CHAPTER 3

EVALUATION OF EMPIRICAL MODEL FOR WAVE RUNUP ELEVATIONS

Robert J. Hallermeier*, Kevin B. Nosek*,
Christopher J. Andrassy+

Abstract

Predicted runup elevations for given waves and nearshore profile are confirmed as accurate by large tank and field studies with over 400 published measurements, the majority exceeding 1 m above static water level. Predictions are provided by a public-domain computer code incorporating detailed empirical guidance for smooth slopes developed by Stoa (1978). This model examines the geometrical match with specified situations, applies the composite-slope method of Saville (1958) where necessary, treats barrier texture using standard runup-reduction coefficients, and executes suitable interpolation and iteration for a fully consistent runup estimate. With irregular wave action, basic empirical guidance for uniform waves gives the mean runup elevation from the mean wave description. There is definite agreement between predictions and measurements for smooth or rough barriers with uniform waves, for controlled irregular waves, and for field situations.

INTRODUCTION

Runup may define the landward limit to wave effects, defined as a vertical distance above static water level on the shore barrier. Expected runup elevations can be important in forecasts of flooding hazards due to storms and in designs of coastal structures meant to halt wave action. The improved prediction of wave runup has been

*Dewberry & Davis, METS Division, 8401 Arlington Blvd., Fairfax, Virginia 22031-4666
+Now with: Los Angeles District, U.S. Army Corps of Engineers, P.O. Box 2711, Los Angeles, CA 90053-2325

a continuing engineering concern, with progress assisted by data collection programs, analytical approaches, and developments in numerical modeling. This paper describes evaluation of a convenient prediction model implementing long-available guidance with an extremely detailed basis in laboratory runup elevations.

Measurements with breaking waves indicate that runup elevation normalized by wave height is primarily related to the value of the surf similarity parameter (ratio of the barrier slope to the square root of wave steepness). With reflecting waves, peak water elevation at the barrier is more susceptible to theoretical treatment but still has an empirically defined dependence on the type of barrier surface. Within an individual study of certain shore geometries, runup effects for a range of wave action may often be summarized by some relatively simple expression spanning the two regimes of behavior. However, runup exhibits appreciable dependences on detailed wave characteristics such as nonlinearity, and on geometrical particulars such as the seaward extent to the shore barrier and its approach slope. Thus, the most accurate runup guidance consists of empirical curves pertaining to a specific range of situations. Examples include the curve sets provided by Horikawa (1978), the U.S. Navy (1982) *Coastal Protection Design Manual*, and the U.S. Army (1984) *Shore Protection Manual*.

The detailed guidance utilized here is that originally documented by Stoa (1978), where each set of runup curves pertains to a precisely specified two-dimensional geometry at small scale. Ten distinct configurations of smooth shore barrier and approach have been addressed for wide ranges of barrier slope and wave steepness, with mean runup elevation indicated for uniform incident waves described in deep water. A computer code provides automated application of the Stoa guidance to a given situation, for an estimate of runup elevation with a definitive empirical basis.

COMPUTER CODE

In 1979, the Federal Emergency Management Agency contracted Stone & Webster Engineering Corporation to develop a consistent method for determining wave runup elevations associated with extreme storms. Such methodology was required within the National Flood Insurance Program to assess coastal wave hazards additional to stillwater inundation during the 100-year flood. The product was a computer code giving an empirically based estimate of representative runup elevation for a profile of linear segments with specified incident waves (Stone & Webster,

1981). Later tests demonstrated that the original code was liable to provide inaccurate results because of oversimplifications in following the basic guidance given by Stoa (1978). The effort reported here has consisted of an extensive upgrade to the code details, along with verification of computed results using the large data base now available.

Automated implementation of detailed runup guidance meant for manual application informed by engineering judgment has entailed the development of several objective analyses to summarize basic shore geometry. The code is fully documented in a comprehensive report on the present study (Dewberry & Davis, 1990), but Figure 1 shows a flowchart indicating the level of detail in these analyses. Each decision block relates to a separate consideration affecting runup estimation, according to basic guidance given by Stoa (1978). This suite of decision-making has required several quantitative distinctions in characterizing shape, and these choices treated shore geometries in documented runup investigations as typical. Results generally show smooth variations of runup for changed input, but the automatic analyses are not foolproof; runup estimates will be most appropriate if engineering judgment is applied in idealizing the actual profile, by taking into account the code's operations.

Initial analysis within the code effects a separation of the specified profile into a steep shore barrier, an appreciably inclined approach, and a seaward portion; for example, the designated barrier sequentially incorporates additional profile segments which do not lower the overall slope appreciably (cotangent increases less than 20%). A major distinction is whether the approach is effectively horizontal or sloped, since there are separate curve sets for these cases; an overall approach slope steeper than 1 on 15 is regarded as equivalent to the 1 on 10 specified by Stoa (1978). Other factors considered in detail are the length of the approach slope, since Stoa specified a minimum extent, and the expected breaker location, to check congruence with basic laboratory situations where waves do not break seaward of the approach.

The strategy implemented in the code is full reliance on Stoa's runup guidance where it is fully appropriate, i.e., where the situation of interest falls within the range covered by that specific guidance. In such cases, runup elevation is defined by wave dimensions along with the overall slope from barrier toe to runup limit, the water depth at the barrier toe, and the approach geometry. Where the geometrical match to tested situations is found to be inexact, some reliance is placed on the original composite-slope method of Saville (1958) with the entire

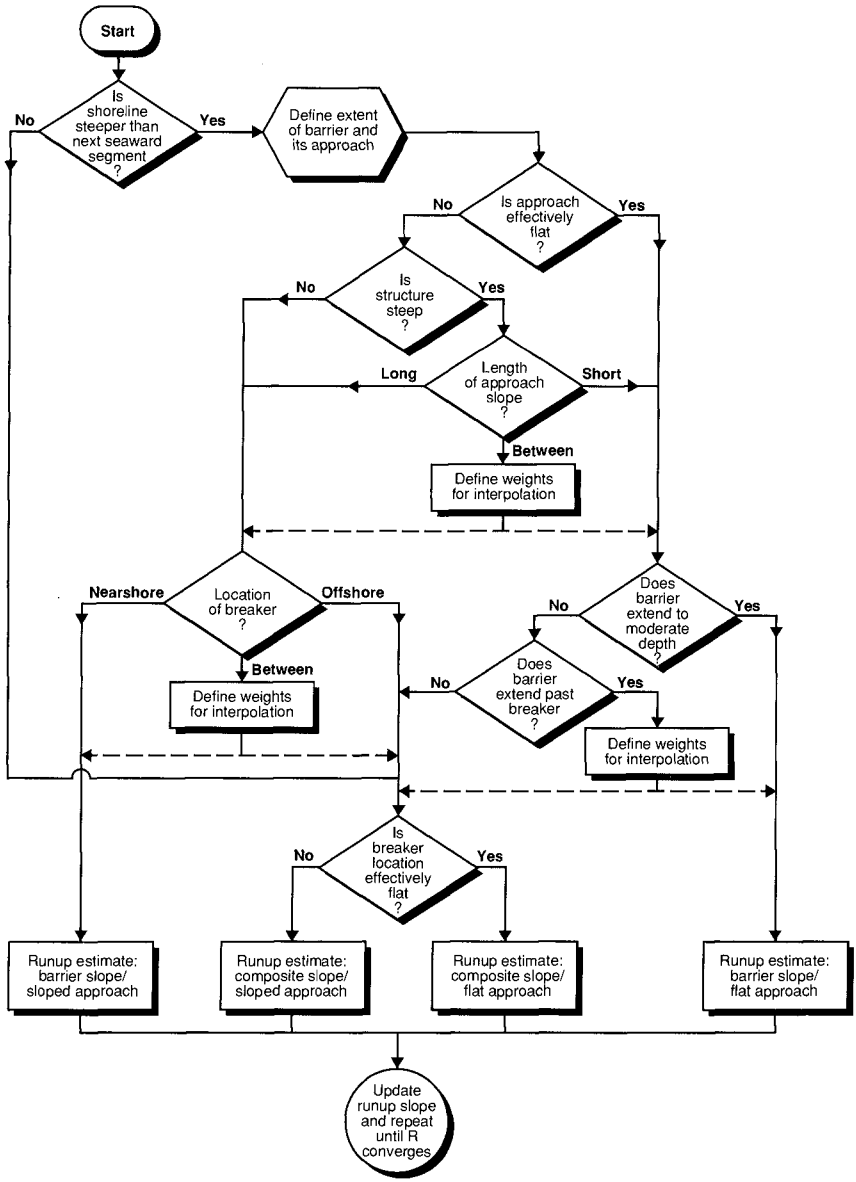

FIGURE 1. FLOWCHART OF ANALYSES WITHIN THE COMPUTER CODE.

breaker zone considered in estimating runup. Then the geometrical parameters are the overall slope from break point to runup limit, along with water depth and approach slope at the break point. The code incorporates Goda's guidance on uniform wave breaking, presented in Horikawa (1978) as normalized water depth versus wave steepness and bottom slope. An allowance for a runup scale effect on smooth slopes is applied using the multipliers proposed by Stoa (1978). Roughness and permeability of the runup surface is treated by means of usual values for a reduction coefficient (r) shown useful in considering barrier texture for wave runup and overtopping computations.

Although all might be utilized, four basic alternatives arise in runup determination: applying a barrier slope or a breaker-zone slope, and treating the approach as horizontal or inclined. The runup curves in Stoa (1978) are used in each case, but with different entry points. Transitions between these distinct computation bases provide finite ranges where runup elevation is determined by more than one viewpoint; Figure 1 indicates the various possibilities in blends of empirical results. Each contribution to the runup estimate is defined where possible by interpolation between separate curve sets bracketing the given situation. In addition, a runup elevation is extracted from an individual curve set by suitable interpolation between results originally provided in logarithmic format. The controlling slope can depend on runup limit, so the computation procedure is repeated until it converges to a self-consistent runup estimate.

For a specified profile and water level, along with wave height and period, the automatic procedure gives a runup prediction firmly based on detailed empirical guidance. Simple geometrical approximations are applied in treating the profile, and results generally reflect a blend of pertinent viewpoints in runup estimation. Computed runups are confirmed to be accurate by the following comparisons with large runup elevations measured in many studies. Data are considered in order of increasing complexity of the situations investigated.

VERIFICATION FOR UNIFORM WAVES

Figure 2 displays measurements versus computations for large tank tests with (a) smooth barriers and (b) rough structures in uniform or monochromatic wave action. These results exhibit extremely strong correlation for runup elevations typically on the order of 1 to 3 m, i.e., of common prototype magnitudes.

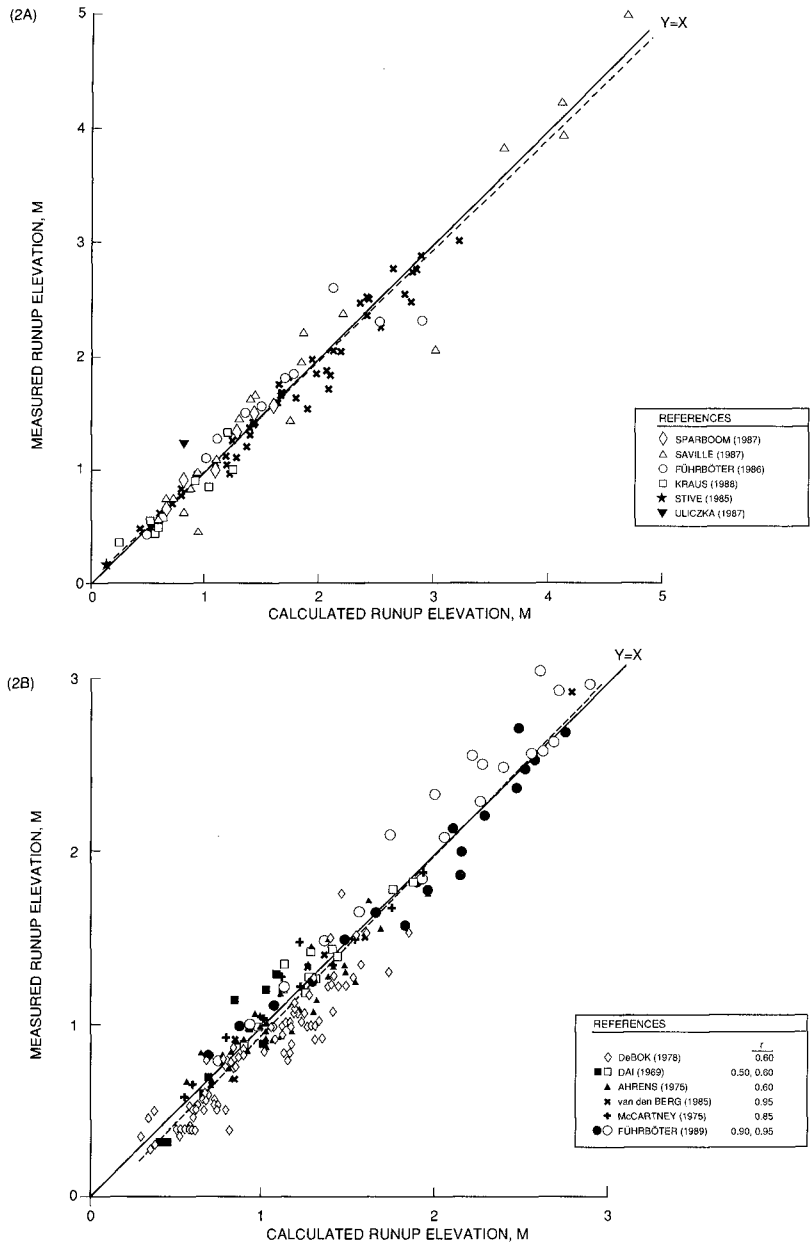

FIGURE 2. RUNUP MEASUREMENTS VERSUS PREDICTIONS FOR LARGE, UNIFORM WAVES.

For the hydraulically smooth surfaces of plywood, sand, or asphalt, almost all these 96 test situations are fully congruent with the shore configurations treated in the Stoa guidance: either a horizontal or a 1 on 10 approach to a plane barrier. Thus, the nearly ideal agreement in Figure 2a isolates the appropriateness of interpolation procedures for runup curves, along with the accuracy of scale-effect allowances up to 12% used for these barrier slopes of 1 on 3, 4, 6, 15, or 40. Differences between measurements and computations may be summarized best as random and about ±0.1 m, rather than as some percentage error. These results are for fairly simple geometries with no very steep barriers.

The results for rough structures in Figure 2b reflect more comprehensive tests of computations. Barrier cotangents are 1.5, 2, 2.5, 3, 3.5, 5, and 6, with surfaces of loose or fitted stones, quadripods, various concrete blocks, or artificial grass. Approach geometries include a notable range in tests by DeBok and Sollitt (1976). The stated r values of runup reduction relative to a smooth barrier conform to standard guidance for these roughness types. There is marked correlation between the 199 measurements and computations, but differences amount to about ±0.15 m; this is appreciable in view of the reduced runups.

Along with the greater uncertainty in runup measurements for rough, permeable structures, some of the increased error in Figure 2b is due to the often noted inaccuracy in assuming a constant r value for each given surface. Runup elevations on rough barriers are not linearly related to those on smooth slopes of similar geometry. The large data set of Ahrens (1975) clearly indicates greatest runup reductions relative to smooth slopes for collapsing breakers, with surf similarity parameter near 3 and minimum stone stability. However, other data sets do not show such notable error introduced by taking r as a constant for uniform waves and more stable structures. In addition, constant r may improve as an approximation in irregular waves, where an appreciable variation of surf similarity parameter must arise for a given case.

Addressing the actual variations in r would appear to require detailed empirical investigations, rather than use of a general expression. Since runup elevations are well defined over a broad range of smooth geometries, for some applications the convenience of taking r as constant can outweigh inaccuracies typically introduced. The evidence of Figure 2 manifests notable predictive capability for runup elevation in independent tests similar to those providing the basic guidance.

APPLICATION TO IRREGULAR WAVES

There is modest variability in runup elevations with uniform waves on a given barrier, but a greatly enlarged runup range occurs for irregular waves. The probability distributions of runup elevation must have some common value for comparable uniform and irregular wave action with a similar shore geometry. In fact, the mean runup elevation for irregular waves is predictable if mean wave condition is taken as the appropriate description to use with empirical guidance for uniform waves. This finding contradicts a runup treatment in terms of significant conditions presented in the *Shore Protection Manual*, but a recent publication (Walton et al., 1989) has described that methodology as "untested." Actually, measurements from small tests with smooth slopes of 1 on 1 through 10 (Kamphuis and Mohamed, 1978; Mase, 1989) demonstrate clearly that mean conditions provide the correct link between runup curves for uniform waves and effects in irregular wave action.

To date, only limited data have been openly published on irregular wave runups measured in large tank situations. Figure 3a compares the documented mean or median runup elevations to computed results using the mean wave description. The major data set here is that presented by Führböter et al. (1989) for 1 on 6 slope and moderate wave steepnesses with a Pierson-Moskowitz spectrum; only periods for peak wave energy were reported, and they are converted into mean wave periods using measured results for the same spectrum and steepnesses provided by Mase and Iwagaki (1984).

There is close agreement in trend here, but an apparent tendency for the 41 measurements to exceed computations. Other runup data from proprietary Delft Hydraulics tests have also been examined (Dewberry & Davis, 1990), with similar agreement between measurements and computations for additional wave conditions and barriers. All this evidence might be taken to indicate that the steady contribution to irregular runup elevation from breaking-wave setup on steep slopes is not fully represented in runup guidance for uniform waves. However, empirical results on wave runup and setup do not appear to permit a definitive judgment in view of the limited ranges of test geometries and wave conditions, and Figure 3a does not demonstrate a significant deficiency in the present runup computations.

Field data on wave runup provide the final level of complexity in variables and processes. Three sets of field measurements serve as useful examples covering a range of situations: Battjes (1971) for a 1 on 3.6 dike,

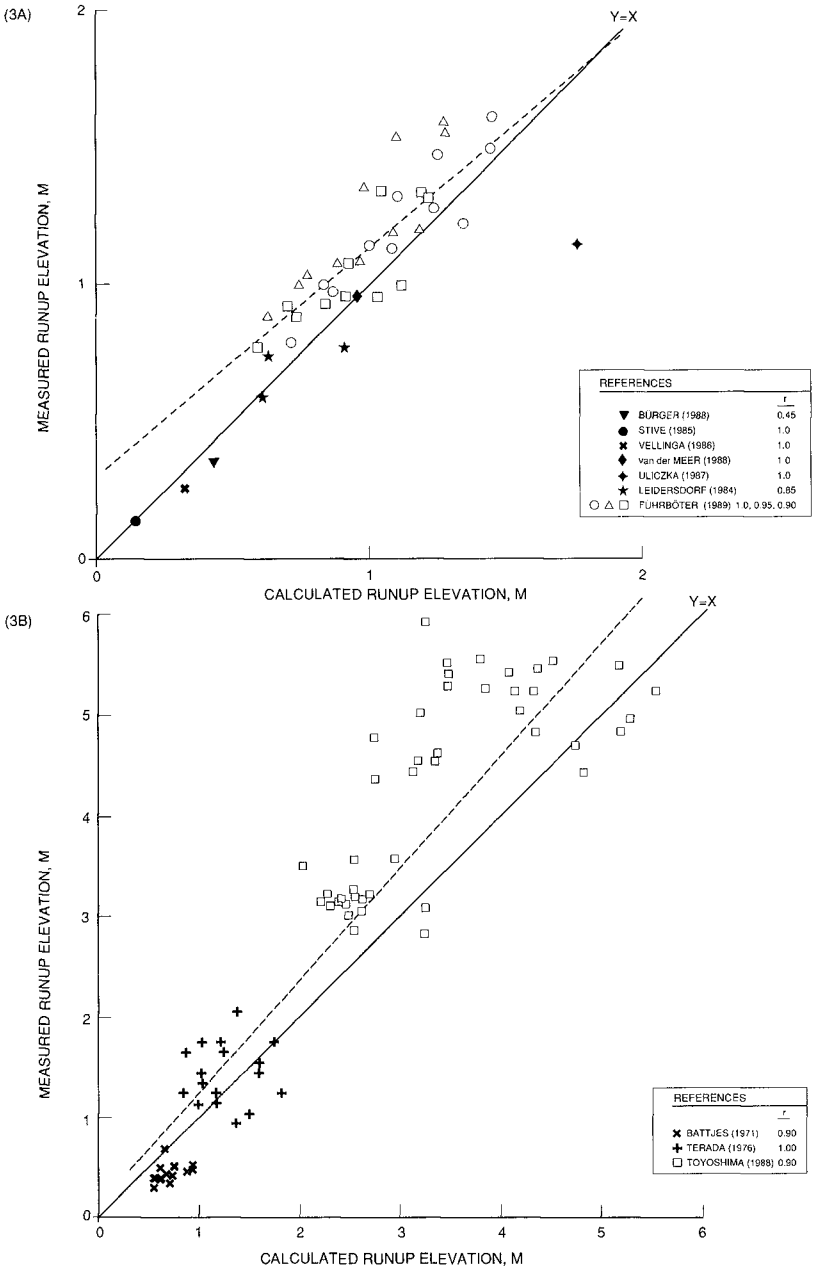

FIGURE 3. RUNUP MEASUREMENTS VERSUS PREDICTIONS FOR LARGE, IRREGULAR WAVES.

Terada (1976) for a 1 on 10 sand foreshore, and Toyoshima (1988) for a 1 on 5 seawall. Runup computations have proceeded using documented conditions in a straightforward way (Dewberry & Davis, 1990), and Figure 3b compares results to the representative elevations as reported for 76 situations. There is notable agreement in magnitudes and trend, but also sizable scatter and a marked tendency to underpredict the large runup elevations of Toyoshima (1988). Those results might be taken to corroborate the finding (Grüne, 1982) that runup elevations are increased as a direct effect of onshore storm winds. However, each of these field data sets has important shortcomings in regard to documentation.

Battjes (1971) reported winds but not waves for 7 days of measurements at two tideless lake sites. Published runup elevations are apparently with respect to mean water level at the shore, thus excluding the wave setup contribution. Presuming a moderate fetch, wave characteristics can be estimated following procedures in the *Shore Protection Manual*, and then converted to a mean wave condition in deep water; this yields a narrow range in wave steepnesses and a typical mean period of 3.5 sec, in agreement with other reported information. Terada (1976) documented deep-water wave conditions, without directions, and runup elevations relative to mean sea level, for 7 days on a Pacific Ocean beach. It is not clear what statistics were used in reported measurements. Toyoshima (1988) provided offshore wave conditions, water levels, and runup heights for 8 days of measurements at a Sea of Japan site. Wave directions are omitted, and statistical measures employed are non-standard, mixed, and somewhat extreme (beyond the significant conditions). Other information pertains to infragravity wave effects, indicated by the numbers of incident waves versus runups; however, basic variations in the numerical ratios with wave steepness are opposite findings from other field data (Holman, 1986). Finally, the total range in reported water level is 0.35 m, much less than the tidal range at the shore, so it appears that runup elevations refer to offshore not local water level.

Given these perplexing aspects in documentation, perhaps only simplified analyses are warranted for these data sets. Note that runup variations in the data of Terada (1976) and Toyoshima (1988) show definite agreement with the dependence on wave steepness given by Hunt's equation for breaking waves, although runup elevations appear magnified by about 20% above that equation in each field situation. Nevertheless, Figure 3b confirms that computed runup elevations over a very wide range are appropriate in some quantitative sense.

ADDITIONAL DISCUSSION ON APPLICATIONS

Usual applications may require a more extreme measure than the mean runup elevation predictable from the mean wave conditions. The Rayleigh distribution seems to provide an appropriate, generally conservative formulation for relating common runup elevations to those occurring only rarely in a given situation. Battjes (1971) documented field runup measurements conforming to the Rayleigh distribution at least for 0.95 to 0.05 exceedance probabilities; he concluded that a submerged berm contributed to this agreement, and expressed the expectation that runup elevations with a plane slope would extend over a narrower range than given by the Rayleigh distribution. Measured runup distributions now documented for a variety of situations all support such an effect of barrier geometry, although other factors may merit consideration in regard to conformance with the Rayleigh distribution. For example, a narrow wave energy spectrum or a sizable contribution from wave setup might act to decrease the runup range relative to the mean elevation.

The Rayleigh distribution must be expected to become inaccurate for truly extreme runup values, perhaps on the order of 0.01 exceedance probability. In addition, extrapolation from the mean elevation can require multiplication by appreciable factors, for example, 2.23 for the exceedance probability of 0.02 commonly considered. This may introduce significant magnification of usual uncertainty associated with a mean elevation prediction. Where possible, direct empirical investigation at large scale must be preferred in defining actual extreme runup elevations for a given situation. Of course, such data need not be organized using the mean wave description.

Some complications clearly require further consideration in predicting wave runup elevations for extreme storms. Several factors ignored in the present treatment seem unlikely to make an appreciable difference, viewed here as a 10% change in runup elevations; oblique incidence of waves is one such factor (Tautenhain et al., 1982), and one more is the runup scale effect on rough barriers (subsumed into chosen r values). Notable difficulties may be involved in the specification of deep-water wave conditions as input to predictions, since runup guidance is fundamentally based on incident wave characteristics at the approach to the shore barrier. Determining those waves and converting to offshore conditions may involve appreciable uncertainties in some situations. However, the most significant questions appear to require further measurements for storm conditions, to clarify effects of winds, wave setup, and infragravity motions.

CONCLUSIONS

The present computer code provides mean runup elevations based on detailed empirical guidance for uniform waves on smooth slopes (Stoa, 1978). The specified situation is analyzed to identify suitable prediction procedures, with interpolation and iteration automatically executed for a consistent runup elevation. Published data sets confirm computations of runup elevations to be usefully accurate for wide ranges of wave action and geometry. Despite the notably larger errors to be expected for increasing complex situations, appropriate magnitudes and trends demonstrate that there is no definite defect in present runup predictions.

This verification of automated computation procedures supports the model's applicability for the full coverage of incorporated runup guidance. Appreciable refinement in empirical runup predictions for steep barriers and storm waves appears to require additional data sets from large tank investigations of realistic situations and from field studies with complete documentation.

Acknowledgments. The present investigation relates to the development of upgraded methodology for predicting wave runup elevations associated with a 100-year flood, a task undertaken by Dewberry & Davis as technical evaluation contractor for the National Flood Insurance Program, Federal Insurance Administration, Federal Emergency Management Agency. However, analyses and determinations reported here represent the views of the authors alone. We wish to thank Chuck Wood of Dewberry & Davis for assistance in the code development. We also are indebted to the following individuals for help in obtaining wave runup data: J. P. Ahrens, J. H. Balsillie, H. H. Dette, S. Kielsgard, M. Klein Breteler, C. B. Leidersdorf, K. W. Pilarczyk, U. Sparboom, O. Toyoshima, and K. Uliczka.

APPENDIX - REFERENCES

Ahrens, J. P. (1975). "Large Wave Tank Tests of Riprap Stability," Technical Memorandum 51, Coastal Engineering Research Center, Fort Belvoir, VA.

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

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

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

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

DeBok, D. H., and Sollitt, C. K. (1978). "A Large Scale Model Study of Placed Stone Breakwaters," Ocean Engineering, Oregon State University, Corvallis, OR.

Dewberry & Davis (1990). "Investigation and Improvement of Capabilities of the FEMA Wave Runup Model," draft report for Federal Insurance Administration, Federal Emergency Management Agency, Fairfax, VA.

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

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

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

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

Horikawa, K. (1978). *Coastal Engineering, An Introduction to Ocean Engineering*, Wiley, New York.

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

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

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

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

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

McCartney, B. L., and Ahrens, J. P. (1975). "Stability of Gobi Block Revetment to Wave Attack," Technical Memorandum 55, Coastal Engineering Research Center, Fort Belvoir, VA.

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

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

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

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

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

Stoa, P. N. (1978). "Reanalysis of Wave Runup on Structures and Beaches," Technical Paper 78-2, Coastal Engineering Research Center, Fort Belvoir, VA.

Stone & Webster Engineering Corporation (1981). "Manual for Wave Runup Analysis, Coastal Flood Insurance Studies," Boston, MA.

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

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

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

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

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

U.S. Navy, Facilities Engineering Command (1982). *Coastal Protection*, Design Manual 26.2, Washington, D.C.

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

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