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# 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

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**April 1991**

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#### 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.

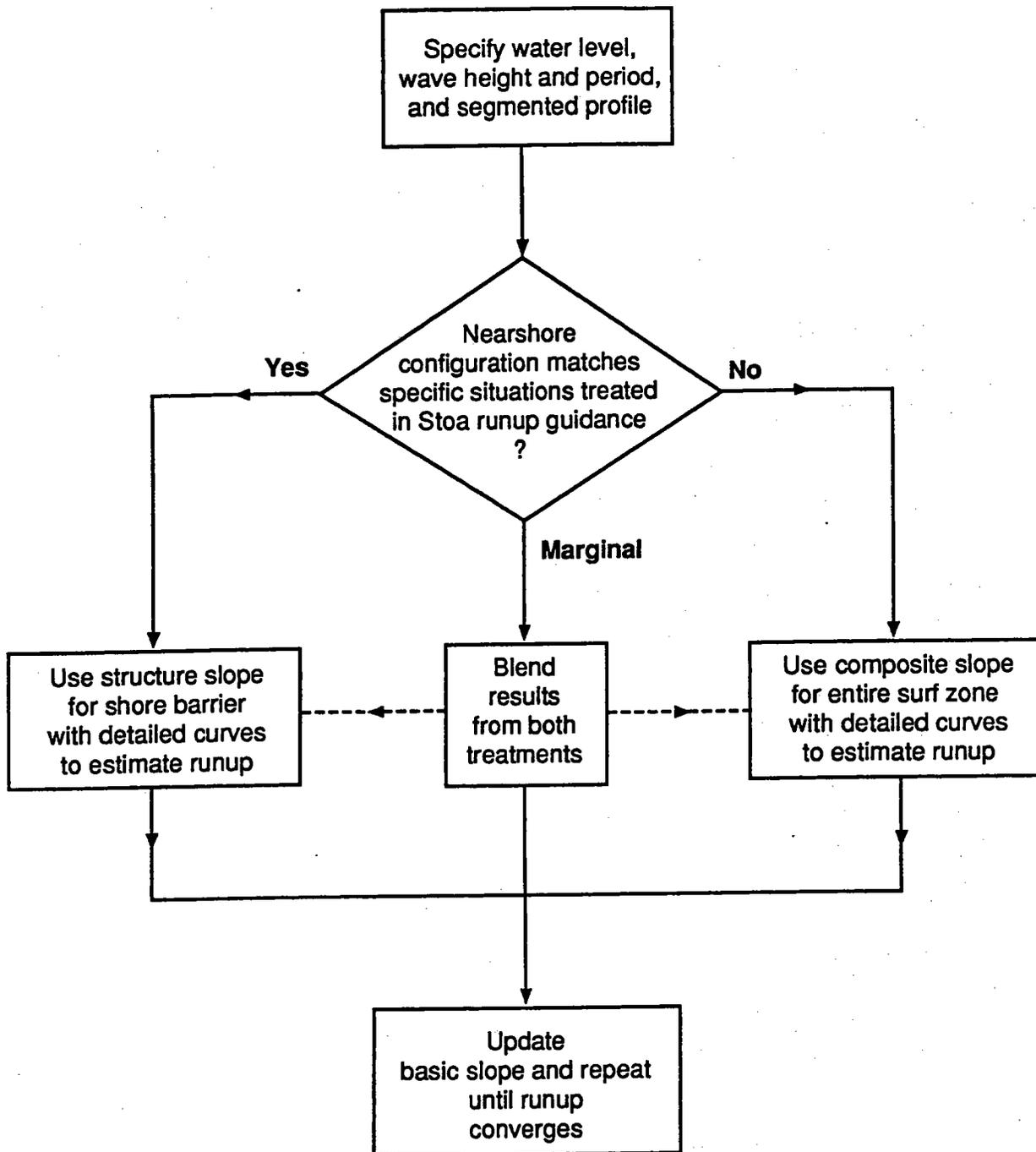


Figure 0. Overview of basic computation procedure implemented in modified FEMA Wave Runup Model.

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.

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## 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                  |
| $\bar{R}$ | 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                               |
| $\bar{T}$ | 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  
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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).

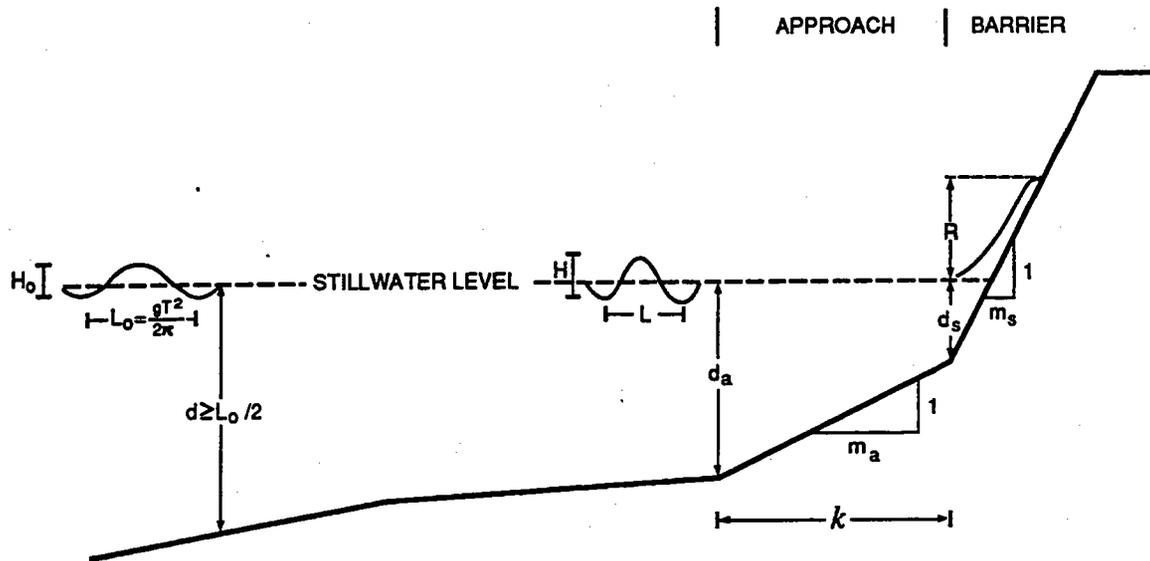
Wave runup analyses are increasingly common in coastal FISs because man-made shore structures are more prevalent, and steep profile segments can also result from expected dune erosion during the 100-year event. A wider range of applications and the long-term accumulation of experience led to an evaluation 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.



$H_0$  = WAVE HEIGHT IN DEEP WATER

$L_0 = gT^2 / 2\pi$  = 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:

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

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.

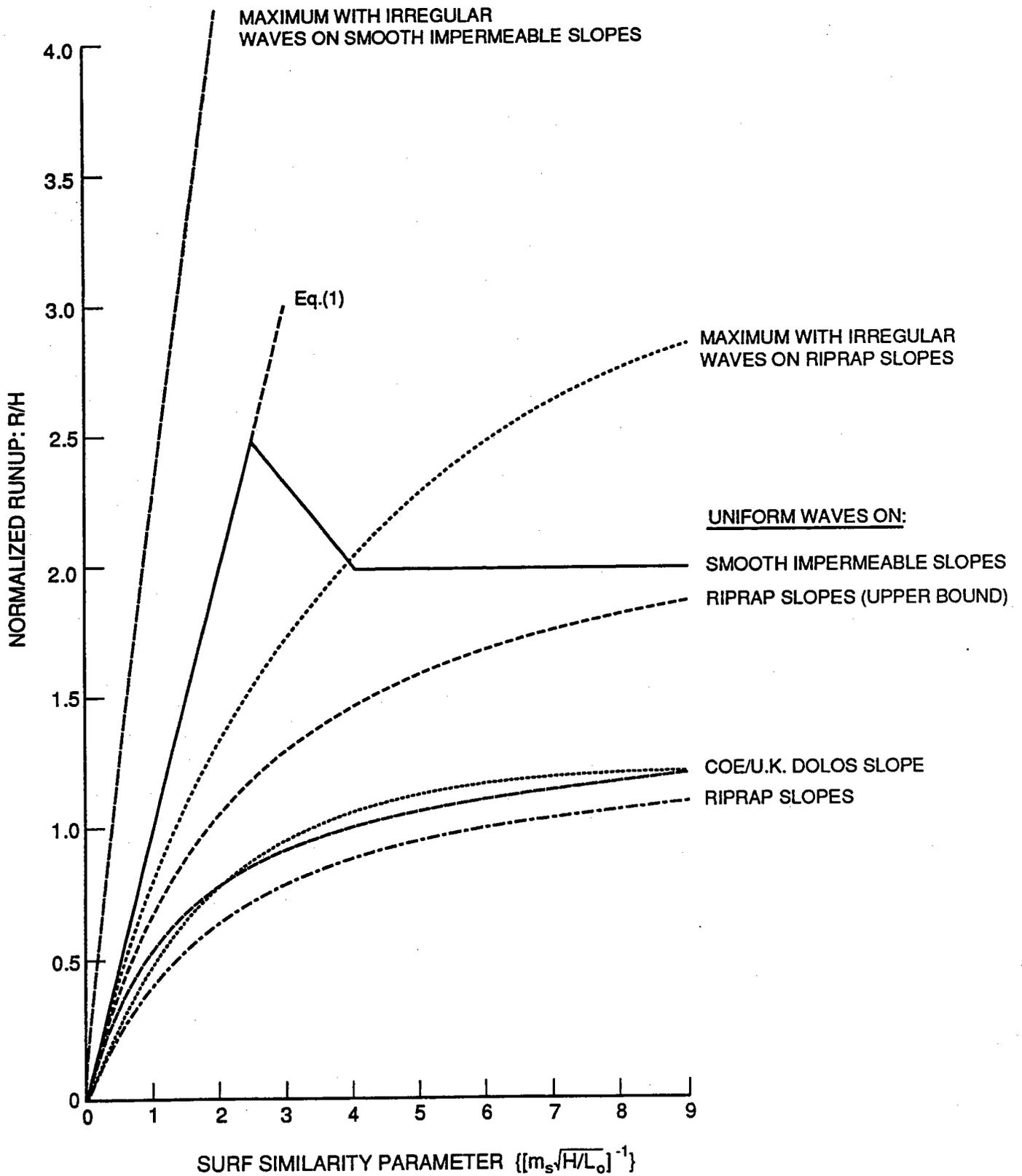


Figure 2. Some expressions for expected wave runup in various situations. Sources are Ahrens and McCartney(1975), Losada and Gimenez-Curto(1981), Ahrens and Heimbaugh(1988), and Mase(1989).

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 ( $R/H_0$ ) versus the structure cotangent ( $m_s$ ) for various values of incident wave steepness referred to deep water ( $H_0/gT^2 = H_0/2\pi L_0$ ). 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  $S_0$  less than about 2 to 3.

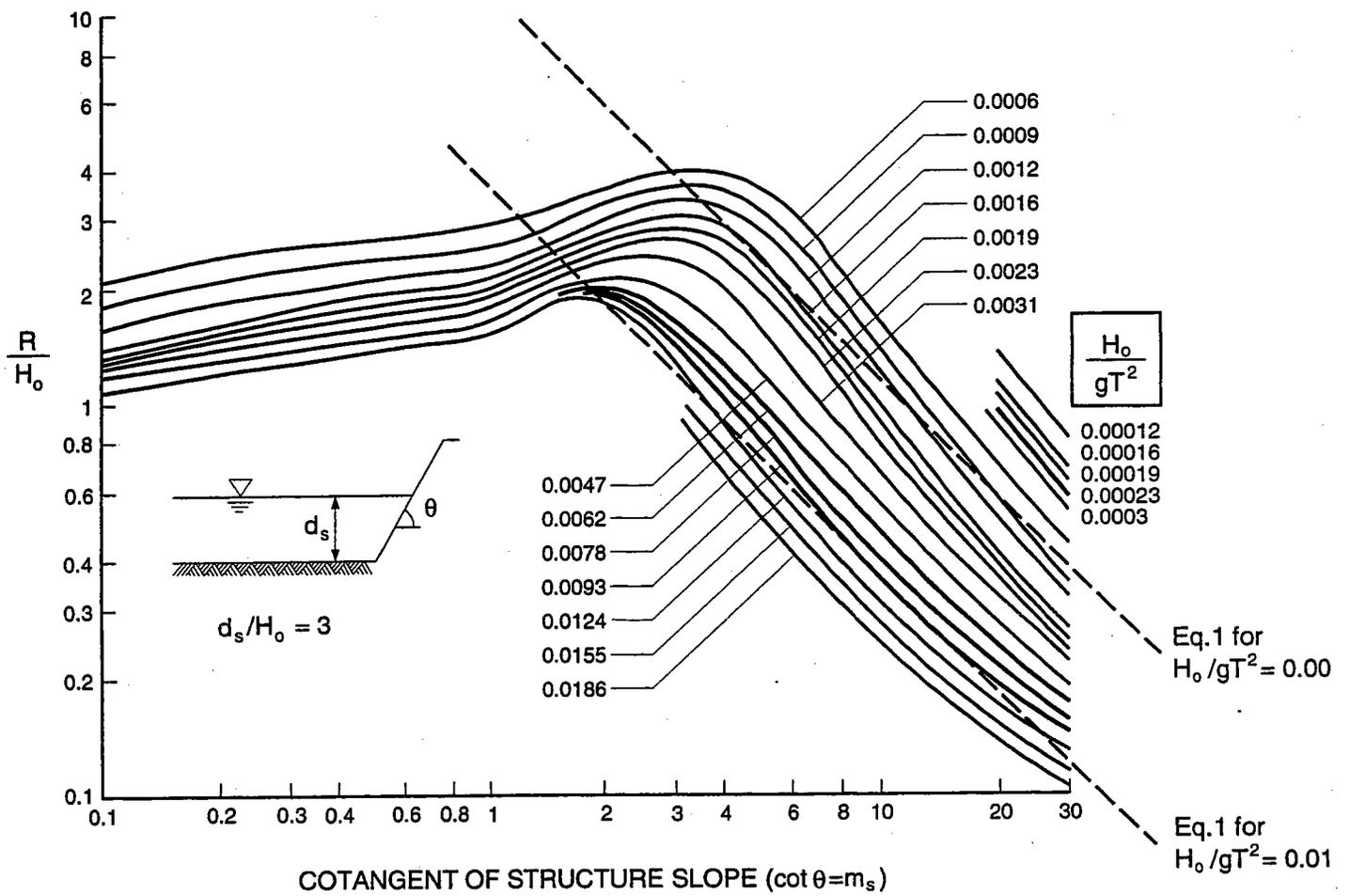


Figure 3. Representative set of empirical curves for wave runup (Stoa, 1978).

The maximum in  $R/H_0$  is associated with the gentlest shore slope resulting in wave reflection rather than breaking (Nagai and Takada, 1972). Conversely, a distinct maximum in  $R/H_0$  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  $(3 H_0)$ , 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.

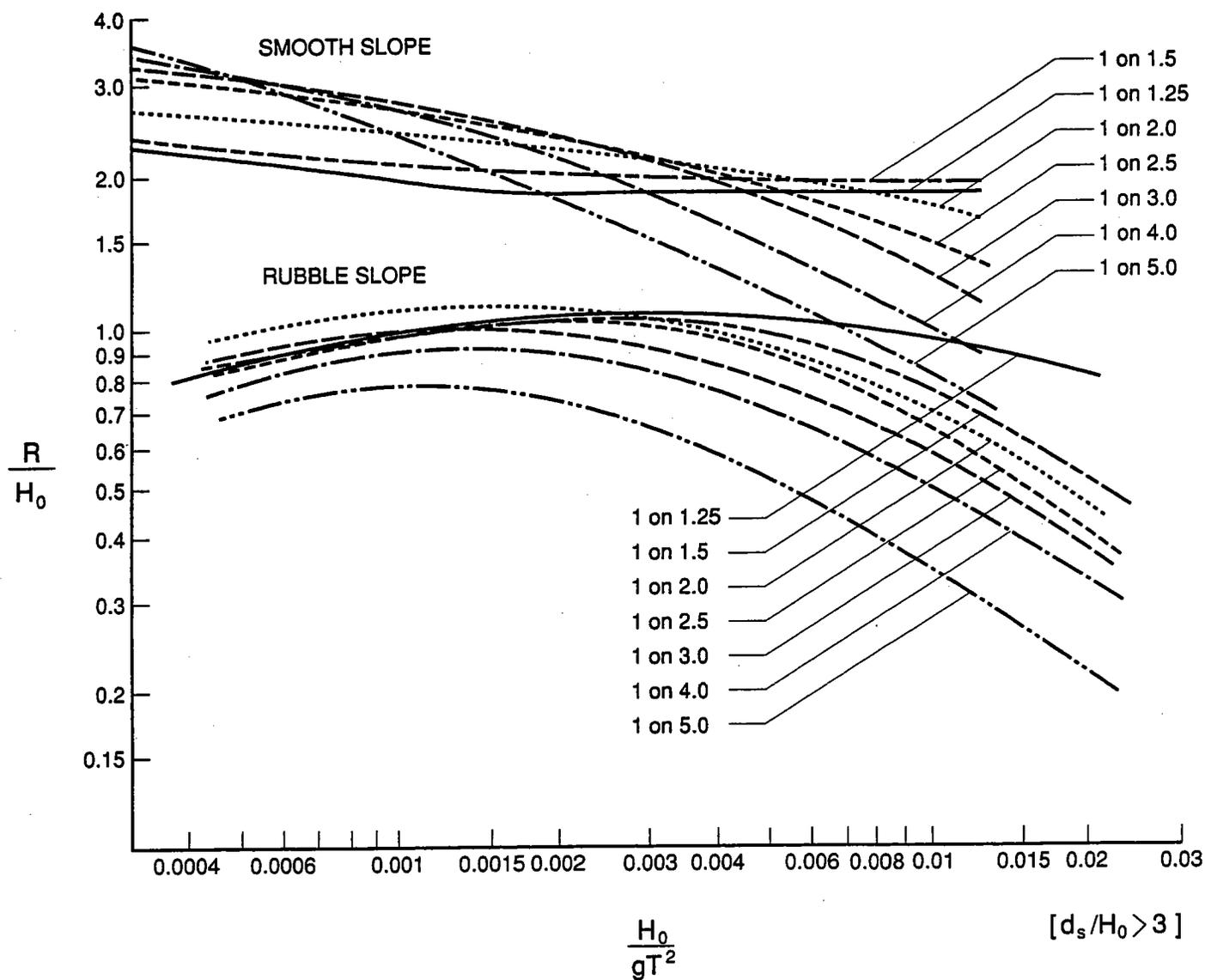


Figure 4. Runup curves in another format, showing different shapes for smooth and rough slopes (Saville, 1959).

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  $\pm 10\%$  for wave directions within  $45^\circ$  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  $(R/H_0)$  versus  $m_s$  for various values of  $(H_0/L_0)$ . 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  $d_s/H_0$  and  $m_a$  determine the family of curves to be utilized (Figure 6).  $R/H_0$  is estimated using  $m_s$ ,  $H_0/L_0$ , 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

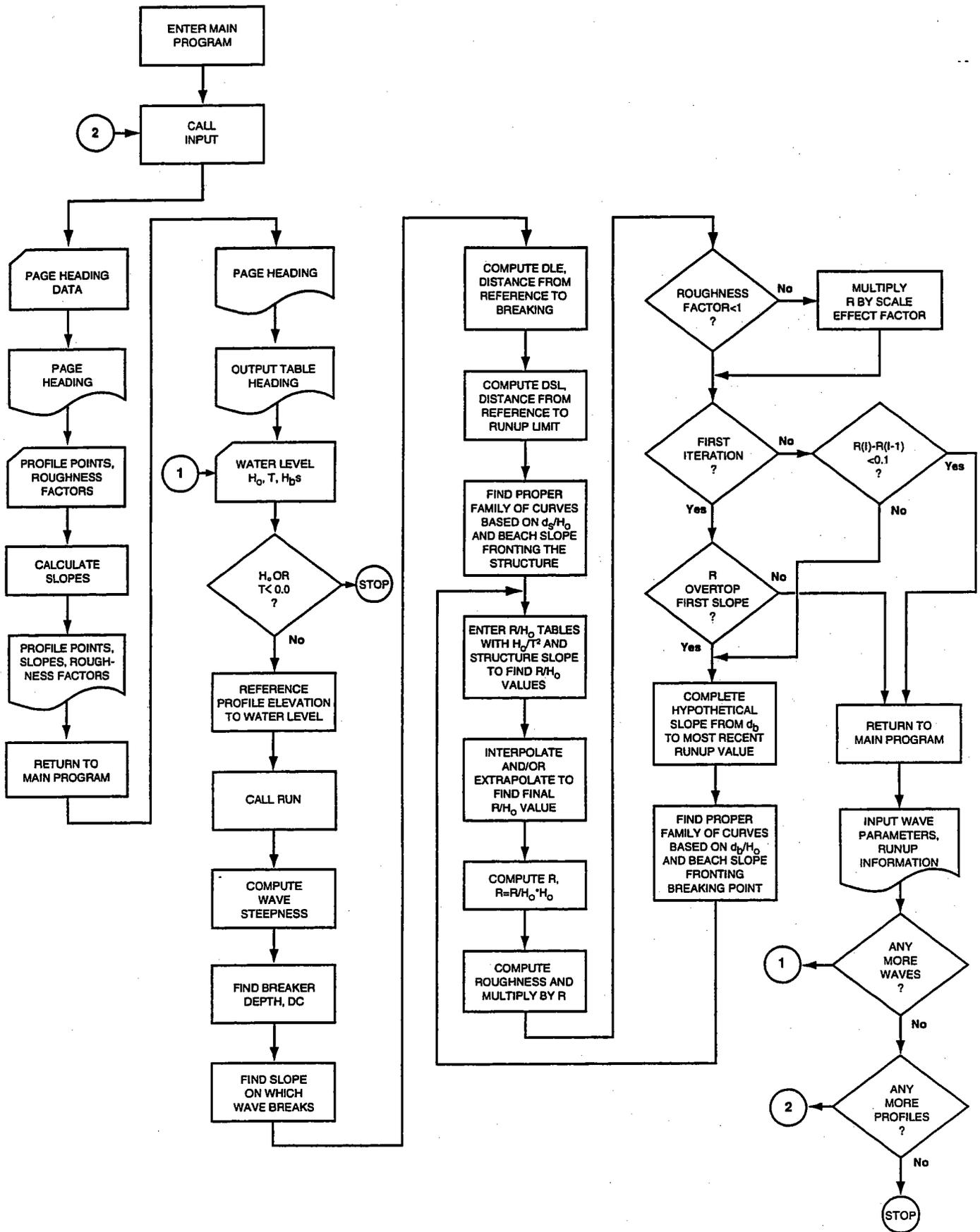


Figure 5. Block Diagram of Wave Runup Program (Stone & Webster, 1981)

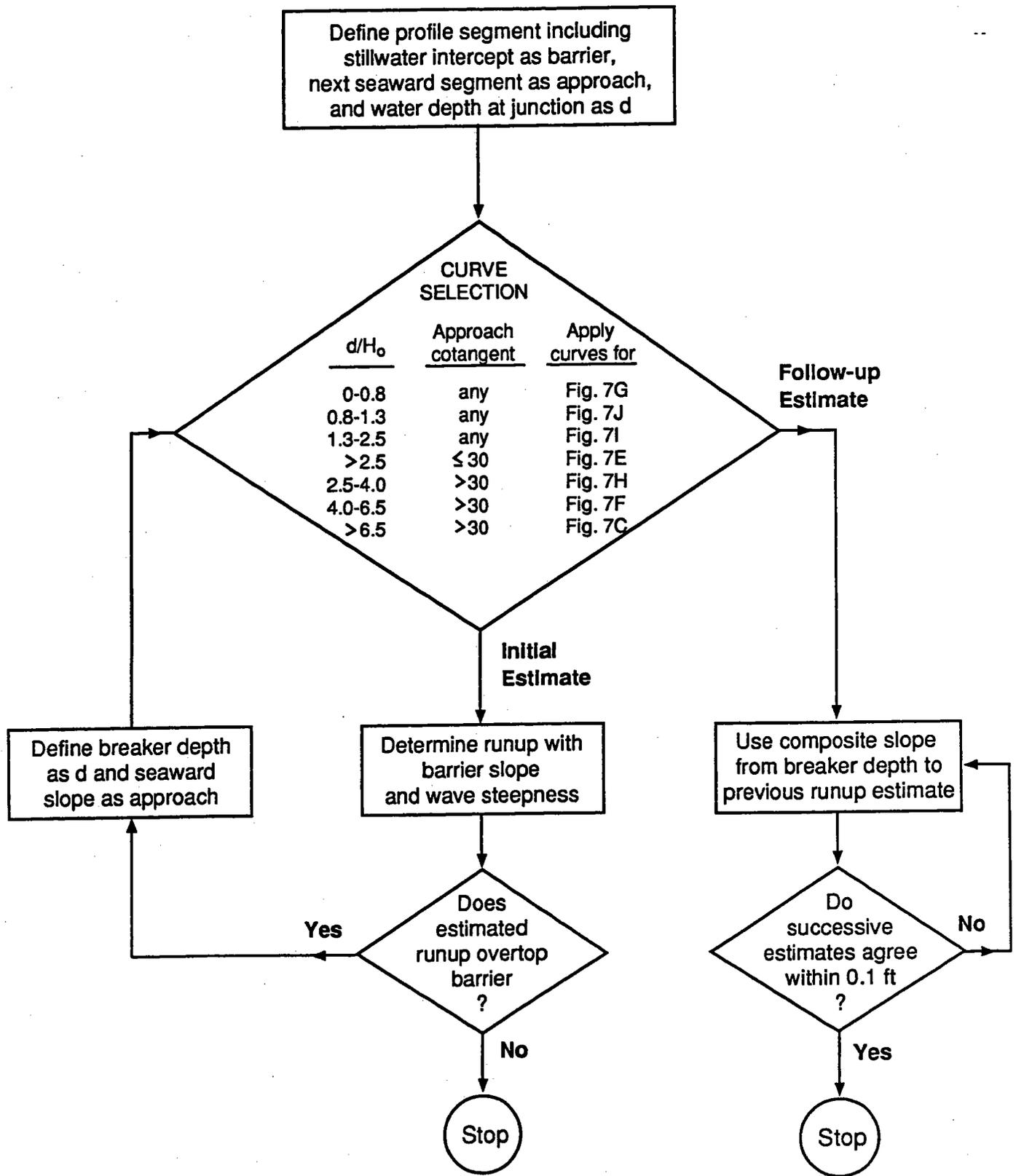


Figure 6. Detailed description of runup determination in 1981 Model.

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,  $H_{o_j}$ , from about 3 feet up to the significant height of the storm waves. For each wave

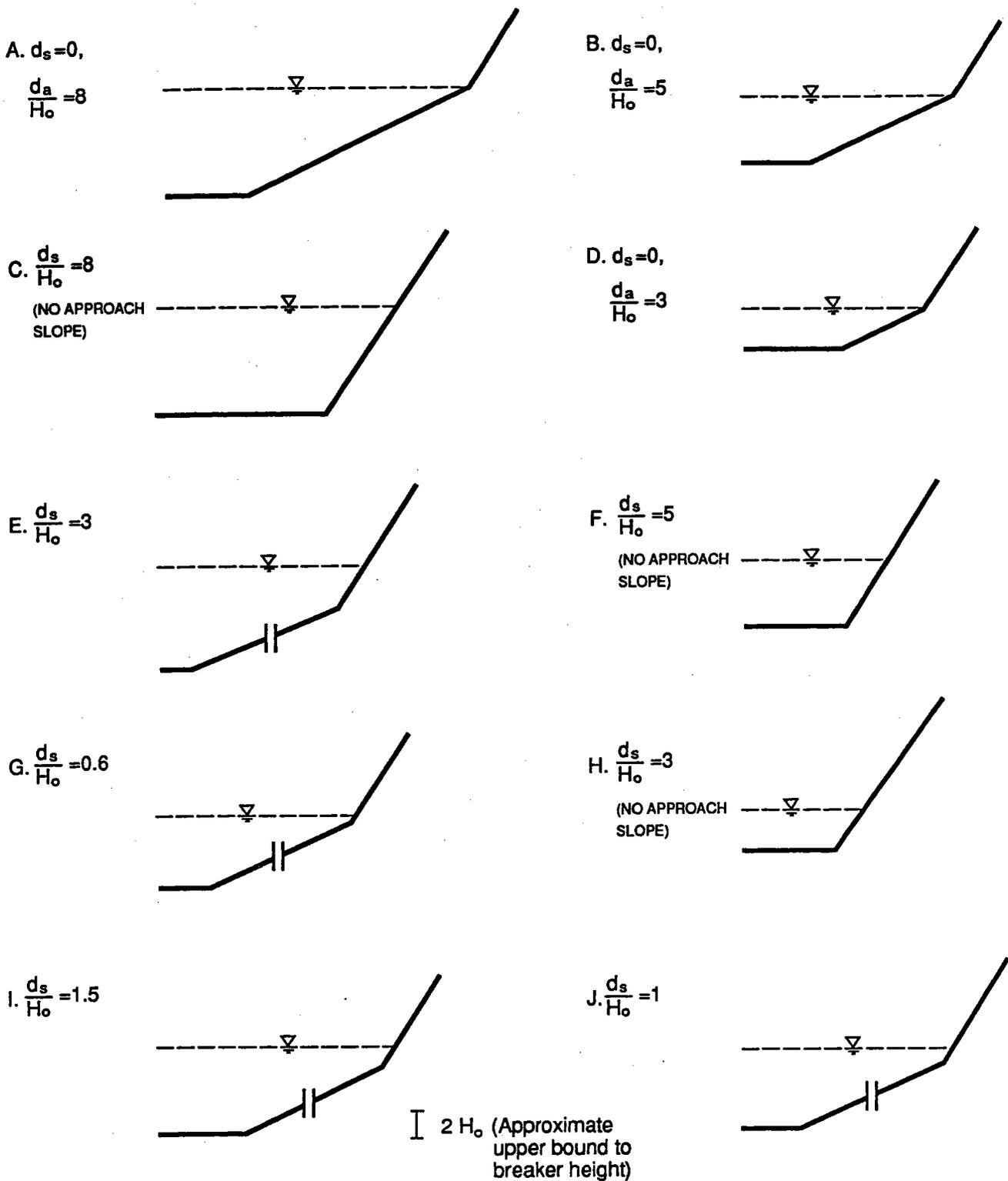


Figure 7. Ten configurations covered in guidance by Stoa(1978), arranged in approximate order of increasing runup elevations. For four cases with approach segment fronting steep shore structure, that slope is specified as 1 on 10 with horizontal extent of at least one-half the incident wavelength.

condition, a breaking wave height is also required for each slope segment below SWFL; that value is to be found manually using  $H_{bj}$ ,  $T$ , 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  $d_s/H_0$  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  $d_s/H_0 = 2.5$  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  $d_s/H_0$ , 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 Shore Protection Manual 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 Shore Protection Manual: 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  $d_b/H_b$

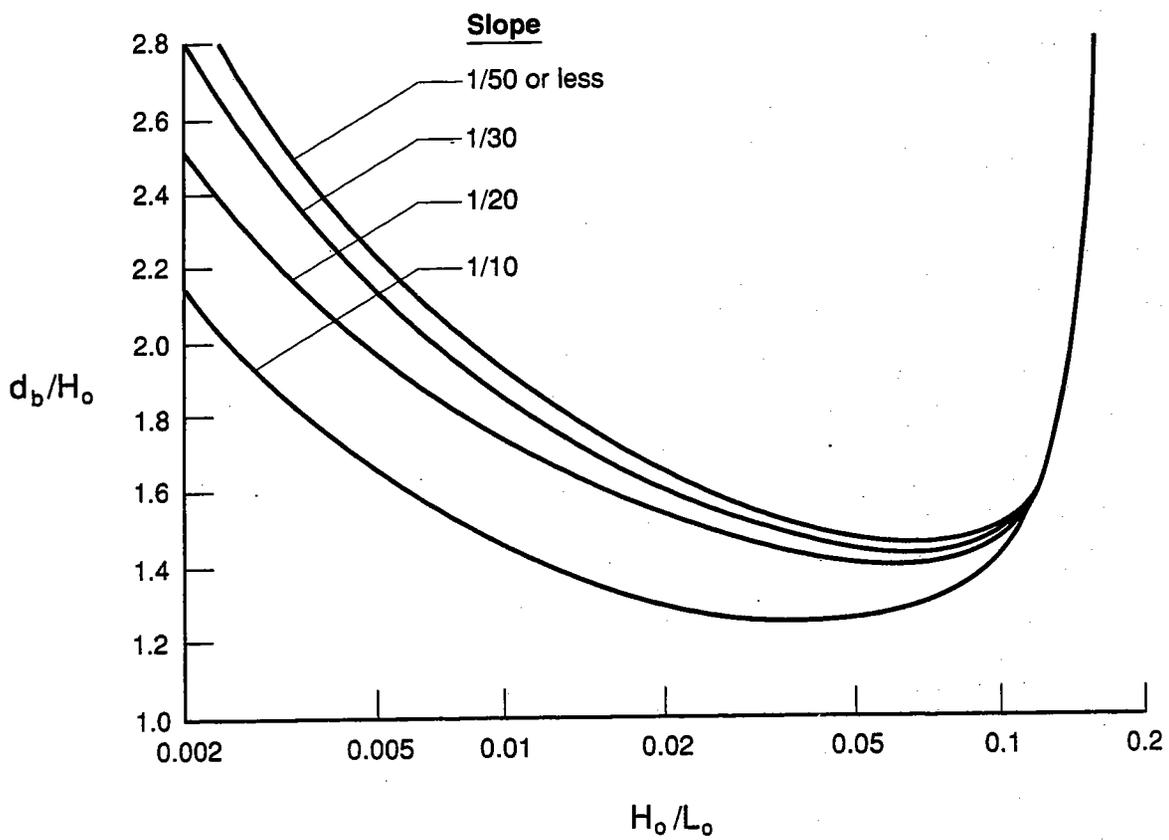


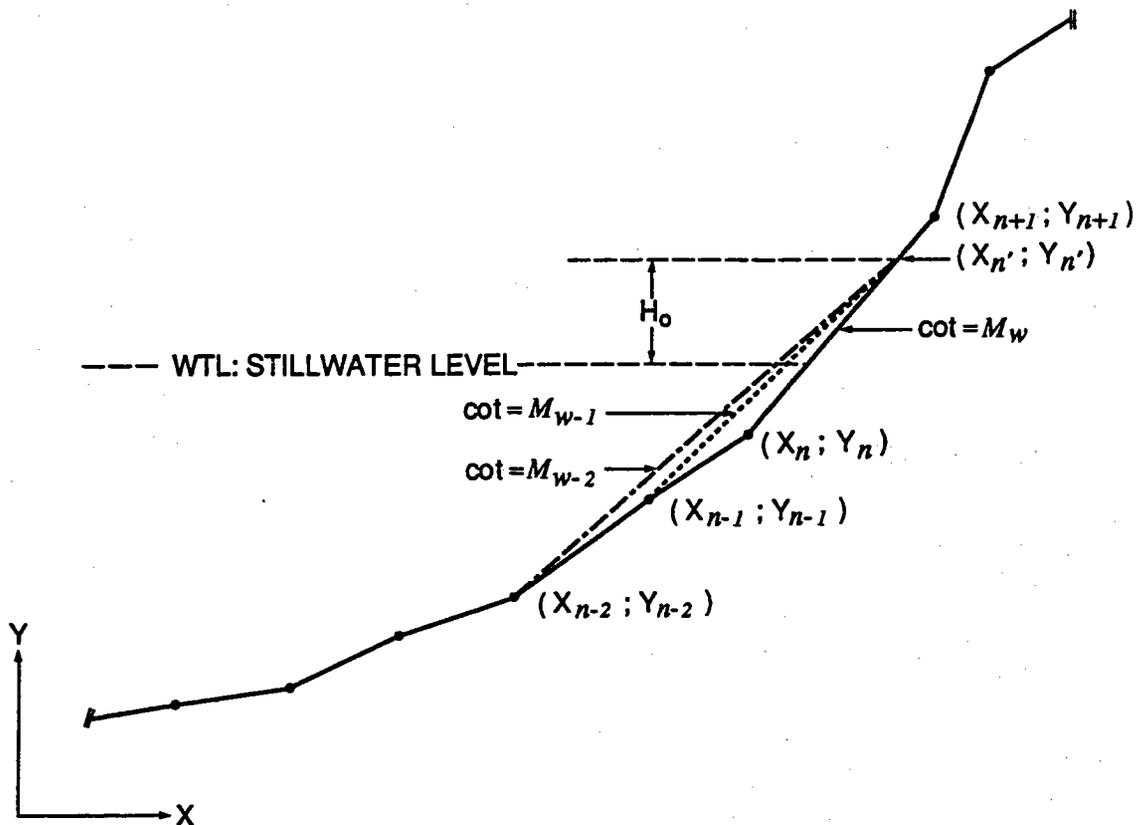
Figure 8. Results by Goda (1970) on water depth for initial wave breaking [from Horikawa, 1978].

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 in place 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 -  $M_{s-1}$  = cotangent 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 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  $d_s/H_0$  value closest to that in the actual situation, but linear interpolation is now employed between runup elevations pertaining to the two  $d_s/H_0$  values having specific guidance and bracketing the actual geometry. This interpolation is omitted only for large  $d_s/H_0$  where no further guidance is available but runup should not vary much, and for small  $d_s/H_0$  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.,  $d_b/H_0$  and  $m_c$  rather than  $d_s/H_0$  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

$$0.25 L_a < k < 0.5 L_a \quad (2a)$$

There the blend of computed runups is

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

and the interpolation parameter is

$$I_2 = (4k - L_a)/L_a \quad (2c)$$

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

$$X_a - 0.1 L_a < X_b < X_a + 0.1 L_a, \quad (3a)$$

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:

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

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

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

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

$$d_b < d_s < 3 H_o, \quad (4a)$$

by this blend of computed runups:

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

where the interpolation parameter is

$$I_4 = (d_s - d_b) / (3 H_o - d_b) \quad (4c)$$

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.

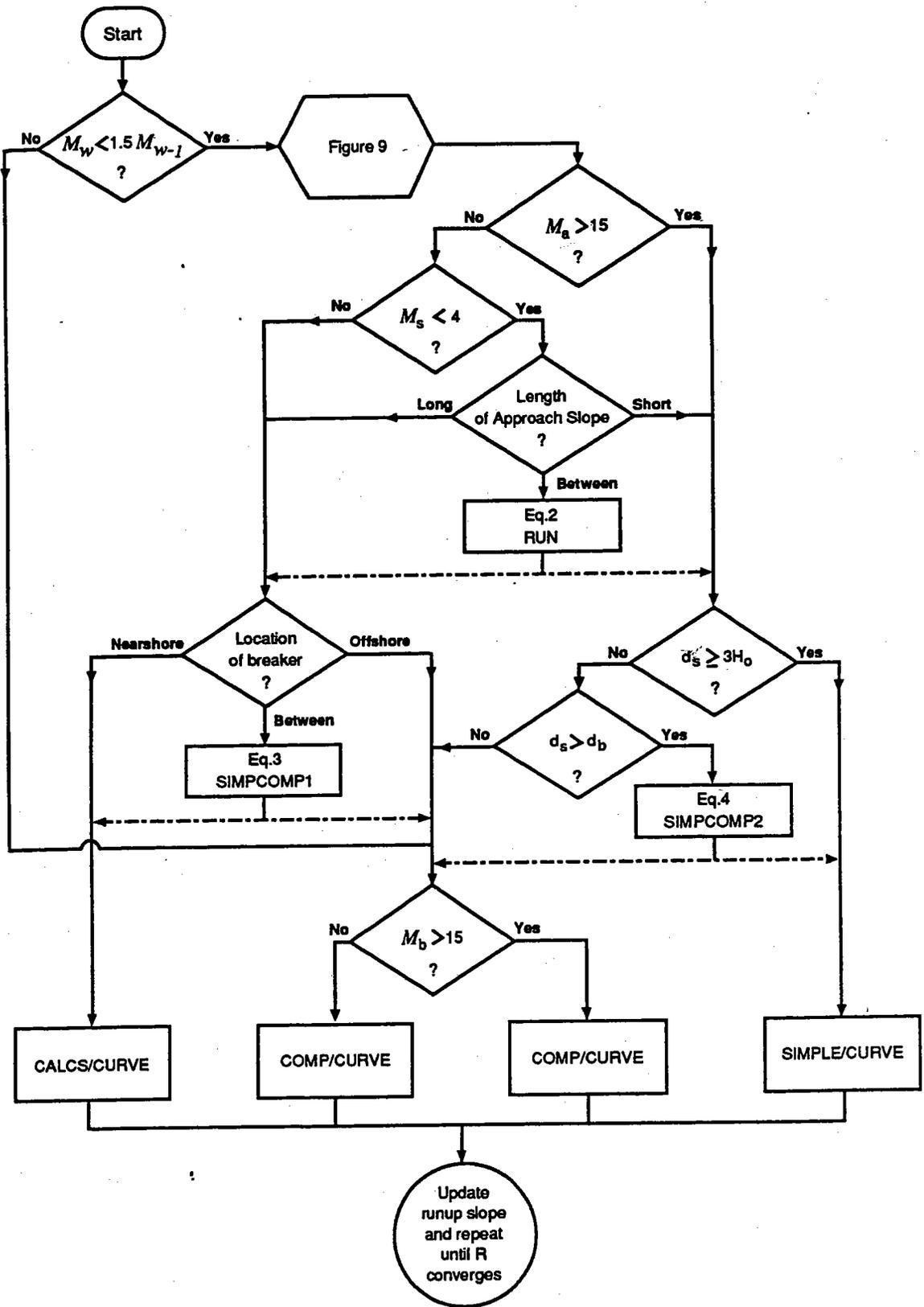


Figure 10. Flowchart of added branching decisions for computations in modified FEMA Wave Runup Model.

## 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

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

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

| <u>Test Program</u>   | <u>Basic Situation</u>  | <u>Wave Conditions</u>  | <u>Summary of Results</u>   |
|---|---|---|---|
| IX. USACE Large Wave Tank, Washington, D.C. (Dai & Kamel, 1969)           | Uniform waves<br>Breakwater with quadripods or quarystone<br>Data for wave bursts                       | H=1.5-4.3 ft<br>T=2.61-11.33 sec<br>d=15.0 ft<br>m <sub>s</sub> =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<br>Slopes armored with riprap<br>Data for wave bursts                           | H=1.8-3.9 ft<br>T=2.8-11.3 sec<br>d=15.0 ft<br>m <sub>s</sub> =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<br>Slope paved with Gobi blocks<br>Data for wave bursts                         | H=1.5-2.9 ft<br>T=2.8-8.5 sec<br>d=15.0 ft<br>m <sub>s</sub> =3.5                       | Mean runup of 1.9-6.4 ft in 11 tests  |
| XII. Wave Research Facility, Corvallis, Oregon (DeBok & Sollitt, 1978)    | Uniform waves<br>Breakwater of fitted quarry-stone with 2 approaches<br>Data after 40 waves             | H=1.3-4.4 ft.<br>T=2.85-5.06 sec<br>d=8.8-10.8 ft<br>m <sub>s</sub> =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<br>Compound slope with concrete block mattress<br>Runup histograms given                | H <sub>s</sub> =3 ft<br>T <sub>p</sub> =4.5 sec<br>d=11.0, 12.0 ft<br>m <sub>s</sub> =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<br>Slope with Armorflex mat (linked concrete blocks)<br>Data over 20-40 minutes           | H=1.1-4.7 ft<br>T=3.0-6.0 sec<br>d=16.4 ft<br>m <sub>s</sub> =3                         | Mean runup of 2.3-10.8 ft in 8 tests  |
| XV. Grosser Wellenkanal, Germany (Bürger et al., 1988)                    | Irregular waves<br>Breakwater with tetrapods<br>Gage record for 6 minutes                               | H <sub>s</sub> =2.4 ft<br>T <sub>p</sub> =4.5 sec<br>d=14.8 ft<br>m <sub>s</sub> =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<br>Slope with artificial grass or roughness cubes<br>Data over 100-400 waves | H=1.2-6.6 ft<br>T=3.0-15.0 sec<br>d=15.75 ft<br>m <sub>s</sub> =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  $\pm 0.5$  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

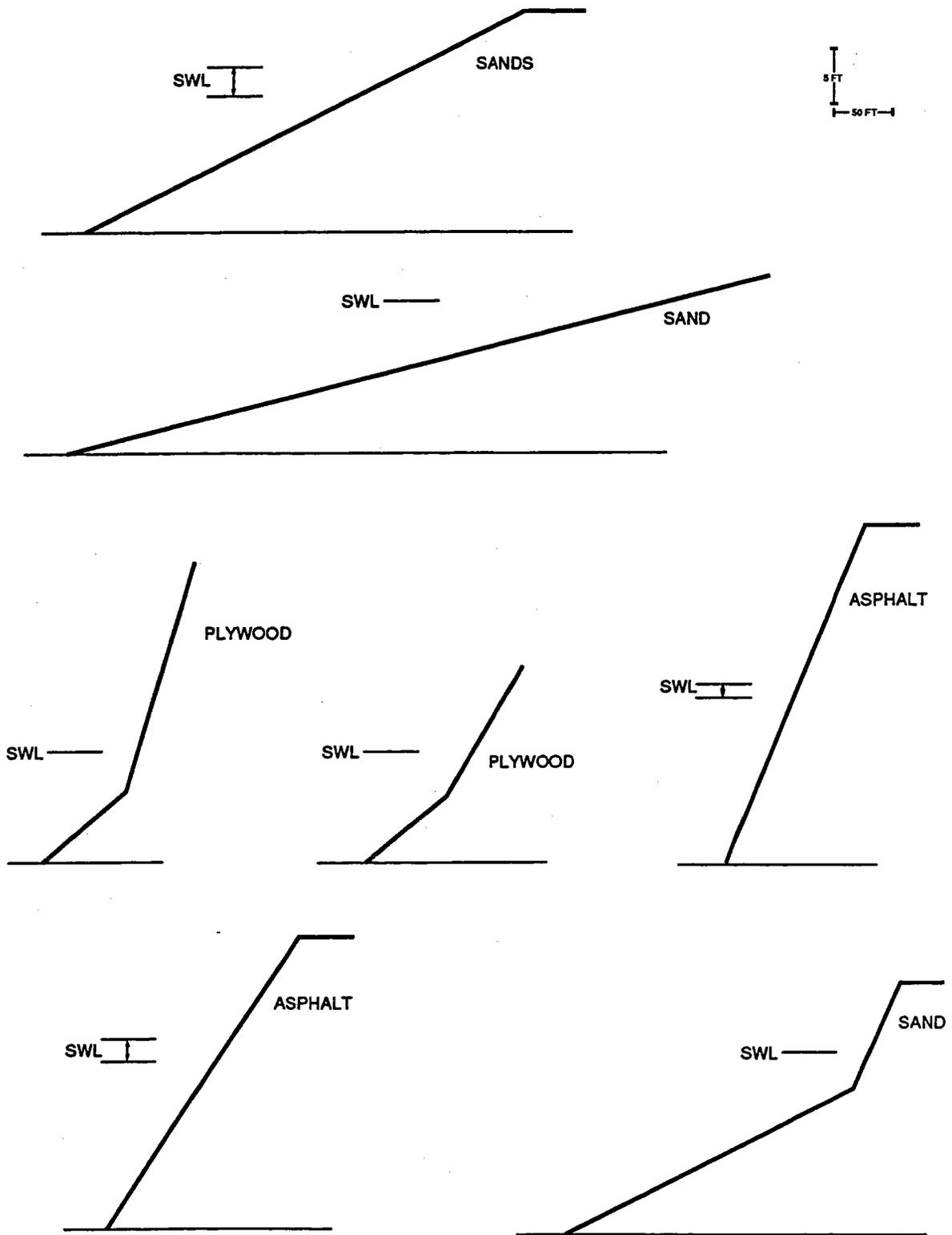


Figure 11. Shore configurations in large tests with smooth slopes and uniform waves.



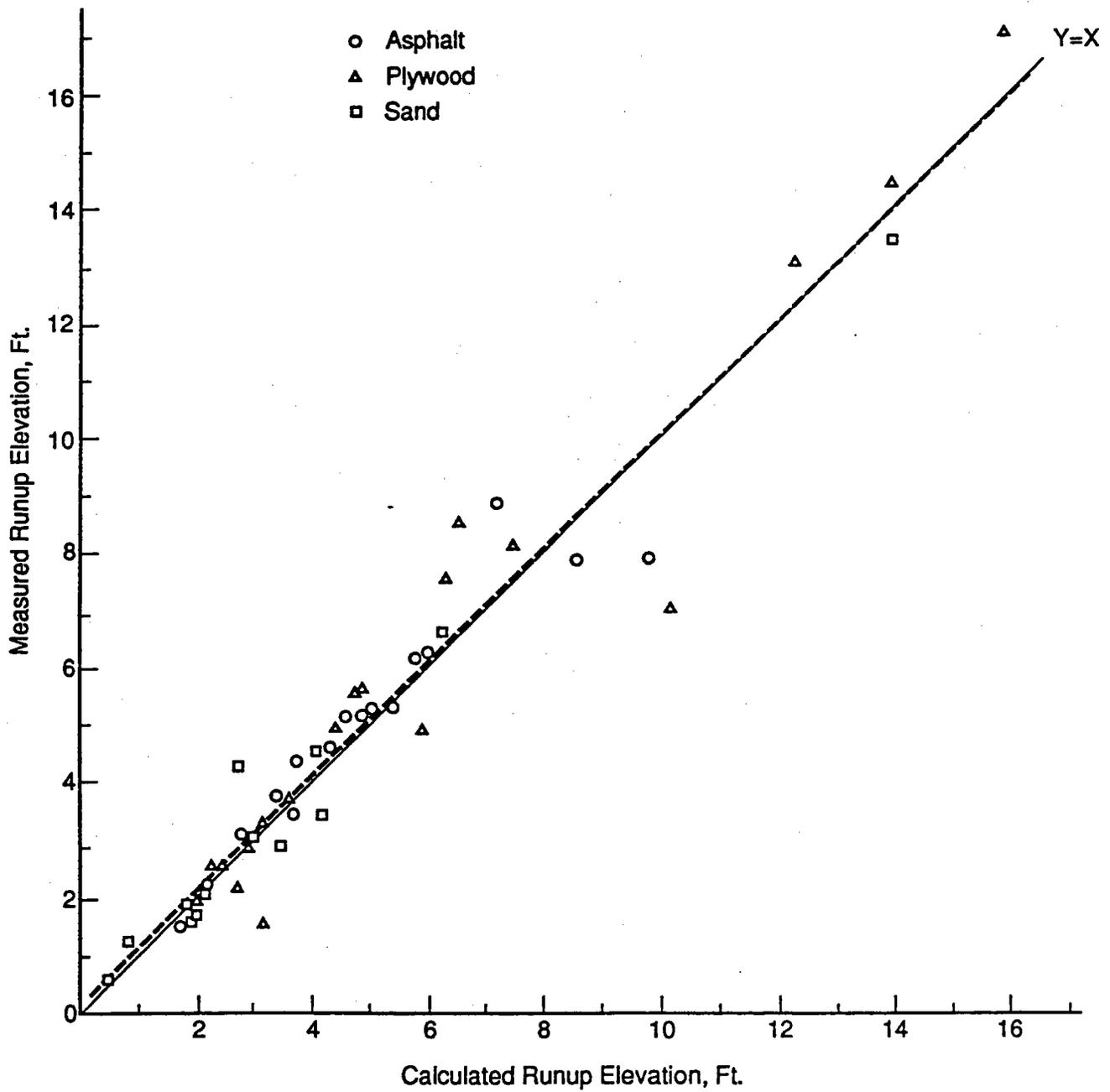


Figure 13. Modified Model Results: Calculated and Measured Runup Elevations in Large Tests with Smooth Slopes.

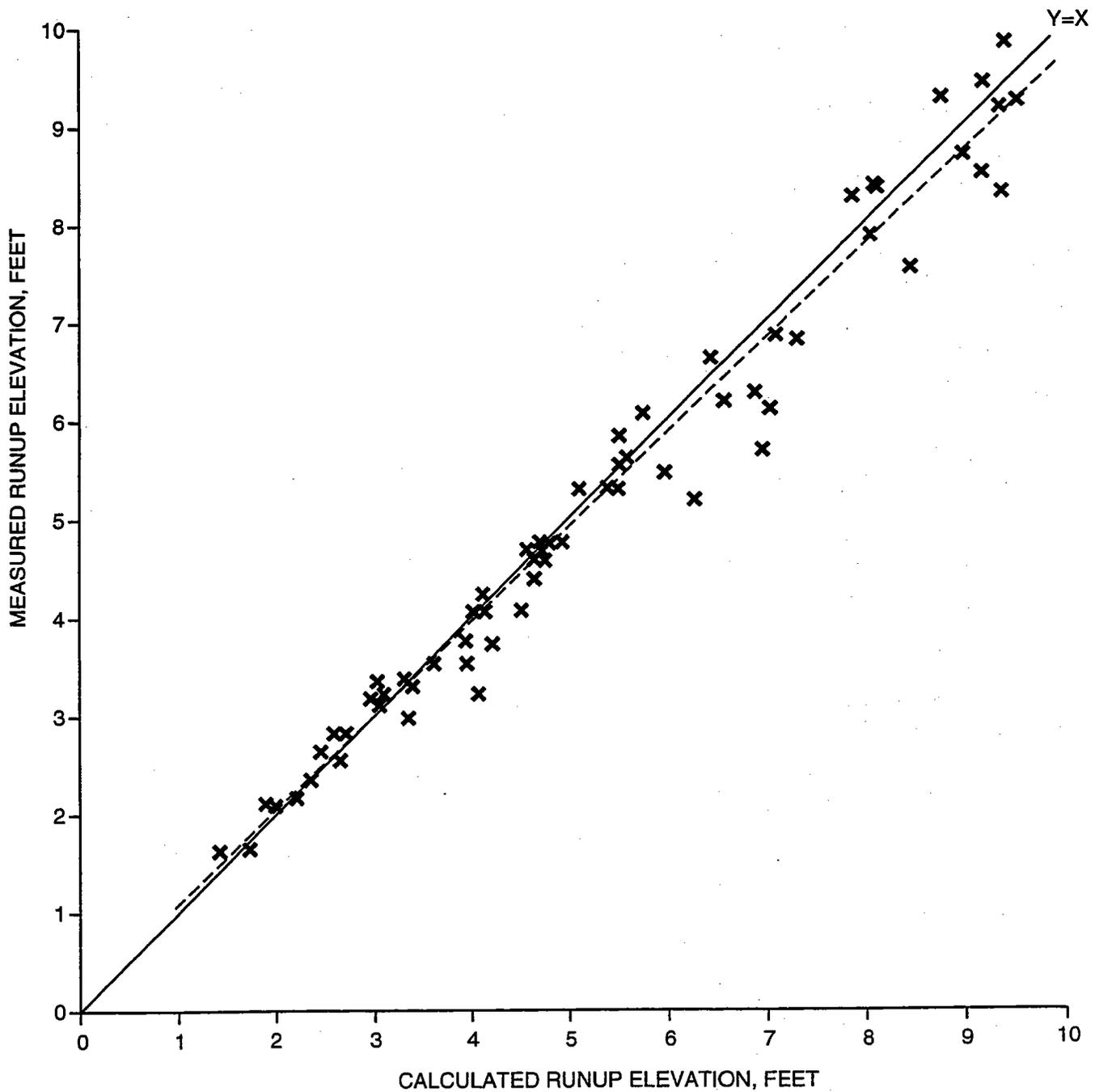


Figure 14. Modified Model Results: Calculated and Measured Runup Elevations in Large Tests with 1:6 Asphalt Slope.

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.

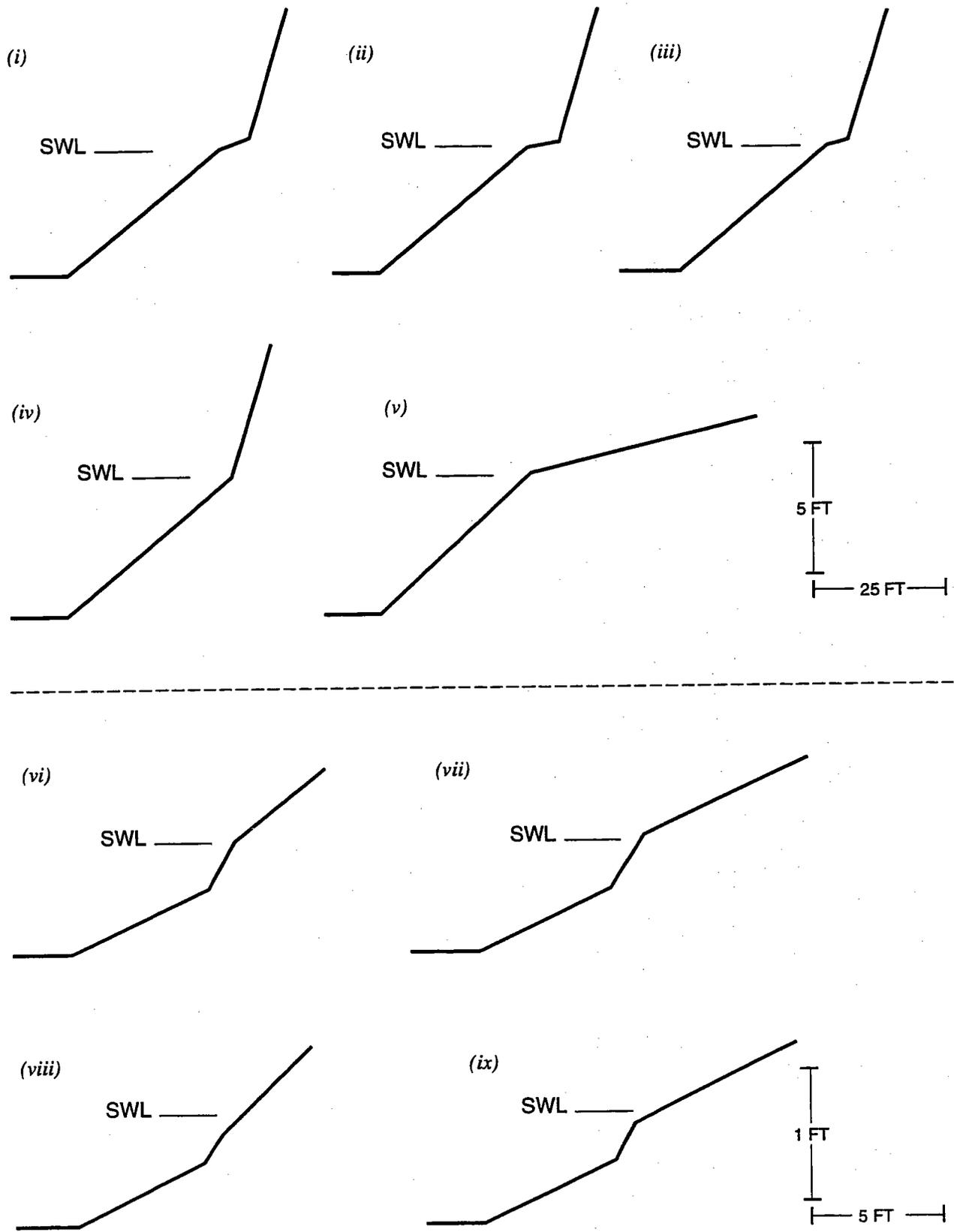


Figure 15. Complex profile configurations in small tests with smooth slopes.  
 Profiles *i-v* tested by Hosui and Mitsui (1963), and profiles *vi-ix* by Saville (1955).

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

| Test Profile:<br>Fig. | Water Depth,<br>Ft | Wave Period,<br>Sec | Wave Height,<br>Ft | Measured Runup,<br>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  $\pm 0.5$  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

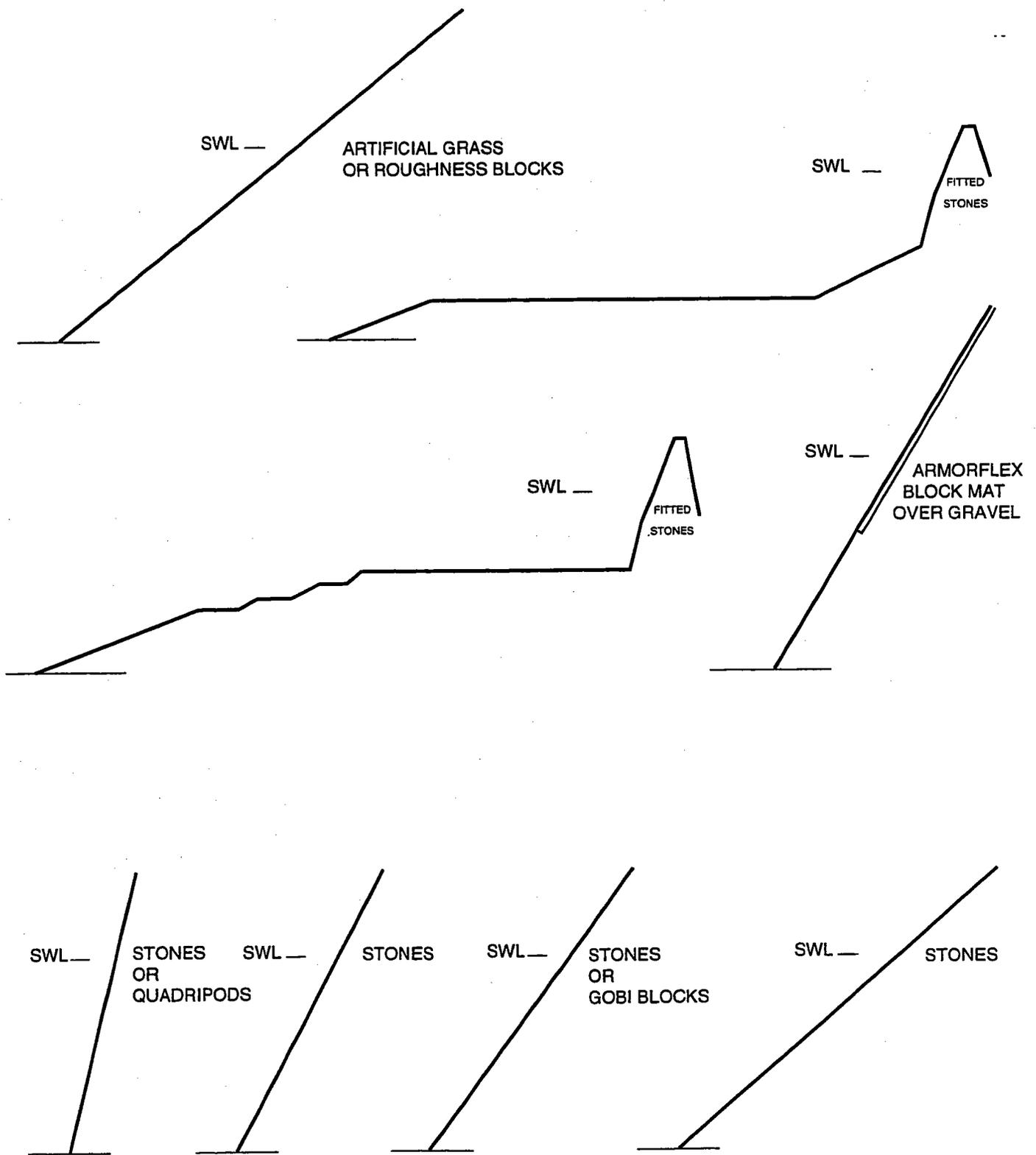


Figure 16. Shore configurations in large tests with rough slopes and uniform waves.

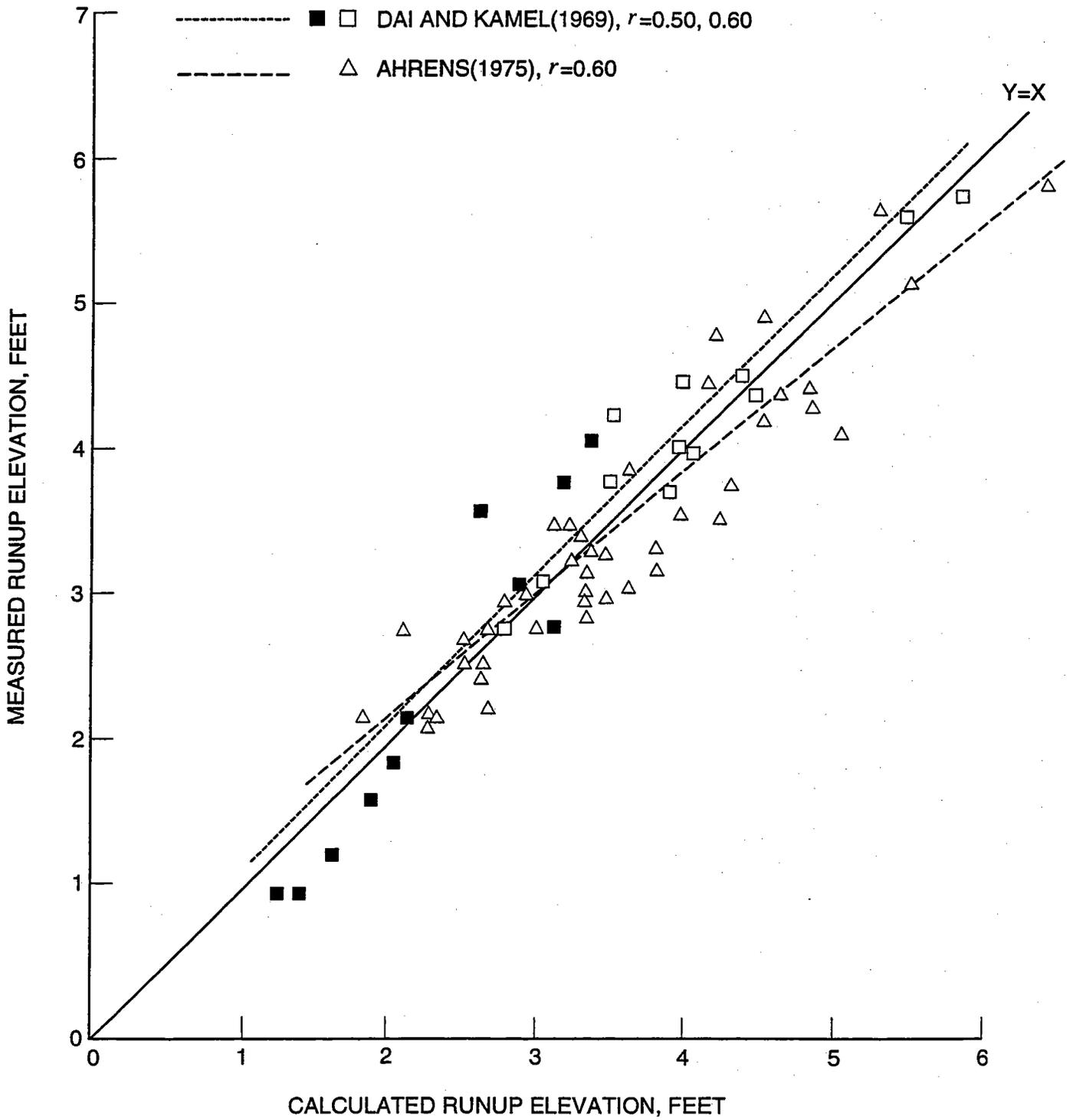


Figure 17. Modified Model Results: Calculated and Measured Runup Elevations for large USACE tests with very rough slopes.

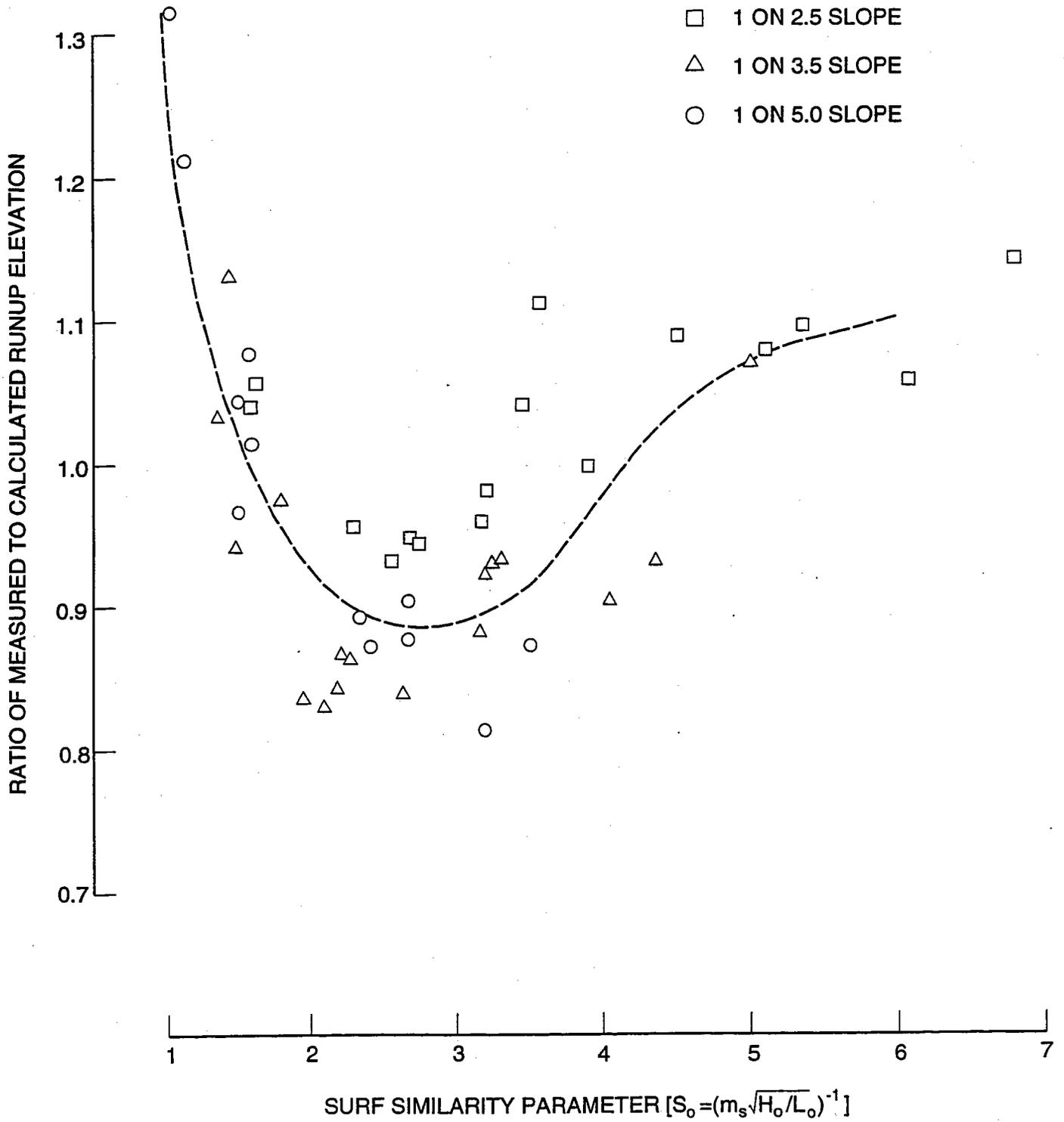


Figure 18. Apparent effect of surf similarity parameter in test results of Ahrens(1975) for very rough slopes.

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  $\pm 0.3$  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.

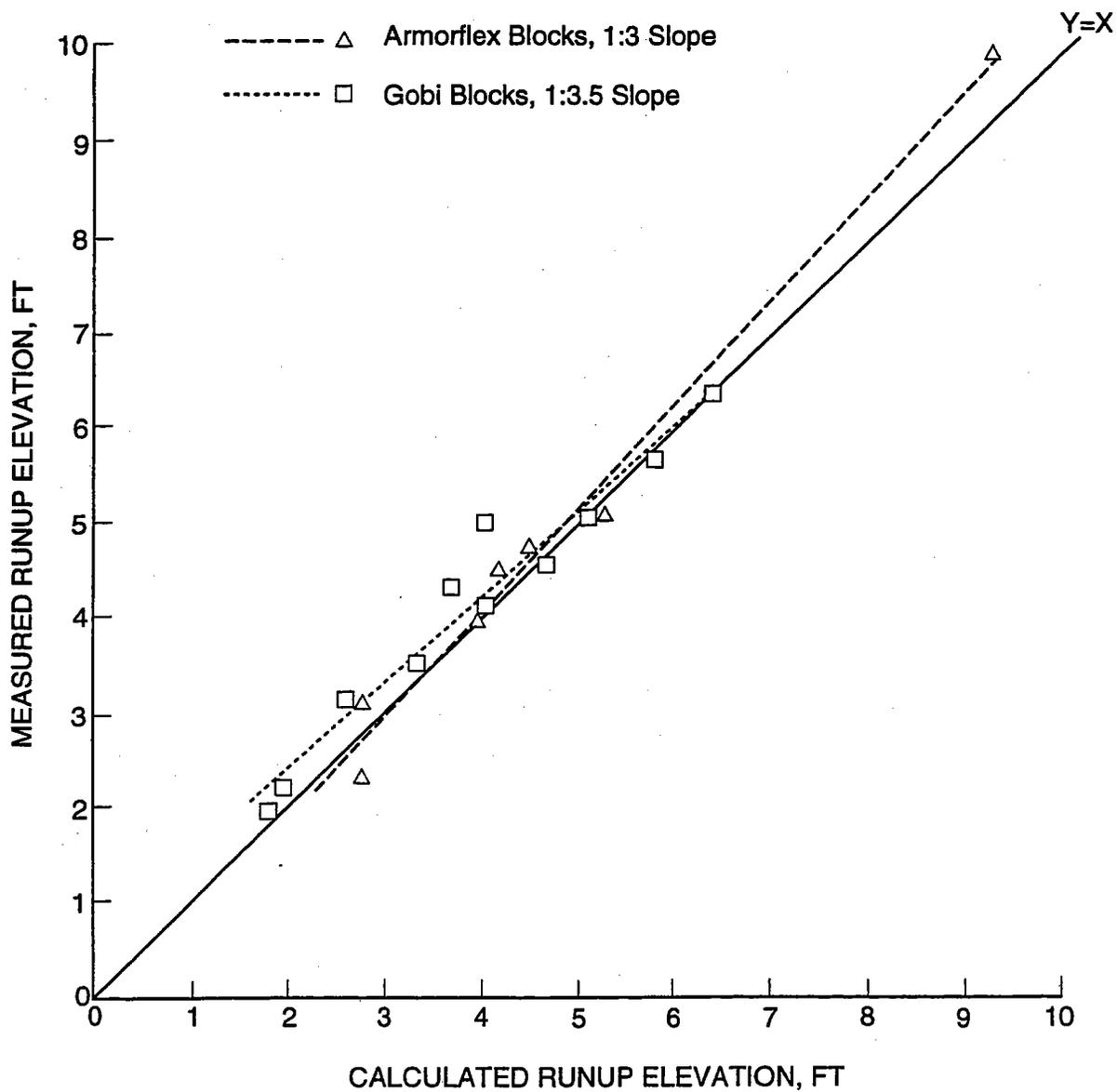


Figure 19. Modified Model Results: Calculated and Measured Runup Elevations in Large Tests with Gobi ( $r=0.85$ ) and Armorflex ( $r=0.95$ ) Blocks.

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  $\pm 0.3$  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

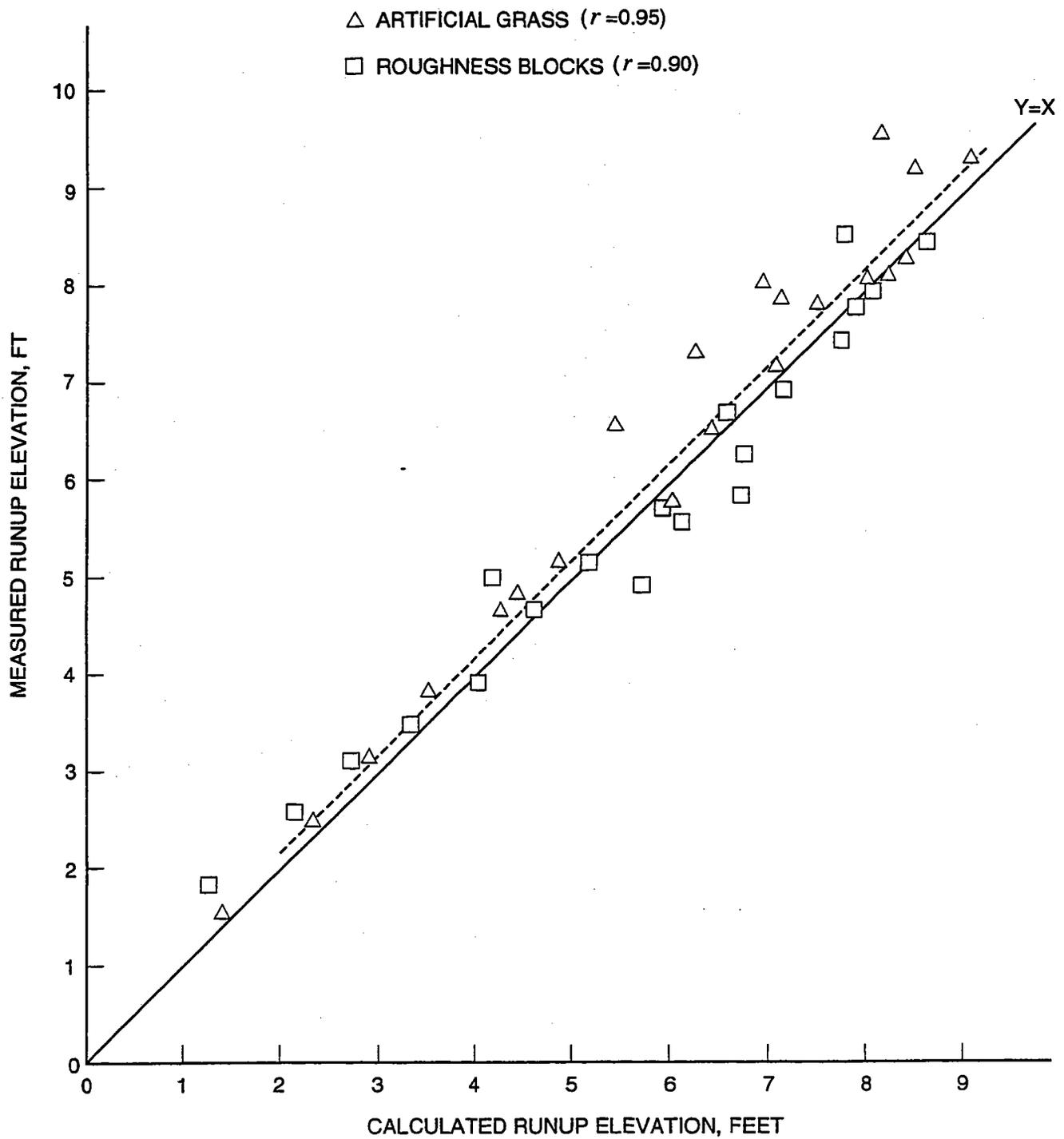


Figure 20. Modified Model Results: Calculated and Measured Runup Elevations in Large Tests with Rough 1:6 Slope.

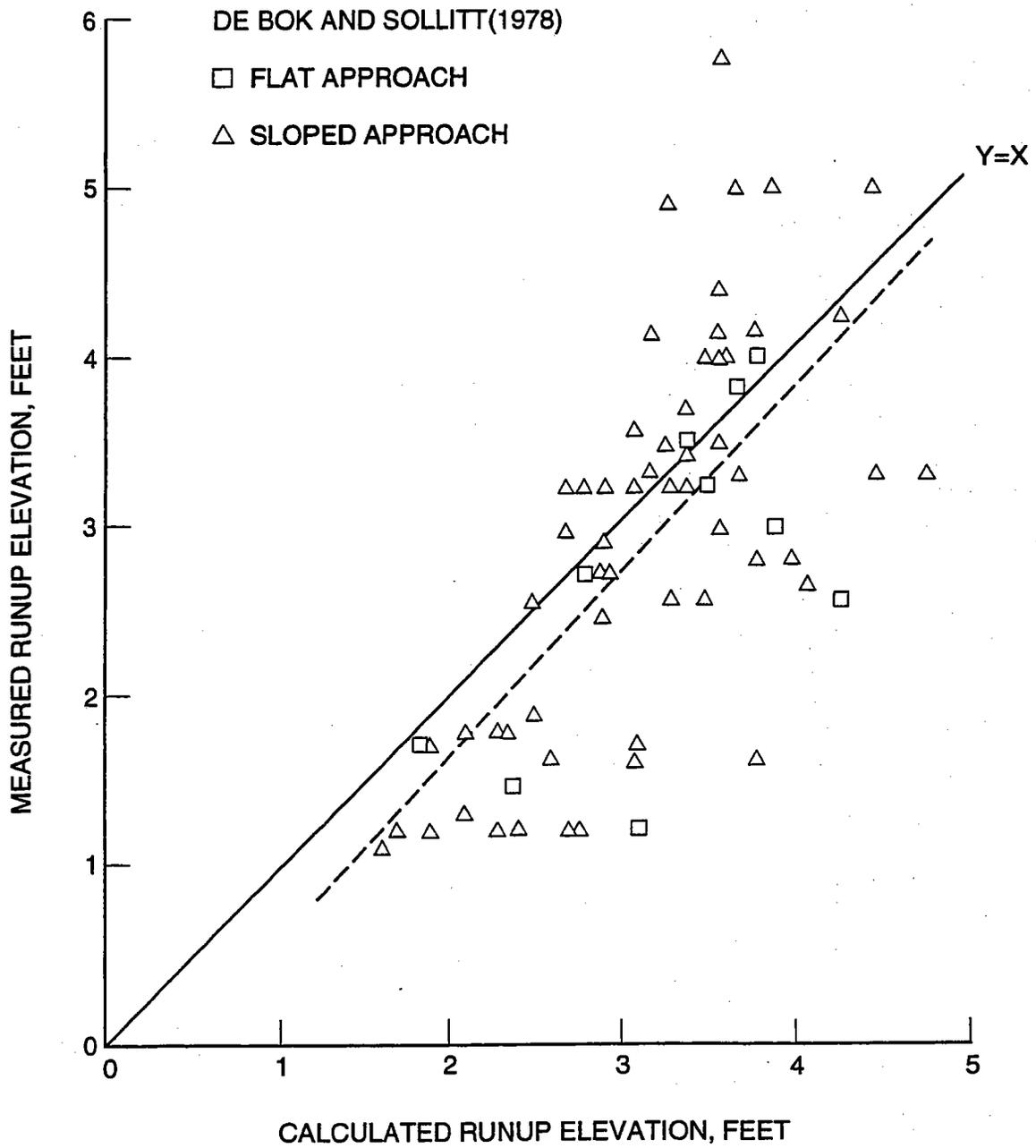


Figure 21. 1981 Model Results: Calculated and measured runup elevations for large tests with rough compound slope.

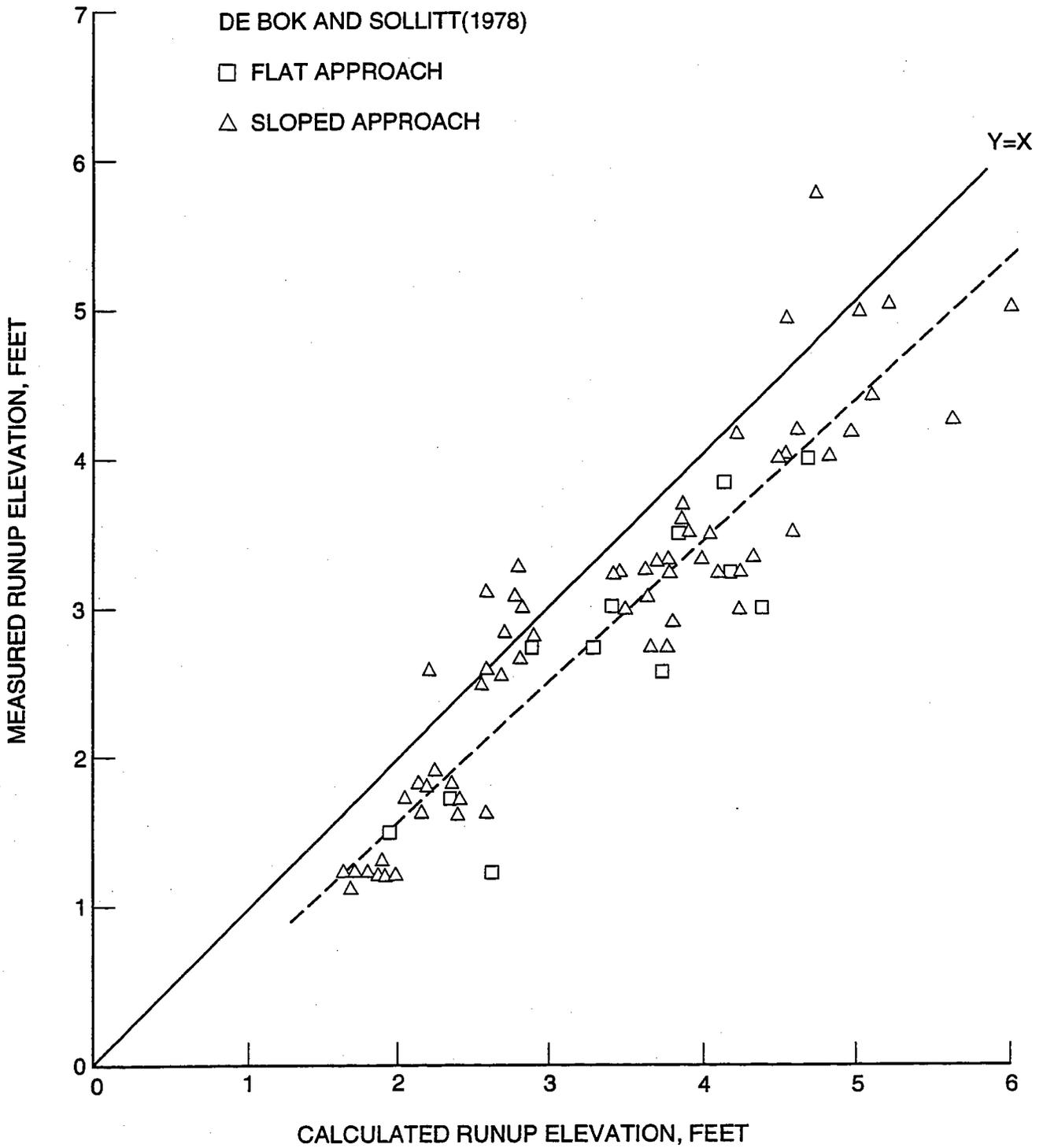


Figure 22. Modified Model Results: Calculated and measured runup elevations for large tests with rough compound slope.

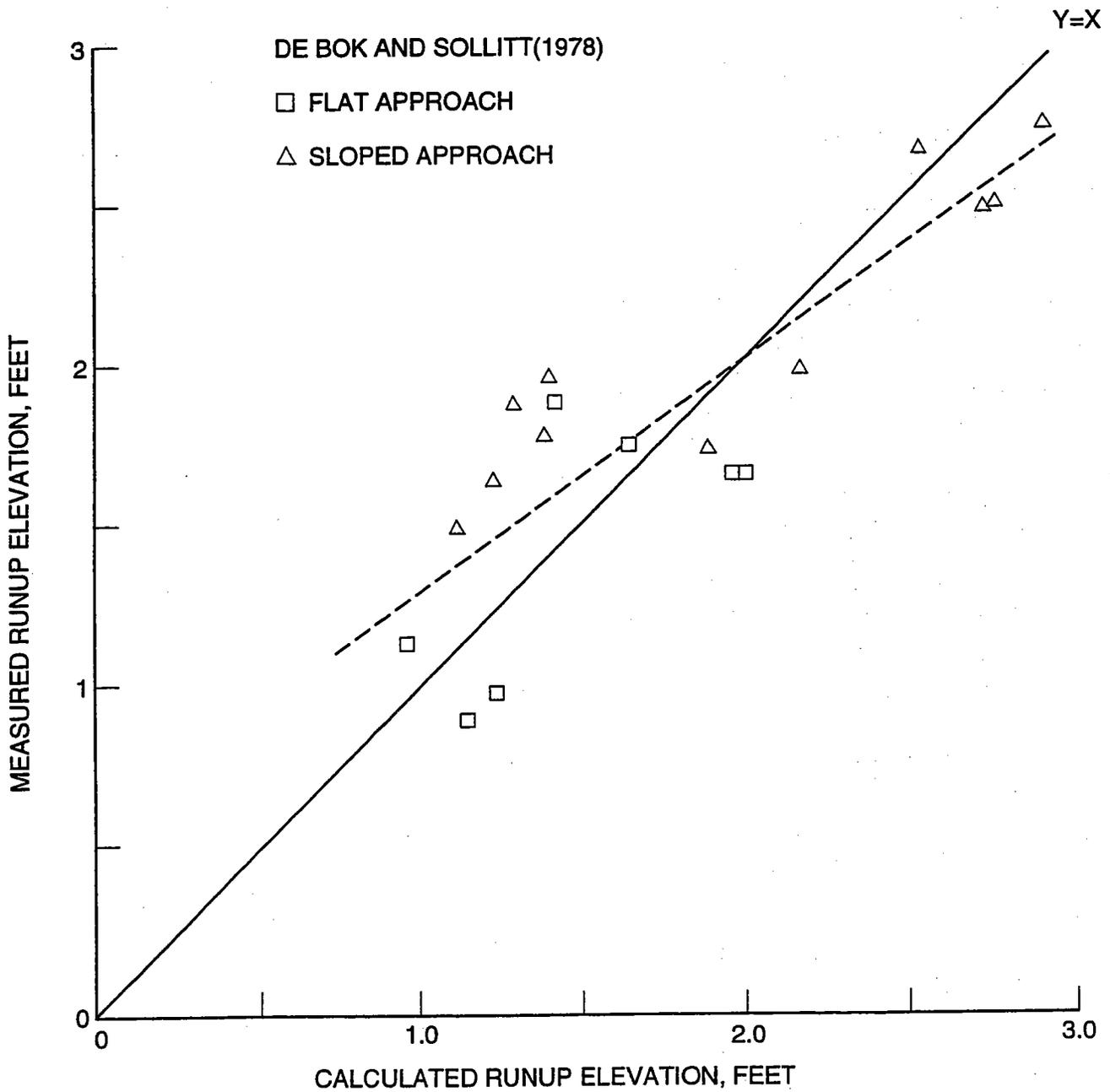


Figure 23. Modified Model Results: Calculated and measured runup elevations for "Half-Size" tests with rough compound slope.

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 ( $\nu$ ). 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

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

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  $(H_0/d)$  remains about one. The second bracketed term also is approximately one, since  $H_0/L_0$  and thus  $d/L_0$  remain relatively small. Thus, it is appropriate to measure wave-induced flow intensity by the approximate form

$$RE^* = (H_0/g)^{0.5} T^2 \quad (6)$$

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  $3 \text{ sec}^3$ , 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  $S_0$  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

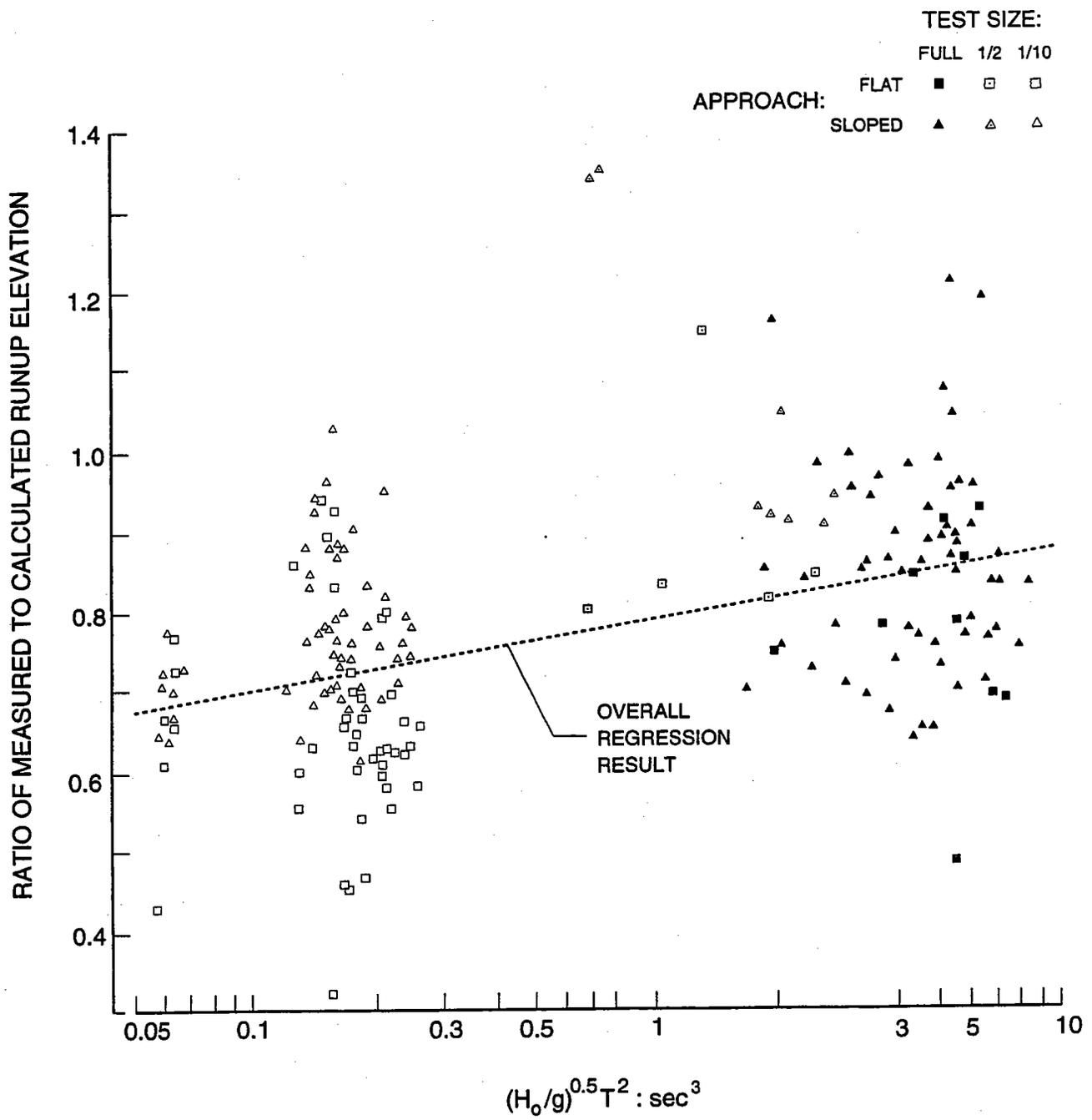


Figure 24. Apparent scale effect in results for rough compound slope (De Bok and Sollitt, 1978).

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  $10 \text{ sec}^3$ . 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  $RE^* = 10 \text{ sec}^3$  corresponds to  $H_0 = 1 \text{ ft}$  and  $T = 7.5 \text{ sec}$ , or to  $H_0 = 5 \text{ ft}$  and  $T = 5 \text{ sec}$ . 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

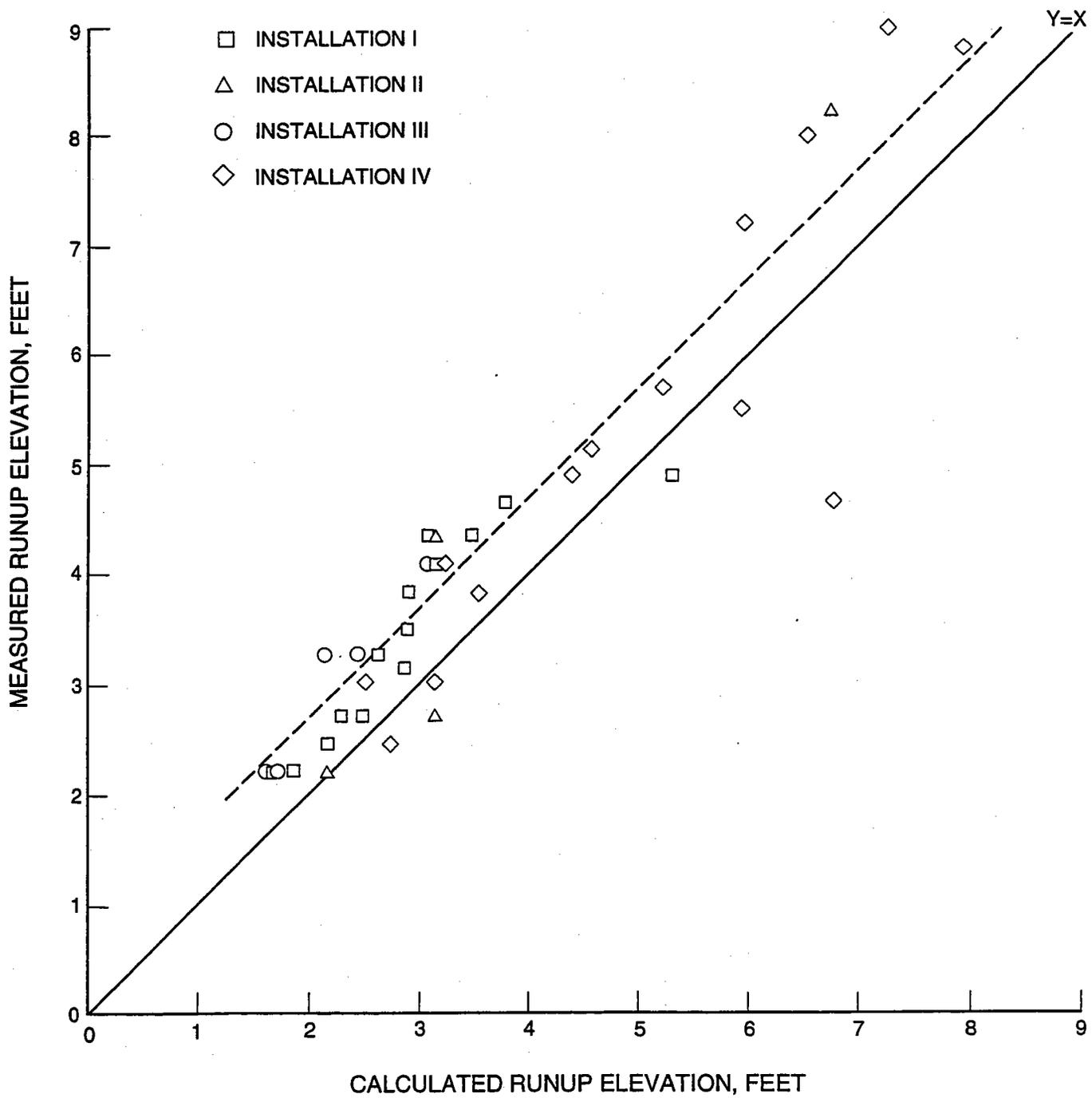


Figure 25. Modified Model Results: Calculated and measured runup elevations in Delft Hydraulics Laboratory tests with concrete blocks(  $r = 0.95$ ).

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  $\pm 20\%$  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

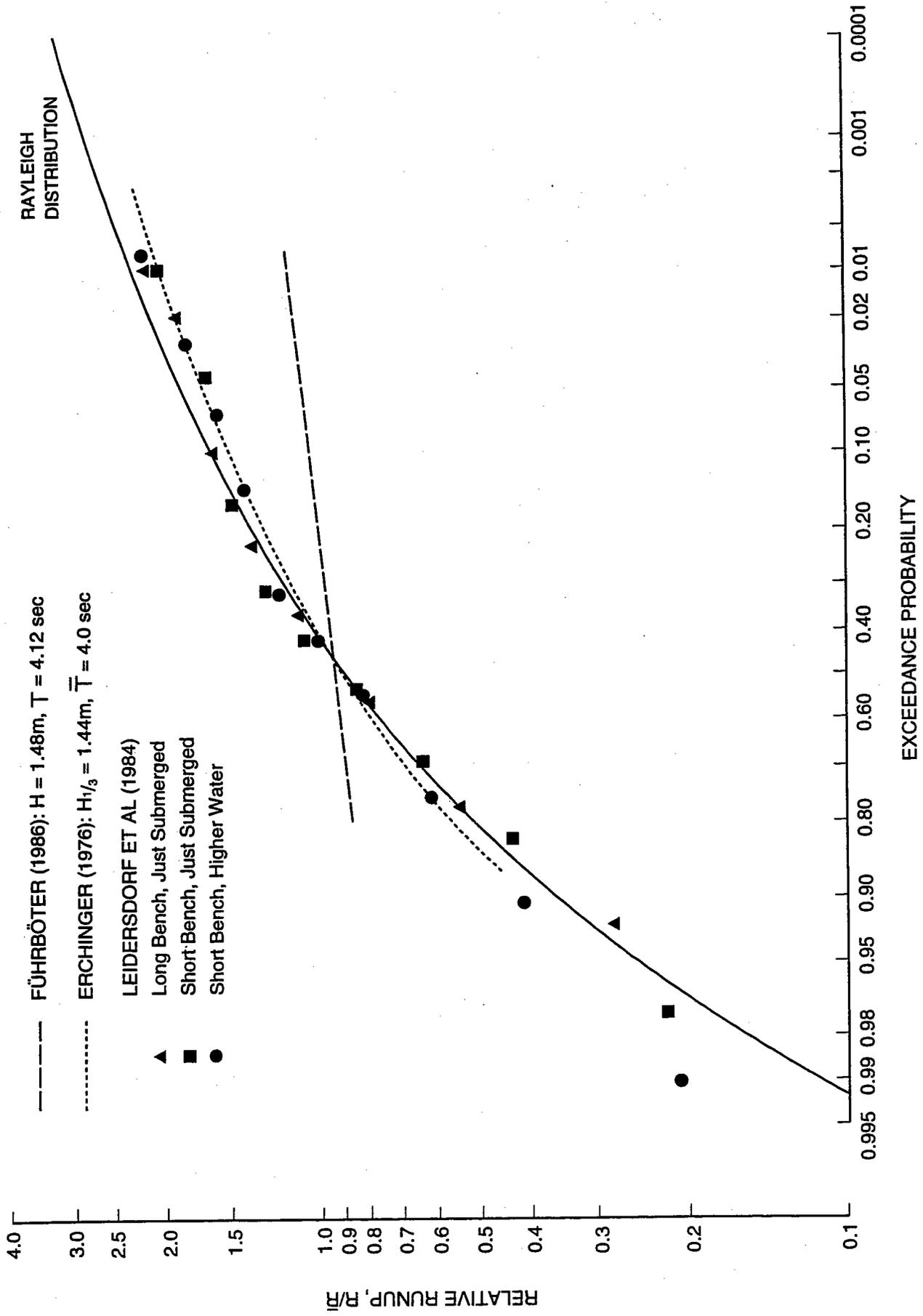


Figure 26. Probability distributions of measured wave runup elevations.

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 elevations 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

.....● GRÜNE(1982) ASPHALT DIKE:  $H_s = 3.9$  ft,  $\bar{T} = 5.3$  sec  
 —□ D.H.L.(1985) BASALT SLOPE:  $H_s = 3.95$  ft,  $\bar{T} = 3.64$  sec

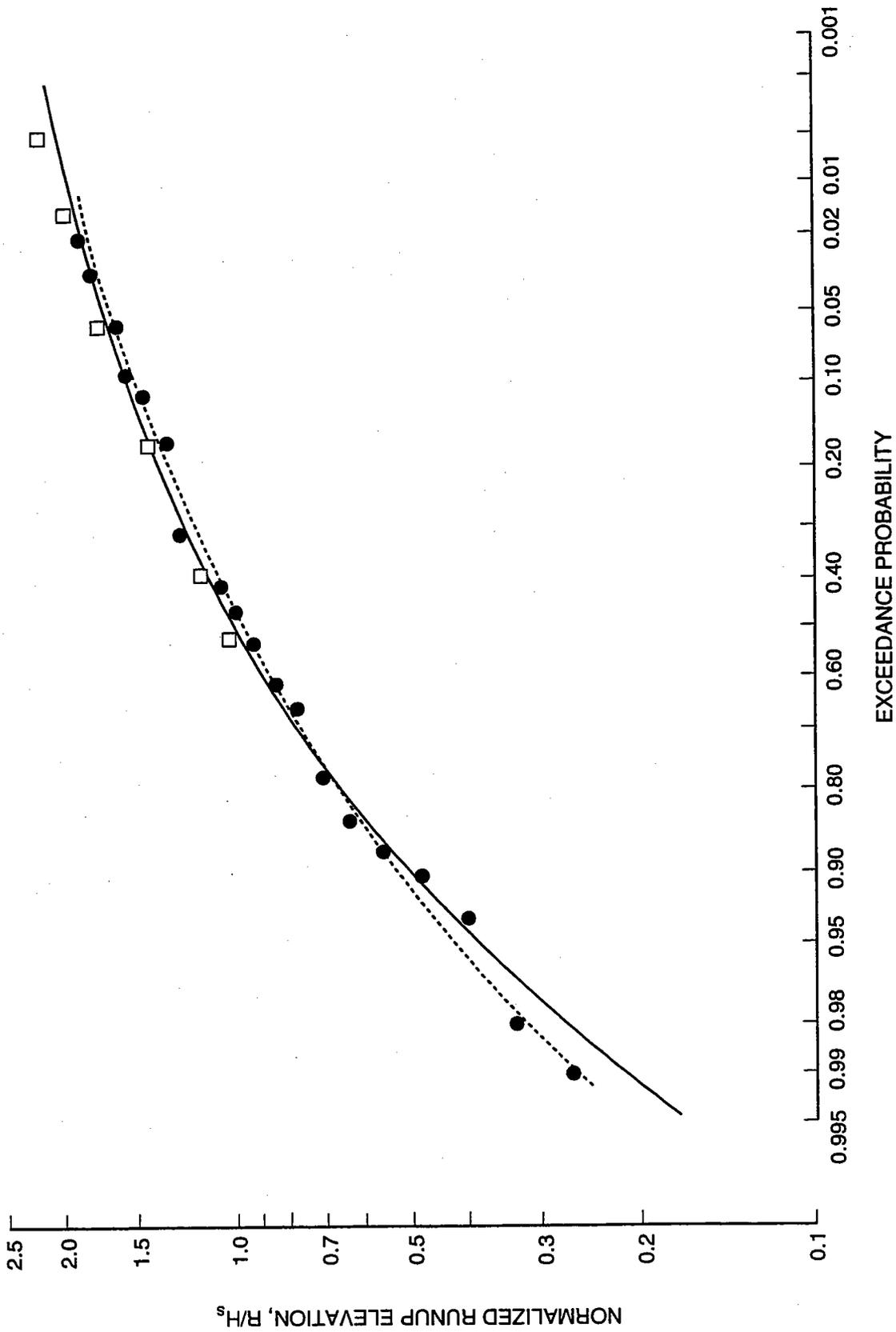


Figure 27. Additional probability distributions of elevations as  $R/H_s$ .

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  $H_0$  covering a wide

\*\*\*\*\*

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      |

\*\*\*\*\*

OUTPUT TABLE

| INPUT PARAMETERS              |                              |                    | RUNUP RESULTS         |                    |                               |                     |
|-------------------------------|------------------------------|--------------------|-----------------------|--------------------|-------------------------------|---------------------|
| WATER LEVEL ABOVE DATUM (FT.) | DEEP WATER WAVE HEIGHT (FT.) | WAVE PERIOD (SEC.) | BREAKING SLOPE NUMBER | RUNUP SLOPE NUMBER | RUNUP ABOVE WATER LEVEL (FT.) | BREAKER DEPTH (FT.) |
| 13.80                         | 0.80                         | 5.40               | 4                     | 5                  | 0.50                          | 1.61                |
| 13.80                         | 1.20                         | 5.40               | 4                     | 5                  | 0.60                          | 2.22                |
| 13.80                         | 1.60                         | 5.40               | 4                     | 5                  | 0.63                          | 2.80                |
| 13.80                         | 2.00                         | 5.40               | 4                     | 5                  | 0.71                          | 3.37                |
| 13.80                         | 2.40                         | 5.40               | 4                     | 5                  | 0.82                          | 3.92                |
| 13.80                         | 2.80                         | 5.40               | 3                     | 5                  | 0.91                          | 4.07                |
| 13.80                         | 3.10                         | 5.40               | 3                     | 5                  | 0.98                          | 4.44                |
| 13.80                         | 3.50                         | 5.40               | 2                     | 5                  | 1.07                          | 5.68                |
| 13.80                         | 4.00                         | 5.40               | 2                     | 5                  | 0.96                          | 6.36                |
| 13.80                         | 4.50                         | 5.40               | 2                     | 5                  | 0.88                          | 7.02                |
| 13.80                         | 5.00                         | 5.40               | 2                     | 5                  | 0.88                          | 7.69                |

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 ( $\bar{R}$ ) 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 ( $\bar{H}_0, \bar{T}$ ) 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  $\bar{H}_0$  and  $\bar{T}$  as input:  $\bar{R}$  shows

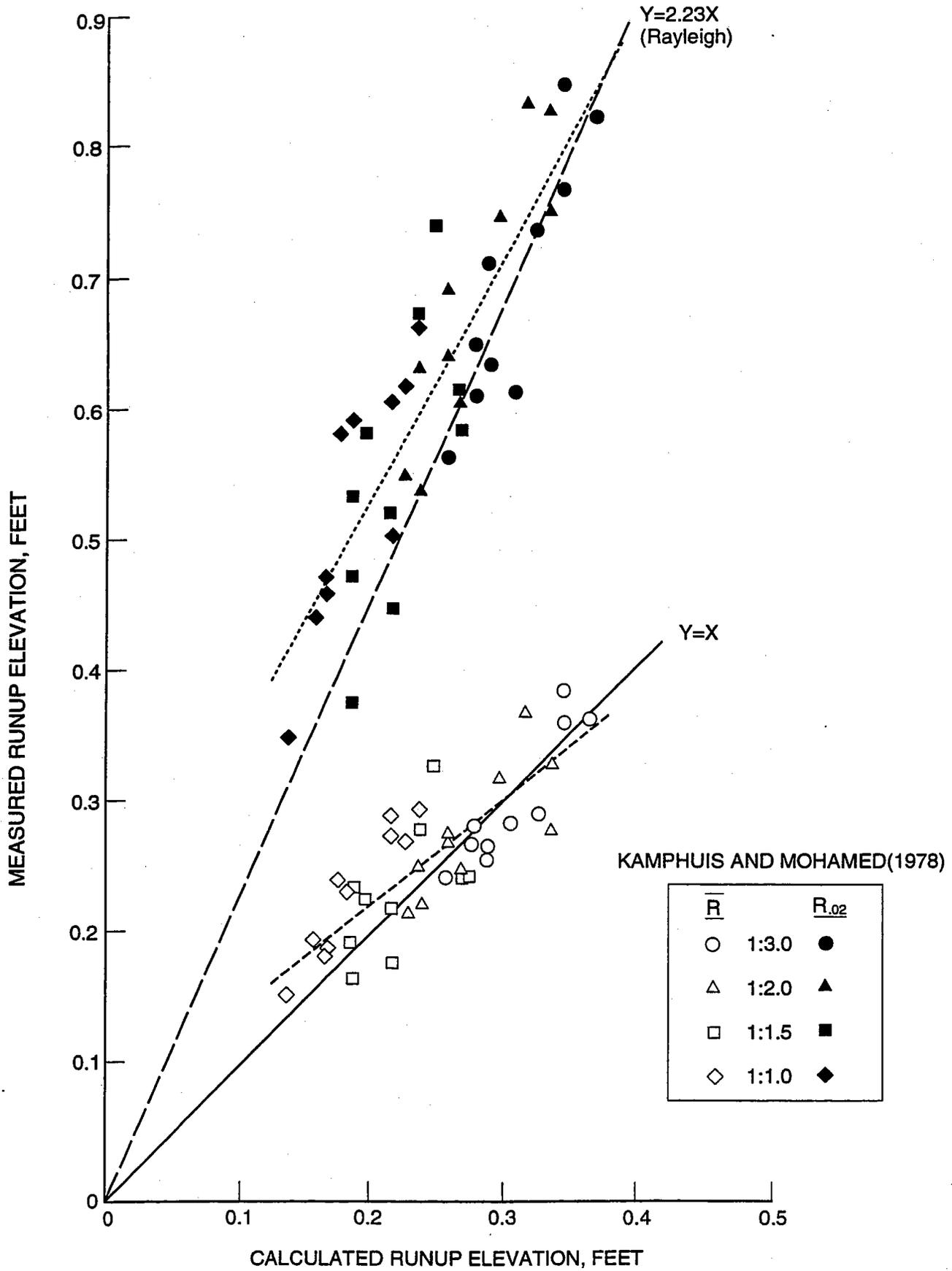


Figure 28a. Modified Model Results: Calculated and measured runup elevations with irregular waves reflecting from smooth slopes, described by the mean wave condition.

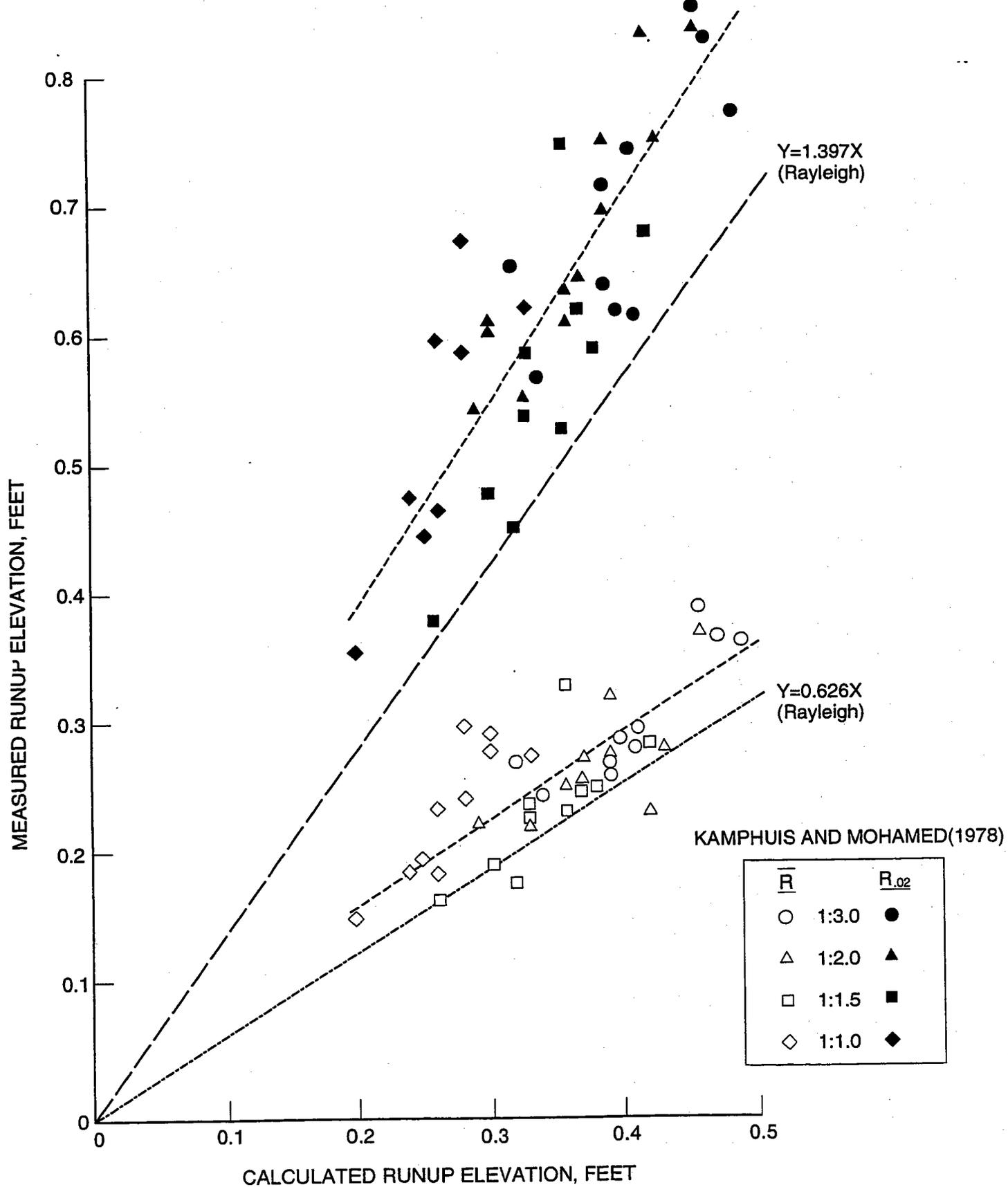


Figure 28b. Modified Model Results: Calculated and measured runup elevations with irregular waves reflecting from smooth slopes, described by the significant wave condition.

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  $H_{0s}$  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,  $H_{0s}$  and  $T_s$ , so runup computations for the mean wave condition proceed by assuming  $\bar{H}_o = 0.626 H_{0s}$  (a Rayleigh distribution) and

$$\bar{T} / T_s = 1.173 (H_{0s}/L_{0s})^{0.0762} \quad (7)$$

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.

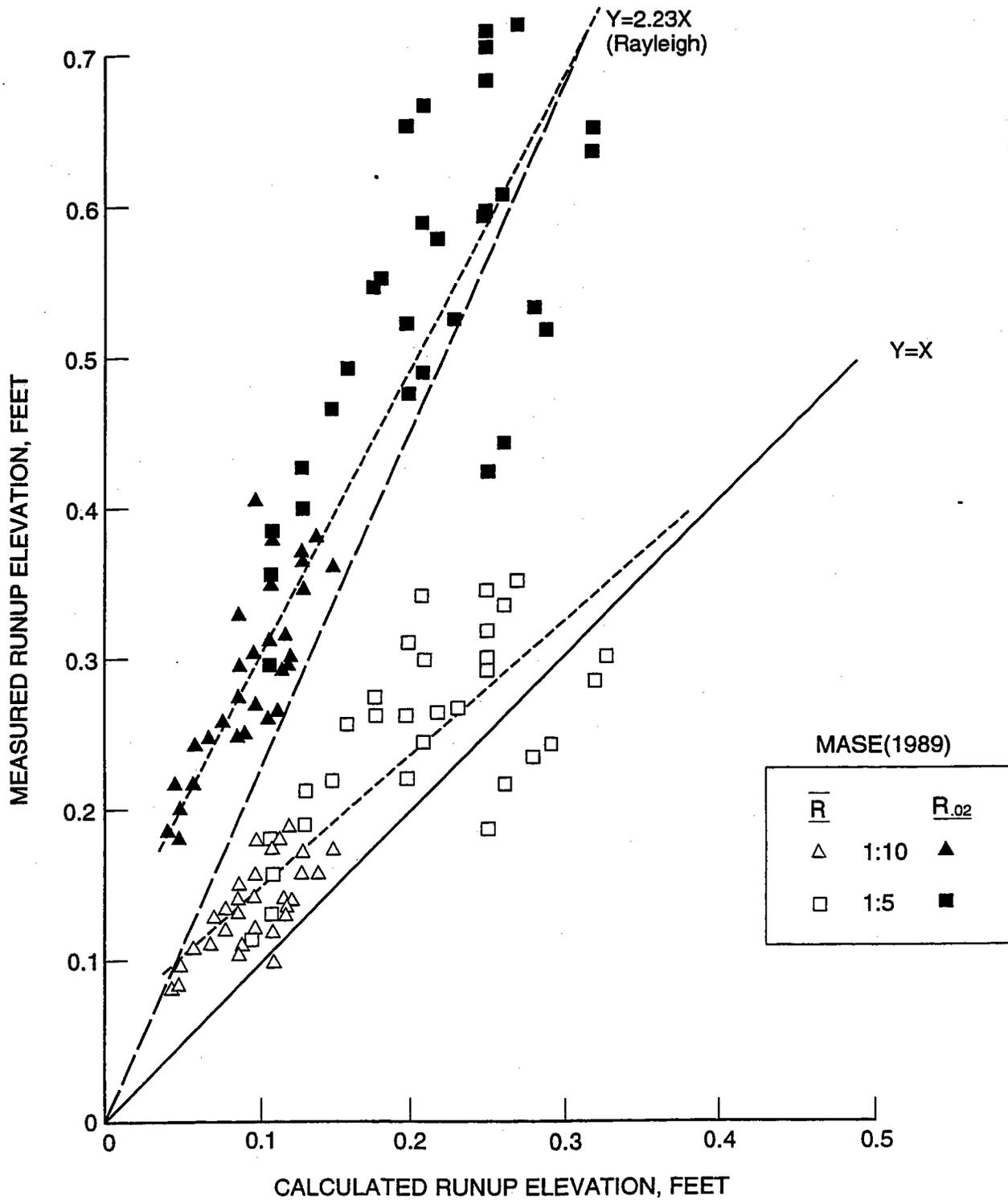


Figure 29a. Modified Model Results: Calculated and measured runup elevations with smooth slopes and irregular waves described by the mean condition.

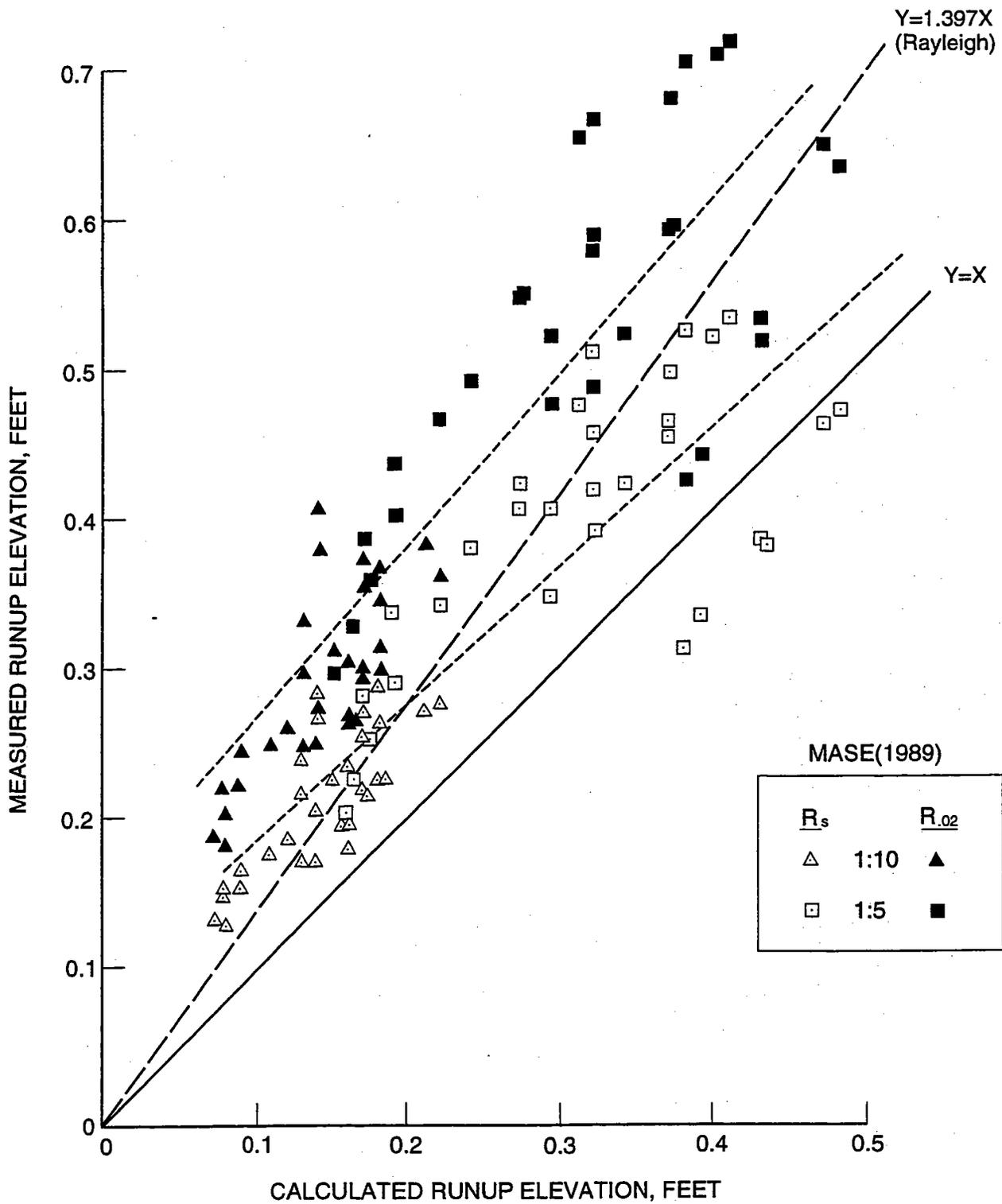


Figure 29b. Modified Model Results: Calculated and measured runup elevations with smooth slopes and irregular waves described by the significant condition.

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

5 FT  
50 FT

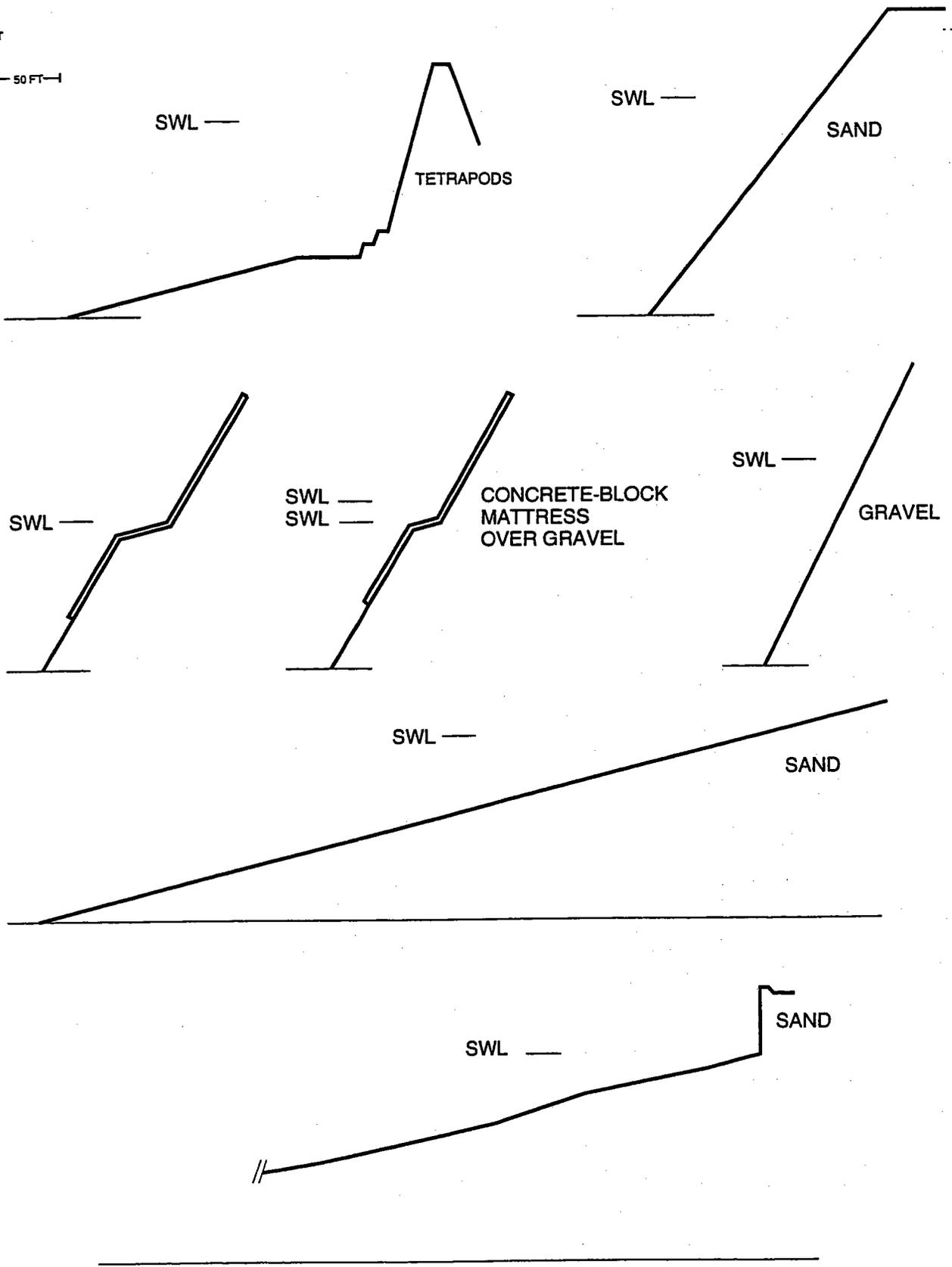


Figure 30. Test configurations with large irregular waves.

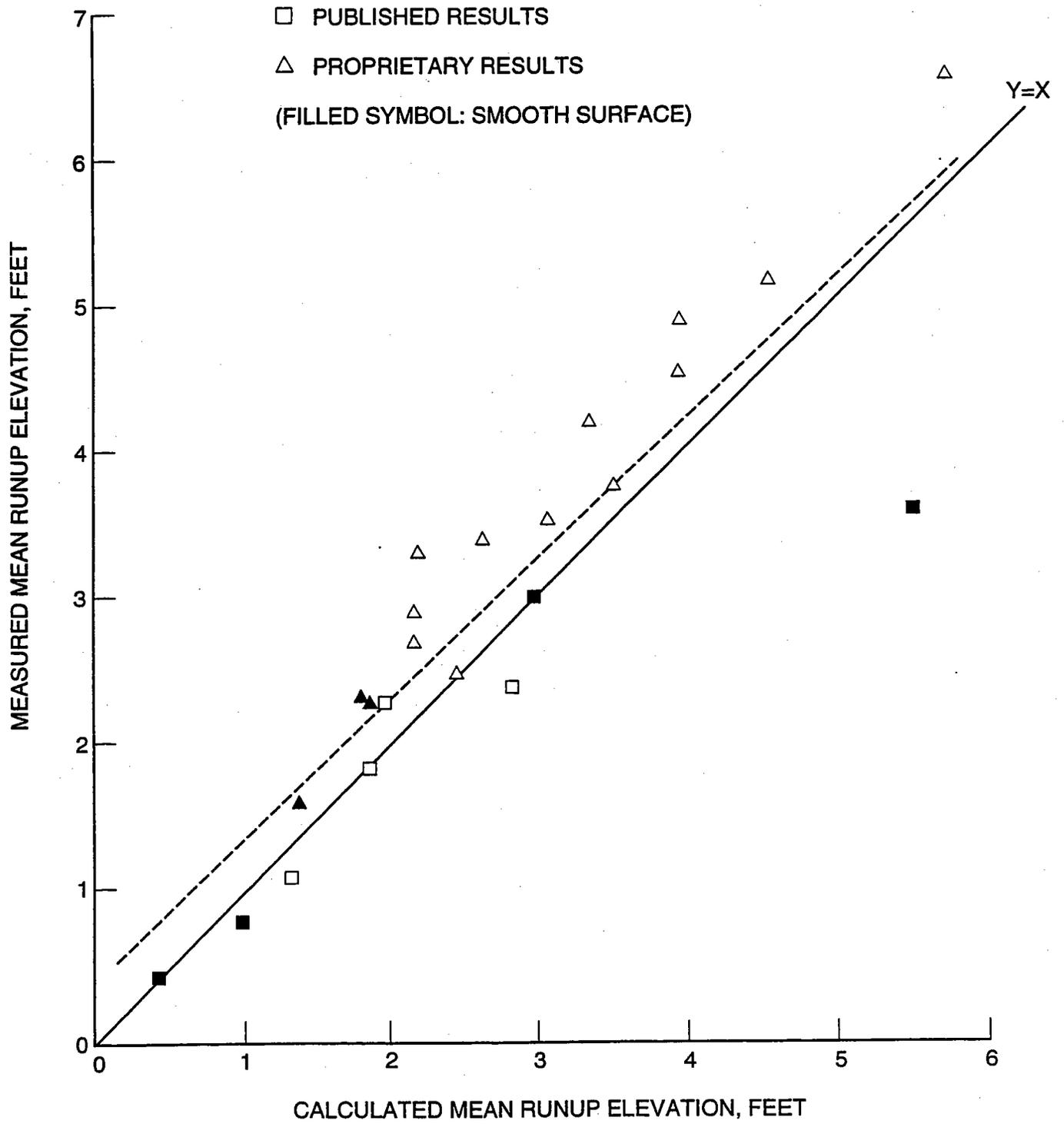


Figure 31. Modified Model Results: Calculated and measured mean runup elevations for large tests with irregular waves.

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  $\pm 0.5$  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  $H_{0s}$  and  $\bar{H}_0 = 0.626 H_{0s}$ ; with  $T_p = T_s$ , Equation 7 gives  $\bar{R}$  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  $\bar{R}$ , 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.

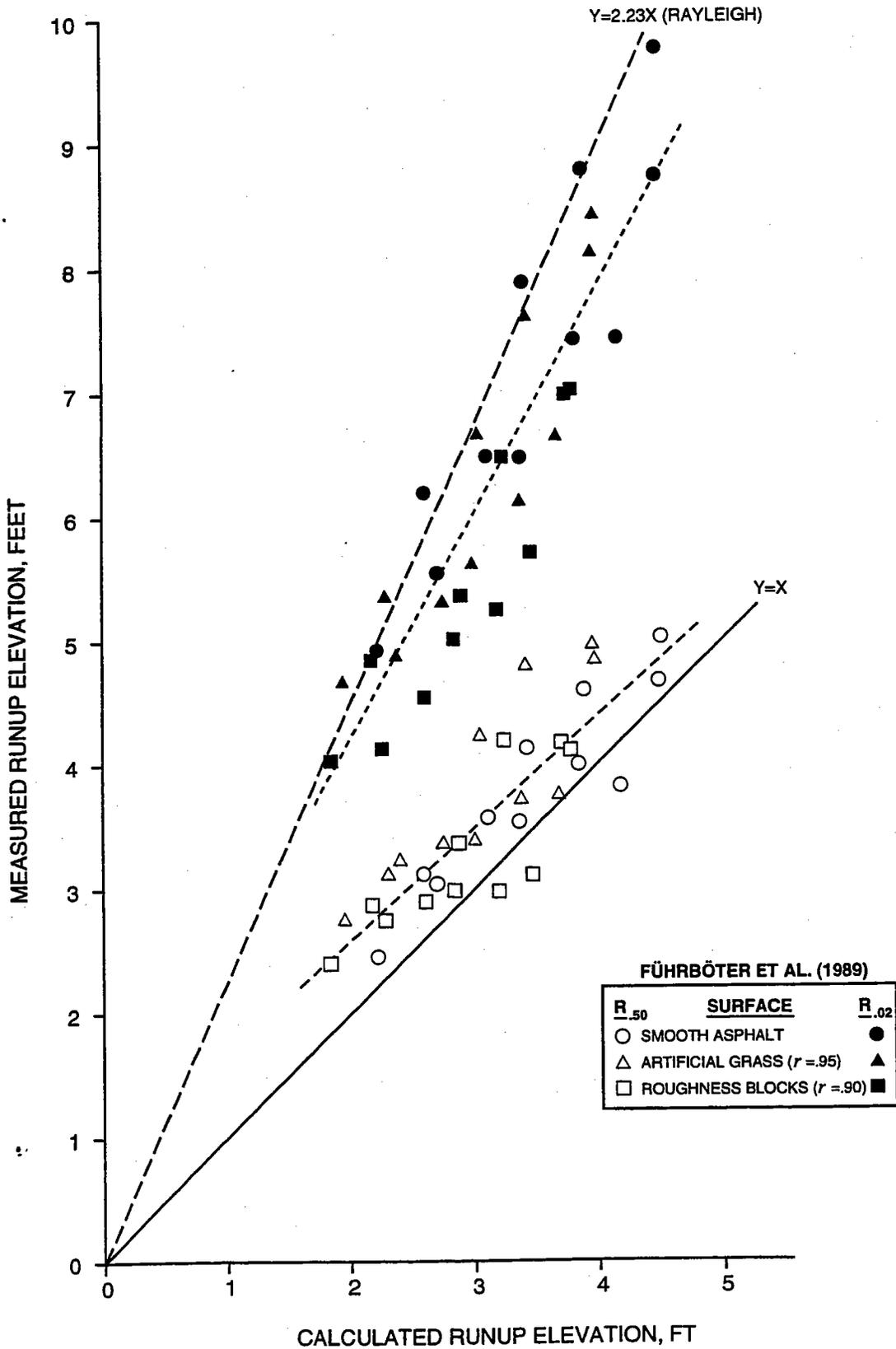


Figure 32. Modified Model Results: Calculated and Measured Runup Elevations with Large Irregular Waves on 1:6 Slope.

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  $\bar{R}$  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  $\pm 1.5$  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

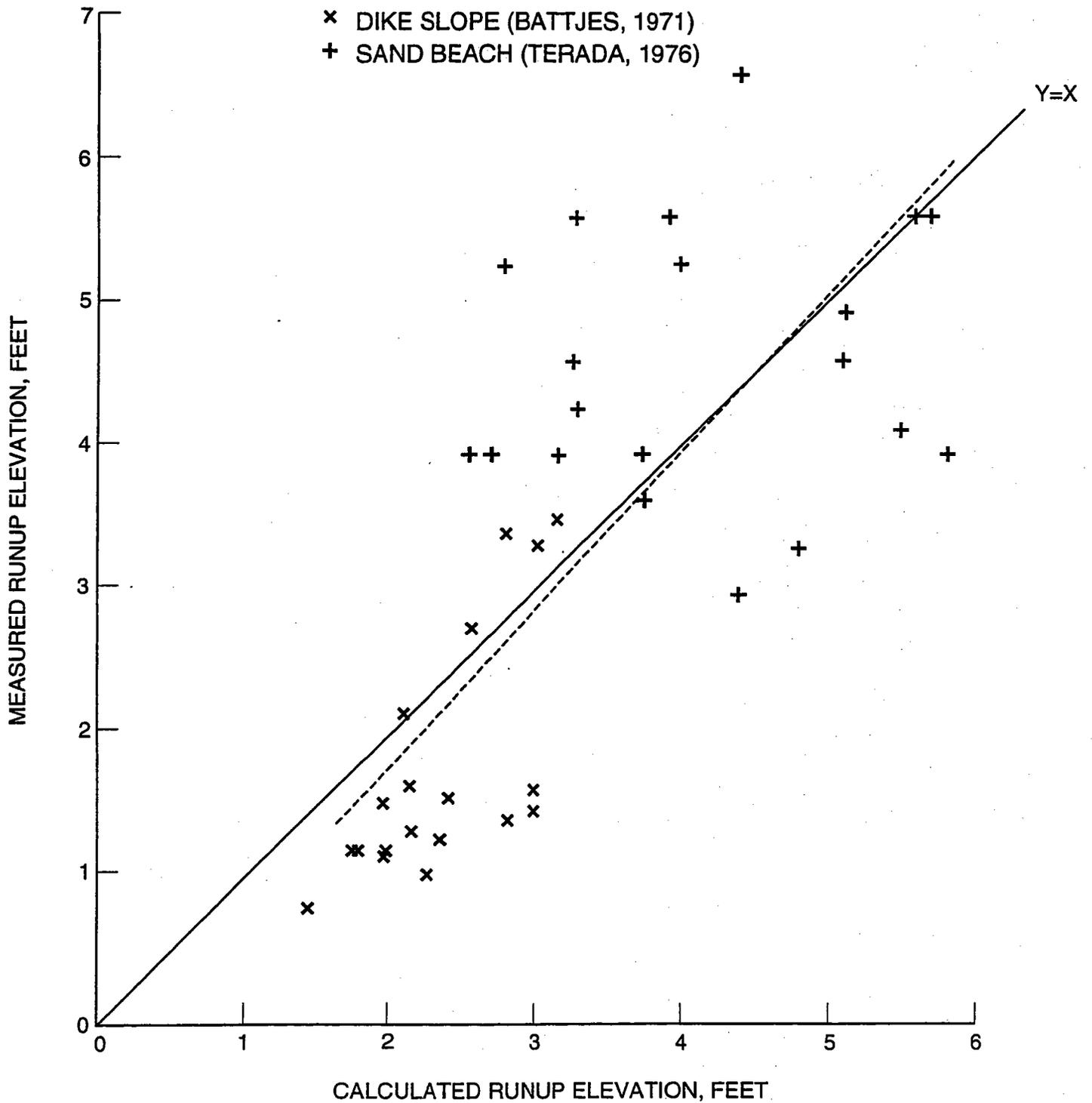


Figure 33. Modified Model Results: Calculated and measured runup elevations in two sets of field data.

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  $H_o=2.6$  ft and  $T=3.6$  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.



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

$$R/H_0 = 0.236 (H_0/L_0)^{-0.498} \quad (8)$$

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

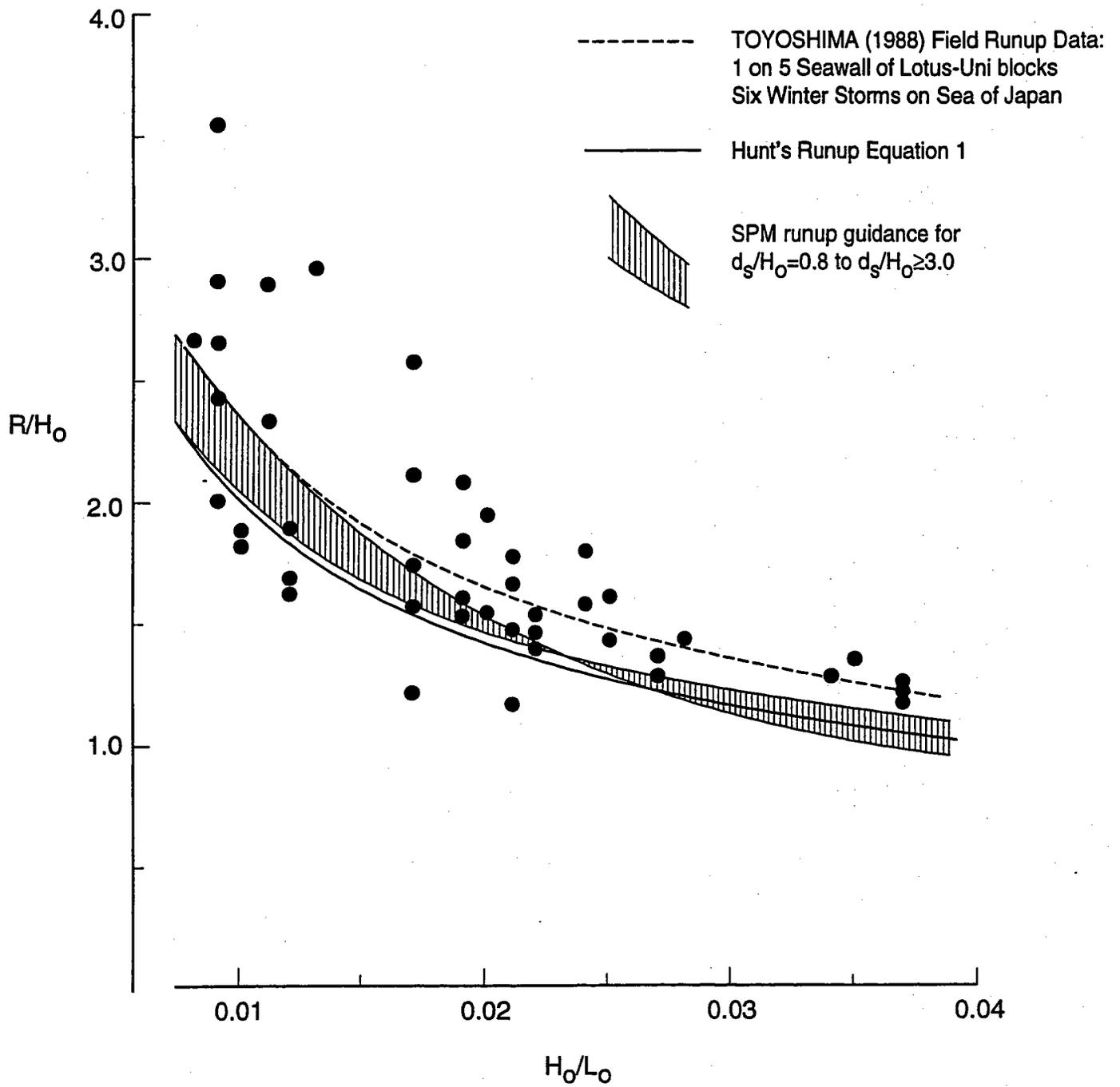


Figure 35. Another analysis of field runup data for a sloping seawall.

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 $Y_0$ (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.

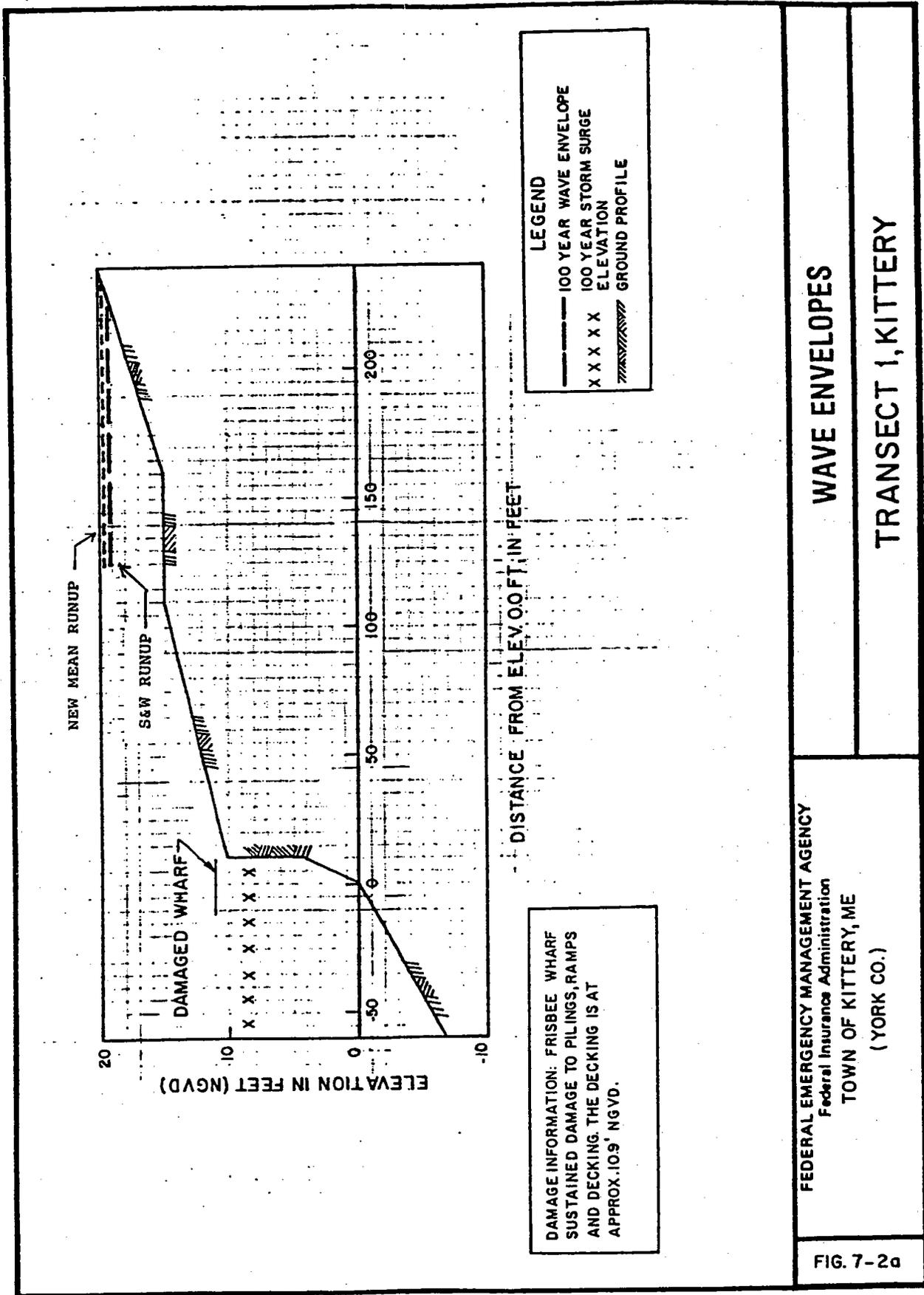
Table 5. Values of the roughness coefficient  $r$  for various slope characteristics, from USACOE Shore Protection Manual (1984).

| 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<br>(impermeable foundation)    | Random    | 0.80         |
| Quarrystone   | Fitted    | 0.75 to 0.80 |
| Rounded quarrystone                                     | Random    | 0.60 to 0.65 |
| Three layers of quarrystone<br>(impermeable foundation) | Random    | 0.60 to 0.65 |
| Quarrystone   | Random    | 0.50 to 0.55 |
| Concrete armor units<br>(~ 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  $\bar{H}_o = 0.626 H_{os} = 19$  ft and  $\bar{T} = 0.85 T_s = 12$  sec. The runup calculations are fully documented in Appendix B and results are displayed in Figure 36.

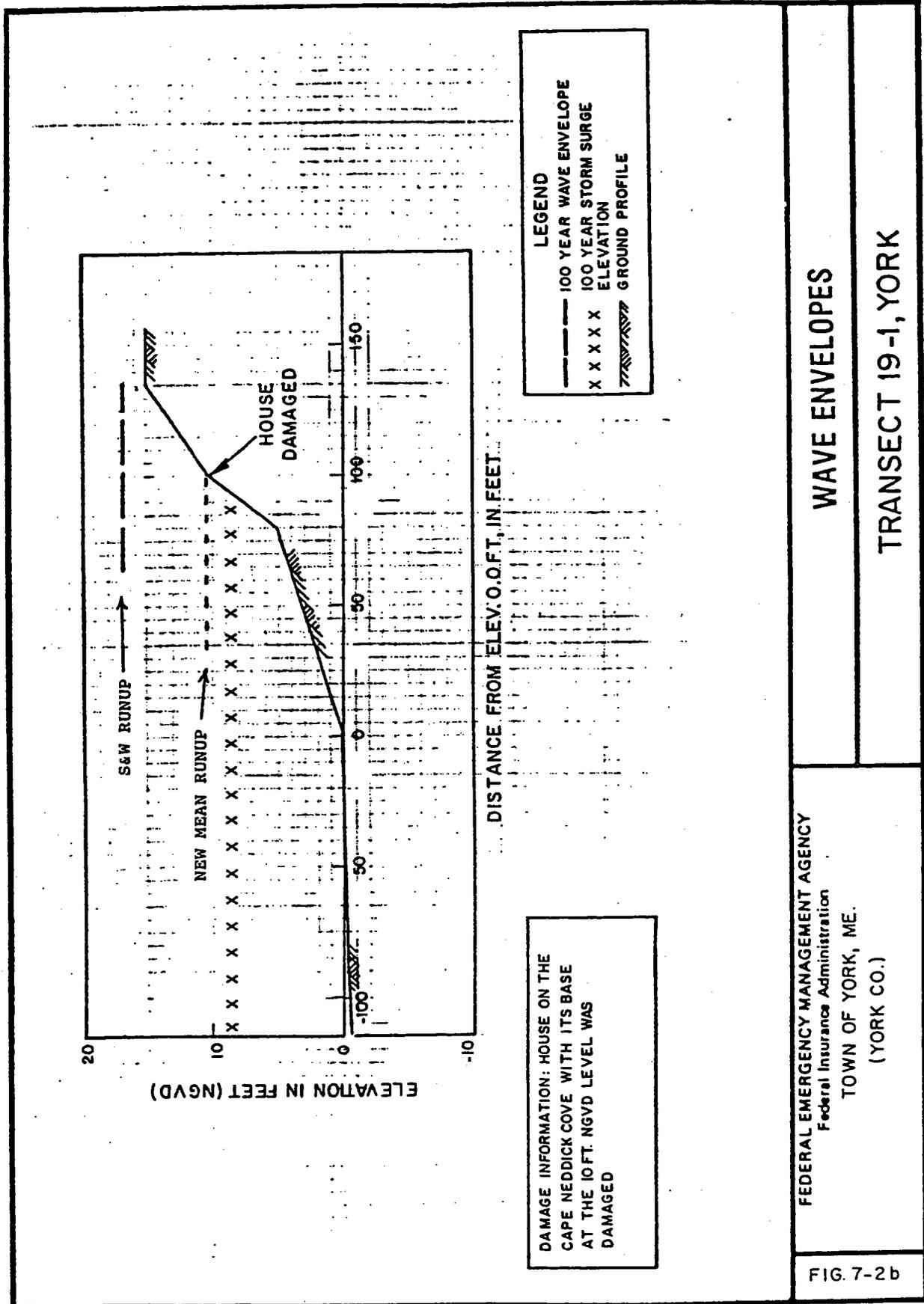
On each transect, the calculated mean elevation of wave runup is above the reported damage location, as was the case with the original Stone & Webster verification in terms of  $R_{max}$ . However, computations with the modified Model have a straightforward statistical interpretation and agree with extensive measurements of large runup elevations due to storm waves. In two of four cases here, calculated  $\bar{R}$  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  $\bar{R}$  indicates usual rather than extreme limits to uprush water.



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

FIG. 7-2a

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

LEGEND  
 --- 100 YEAR WAVE ENVELOPE  
 X X X X 100 YEAR STORM SURGE  
 ELEVATION  
 [Hatched] GROUND PROFILE

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]

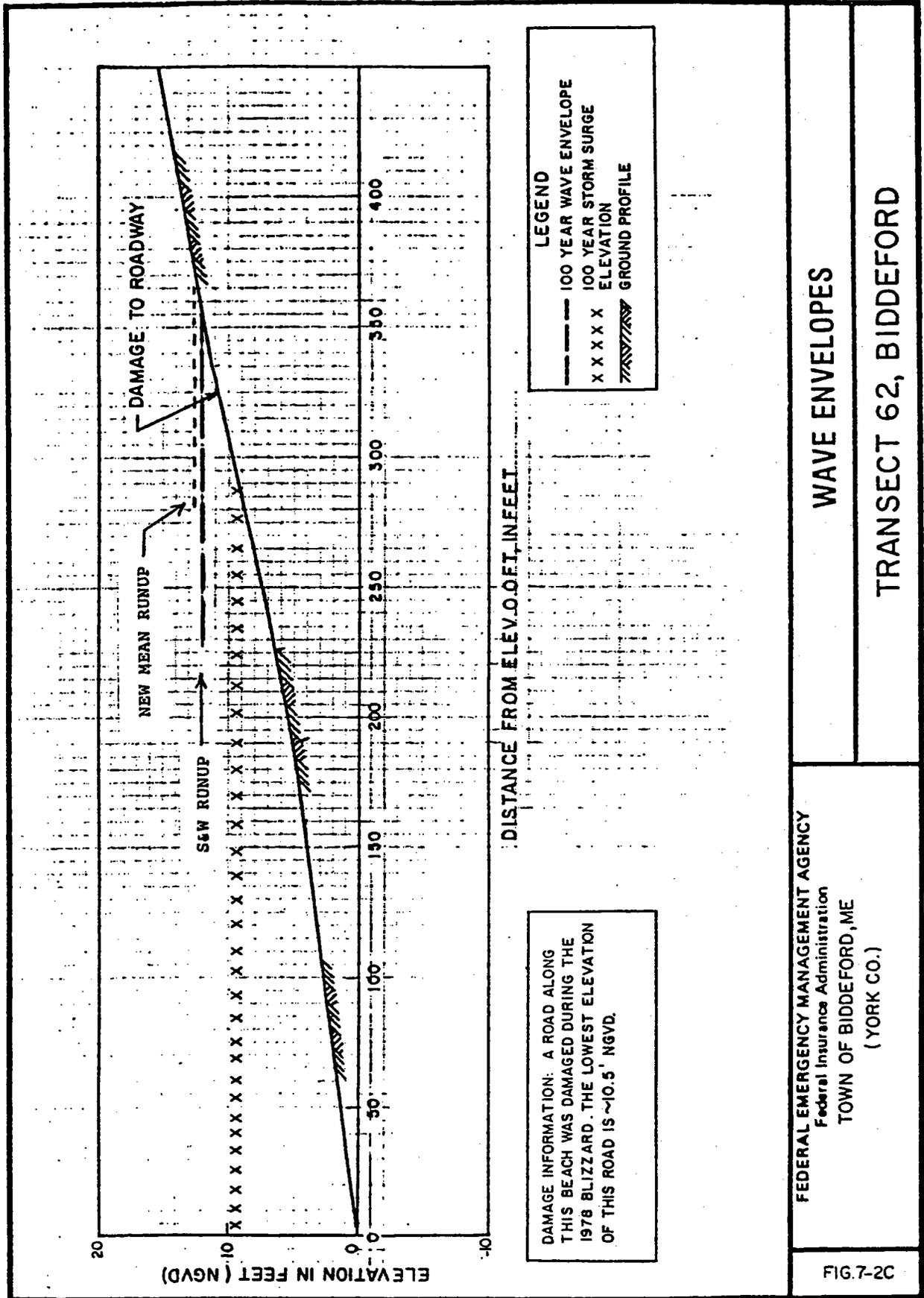
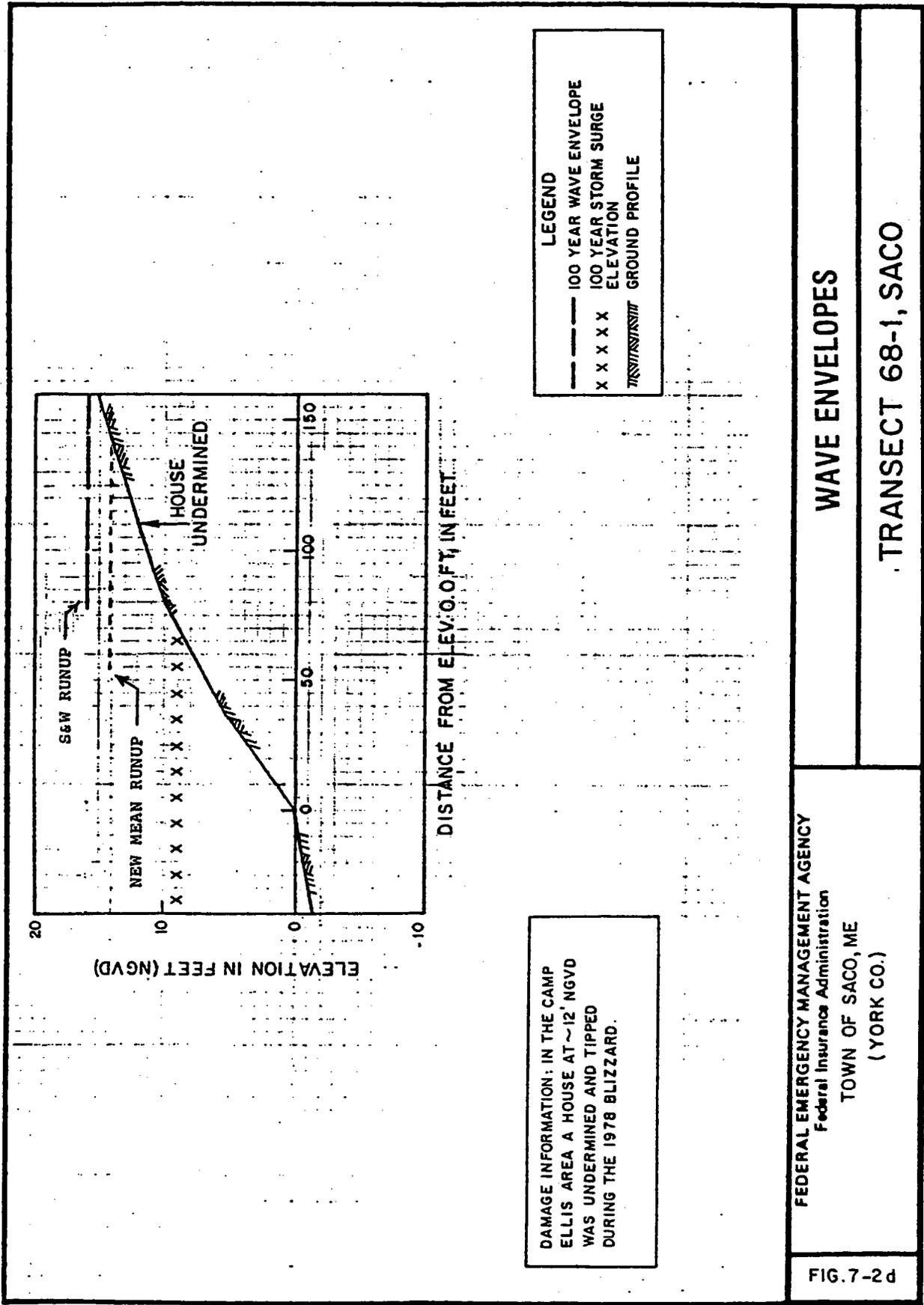


Figure 36. Model verification for historical runup damages in Maine. [3 of 4]



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

**LEGEND**  
 ——— 100 YEAR WAVE ENVELOPE  
 x x x x 100 YEAR STORM SURGE ELEVATION  
 - - - - - GROUND PROFILE

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

| <u>Mean Wave<br/>Period<br/>(sec)</u> | <u>Mean Deep-Water<br/>Wave Height<br/>(ft)</u> |
|---------------------------------------|---|
| <u>Hurricanes</u>                     |   |
| 8                                     | 12  |
| 9                                     | 15½   |
| 10                                    | 19  |
| 11                                    | 23  |
| 12                                    | 27½   |
| <u>Extratropical Storms</u>           |   |
| 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.

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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 (KITTELY)

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 (KITTELY)

RUN

PAGE 2

\*\*\*\*\*

OUTPUT TABLE

INPUT PARAMETERS

RUNUP RESULTS

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

\*\*\*\*\*

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

| INPUT PARAMETERS              |                              |                    | RUNUP RESULTS         |                    |                               |                     |
|-------------------------------|------------------------------|--------------------|-----------------------|--------------------|-------------------------------|---------------------|
| WATER LEVEL ABOVE DATUM (FT.) | DEEP WATER WAVE HEIGHT (FT.) | WAVE PERIOD (SEC.) | BREAKING SLOPE NUMBER | RUNUP SLOPE NUMBER | RUNUP ABOVE WATER LEVEL (FT.) | BREAKER DEPTH (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

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

-----  
 INPUT PARAMETERS  
 -----

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

PROJECT-STONE & WEBSTER TESTS (SACCO)

RUN

PAGE 7

\*\*\*\*\*

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

CLIENT- FEMA  
 PROJECT-STONE & WEBSTER TESTS (SACCD)

\*\* WAVE RUNUP COMPUTATIONS \*\* ENGINEERED BY

RUN PAGE B

\*\*\*\*\*

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

-----  
 INPUT PARAMETERS  
 -----

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



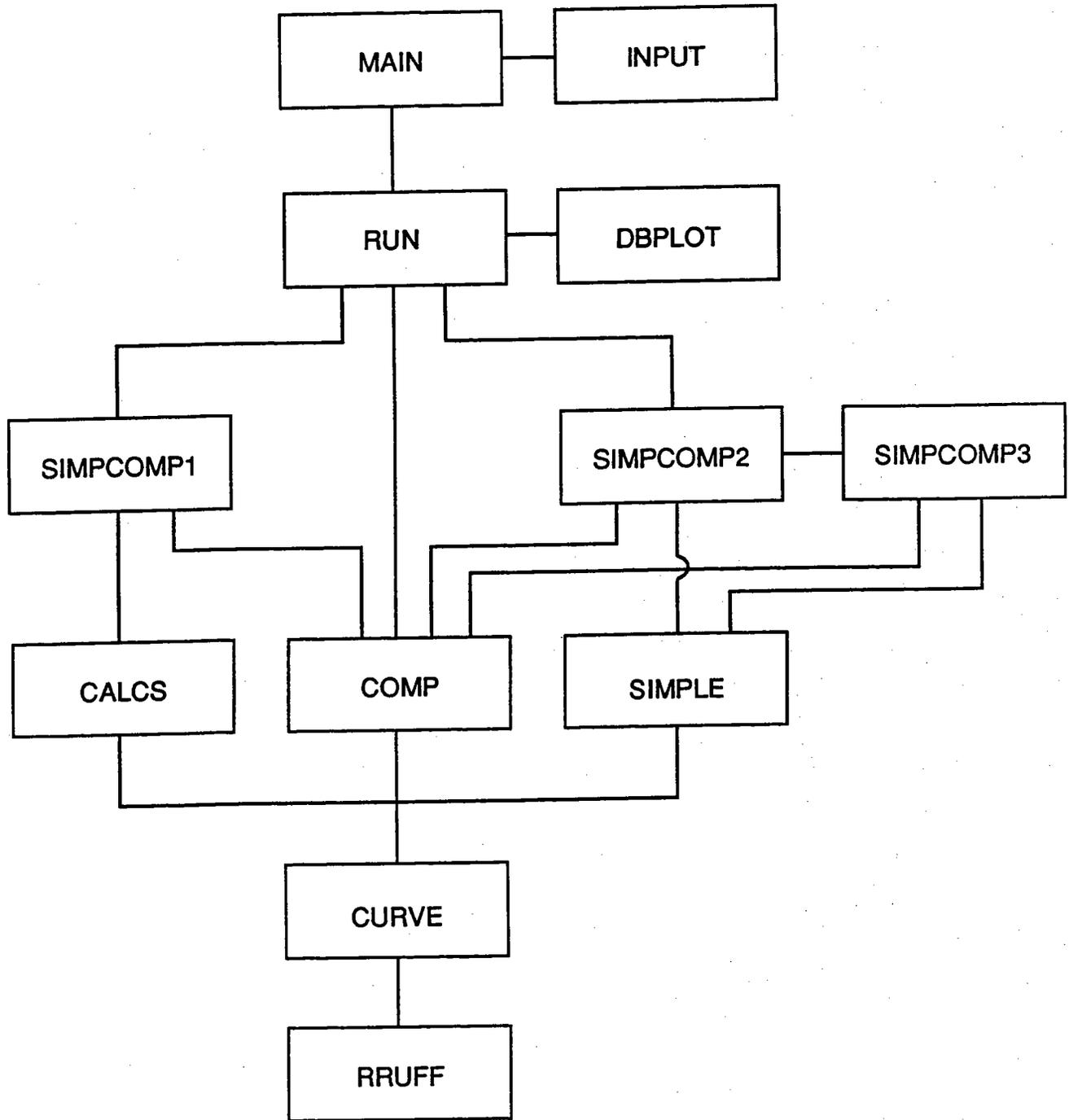


Figure B1. Additional flowcharts for upgraded Wave Runup Model:  
 b - Operation of nested computation subroutines by major  
 subroutine RUN (general utility subroutines omitted).

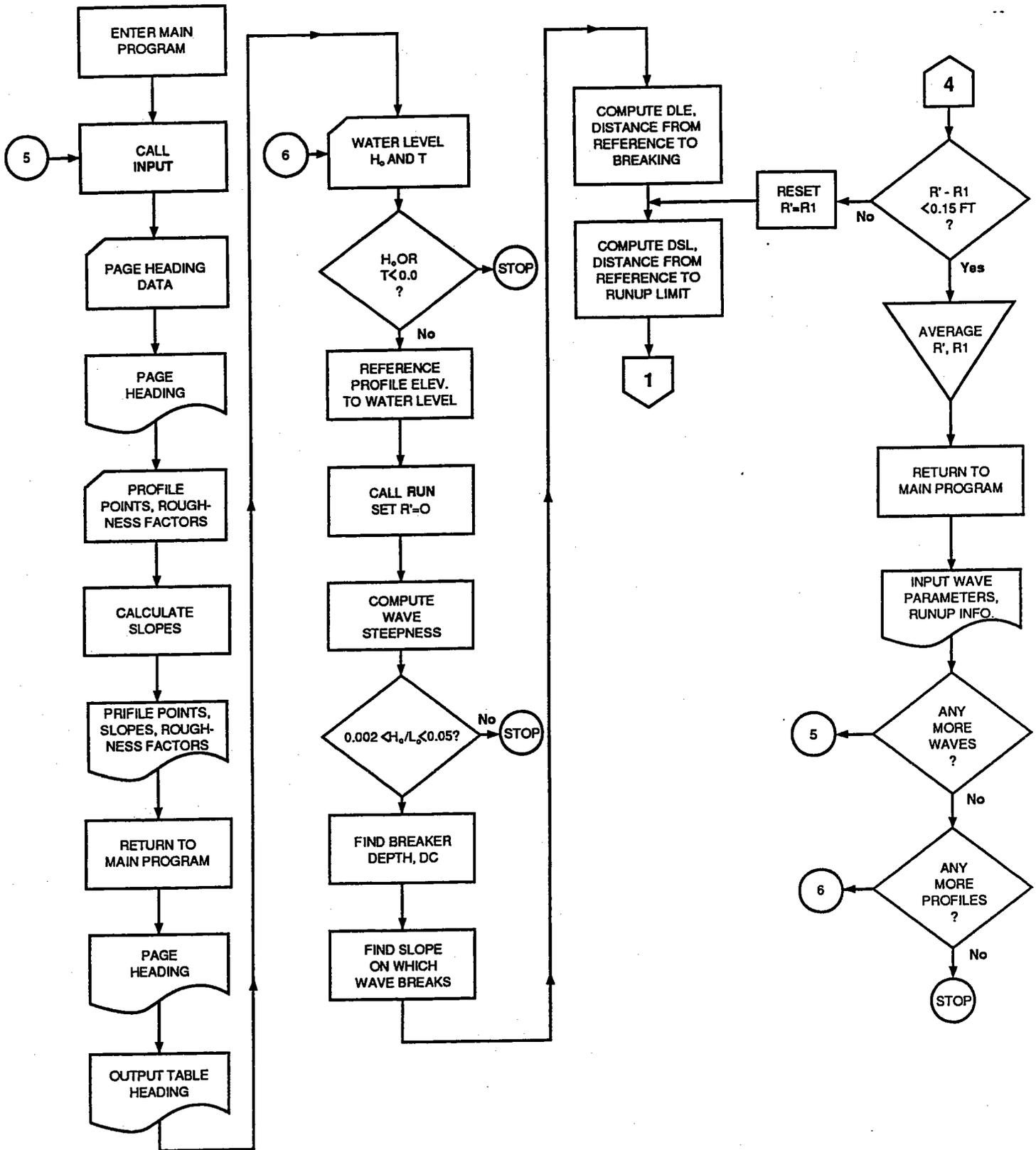
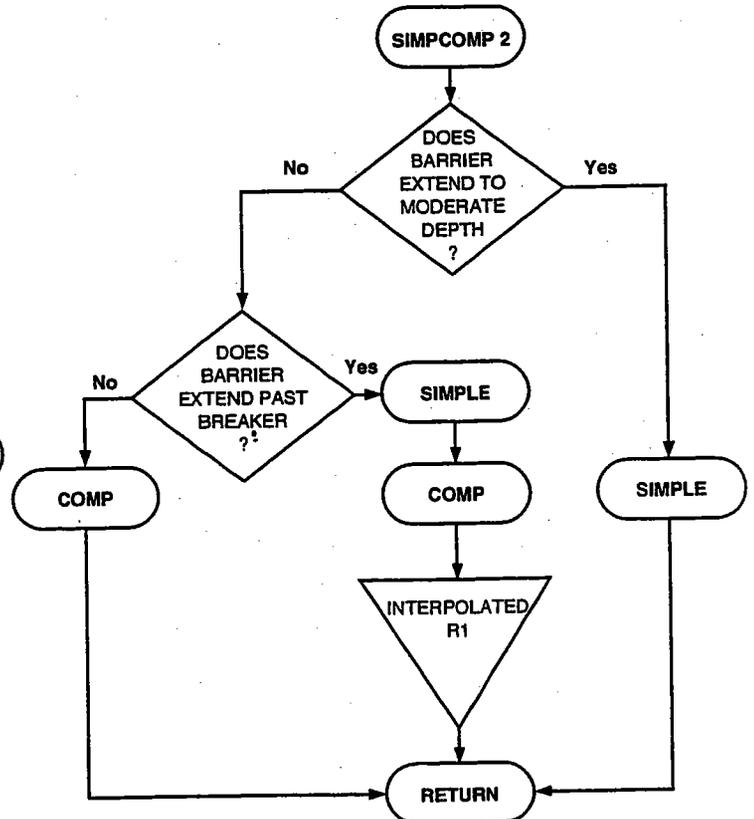
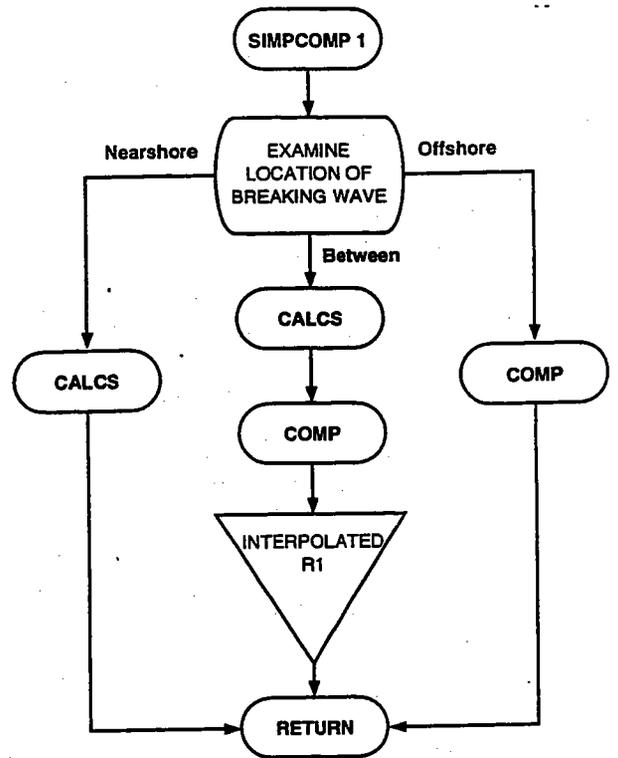
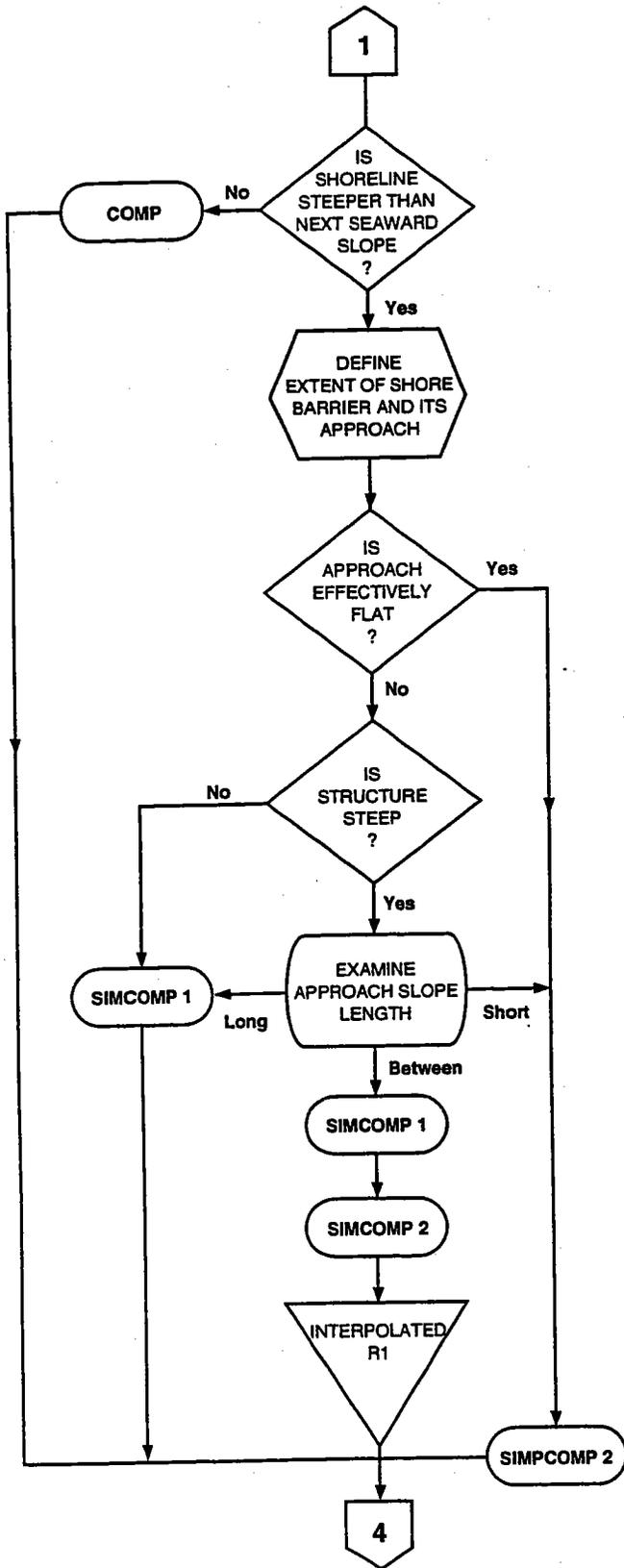
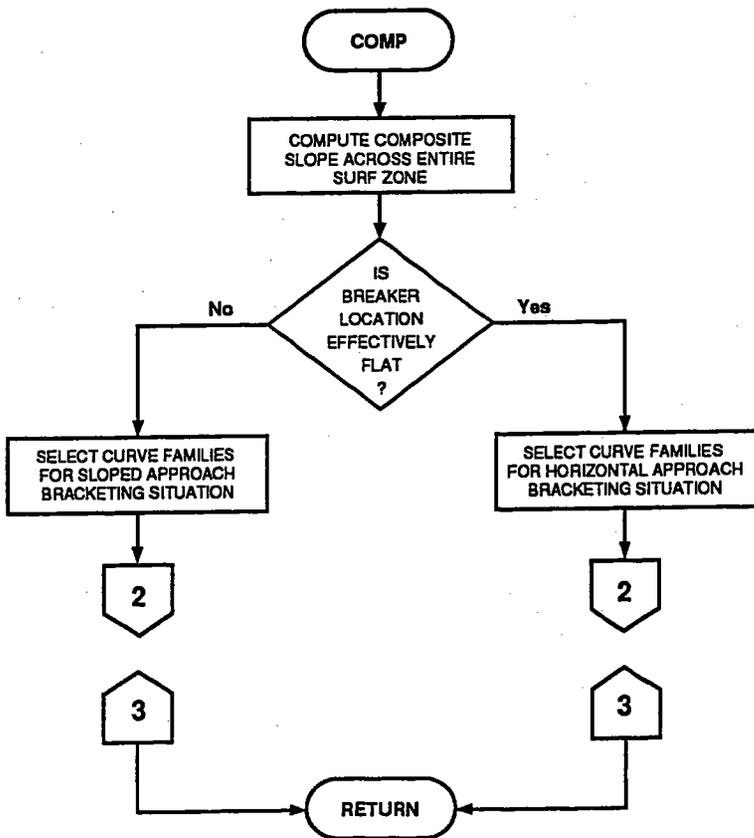
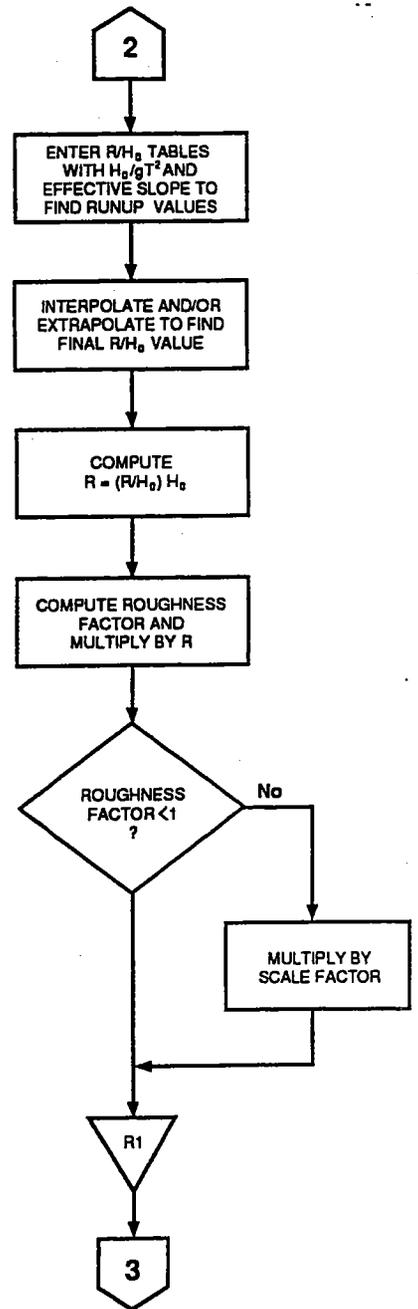
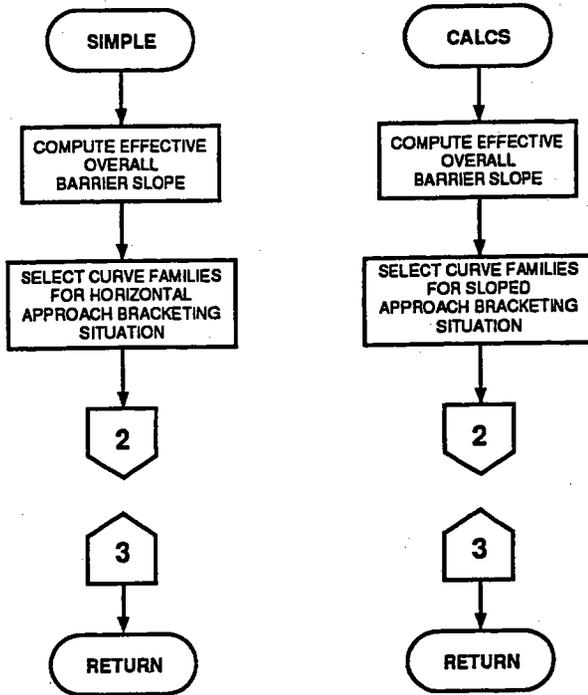


Figure B1. Additional flowcharts for upgraded Wave Runup Model: c-new version of Figure 6 showing the major steps in runup computation. [1 of 3]





C PROGRAM RUNUP--VERSION 2.0--MARCH 1990 MAIN0010  
 C THIS PROGRAM CALCULATES THE RUNUP OF WAVES ON SEGMENTED PROFILES MAIN0020  
 C

C\*\*\*\*\*VARIABLE DICTIONARY

| NAME  | MODE | SIZE | DESCRIPTION                                 | UNITS  |          |
|-------|------|------|---|--------|----------|
| DEF   | I*4  | 16   | VERT DIMENSION OF PROFILE,SEA TO LAND       | FT*100 | MAIN0060 |
| DL    | I*4  | 16   | HORIZ DIMENSION OF PROFILE,SEA TO LAND      | FT     | MAIN0070 |
| S     | R*4  | 16   | SLOPES OF PROFILE                           |        | MAIN0080 |
| NP    | I*4  | 1    | NUMBER OF POINTS IN PROFILE                 |        | MAIN0090 |
| IPAGE | I*4  | 1    | CURRENT PAGE NUMBER                         |        | MAIN0100 |
| DT    | I*4  | 118  | PAGE HEADING                                |        | MAIN0110 |
| H     | R*4  | 1    | HEIGHT OF DEEP-WATER WAVE                   | FEET   | MAIN0120 |
| T     | R*4  | 1    | PERIOD OF DEEP-WATER WAVE                   | SEC    | MAIN0130 |
| R     | R*4  | 1    | CALCULATED RUNUP                            | FEET   | MAIN0140 |
| II    | I*4  | 1    | NO. OF SLOPE ON WHICH WAVE BREAKS           |        | MAIN0150 |
| ISL   | I*4  | 1    | NO. OF SLOPE ON WHICH RUNUP LIMIT FALLS     |        | MAIN0160 |
| IFC   | I*4  | 16   | CONVERGENCE FLAGS                           |        | MAIN0170 |
| IFG   | I*4  | 16   | EXCEED TABLE FLAG                           |        | MAIN0180 |
| IFD   | I*4  | 1    | DUMMY                                       |        | MAIN0190 |
| LISL  | I*4  | 16   | TABLE OF STARTING SLOPES                    |        | MAIN0200 |
| LII   | I*4  | 16   | TABLE OF ENDING SLOPES                      |        | MAIN0210 |
| RAS   | R*4  | 16   | TABLE OF CALCULATED RUNUPS                  | FEET   | MAIN0220 |
| WTB   | R*4  | 1    | INPUT WATER LEVEL                           |        | MAIN0230 |
| WTL   | I*4  | 1    | WATER LEVEL MULTIPLIED BY 100               | FT*100 | MAIN0240 |
| W TTL | I*4  | 1    | VALUE OF WTL AT PREVIOUS STEP               | FT*100 | MAIN0250 |
| IZ    | I*4  | 1    | POINTER INTO ARRAYS OF ANSWERS AND FLAGS    |        | MAIN0260 |
| IM    | I*4  | 1    | POINTER TO MAXIMUM RUNUP                    |        | MAIN0270 |
| DA    | I*4  | 25   | ARRAY OF ERROR CODES                        |        | MAIN0280 |
| MD    |      |      | FLAG FOR VIOLATION OF WAVE STEEPNESS LIMITS |        | MAIN0290 |

C\*\*\*\*\*START OF PROGRAM MAIN0320

IMPLICIT INTEGER\*4(D,P) MAIN0330

REAL MWST,MWA,MW,MWSE,MW1,I3

REAL MS1,MS1H,MS2,MS2H

INTEGER\*4 HOT2,SLO(12),SCC(12),RS MAIN0340

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

DIMENSION DA(25)

DATA DA/' ','SO','LU','TI','ON','D','OE','S ','NO','T ','CO', MAIN0380

1'NV','ER','GE',' ','DA','TA','E','XC','EE','DE','D ','TA','BL', MAIN0390

2'E '/ MAIN0400

C \_\_\_\_\_ OPEN INPUT FILES

C CALL FILES

C \_\_\_\_\_ READ IN PROFILE MAIN0420

C 10 CALL INPUT MAIN0430

|   |          |
|---|----------|
| IJK=0   | MAIN0440 |
| WTTL=0  | MAIN0450 |
| KJ=0  | MAIN0460 |
| IPAGE =IPAGE+1  | MAIN0470 |
| WRITE(6,1100) DT,IPAGE  | MAIN0480 |
| C   |          |
| C _____ OUTPUT TABLE  | MAIN0490 |
| C   |          |
| WRITE(6,1300)   | MAIN0500 |
| 20 IF(KJ.EQ.1)GO TO 10  | MAIN0510 |
| IF(IJK.GT.0) WTTL=WTB*100   | MAIN0520 |
| READ(5,1000,END=70)KJ,WTB,HO,T  | MAIN0530 |
| MD=0  |          |
| C   |          |
| C _____ BRANCH ON NEGATIVE RUN PARAMETERS                             | MAIN0540 |
| C   |          |
| IF(HO.LE.0.OR.T.LE.0) GOTO 80   | MAIN0550 |
| WTL=WTB*100.  | MAIN0560 |
| IQ=1  | MAIN0570 |
| C   |          |
| C _____ REFERENCE PROFILE TO STILL WATER LEVEL                        | MAIN0580 |
| C   |          |
| DO 30 I=1,NP  | MAIN0590 |
| DEP(I)=DEP(I)-WTL+WTTL  | MAIN0600 |
| 30 CONTINUE   |          |
| IJK=IJK+1   | MAIN0610 |
| WTL=0   | MAIN0620 |
| CS=0  |          |
| C 40 CALL RUN(HO,T,R,II,IQ,ADC)                                       | MAIN0630 |
| 40 CALL RUN(IQ,ADC)   | MAIN0630 |
| IF (MD .EQ. 25) GOTO 20   |          |
| C   | MAIN0640 |
| IM=IQ-1   | MAIN0650 |
| IF (CS.EQ.1) WRITE (6,1700)   |          |
| IF(IFG(IQ).EQ.1) GO TO 60   | MAIN0660 |
| IF(IFC(IQ).EQ.1) GO TO 50   | MAIN0670 |
| WRITE (6,1400) WTB,HO,T,LII(IQ),LISL(IQ),RAS(IQ),ADC                  | MAIN0680 |
| GO TO 20  | MAIN0690 |
| 50 WRITE (6,1500) WTB,HO,T,LII(IQ),LISL(IQ),RAS(IM),RAS(IQ),ADC,      | MAIN0700 |
| 1 (DA(J),J=1,14)  | MAIN0710 |
| GO TO 20  | MAIN0720 |
| 60 WRITE (6,1600) WTB,HO,T,(DA(J),J=1,25)                             | MAIN0730 |
| GOTO 20   | MAIN0740 |
| 70 STOP   | MAIN0750 |
| 80 WRITE (6,1200)   | MAIN0760 |
| STOP  | MAIN0770 |
| 1000 FORMAT(I1,F5.2,12(1X,F5.2))                                      | MAIN0780 |
| 1100 FORMAT('1 ',59A2/'0',59A2,T119,I2//,60('*')////)                 | MAIN0790 |
| 1200 FORMAT(' NEGATIVE RUN PARAMETER, PROGRAM STOPS')                 | MAIN0800 |
| 1300 FORMAT(T45,'OUTPUT TABLE'/T45,6('--')////T20,'INPUT PARAMETERS', | MAIN0810 |
| 1T69,'RUNUP RESULTS',/T20,8('--'),T69,13('-')//T9,'WATER LEVEL',      | MAIN0820 |
| 2T24,'DEEP WATER',T58,'BREAKING SLOPE',T76,'RUNUP SLOPE',T91,         | MAIN0830 |
| 3'RUNUP ABOVE',T110,'BREAKER'/T9,'ABOVE DATUM',T24,'WAVE HEIGHT',     | MAIN0840 |
| 4T39,'WAVE PERIOD',T62,'NUMBER',T79,'NUMBER',T91,'WATER LEVEL',       | MAIN0850 |
| 5 T110,'DEPTH'/T12,   |          |
| 6'(FT.)',T27,'(FT.)',T42,'(SEC.)',T94,'(FT.)',T111,'(FT.)'//)         | MAIN0860 |
| 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',' ' /
      EQUIVALENCE (RDEP(1),S(1))
C                                                                    INPU0350
C                                                                    INPU0360
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,RDP
      WRITE (6,1900) I,RDL(I),RDP
      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     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

```

```

INPU0790
INPU0800
INPU0800
INPU0810
INPU0820
INPU0830
INPU0840
INPU0850
INPU0860
INPU0870
INPU0880
INPU0890
INPU0900
INPU0910
INPU0920
INPU0930
INPU0940
INPU0950
INPU0960
INPU0970
INPU0980
INPU0990
INPU1000
INPU1010
INPU1020
INPU1030

```

```

      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*****VARIABLE DICTIONARY
C     NAME  MODE  SIZE  DESCRIPTION
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*****START OF SUBROUTINE
      INTEGER*4 IV,X(1)
      L=1
      M=N
C-----CHECK TO SEE IF DATA EXCEEDS TABLE

```

```

LOOK0010
LOOK0020
LOOK0030
LOOK0040
LOOK0050
LOOK0060
LOOK0070
LOOK0080
LOOK0090
LOOK0100
LOOK0110
LOOK0120
LOOK0130
LOOK0140
LOOK0150
LOOK0160
LOOK0170
LOOK0180
LOOK0190
LOOK0200

```

|  |          |
|--|----------|
| IF(X(L).GT.IV) GOTO 30                       | LOOK0210 |
| IF(X(M)-IV)40,20,20                          | LOOK0220 |
| C  |          |
| C-----PERFORM LOOKUP                         | LOOK0230 |
| C  |          |
| 10 IF(X(M).GT.IV) GOTO 20                    | LOOK0240 |
| C  |          |
| C-----MOVE LOW POINTER UP                    | LOOK0250 |
| C  |          |
| L=M  | LOOK0260 |
| M=MO   | LOOK0270 |
| C  |          |
| C-----MOVE HI POINTER DOWN                   | LOOK0280 |
| C  |          |
| 20 MO=M                                      | LOOK0290 |
| M=(M-L)/2+L                                  | LOOK0300 |
| C  |          |
| C-----CHECK TO SEE IF DONE                   | LOOK0310 |
| C  |          |
| IF(M.NE.L) GOTO 10                           | LOOK0320 |
| IF(N.NE.M) M=L+1                             | LOOK0330 |
| RETURN                                       | LOOK0340 |
| C  |          |
| C-----DATA LESS THAN 1ST ENTRY IN TABLE      | LOOK0350 |
| C  |          |
| 30 M=1                                       | LOOK0360 |
| IFG=1  | LOOK0370 |
| RETURN                                       | LOOK0380 |
| C  |          |
| C----- DATA GREATER THAN LAST ENTRY IN TABLE | LOOK0390 |
| C  |          |
| 40 L=N                                       | LOOK0400 |
| IFG=1  | LOOK0410 |
| RETURN                                       | LOOK0420 |
| END  | LOOK0430 |

|  |          |
|--|----------|
| SUBROUTINE LOGLOG(X1,X2,Y1,Y2,X,Y)                                 | LOL00010 |
| C  | LOL00020 |
| C THIS SUBROUTINE PERFORMS A LOGLOG INTERPOLATION FOR COMPUTED     | LOL00030 |
| C VALUE X CONTAINED BETWEEN KNOWN VALUES X1 AND X2. THE OUTPUT IS  | LOL00040 |
| C THE REAL VALUE Y, WHICH IS CONTAINED BETWEEN KNOWN VALUES Y1 AND | LOL00050 |
| C Y2. INPUT VARIABLES TO THE SUBROUTINE ARE REAL. THE LOGARITHM    | LOL00060 |
| C OF EACH VARIABLE IS TAKEN IN THE SUBROUTINE.                     | LOL00070 |
| C  | LOL00080 |
| IMPLICIT INTEGER*4(X,Y)  | LOL00090 |
| RX1=X1   | LOL00100 |
| RX2=X2   | LOL00110 |
| RY1=Y1   | LOL00120 |
| RY2=Y2   | LOL00130 |
| RX=X   | LOL00140 |
| RX1=ALOG10(RX1)  | LOL00150 |

```

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

```

LOLO0160  
LOLO0170  
LOLO0180  
LOLO0190  
LOLO0200  
LOLO0210  
LOLO0220  
LOLO0230

```

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

```

LOLI0010  
LOLI0020  
LOLI0030  
LOLI0040  
LOLI0050  
LOLI0060  
LOLI0070  
LOLI0080  
LOLI0090  
LOLI0100  
LOLI0110  
LOLI0120  
LOLI0130  
LOLI0140  
LOLI0150  
LOLI0160  
LOLI0170  
LOLI0180

```

C * SUBROUTINE RUN(HO,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 *****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/HO FUNCTION OF PDB,PDB1,PCH *100

```

RUN00010  
RUN00010  
RUN00020  
RUN00030  
RUN00040  
RUN00050  
RUN00060  
RUN00070  
RUN00080  
RUN00090  
RUN00100  
RUN00110  
RUN00120

|   |         |        |  |        |          |
|---|---------|--------|--|--------|----------|
| 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  | H0/T**2  | *10000 | RUN00360 |
| C | LISL    | I*4 16 | TABLE OF STARTING SLOPES                         |        | RUN00370 |
| C | PDB1    | I*4 13 | VALUES OF H0/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 (ORIGINAL 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 |        | H0*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\*\*\*\*\*START OF SUBROUTINE\*\*\*\*\*

RUN00400  
RUN00410

```

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),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,H0
COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
COMMON /DND/ SLO,SCC,T,CS,MD
COMMON /SY/ FDB(27),FDB1(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
C      DATA SLO/ 10, 20, 40, 60, 80, 100, 140, 200, 300,
1      500, 800, 1500/
C      DATA SCC/ 1000, 1049, 1097, 1119, 1131, 1136, 1140, 1136, 1120,
1      1089, 1052, 1000/
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      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
C      IFG(IQ)=0
C      IFC(IQ)=0
C
C      WAVE STEEPNESS
C
C      HOT2=H0*10000/(T*T)+.5
C
C      COMPUTATION TO FIND BREAKING DEPTH AND SLOPE ON WHICH WAVE BREAKS
C
C      DO 10 IX=1,10
C**** IF(HB(IX).EQ.0.0) GO TO 10
C      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 SUBROUTINE DBPLOT: COMPUTE WAVE BREAKING HEIGHT AT A SLOPE FOR
C      KNOWN DEEP WATER WAVE USING GRAPHICAL RESULTS
C      INPUT H0: DEEP WATER WAVE HEIGHT
C      T: WAVE PERIOD
C      SLP: SEGMENT SLOPE (COTANGENT)

```

RUN00420

RUN00430

RUN00470

RUN00490

RUN00500

RUN00510

RUN00520

RUN00530

RUN00540

RUN00550

RUN00500

RUN00570

RUN00580

RUN00590

RUN00600

RUN00610

RUN00620

RUN00630

RUN00640

RUN00650

RUN00660

RUN00670

RUN00680

RUN00690

RUN00700

RUN00710

RUN00720

```

C
C      OUTPUT  ADC:WAVE BREAKING DEPTH
C-----
C
C
C      CALL DBPLOT(SLP,ADC)
C      IF (MD .EQ. 25) RETURN
C      DC=ADC*100.
C
C
C      DTT=WTL-DC
C      IF(DTT.LT.DEP(IX+1)) GO TO 20
C      IF(DTT.GT.DEP(NP-1)) GO TO 40
C      10 CONTINUE
C
C      WAVE CANNOT BREAK ON SLOPE BEFORE SLOPE IX
C
C      20 IF(DTT.GE.DEP(IX)) GO TO 30
C      DC=WTL-DEP(IX)
C      DTT=WTL-DC
C      30 II=IX
C      JJ=IX+1
C
C      COMPUTE DISTANCE FROM REFERENCE TO BREAKING POINT
C
C      CALL RINT(DEP(II),DEP(JJ),DL(II),DL(JJ),DTT,DLE)
C      IFD=0
C      GO TO 50
C      40 II=NP-1
C      DLE=DL(II)+((WTL-DC-DEP(II))*S(II))/100.+5
C
C      FIND FAMILY OF CURVES
C
C      50 R=0.
C      IF (H0.EQ.0.) GO TO 220
C      DH = DC/H0
C
C      LOOP UNTIL R SAME AS R1
C
C      CALL LOOK(PDB1,13,HOT2,KK,LL,IFG(I0))
C      IFD=0
C      DO 210 N=1,10
C      IFD=0
C      R10=R*100.
C      DTR=WTL+R10
C      NPP=NP-1
C
C      FIND SLOPE THAT RUNUP LIMIT INTERSECTS
C
C      DO 60 IT=1,NPP
C      IF(DTR.LT. DEP(IT)) GO TO 70
C      60 CONTINUE
C      GO TO 80
C      70 IAL=IT-1
C      ISL1=IT

```

```

RUN00730
RUN00740
RUN00750
RUN00760
RUN00770
RUN00780
RUN00790
RUN00800
RUN00810
RUN00820
RUN00830
RUN00840
RUN00850
RUN00860
RUN00870
RUN00880
RUN00890
RUN00900
RUN00910
RUN00920
RUN00930
RUN00940
RUN00950
RUN00960
RUN00970
RUN00980
RUN00990
RUN01000
RUN01010
RUN01020
RUN01030
RUN01040
RUN01050
RUN01060
RUN01070

```

```

C
C _____ COMPUTE DSL, DISTANCE FROM SEAWARD REFERENCE TO THE RUNUP LIMIT      RUN01080
C
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
C          GO TO 90                                                                RUN01150
C          80 IAL=NF-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
C          90  HOSCALE = H0*100.
C              SWL = WTB*100.
C              DO 5 I=1,MAXPTS-1
C                IF (SWL .LE. VERT(I+1)) THEN
C                  CALL SWLINT(VERT(I),VERT(I+1),HORIZ(I),HORIZ(I+1),SWL,REFSWL)
C                  GO TO 6
C                ENDIF
C          5   CONTINUE
C          6   CONTINUE
C              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
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)/H0                                                 RUN01220
C              IF (DS.LE.25) GO TO 110                                           RUN01230
C              IF (S(IAL-1).GT.30) DS=DS*100                                    RUN01240
C          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
```

```
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
C CHECK TO SEE IF NEXT SEAWARD SLOPE SHOULD BE ADDED TO
C CALCULATE THE (COT) STRUCTURE SLOPE.
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

```



```

C
C***** VARIABLE DICTIONARY ****
C
C NAME MODE SIZE
C
C SLPLEN R*4 1 DISTANCE ALONG ONE SLOPE
C ROUGH R*4 16 ROUGHNESS FACTOR ON ONE SLOPE
C FROUGH R*4 1 FINAL ROUGHNESS FACTOR FOR THE TOTAL SLOPE
C LENGTH FROM WTL TO RAS(IM)
C NM1 I*4 1 NO. OF POINTS IN THE PROFILE
C TOTLEN R*4 1 TOTAL SLOPE LENGTH FROM WTL TO RAS(IM)
C RL R*4 1 ROUGHNESS FACTOR TIMES SLOPE LENGTH
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,RE,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
COMMON /DND/ SLO,SCC,T,CS,MD

NM1=NP-1
TOTLEN=0.0
TOTRL=0.0

C
C_____ FIND SLOPE THAT STILLWATER LEVEL INTERSECTS, LI
C
IF(N.GT.1) GO TO 30
DO 10 J1=1,NM1
IF(WTL.LT.DEF(J1+1)) GO TO 20
10 CONTINUE
20 LI=J1
30 DDTR=WTL+R1*100

C
C_____ FIND SLOPE THAT RUNUP INTERSECTS, LIS
C
DO 40 J2=1,NM1
IF(DDTR.LT.DEF(J2+1)) GO TO 50
40 CONTINUE
50 LIS=J2
DO 60 K=LI,LIS

C
C_____ FIND LENGTH OF INDIVIDUAL SLOPE SECTION
C
SLPLEN=(((DEF(K+1)-DEF(K))/100.))**2+(DL(K+1)-DL(K))**2)**0.5

C
C_____ MULTIPLY SLOPE SECTION LENGTH BY ROUGHNESS FACTOR
C
RL=SLPLEN*ROUGH(K)
IF(K.EQ.LI)SLPLEN=(((DEF(LI+1)-WTL)*S(LI))/100.))**2+((DEF(LI+1)-
1 WTL)/100.))**2)**0.5
IF(K.EQ.LI) RL=SLPLEN*ROUGH(LI)

```

RUFF0050  
RUFF0060  
RUFF0070  
RUFF0080  
RUFF0090  
RUFF0100  
RUFF0110  
RUFF0120  
RUFF0130  
RUFF0140  
RUFF0150  
RUFF0160  
RUFF0170

RUFF0210  
RUFF0220  
RUFF0230

RUFF0240

RUFF0250  
RUFF0260  
RUFF0270  
RUFF0280  
RUFF0290  
RUFF0300

RUFF0310

RUFF0320  
RUFF0330  
RUFF0340  
RUFF0350  
RUFF0360

RUFF0370

RUFF0380

RUFF0390

RUFF0400  
RUFF0410  
RUFF0420  
RUFF0430

```

IF(K.EQ.LIS)SLPLEN=((R1-(DEF(LIS)/100.))*S(LIS))**2+(R1-(DEF(LIS)
1 /100.))*2)**0.5
IF(K.EQ.LIS) RL=SLPLEN*ROUGH(LIS)
C
C ADD UP SLOPE SECTION LENGTHS
C
C TOTLEN=TOTLEN+SLPLEN
C
C ADD UP (SLOPE LENGTH *ROUGHNESS FACTOR) VALUES
C
60 TOTRL=TOTRL+RL
C
C COMPUTE FINAL ROUGHNESS FACTOR
C
70 FROUGH=TOTRL/TOTLEN
RETURN
END

```

```

SUBROUTINE RINT(X1,X2,Y1,Y2,X,Y)
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)
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 I*4
C
C*****START OF SUBROUTINE
IMPLICIT INTEGER*4(X,Y)
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

```

```

SUBROUTINE SWLINT(X1,X2,Y1,Y2,X,Y)
C
C      SUBROUTINE SWLINT, CORRESPONDING 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*****START OF SUBROUTINE
      G=X2-X1
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
C
C      THIS SUBROUTINE INITIALIZES MEMORY
C
C*****VARIABLE DICTIONARY
C
C      NAME  MODE  SIZE  DESCRIPTION  UNITS  BLOC0010
C      PDB   I*4  27   VALUES OF SLOPE FOR ENTRY INTO DB  *100  BLOC0020
C      PDB1  I*4  13   VALUES OF H/T**2 FOR ENTRY INTO DB  *1000 BLOC0030
C      PCH   I*4  9    VALUES OF D/HO FOR ENTRY INTO DB  *10   BLOC0040
C      DB    I*4  2457  VALUES OF R/HO AS FUNCT. OF PDB,PDB1,PCH *100  BLOC0050
C      DB  CONSISTS OF THE DUMMY ARRAYS D101-DB07, DL1-DL3  BLOC0060
C      IPAGE I*4  1    CURRENT PAGE NUMBER  BLOC0070
C      DT    I*4  118  PAGE HEADING  BLOC0080
C
C*****START OF SUBROUTINE
      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,H0
COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
COMMON /DND/ SLO,SCC,T,CS,MD
COMMON /SY/ FDB(27),FDB1(13),PCH(9)
COMMON /SZ/ D101(180),D107(171),D201(180),D207(171),D301(180),
1 D307(171),D401(180),D407(171),D501(180),D507(171),D601(180),
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',
1 'P ','CO','MP','UT','AT','IO','NS','*','* ',4*0,'EN','GI','NE',
2 'ER','ED','B ','Y ',6*0,'JO','B ',5*0,'PR','OJ','EC','T-',46*0,
3 'RU','N ',3*0,'P','AG','E ',0/,IPAGE/0/
DATA FDB1/ 97, 193, 290, 386, 515, 611, 740, 997, 1512,
1 1995, 2509, 2992, 3989/
DATA PCH/ 0, 60, 100, 150, 300, 4000, 6000, 9000, 31000/
C
DATA FDB/ 10, 15, 20, 30, 40, 50, 60, 80, 100,
1 112, 130, 150, 170, 200, 250, 300, 350, 400,
2 450, 500, 600, 700, 800, 1000, 1500, 2000, 3000/
BLOC0200
BLOC0210
BLOC0220
BLOC0240
BLOC0250
BLOC0260
BLOC0270
BLOC0280
BLOC0290
BLOC0300
BLOC0310
BLOC0320
BLOC0330
BLOC0340

```

C FIGURE 5

```

DATA D101/ 600, 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, 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

|            |      |      |      |      |      |      |       |       |       |          |
|------------|------|------|------|------|------|------|-------|-------|-------|----------|
| DATA D201/ | 600, | 600, | 600, | 600, | 600, | 600, | 590,  | 575,  | 560,  | BLOC0350 |
| 2          | 550, | 540, | 540, | 540, | 540, | 530, | 520,  | 500,  | 490,  | BLOC0360 |
| 3          | 480, | 460, | 410, | 370, | 330, | 260, | -999, | -999, | -999, | BLOC0370 |
| 1          | 540, | 540, | 540, | 540, | 540, | 540, | 520,  | 505,  | 495,  | BLOC0380 |
| 2          | 490, | 480, | 475, | 470, | 460, | 445, | 430,  | 420,  | 410,  | BLOC0390 |
| 3          | 400, | 390, | 350, | 290, | 245, | 180, | -999, | -999, | -999, | BLOC0400 |
| 1          | 460, | 460, | 460, | 460, | 460, | 460, | 460,  | 460,  | 460,  | BLOC0410 |
| 2          | 460, | 460, | 450, | 445, | 435, | 420, | 400,  | 380,  | 360,  | BLOC0420 |
| 3          | 340, | 320, | 275, | 225, | 190, | 140, | -999, | -999, | -999, | BLOC0430 |
| 1          | 415, | 415, | 415, | 415, | 415, | 415, | 420,  | 430,  | 440,  | BLOC0440 |
| 2          | 440, | 435, | 430, | 425, | 415, | 395, | 375,  | 350,  | 325,  | BLOC0450 |
| 3          | 300, | 270, | 220, | 185, | 160, | 120, | -999, | -999, | -999, | BLOC0460 |
| 1          | 365, | 365, | 365, | 365, | 365, | 365, | 375,  | 390,  | 395,  | BLOC0470 |
| 2          | 400, | 400, | 395, | 390, | 380, | 360, | 340,  | 310,  | 280,  | BLOC0480 |
| 3          | 250, | 230, | 190, | 160, | 140, | 105, | -999, | -999, | -999, | BLOC0490 |
| 1          | 320, | 320, | 320, | 320, | 320, | 320, | 330,  | 345,  | 350,  | BLOC0500 |
| 2          | 355, | 355, | 350, | 340, | 330, | 315, | 300,  | 275,  | 245,  | BLOC0510 |
| 3          | 220, | 195, | 160, | 140, | 120, | 94,  | -999, | -999, | -999, | BLOC0520 |
| 1          | 285, | 285, | 285, | 285, | 285, | 285, | 295,  | 305,  | 320,  | BLOC0530 |
| 2          | 320, | 320, | 315, | 310, | 300, | 280, | 255,  | 235,  | 210/  | BLOC0540 |
| DATA D207/ | 185, | 165, | 140, | 120, | 105, | 82,  | -999, | -999, | -999, | BLOC0550 |
| 1          | 250, | 250, | 250, | 250, | 250, | 250, | 250,  | 255,  | 260,  | BLOC0560 |
| 2          | 265, | 265, | 260, | 260, | 245, | 230, | 210,  | 185,  | 165,  | BLOC0570 |
| 3          | 145, | 135, | 112, | 97,  | 86,  | 69,  | -999, | -999, | -999, | BLOC0580 |
| 1          | 195, | 195, | 195, | 195, | 195, | 195, | 200,  | 210,  | 220,  | BLOC0590 |
| 2          | 220, | 220, | 220, | 215, | 205, | 185, | 160,  | 140,  | 125,  | BLOC0600 |
| 3          | 110, | 103, | 88,  | 76,  | 68,  | 54,  | -999, | -999, | -999, | BLOC0610 |
| 1          | 170, | 170, | 170, | 170, | 170, | 170, | 180,  | 190,  | 195,  | BLOC0620 |
| 2          | 198, | 200, | 198, | 192, | 182, | 165, | 145,  | 125,  | 110,  | BLOC0630 |
| 3          | 98,  | 88,  | 75,  | 65,  | 57,  | 47,  | -999, | -999, | -999, | BLOC0640 |
| 1          | 155, | 155, | 155, | 155, | 155, | 155, | 165,  | 175,  | 180,  | BLOC0650 |
| 2          | 185, | 185, | 180, | 175, | 160, | 140, | 120,  | 105,  | 95,   | BLOC0660 |
| 3          | 84,  | 76,  | 65,  | 56,  | 49,  | 40,  | -999, | -999, | -999, | BLOC0670 |
| 1          | 142, | 142, | 142, | 142, | 142, | 142, | 150,  | 158,  | 165,  | BLOC0680 |
| 2          | 168, | 170, | 165, | 155, | 142, | 125, | 110,  | 96,   | 85,   | BLOC0690 |
| 3          | 75,  | 69,  | 58,  | 50,  | 43,  | 35,  | -999, | -999, | -999, | BLOC0700 |
| 1          | 120, | 120, | 120, | 120, | 120, | 120, | 130,  | 140,  | 145,  | BLOC0710 |
| 2          | 150, | 150, | 145, | 140, | 130, | 112, | 96,   | 85,   | 75,   | BLOC0720 |
| 3          | 67,  | 60,  | 51,  | 44,  | 37,  | 32,  | -999, | -999, | -999/ | BLOC0730 |
|            |      |      |      |      |      |      |       |       |       | BLOC0740 |
|            |      |      |      |      |      |      |       |       |       | BLOC0750 |

C FIGURE 9

|            |      |      |      |      |      |      |       |       |       |          |
|------------|------|------|------|------|------|------|-------|-------|-------|----------|
| 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/ |      |      |      |      |      |      |       |       |       |          |
| 1          | 200, | 180, | 150, | 125, | 110, | 84,  | -999, | -999, | -999, | BLOC0960 |
| 2          | 405, | 405, | 405, | 405, | 405, | 405, | 400,  | 395,  | 390,  | BLOC0970 |
| 3          | 385, | 375, | 365, | 345, | 320, | 280, | 250,  | 215,  | 185,  | BLOC0980 |
| 1          | 165, | 145, | 120, | 100, | 88,  | 70,  | -999, | -999, | -999, | BLOC0990 |
| 2          | 345, | 345, | 345, | 345, | 345, | 345, | 340,  | 330,  | 325,  | BLOC1000 |
| 3          | 320, | 310, | 300, | 290, | 275, | 240, | 205,  | 175,  | 150,  | BLOC1010 |
| 1          | 130, | 120, | 96,  | 80,  | 70,  | 55,  | -999, | -999, | -999, | BLOC1020 |
| 2          | 300, | 300, | 300, | 300, | 300, | 300, | 295,  | 285,  | 280,  | BLOC1030 |
| 3          | 278, | 270, | 260, | 255, | 235, | 205, | 170,  | 145,  | 125,  | BLOC1040 |
| 1          | 115, | 100, | 82,  | 70,  | 60,  | 48,  | -999, | -999, | -999, | BLOC1050 |
| 2          | 265, | 265, | 265, | 265, | 265, | 265, | 260,  | 260,  | 255,  | BLOC1060 |
| 3          | 252, | 248, | 240, | 230, | 210, | 182, | 155,  | 130,  | 115,  | BLOC1070 |
| 1          | 100, | 89,  | 72,  | 60,  | 52,  | 41,  | -999, | -999, | -999, | BLOC1080 |
| 2          | 233, | 233, | 233, | 233, | 233, | 233, | 233,  | 233,  | 233,  | BLOC1090 |
| 3          | 233, | 230, | 225, | 218, | 195, | 165, | 135,  | 115,  | 100,  | BLOC1100 |
| 1          | 88,  | 78,  | 64,  | 53,  | 46,  | 36,  | -999, | -999, | -999, | BLOC1110 |
| 2          | 203, | 203, | 203, | 203, | 203, | 203, | 203,  | 205,  | 206,  | BLOC1120 |
| 3          | 208, | 205, | 200, | 190, | 173, | 146, | 122,  | 102,  | 88,   | BLOC1130 |
| 1          | 76,  | 68,  | 56,  | 46,  | 40,  | 32,  | -999, | -999, | -999/ | BLOC1140 |
| C          |      |      |      |      |      |      |       |       |       |          |
| FIGURE 10  |      |      |      |      |      |      |       |       |       |          |
| DATA D401/ |      |      |      |      |      |      |       |       |       |          |
| 2          | 460, | 460, | 460, | 460, | 460, | 460, | 460,  | 460,  | 465,  | BLOC1160 |
| 3          | 465, | 470, | 480, | 490, | 495, | 500, | 505,  | 505,  | 495,  | BLOC1170 |
| 1          | 480, | 470, | 430, | 370, | 315, | 235, | -999, | -999, | -999, | BLOC1180 |
| 2          | 395, | 395, | 400, | 400, | 400, | 400, | 395,  | 390,  | 395,  | BLOC1190 |
| 3          | 395, | 400, | 410, | 420, | 420, | 415, | 400,  | 390,  | 375,  | BLOC1200 |
| 1          | 365, | 345, | 315, | 270, | 230, | 170, | -999, | -999, | -999, | BLOC1210 |
| 2          | 330, | 330, | 340, | 340, | 340, | 350, | 355,  | 370,  | 370,  | BLOC1220 |
| 3          | 380, | 390, | 400, | 405, | 400, | 390, | 370,  | 350,  | 330,  | BLOC1230 |
| 1          | 310, | 290, | 250, | 220, | 185, | 140, | -999, | -999, | -999, | BLOC1240 |
| 2          | 310, | 315, | 320, | 330, | 330, | 335, | 340,  | 360,  | 365,  | BLOC1250 |
| 3          | 370, | 400, | 400, | 400, | 390, | 380, | 360,  | 335,  | 310,  | BLOC1260 |
| 1          | 285, | 260, | 220, | 185, | 160, | 120, | -999, | -999, | -999, | BLOC1270 |
| 2          | 295, | 300, | 305, | 310, | 320, | 325, | 330,  | 350,  | 370,  | BLOC1280 |
| 3          | 390, | 400, | 400, | 390, | 380, | 360, | 345,  | 320,  | 295,  | BLOC1290 |
| 1          | 265, | 240, | 195, | 160, | 140, | 105, | -999, | -999, | -999, | BLOC1300 |
| 2          | 270, | 285, | 295, | 300, | 305, | 310, | 320,  | 340,  | 360,  | BLOC1310 |
| 3          | 375, | 390, | 395, | 395, | 380, | 355, | 325,  | 295,  | 265,  | BLOC1320 |
| 1          | 240, | 215, | 175, | 145, | 125, | 95,  | -999, | -999, | -999, | BLOC1330 |
| 2          | 260, | 265, | 275, | 290, | 295, | 305, | 315,  | 335,  | 360,  | BLOC1340 |
| 3          | 375, | 385, | 390, | 385, | 365, | 330, | 295,  | 265,  | 235/  | BLOC1350 |
| DATA D407/ |      |      |      |      |      |      |       |       |       |          |
| 1          | 205, | 190, | 155, | 130, | 110, | 86,  | -999, | -999, | -999, | BLOC1360 |
| 2          | 240, | 240, | 245, | 245, | 250, | 260, | 275,  | 300,  | 325,  | BLOC1370 |
| 3          | 340, | 350, | 350, | 345, | 330, | 295, | 255,  | 225,  | 200,  | BLOC1380 |
| 1          | 175, | 160, | 130, | 110, | 95,  | 74,  | -999, | -999, | -999, | BLOC1390 |
| 2          | 210, | 210, | 210, | 215, | 220, | 225, | 235,  | 255,  | 270,  | BLOC1400 |
| 3          | 280, | 280, | 280, | 275, | 265, | 235, | 200,  | 175,  | 155,  | BLOC1410 |
| 1          | 135, | 120, | 100, | 85,  | 73,  | 57,  | -999, | -999, | -999, | BLOC1420 |
| 2          | 190, | 190, | 190, | 190, | 195, | 200, | 205,  | 220,  | 240,  | BLOC1430 |
| 3          | 245, | 245, | 245, | 240, | 230, | 205, | 175,  | 150,  | 135,  | BLOC1440 |
| 1          | 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 |
|   |      |      |      |      |      |      |       |       |       | BLOC1550 |

C

FIGURE 11

|   |            |      |      |      |      |      |      |       |       |       |          |
|---|------------|------|------|------|------|------|------|-------|-------|-------|----------|
|   | 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 |
|   |            |      |      |      |      |      |      |      |      |      | BLOC2350 |
| C | FIGURE 3   |      |      |      |      |      |      |      |      |      |          |
|   | 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 |

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FIGURE 4

|            |      |      |      |      |      |      |      |      |      |          |
|------------|------|------|------|------|------|------|------|------|------|----------|
| DATA DB01/ | 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 DB07/ | 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 |

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|           |      |      |      |      |      |      |      |      |      |
|-----------|------|------|------|------|------|------|------|------|------|
| 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, 5009, 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  
C  
C  
C

SUBROUTINE DBFLOT(HO,T,SLP,ADC)  
SUBROUTINE DBFLOT(SLP,ADC)

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,H0  
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=H0/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/ FDB(27), FDB1(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  
C  
C

DETERMINE WHICH LOOKUP TABLES SHOULD BE ENTERED.

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.)

RUN01280  
RUN01290

C  
C  
C  
C  
C  
C

EXTRAPOLATE TO GET R

RUN01300

XN=ALOG10(DCS/100.)  
IF (IZ .LE. 5) GO TO 130

RUN01310  
RUN01320  
RUN01330

C

EXTRAPOLATE IN STOA TABLES 2,3,4

RUN01340

C  
C  
C  
C  
C  
C  
C  
C  
C  
C  
C  
C  
C

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

RUN01350  
RUN01360  
RUN01370  
RUN01380  
RUN01390  
RUN01400  
RUN01410  
RUN01420  
RUN01430  
RUN01440

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  
C EXTRAPOLATE IN STOA TABLES 5,8,9,10,11

RUN01460  
RUN01470

C 130 Y7K=DB(24,KK,IZ)  
C Y7K=ALOG10(Y7K)  
C Y4K=DB(21,KK,IZ)  
C Y4K=ALOG10(Y4K)  
C Y7L=DB(24,LL,IZ)  
C Y7L=ALOG10(Y7L)  
C Y4L=DB(21,LL,IZ)  
C Y4L=ALOG10(Y4L)  
C D1=10.\*\*(((Y7K-Y4K)/0.222)\*(XN-1.000)+Y7K)  
C D2=10.\*\*(((Y7L-Y4L)/0.222)\*(XN-1.000)+Y7L)

RUN01480  
RUN01490  
RUN01500  
RUN01510  
RUN01520  
RUN01530  
RUN01540  
RUN01550  
RUN01560  
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
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)
C CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH, KK, IZ),DB(JJ, KK, IZ),DCS,D11)
C CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH, LL, IZ),DB(JJ, LL, IZ),DCS,D12)
C IF (IZ .EQ. K) GO TO 155
C CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH, KK, K),DB(JJ, KK, K),DCS,D21)
C CALL LOGLOG(PDB(IH),PDB(JJ),DB(IH, LL, K),DB(JJ, LL, K),DCS,D22)
C 150 CONTINUE
C CALL LOGLOG(PDB1(KK),PDB1(LL),D11,D12,HOT2,D31)
C CALL LOGLOG(PDB1(KK),PDB1(LL),D21,D22,HOT2,D32)
C CALL RINT(PCH(IZ),PCH(K),D31,D32,DS,D3)
C GO TO 156
C 155 CONTINUE
C CALL LOGLOG(PDB1(KK),PDB1(LL),D11,D12,HOT2,D3)
C 156 CONTINUE
C R1=H0*D3/100.
C 157 CONTINUE
C R1=XF1*R11+XF2*R12
C 158 CONTINUE
C CALL RRUFF(R1,FROUGH,N)
C CALL RRUFF(FROUGH,N)
C R1=R1*FROUGH
C IF((1.0-FROUGH).GT.0.01) GO TO 180
C IF((1.0-FROUGH).GT.0.01) GO TO 200
C
C _____ SCALE EFFECT (RS)
C
C IF((DCS.LT.1500).AND.(DCS.GT.10)) GO TO 160
C RS=1000.
C GO TO 170
C 160 CALL LOOK(SLO,12,DCS,IP,IP1,IFD)
C
C _____ INTERPOLATE TO FIND SCALE EFFECT
C
C CALL LOGLIN(SLO(IP),SLO(IP1),SCC(IP),SCC(IP1),DCS,RS)
C 170 R1=R1*RS/1000.
C 200 CONTINUE
C RETURN
C END

```

RUN01590  
RUN01600

RUN01610

RUN01620

RUN01630

RUN01640

RUN01650

RUN01650

RUN01660

RUN01670

RUN01670

RUN01680

RUN01690

RUN01700

RUN01710

RUN01720

RUN01730

RUN01740

RUN01750

RUN01760

RUN01770

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)
C          REAL MWST,MWA,MW,MWSE,MW1,I2
C          REAL MS1,MS1H,MS2,MS2H
C          INTEGER*4 HOT2,SLO(12),SCC(12),RS
C          COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
C          COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NF,WTL
C          COMMON /HD/ IPAGE,DT
C          DIMENSION DT(118),RDEP(20)
C          COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
C          COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
C          COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,H0
C          COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
C          COMMON /DND/ SLO,SCC,T,CS,MD

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

```

SUBROUTINE SIMPCOMP2

```

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      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,H0
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

```

```

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

```



```
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
C
C
C
C

CALCS

SUBROUTINE CALCS---CALCULATES RUNUP FOR SIMPLE STRUCTURES USING THE
STRUCTURE SLOPE AND STOA CURVES FOR SLOPED APPROACH

```
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
C
C
C
C

USE SIMPLE RUNUP CURVES 5/8/9/10/11, BRACKETING ds/H0
AND ITERATING UNTIL CONVERGENCE.

```
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
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      RHOLD - H0/L0      (WAVE STEEPNES)                     *
C      S(II) - SLOPE (COT) AT BREAKER POINT                   *
C      CS  - FLAG REGARDING WAVE REFLECTION                     *
C      DCS - EFFECTIVE SLOPE                                  *
C*****
C
C      IMPLICIT INTEGER*4(D,P)
C      REAL MWST,MWA,MW,MWSE,MW1,I3
C      REAL MS1,MS1H,MS2,MS2H,RHOLD
C      INTEGER*4 HOT2,SLO(12),SCC(12),RS
C      COMMON /OUT/ LISL(20),LII(20),RAS(20),IFG(20),IFC(20)
C      COMMON /TD/ DEP(20),DL(20),S(20),HB(20),ROUGH(20),NP,WTL
C      COMMON /HD/ IPAGE,DT
C      DIMENSION DT(118),RDEP(20)
C      COMMON /DND/ HORIZ(20),VERT(20),WTB,MAXPTS,RDL(20)
C      COMMON /DND/ MWA(20),SA,MS1,MS1H,MS2,MS2H,DS1,DTR,DLE,DSL
C      COMMON /DND/ HOSCALE,DC,DS,II,R1,R,DCS,KK,LL,HOT2,H0
C      COMMON /DND/ RS,RB,DXLA,DXLA1,DXLA2,DXLA4,HST,MWST,HSA,SA1(20),RZ
C      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(H0/L0 < 0.195mb**2)
C
C      RHOLD=H0/(5.12*T**2)
C      RFLCT=0.195/(S(II)**2)
C      IF((RHOLD.LT.RFLCT).AND.(S(II).LT.10)) CS=1
C      IF (S(II) .LT. 15) THEN
C
C          CALCULATE RUNUP USING COMPOSITE SLOPE CURVES WITH mb 5/8/9/10
C          BRACKETING db/H0 ITERATING UNTIL RUNUP CONVERGES.
C
C          SA=S(II)
C          DS=(DC/H0)
C          DCS=(10000.*(DSL-DLE))/(DTR+DC)
C          CALL CURVE
C      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
```