  125,  135,  140,  145,  147,  152,  160,  BLOC2290
     2           170,  180,  190,  190,  190,  165,  142,  118,  102,  BLOC2300
     3            90,   80,   65,   55,   47,   36,   25,   19,   15,  BLOC2310
     1           110,  115,  120,  128,  132,  138,  140,  150,  155,  BLOC2320
     2           165,  175,  185,  185,  180,  155,  125,  105,   90,  BLOC2330
     3            78,   68,   55,   47,   40,   32,   22,   17,   13/  BLOC2340
C        FIGURE 3                                                     BLOC2350
      DATA D701/ 250,  265,  275,  290,  300,  310,  315,  335,  365,  BLOC2360
     2           380,  405,  420,  425,  430,  438,  438,  435,  432,  BLOC2370
     3           432,  430,  420,  380,  320,  245,  145,  100,   60,  BLOC2380
     1           180,  190,  195,  205,  210,  215,  220,  230,  240,  BLOC2390
     2           250,  265,  280,  295,  315,  340,  350,  360,  360,  BLOC2400
     3           360,  350,  320,  270,  220,  170,  100,   70,   42,  BLOC2410
     1           150,  160,  162,  170,  174,  177,  180,  188,  195,  BLOC2420
     2           210,  240,  260,  270,  280,  295,  305,  305,  305,  BLOC2430
     3           290,  275,  245,  210,  175,  135,   82,   57,   35,  BLOC2440
     1           135,  140,  142,  145,  150,  152,  155,  162,  175,  BLOC2450
     2           185,  215,  240,  250,  255,  270,  275,  280,  275,  BLOC2460
     3           260,  250,  205,  175,  150,  110,   70,   50,   32,  BLOC2470
     1           128,  130,  132,  135,  140,  142,  145,  150,  165,  BLOC2480
     2           175,  200,  225,  230,  240,  250,  255,  260,  260,  BLOC2490
     3           230,  215,  175,  145,  125,  100,   62,   44,   28,  BLOC2500
     1           125,  128,  130,  133,  138,  140,  142,  149,  155,  BLOC2510
     2           162,  190,  210,  215,  220,  230,  240,  242,  235,  BLOC2520
     3           210,  190,  150,  135,  115,   90,   56,   41,   26,  BLOC2530
     1           125,  128,  130,  135,  138,  140,  142,  150,  155,  BLOC2540
     2           162,  190,  200,  202,  210,  225,  230,  225,  210/  BLOC2550
      DATA D707/ 190,  170,  140,  120,  100,   72,   53,   38,   25,  BLOC2560
     1           125,  128,  130,  135,  138,  140,  142,  150,  155,  BLOC2570
     2           165,  180,  190,  202,  210,  215,  215,  200,  180,  BLOC2580
     3           160,  140,  120,  105,   92,   72,   48,   35,   23,  BLOC2590
     1           118,  120,  121,  122,  125,  128,  132,  135,  142,  BLOC2600
     2           155,  170,  185,  195,  200,  202,  185,  160,  140,  BLOC2610
```

```
     3            120,  110,   92,   77,   68,   55,   37,   28,   19,  BLOC2620
     1            115,  116,  117,  119,  120,  121,  125,  135,  147,  BLOC2630
     2            155,  165,  175,  185,  190,  190,  175,  145,  120,  BLOC2640
     3            110,   97,   80,   70,   60,   47,   32,   29,   17,  BLOC2650
     1            115,  116,  117,  119,  120,  121,  125,  135,  147,  BLOC2660
     2            155,  165,  175,  185,  190,  180,  150,  130,  110,  BLOC2670
     3             95,   85,   70,   60,   51,   41,   28,   22,   16,  BLOC2680
     1            115,  116,  117,  119,  120,  121,  125,  135,  147,  BLOC2690
     2            152,  162,  175,  180,  180,  165,  140,  117,  100,  BLOC2700
     3             85,   75,   63,   52,   45,   35,   25,   20,   15,  BLOC2710
     1            105,  106,  109,  111,  115,  118,  122,  132,  143,  BLOC2720
     2            150,  162,  168,  169,  164,  145,  125,  108,   90,  BLOC2730
     3             78,   68,   56,   48,   40,   32,   23,   18,   14/  BLOC2740
C        FIGURE 4                                                       BLOC2750
      DATA D801/  200,  205,  210,  210,  215,  220,  230,  250,  270,  BLOC2760
     2            280,  290,  315,  325,  345,  365,  380,  395,  405,  BLOC2770
     3            408,  412,  408,  360,  310,  230,  145,  100,   62,  BLOC2780
     1            145,  147,  148,  149,  150,  152,  154,  165,  182,  BLOC2790
     2            200,  230,  255,  262,  270,  280,  290,  295,  300,  BLOC2800
     3            305,  310,  300,  250,  215,  165,  100,   70,   43,  BLOC2810
     1            130,  130,  130,  130,  133,  135,  137,  145,  160,  BLOC2820
     2            175,  205,  228,  238,  245,  255,  265,  268,  270,  BLOC2830
     3            270,  265,  240,  205,  180,  135,   85,   59,   36,  BLOC2840
     1            120,  120,  120,  122,  125,  128,  130,  137,  145,  BLOC2850
     2            165,  190,  210,  220,  228,  235,  245,  250,  248,  BLOC2860
     3            240,  225,  195,  165,  145,  115,   74,   52,   33,  BLOC2870
     1            120,  120,  120,  122,  125,  128,  130,  137,  145,  BLOC2880
     2            160,  180,  190,  200,  210,  225,  235,  235,  225,  BLOC2890
     3            215,  200,  175,  150,  130,  105,   66,   47,   30,  BLOC2900
     1            120,  120,  120,  122,  125,  128,  130,  137,  145,  BLOC2910
     2            160,  170,  185,  195,  200,  210,  220,  225,  210,  BLOC2920
     3            195,  180,  155,  135,  120,   95,   60,   44,   27,  BLOC2930
     1            120,  120,  120,  122,  125,  128,  130,  137,  145,  BLOC2940
     2            155,  165,  180,  190,  200,  215,  220,  210,  195/  BLOC2950
      DATA D807/  175,  160,  135,  115,  100,   80,   53,   39,   26,  BLOC2960
     1            110,  112,  114,  118,  120,  122,  125,  132,  142,  BLOC2970
     2            150,  160,  170,  180,  190,  200,  205,  180,  160,  BLOC2980
     3            145,  135,  112,   98,   83,   67,   44,   33,   23,  BLOC2990
     1            105,  107,  109,  112,  115,  119,  122,  126,  135,  BLOC3000
     2            145,  155,  165,  175,  180,  190,  180,  155,  135,  BLOC3010
     3            120,  108,   90,   75,   66,   52,   37,   29,   20,  BLOC3020
     1            105,  107,  109,  112,  115,  119,  122,  126,  132,  BLOC3030
     2            140,  152,  162,  170,  180,  180,  155,  135,  115,  BLOC3040
     3            105,   92,   76,   66,   56,   46,   35,   25,   18,  BLOC3050
     1            105,  107,  109,  112,  115,  119,  122,  126,  132,  BLOC3060
     2            138,  150,  160,  168,  175,  168,  140,  120,  105,  BLOC3070
     3             92,   82,   70,   58,   52,   40,   29,   23,   17,  BLOC3080
     1            105,  107,  109,  112,  115,  119,  122,  126,  132,  BLOC3090
     2            140,  150,  160,  170,  170,  155,  130,  110,   95,  BLOC3100
     3             85,   76,   63,   53,   43,   37,   27,   22,   16,  BLOC3110
     1            100,  102,  106,  110,  112,  116,  118,  122,  127,  BLOC3120
     2            133,  148,  156,  165,  165,  140,  115,   98,   83,  BLOC3130
     3             75,   65,   54,   45,   40,   31,   23,   19,   14/  BLOC3140
C
C
C
      DATA DL1/    40,   56,   69,   80,   89,   98,  106,  113,  120,
     2            126,  133,  138,  144,  150,  155,  160,  165,  170,
```

```
     3             174,  179,  183,  188,  192,  196,  200,  204,  208,
     4             212,  216,  219,  223,  226,  230,  234,  237,  240,
     5             244,  247,  250,  253,  257,  260,  263,  266,  269,
     6             272,  275,  278,  281,  284,  286,  289,  292,  295,
     7             298,  300,  303,  306,  308,  311,  314,  316,  319,
     8             321,  324,  326,  329,  331,  334,  336,  339,  341,
     9             344,  346,  348,  351,  353,  355,  358,  360,  362,
     1             364,  367,  369,  371,  373,  376,  378,  380,  382,
     1             384,  386,  389,  391,  393,  395,  397,  399,  401,
     2             403,  423,  443,  461,  479,  496,  513,  530,  546,
     3             561,  576,  591,  606,  620,  634,  648,  661,  675,
     4             688,  701,  714,  726,  739,  751,  763,  775,  787,
     5             798,  810,  822,  833,  844,  855,  866,  877,  888,
     6             899,  910,  921,  931,  942,  952,  962,  972,  983,
     7             993, 1003, 1013, 1023, 1033, 1043, 1053, 1063, 1073,
     8            1082, 1092, 1101, 1111, 1120, 1130, 1139, 1149, 1158,
     9            1168, 1177, 1186, 1195, 1205, 1214, 1223, 1232, 1241,
     2            1251, 1259, 1268, 1277, 1286, 1295, 1304, 1313, 1322,
     1            1331, 1340, 1349, 1357, 1366, 1375, 1384, 1392, 1401,
     2            1410, 1419, 1427, 1436, 1445, 1453, 1462, 1470, 1479/
      DATA DL2/   1488, 1496, 1505, 1513, 1522, 1530, 1539, 1547, 1556,
     2            1564, 1573, 1581, 1590, 1598, 1607, 1615, 1624, 1632,
     3            1640, 1649, 1657, 1665, 1674, 1682, 1691, 1699, 1708,
     4            1716, 1724, 1733, 1741, 1749, 1758, 1766, 1774, 1783,
     5            1791, 1800, 1808, 1816, 1825, 1833, 1841, 1850, 1858,
     6            1866, 1875, 1883, 1891, 1900, 1908, 1917, 1925, 1933,
     7            1941, 1950, 1958, 1966, 1975, 1983, 1992, 2000, 2008,
     8            2017, 2025, 2033, 2042, 2050, 2058, 2066, 2075, 2083,
     9            2092, 2100, 2108, 2117, 2125, 2134, 2142, 2150, 2159,
     1            2167, 2176, 2184, 2192, 2201, 2209, 2218, 2226, 2234,
     1            2243, 2251, 2260, 2268, 2277, 2285, 2293, 2302, 2310,
     2            2319, 2328, 2336, 2344, 2353, 2361, 2370, 2378, 2387,
     3            2395, 2404, 2412, 2421, 2429, 2439, 2446, 2455, 2463,
     4            2472, 2481, 2489, 2498, 2506, 2515, 2523, 2532, 2540,
     5            2549, 2558, 2566, 2575, 2584, 2592, 2601, 2610, 2618,
     6            2627, 2635, 2644, 2653, 2661, 2670, 2679, 2687, 2696,
     7            2705, 2714, 2722, 2731, 2740, 2749, 2757, 2766, 2775,
     8            2784, 2792, 2801, 2810, 2819, 2827, 2836, 2845, 2854,
     9            2863, 2872, 2880, 2889, 2898, 2907, 2916, 2924, 2933,
     2            2942, 2951, 2960, 2969, 2978, 2987, 2996, 3005, 3014,
     1            3022, 3031, 3040, 3049, 3058, 3067, 3076, 3085, 3094,
     2            3103, 3112, 3121, 3130, 3139, 3148, 3157, 3166, 3175/
      DATA DL3/   3184, 3193, 3202, 3211, 3220, 3230, 3239, 3248, 3257,
     2            3266, 3275, 3284, 3294, 3302, 3311, 3321, 3330, 3339,
     3            3349, 3357, 3367, 3376, 3385, 3394, 3403, 3413, 3422,
     4            3431, 3440, 3449, 3459, 3468, 3477, 3468, 3495, 3504,
     5            3514, 3523, 3532, 3542, 3551, 3560, 3570, 3579, 3588,
     6            3598, 3607, 3616, 3625, 3635, 3644, 3653, 3663, 3672,
     7            3682, 3691, 3700, 3709, 3719, 3728, 3737, 3747, 3756,
     8            3766, 3775, 3785, 3794, 3804, 3813, 3822, 3832, 3841,
     9            3850, 3860, 3869, 3879, 3888, 3898, 3907, 3917, 3926,
     1            3936, 3945, 3955, 3964, 3974, 3983, 3993, 4002, 4012,
     1            4021, 4031, 4040, 4050, 4059, 4069, 4078, 4088, 4098,
     2            4107, 4116, 4126, 4136, 4145, 4155, 4164, 4174, 4183,
     3            4193, 4203, 4212, 4222, 4231, 4241, 4251, 4260, 4270,
     4            4280, 4289, 4298, 4308, 4318, 4328, 4337, 4347, 4356,
     5            4366, 4376, 4385, 4395, 4405, 4414, 4424, 4434, 4443,
     6            4453, 4463, 4472, 4482, 4492, 4501, 4511, 4521, 4531,
```

```
     7          4540, 4550, 4560, 4569, 4579, 4589, 4599, 4608, 4618,
     8          4628, 4637, 4647, 4657, 4666, 4676, 4686, 4695, 4705,
     9          4715, 4725, 4735, 4744, 4754, 4764, 4774, 4783, 4793,
     2          4803, 4813, 4822, 4832, 4842, 4852, 4862, 4871, 4881,
     1          4891, 4901, 4911, 4920, 4930, 4940, 4950, 4960, 4969,
     2          4979, 4989, 4999, 5909, 5018, 5028, 5038, 5048, 5058/
      DATA DL4/ 5067, 5077, 5087, 5097, 5107, 5117, 5126, 5136, 5146,
     2          5156, 5166, 5176, 5185, 5195, 5205, 5215, 5225, 5235,
     3          5244, 5254, 5264, 5274, 5284, 5294, 5304, 5314, 5323,
     4          5333, 5343, 5353, 5363, 5373, 5383, 5393, 5402, 5412,
     5          5422, 5432, 5442, 5452, 5461, 5471, 5481, 5491, 5501,
     6          5511, 5521, 5531, 5541, 5551, 5560, 5570, 5580, 5590,
     7          5600, 5610, 5620, 5630, 5640, 5649, 5659, 5669, 5679,
     8          5689, 5699, 5709, 5719, 5729, 5738, 5748, 5758, 5768,
     9          5778, 5788, 5798, 5808, 5818, 5828, 5838, 5848, 5858,
     1          5867, 5877, 5887, 5897, 5907, 5917, 5927, 5937, 5947,
     1          5957, 5967, 5977, 5987, 5996, 6006, 6106, 6205, 6305,
     2          6404, 6505, 6603, 6703, 6803, 6902, 7002, 7102, 7202,
     3          7302, 7401, 7501, 7601, 7701, 7801, 7901, 8001, 8101,
     4          8201, 8301, 8400, 8500, 8600, 8700, 8800, 8900, 9000,
     5          9100, 9200, 9300, 9400, 9500, 9600, 9700, 9800, 9900,
     6         10000/
      END
C
C
C
C
C      SUBROUTINE DBPLOT(HO,T,SLP,ADC)
      SUBROUTINE DBPLOT(SLP,ADC)
C
C      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 A
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NF,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
      REAL LO
      YL(X,X1,X2,Y1,Y2)=(Y1-Y2)*(X-X1)/(X1-X2)+Y1
      PI=4.*ATAN(1.)
      LO=16.1*T*T/PI
      WR=HO/LO
      IF(WR.LT.0.002) GO TO 997
      IF(WR.GT.0.05) GO TO 998
      X=ALOG10(WR)
      SLOPE=1./SLP
      S2=1./30.
      IF(SLOPE.LE.0.02) GO TO 10
      IF(SLOPE.LE.S2) GO TO 20
      IF(SLOPE.LE.0.05) GO TO 30
      IF(SLOPE.LE.0.1) GO TO 40
```

```
2     Y=YL(X,-1.6021,-2.6990,-0.9838,-0.4783)
      IF(WR.GT.0.025) Y=-0.9838
      GO TO 900
   10 Y=YL(X,-1.3979,-2.5229,-0.7543,-0.382)
      GO TO 900
   20 YU=YL(X,-1.3979,-2.5229,-0.7543,-0.382)
      YD=YL(X,-1.3979,-2.6990,-0.7689,-0.3511)
      Y=YL(SLOPE,0.02,S2,YU,YD)
      GO TO 900
   30 YU=YL(X,-1.3979,-2.6990,-0.7689,-0.3511)
      YD=YL(X,-1.3979,-2.6990,-0.8173,-0.3983)
      Y=YL(SLOPE,S2,0.05,YU,YD)
      GO TO 900
   40 YU=YL(X,-1.3979,-2.6990,-0.8173,-0.3978)
      YD=YL(X,-1.6021,-2.6990,-0.9838,-0.4783)
      IF(WR.GT.0.025) YD=-0.9838
      Y=YL(SLOPE,0.05,0.1,YU,YD)
C
  900 DBL=10.**(10.**Y)
      ADC=HO*DBL
      GO TO 999
  997 WRITE(6,3)
    3 FORMAT(/15X,'******* HO/LO LESS THAN 0.002 *******')
C       STOP
        MD=25
         RETURN
  998 WRITE(6,1)
    1 FORMAT(5X,'**** HO/LO GREATER THAN 0.05 ****')
C       STOP
         MD=25
         RETURN
  999 RETURN
      END




C**********SUBROUTINE CURVE ENTERS THE PROPER SETS OF STOA TABLES
C**********(CURVES) WITH THE CALCULATED INFORMATION IN ORDER TO
C**********INTERPOLATE WAVE RUNUP ELEVATIONS.
C*****************************************************************************
C
      SUBROUTINE CURVE

      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
```

```
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
      COMMON /SY/ PDB(27),PDB1(13),PCH(9)
      COMMON /SZ/ DB(27,13,8)
      COMMON /SDL/ DLL(730)

C     D11    I*4  1     R/HO AT LOW HOT2 FROM 1ST CURVE SET
C     D12    I*4  1     R/HO AT HIGH HOT2 FROM 1ST CURVE SET
C     D21    I*4  1     R/HO AT LOW HOT2 FROM 2ND CURVE SET
C     D22    I*4  1     R/HO AT HIGH HOT2 FROM 2ND CURVE SET
C     D31    I*4  1     FOR HOT2 FROM 1ST CURVE SET
C     D32    I*4  1     FOR HOT2 FROM 2ND CURVE SET
C     D3                FINAL INTERPOLATED VALUE OF R/HO
C     R1                RUNUP ELEVATION ADJUSTED FOR ROUGHNESS AND SCALE
C
C

      INUM=0
      INUM=INUM+1
C
C           DETERMINE WHICH LOOKUP TABLES SHOULD BE ENTERED.
C
C
      CALL LOOK(PCH,9,DS,IZ,K,IFD)
      IF ((IZ.EQ.5).OR.(IZ.EQ.8)) K=IZ
      IF ((IZ.EQ.5).AND.(SA.GE.15.)) THEN
         IZ=IZ+1
          K=K+1
      ENDIF
      IF  ((IZ.EQ.1).AND.(DS1.EQ.0)) K=IZ
      IF(DCS.LT.1000.) GO TO 140
      IF((DCS.LT.3000.).AND.(IZ.GT.5)) GO TO 140
      XN=ALOG10(DCS/100.)
C
C_____EXTRAPOLATE TO GET R
C
C     XN=ALOG10(DCS/100.)
      IF (IZ .LE. 5) GO TO 130
C

C     EXTRAPOLATE IN STOA TABLES 2,3,4

C     Y7K=DB(27,KK,IZ)
C     Y7K=ALOG10(Y7K)
C     Y4K=DB(24,KK,IZ)
C     Y4K=ALOG10(Y4K)
C     Y7L=DB(27,LL,IZ)
C     Y7L=ALOG10(Y7L)
C     Y4L=DB(24,LL,IZ)
C     Y4L=ALOG10(Y4L)
C     D1=10.**(((Y7K-Y4K)/0.477)*(XN-1.477)+Y7K)
C     D2=10.**(((Y7L-Y4L)/0.477)*(XN-1.477)+Y7L)


      Y7K1=DB(27,KK,IZ)
      Y7K1=ALOG10(Y7K1)
      Y4K1=DB(24,KK,IZ)
```

```
      Y4K1=ALOG10(Y4K1)
      Y7L1=DB(27,LL,IZ)
      Y7L1=ALOG10(Y7L1)
      Y4L1=DB(24,LL,IZ)
      Y4L1=ALOG10(Y4L1)
      D11=10.**(((Y7K1-Y4K1)/0.477)*(XN-1.477)+Y7K1)
      D12=10.**(((Y7L1-Y4L1)/0.477)*(XN-1.477)+Y7L1)
      IF (IZ .EQ. K) GO TO 125
      Y7K2 = DB(27,KK,K)
      Y7K2 = ALOG10(Y7K2)
      Y4K2 = DB(24,KK,K)
      Y4K2 = ALOG10(Y4K2)
      Y7L2 = DB(27,LL,K)
      Y7L2 = ALOG10(Y7L2)
      Y4L2 = DB(24,LL,K)
      Y4L2 = ALOG10(Y4L2)
      D21 = 10.**(((Y7K2-Y4K2)/0.477)*(XN-1.477)+Y7K2)
      D22 = 10.**(((Y7L2-Y4L2)/0.477)*(XN-1.477)+Y7L2)
      GO TO 150                                                         RUN01450
  125 CONTINUE
      GO TO 155
C                                                                       RUN01460
C     EXTRAPOLATE IN STOA TABLES 5,8,9,10,11                            RUN01470

C 130 Y7K=DB(24,KK,IZ)                                                  RUN01480
C     Y7K=ALOG10(Y7K)                                                   RUN01490
C     Y4K=DB(21,KK,IZ)                                                  RUN01500
C     Y4K=ALOG10(Y4K)                                                   RUN01510
C     Y7L=DB(24,LL,IZ)                                                  RUN01520
C     Y7L=ALOG10(Y7L)                                                   RUN01530
C     Y4L=DB(21,LL,IZ)                                                  RUN01540
C     Y4L=ALOG10(Y4L)                                                   RUN01550
C     D1=10.**(((Y7K-Y4K)/0.222)*(XN-1.000)+Y7K)                        RUN01560
C     D2=10.**(((Y7L-Y4L)/0.222)*(XN-1.000)+Y7L)                        RUN01570

  130 Y7K1=DB(24,KK,IZ)
      Y7K1=ALOG10(Y7K1)
      Y4K1=DB(21,KK,IZ)
      Y4K1=ALOG10(Y4K1)
      Y7L1=DB(24,LL,IZ)
      Y7L1=ALOG10(Y7L1)
      Y4L1=DB(21,LL,IZ)
      Y4L1=ALOG10(Y4L1)
      D11=10.**(((Y7K1-Y4K1)/0.222)*(XN-1.000)+Y7K1)
      D12=10.**(((Y7L1-Y4L1)/0.222)*(XN-1.000)+Y7L1)
      IF (IZ .EQ. K) GO TO 135
      Y7K2 = DB(24,KK,K)
      Y7K2 = ALOG10(Y7K2)
      Y4K2 = DB(21,KK,K)
      Y4K2 = ALOG10(Y4K2)
      Y7L2 = DB(24,LL,K)
      Y7L2 = ALOG10(Y7L2)
      Y4L2 = DB(21,LL,K)
      Y4L2 = ALOG10(Y4L2)
      D21 = 10.**(((Y7K2-Y4K2)/0.222)*(XN-1.000)+Y7K2)
      D22 = 10.**(((Y7L2-Y4L2)/0.222)*(XN-1.000)+Y7L2)
      GO TO 150                                                         RUN01580
  135 CONTINUE
```

```
      GO TO 155
C
C_____PULL DATA OUT OF TABLE DB
C
  140 CALL LOOK(PDB,27,DCS,IH,JJ,IFG(IQ))
C
C_____INTERPOLATE TO FIND R
C
C     CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH,KK,IZ),DB(JJ,KK,IZ),DCS,D1)
C     CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH,LL,IZ),DB(JJ,LL,IZ),DCS,D2)
C 150 CALL LOGLOG(PDB1(KK),PDB1(LL),D1,D2,HOT2,D3)
      CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH,KK,IZ),DB(JJ,KK,IZ),DCS,D11)
      CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH,LL,IZ),DB(JJ,LL,IZ),DCS,D12)
      IF (IZ .EQ. K) GO TO 155
      CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH,KK,K),DB(JJ,KK,K),DCS,D21)
      CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH,LL,K),DB(JJ,LL,K),DCS,D22)
  150 CONTINUE
      CALL LOGLOG(PDB1(KK),PDB1(LL),D11,D12,HOT2,D31)
      CALL LOGLOG(PDB1(KK),PDB1(LL),D21,D22,HOT2,D32)
      CALL RINT(PCH(IZ),PCH(K),D31,D32,DS,D3)
      GO TO 156
  155 CONTINUE
      CALL LOGLOG(PDB1(KK),PDB1(LL),D11,D12,HOT2,D3)
  156 CONTINUE
      R1=H0*D3/100.
  157 CONTINUE
C     R1=XF1*R11+XF2*R12
  158 CONTINUE
C     CALL RRUFF(R1,FROUGH,N)
      CALL RRUFF(FROUGH,N)
      R1=R1*FROUGH
C     IF((1.0-FROUGH).GT.0.01) GO TO 180
      IF((1.0-FROUGH).GT.0.01) GO TO 200
C
C_____SCALE EFFECT (RS)
C
      IF((DCS.LT.1500).AND.(DCS.GT.10)) GO TO 160
      RS=1000.
      GO TO 170
  160 CALL LOOK(SLO,12,DCS,IP,IP1,IFD)
C
C_____INTERPOLATE TO FIND SCALE EFFECT
C
      CALL LOGLIN(SLO(IP),SLO(IP1),SCC(IP),SCC(IP1),DCS,RS)
  170 R1=R1*RS/1000.
  200 CONTINUE
      RETURN
      END



      SUBROUTINE SIMPCOMP1
C
```

```
C                         SIMPCOMP1
C
C   SUBROUTINE SIMPCOMP1---IS THE FIRST BRANCHING POSSIBILITY FOR
C            CALCULATING RUNUP BY BOTH STRUCTURE AND BREAKER ZONE
C            CHARACTERISTICS. THIS BRANCH IS ENTERED FOR
C            A MILD STRUCTURE SLOPE OR WHEN THE APPROACH LENGTH IS
C            GREATER THAN 1/4 OF THE WAVELENGTH.
C***********************************************************************
C        DLE    STATION OF THE BREAKING WAVE.                          *
C        HSA    HORIZONTAL STATION OF THE APPROACH SLOPE START.        *
C        DXLA   WAVELENGTH                                             *
C        DXLA1  DXLA/10                                                *
C***********************************************************************
C
C
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I2
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD

      IF (DLE .LT. (HSA-DXLA1)) CALL COMP
      IF ((HSA-DXLA1) .LE. DLE .AND. DLE .LE. (HSA+DXLA1)) THEN
        I3=(DLE-HSA + DXLA1)/(0.2*DXLA)
        CALL CALCS
        RK=R1
        CALL COMP
        RB=R1
        R1=I3*RK+(1-I3)*RB
      ENDIF
      IF (DLE .GT. (HSA+DXLA1)) CALL CALCS
      RETURN
      END




      SUBROUTINE SIMPCOMP2
C
C                         SIMPCOMP2
C
C   SUBROUTINE SIMPCOMP2---IS THE SECOND BRANCHING POSSIBILITY FOR
C            CALCULATING RUNUP BY  BOTH STRUCTURE AND BREAKER ZONE
C            CHARACTERISTICS. THIS BRANCH IS ENTERED IF THE APPROACH
C            LENGTH IS LESS THAN 1/2 WAVELENGTH OR IF THE APPROACH IS FLAT.
C
C***********************************************************************
```

```
C        DS1      DEPTH OF THE STRUCTURE TOE X 100                          *
C        DC       BREAKER DEPTH X 100                                       *
C        HOSCALE  DEEPWATER WAVEHEIGHT X 100                                *
C*************************************************************************
C
C
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3,I4
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
C
      IF (DS1.GE.(3*HOSCALE)) THEN
        CALL SIMPLE
      ELSE
        IF (DS1 .GT. DC .AND. DS1 .LT. (3*HOSCALE)) THEN
          CALL SIMPCOMP3
          I4=(DS1-DC)/(3*HOSCALE-DC)
          R1=I4*RZ+(1-I4)*RB
        ELSE
          CALL COMP
        ENDIF
      ENDIF
      RETURN
      END




      SUBROUTINE SIMPCOMP3

C
C                  SIMPCOMP3
C
C  SIMPCOMP3---IS THE THIRD BRANCHING POSSIBILITY FOR CALCULATING RUNUP
C          BY BOTH STRUCTURE AND BREAKER ZONE CHARACTERISTICS. THIS
C          BRANCH IS ENTERED IF THE DEPTH OF THE STRUCTURE TOE IS
C          LESS THAN 3 TIMES THE DEEPWATER WAVEHEIGHT, BUT
C          GREATER THAN THE BREAKER DEPTH.
C


C
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H
```

```
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD

      CALL SIMPLE
      RZ=R1
      CALL COMP
      RB=R1
      R1=0
      RETURN
      END




      SUBROUTINE SIMPLE


C                         SIMPLE
C
C   SUBROUTINE SIMPLE---CALCULATES RUNUP FOR SIMPLE STRUCTURE
C             SITUATIONS USING THE SLOPE OF THE STRUCTURE AND
C             STOA CURVES FOR A FLAT APPROACH.
C
C
C
C******************************************************************************
C    DSL - DISTANCE FROM REFERENCE POINT TO RUNUP LIMIT                       *
C    DTR - (WATER LEVEL + RUNUP)*100                                          *
C    DS  - NORMALIZED DEPTH OF STRUCTURE                                      *
C    DCS - EFFECTIVE SLOPE OF STRUCTURE                                       *
C                                                                             *
C---- CALCULATE RUNUP FOR SIMPLE STRUCTURE FROM CURVES USING                  *
C     ms AND 2/3/4 BRACKETING ds/H0, ITERATING UNTIL                          *
C     IT CONVERGES.                                                           *
C******************************************************************************
C
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
```

```
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
C
        DS=(((DS1+1)/H0)*10.)+1000.
        DCS = (10000.*(DSL-HST))/(DTR+DS1)
        CALL CURVE
        RETURN
        END




      SUBROUTINE CALCS
C
C                           CALCS
C
C   SUBROUTINE CALCS---CALCULATES RUNUP FOR SIMPLE STRUCTURES USING THE
C               STRUCTURE SLOPE AND STOA CURVES FOR SLOPED APPROACH
C
C******************************************************************************
C    DSL - DISTANCE FROM REFERENCE TO RUNUP LIMIT                             *
C    DTR - (WATER LEVEL + RUNUP)*100                                          *
C    DS1 - DEPTH OF STRUCTURE TOE * 100                                       *
C    DCS - EFFECTIVE SLOPE
C******************************************************************************

      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,H0
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD

C    USE SIMPLE RUNUP CURVES 5/8/9/10/11, BRACKETING ds/H0
C    AND ITERATING UNTIL CONVERGENCE.
C
C
C
       DS=(DS1+1)/H0
      IF ((DS1 .EQ. 0.).AND.(R.EQ.0)) THEN
        DCS=100.*MWST
      ELSE
        DCS=(10000.*(DSL-HST))/(DTR+DS1)
      ENDIF
      CALL CURVE
      RETURN
      END
```

```
C
C
      SUBROUTINE COMP
C
C                        COMP
C
C   SUBROUTINE COMP---CALCULATES RUNUP BY THE COMPOSITE SLOPE METHOD.
C            CONSIDERING SLOPE WHERE THE WAVE BREAKS IN SELECTING
C            STOA CURVES.
C
C*****************************************************************************
C    DSL - DISTANCE FROM RUNUP POINT TO RUNUP LIMIT                          *
C    DLE - STATION OF BREAKING WAVE                                          *
C    DTR - (WATER LEVEL + RUNUP)*100                                         *
C    DC  - BREAKER HEIGHT * 100                                              *
C    RFLCT - BREAKING CRITERIA                                               *
C    RHOLO - HO/LO    (WAVE STEEPNES)                                        *
C    S(II) - SLOPE (COT) AT BREAKER POINT                                    *
C    CS - FLAG REGARDING WAVE REFLECTION                                     *
C    DCS - EFFECTIVE SLOPE                                                   *
C*****************************************************************************
C
      IMPLICIT INTEGER*4(D,P)
      REAL MWST,MWA,MW,MWSE,MW1,I3
      REAL MS1,MS1H,MS2,MS2H,RHOLO
      INTEGER*4 HOT2,SLO(12),SCC(12),RS
      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
      COMMON /HD/ IPAGE,DT
      DIMENSION DT(118),RDEP(20)
      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,HO
      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
      COMMON /DND/ SLO,SCC,T,CS,MD
C
C    WHEN COMPOSITE SLOPE METHOD IS USED TO CALCULATE RUNUP, WAVES
C    MAY REFLECT RATHER THAN BREAK AT SHORE(HO/LO < 0.195mb**2)
C
      RHOLO=HO/(5.12*T**2)
      RFLCT=0.195/(S(II)**2)
      IF((RHOLO.LT.RFLCT).AND.(S(II).LT.10)) CS=1
      IF (S(II) .LT. 15) THEN
C
C         CALCULATE RUNUP USING COMPOSITE SLOPE CURVES WITH mb 5/8/9/10
C         BRACKETING db/HO ITERATING UNTIL RUNUP CONVERGES.
C
        SA=S(II)
        DS=(DC/HO)
        DCS=(10000.*(DSL-DLE))/(DTR+DC)
        CALL CURVE
      ELSE
C
C         CALCULATE RUNUP USING COMPOSITE SLOPE AND mb.  USE FIG. 2,
C         ITERATING UNTIL RUNUP CONVERGES.
```

```
C
          SA=S(II)
          DS=((DC/HO)*10)+1000
          DCS=(10000.*(DSL-DLE))/(DTR+DC)
          CALL CURVE
        ENDIF
        RETURN
        END
```