SANDBAG STABILITY AND WAVE RUNUP ON BENCH SLOPES

by

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ABSTRACT

This study was performed to investigate the effects of bench-type slopes on sandbag stability and wave runup as compared to uniform slopes and to develop preliminary design guidelines for use of a bench-type slope on sandbag retained islands.

Hydraulic model tests with scale ratios of 1:20 and 1:25, corresponding to 2 cubic-yard and 4 cubic-yard prototype sandbag sizes, respectively, were conducted on 1:3 uniform slopes using different underlayer materials and sandbag placement methods as well as nine different bench slope configurations with single layer sandbag placement. Measurements of wave runup, rundown, wave height, breaker type and sandbag response were made for each test. The uniform slope test data was first analyzed using important dimensionless parameters to establish empirical coefficients associated with sandbag stability and wave runup. The bench slope test data was then analyzed using the method proposed by Saville (1958) for predicting wave runup on composite slopes. This method was shown to be not applicable for the stability of sandbags on composite slopes. Alternatively, a modified Saville's method was proposed and shown to yield good agreement with the test results. This modified method enables us to predict the stability of armor units and wave runup on a composite slope using the results obtained from the corresponding uniform slope tests. An analysis procedure was then developed to compute the critical sandbag volume required for sandbag stability and associated wave runup for given bench configuration and characteristics of incident regular waves.

An example computation was made for a hypothetical sandbag retained island in the Southern Beaufort Sea. The bench width, the bench slope and the depth of the shallowest point on the bench are systematically varied so as to determine the optimal bench configuration for the stability of sandbags under the assumed wave conditions. The example computation indicates that a properly designed bench slope will significantly increase the stability of sandbags and reduce wave runup as compared to the corresponding uniform slope. For example, a bench slope with a 40-ft wide bench located below the design water level was found to require sandbags of approximately a quarter the size required for the corresponding uniform slope.

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NOTATION

The following symbols are used in this report. The symbols used in the appendices are explained in each appendix.

a_1 = empirical runup coefficient

a_2 = coefficient for stability number

a_3 = stability coefficient

A_b = volume of water per unit slope width inside break point below SWL for benched slope (L^2)

A_e = volume of water per unit slope width inside break point below SWL for equivalent uniform slope (L^2)

b_1 = empirical runup coefficient

b_2 = coefficient for stability number

b_3 = stability curve coefficient

B = bench width (L)

c_2 = coefficient for stability number

c_3 = stability curve coefficient

g = gravitational acceleration (L/T^2)

h = water depth on horizontal seafloor (L)

h_1 = bench depth at shallowest point of bench (L)

h_2 = bench depth at deepest point of bench (L)

h_b = water depth at the breaker point (L)

H = incident waveheight at the toe of a slope (L)

H_c = critical waveheight (L)

H_e = equivalent waveheight inside breaker point (L)

H_{ec} = critical equivalent waveheight (L)

K_D = armor unit stability coefficient

K_{Dc} = critical stability coefficient

K_{ec} = critical equivalent stability coefficient

l = alongslope length of bench (L)

L_o = deep-water wave length (L)

m = coefficient related to H_e

n = slope effect coefficient related to K_D

N_s = stability number

N_{sc} = critical stability number

N_{ec} = critical equivalent stability number

R_u = wave runup (L)

R_d = wave rundown (L)

s = specific weight of armor unit

T = wave period at the toe of a slope (T)

$\tan\theta$ = constant slope of a structure on a beach

$\tan\theta_1$ = slope of landward portion of bench slope

$\tan\theta_2$ = slope of seaward portion of bench slope

$\tan\theta_B$ = bench slope

$\tan\theta_e$ = equivalent uniform slope

V_c = critical volume of armor unit (L^3)

W = weight of an armor unit (F)

W_c = critical weight of armor unit (F)

x_b = horizontal distance to breaker point (L)

α_b = breaker index

γ = unit weight of an armor unit (F/L^3)

γ_w = unit weight of sea water (F/L^3)

ξ = surf similarity parameter

ξ_s = equivalent surf similarity parameter based on Saville's method

ξ_e = equivalent surf similarity parameter based on modified Saville's method

Note: The symbols in the parantheses show the dimension of each parameter where

F = force (lbs)

L = length (ft)

T = time (sec)

1.0 INTRODUCTION

1.1 Background

Sandbag retained islands with uniform side slopes have been built in the Southern Beaufort Sea as exploration drilling platforms. The use of sandbags as a slope protection system is advantageous in the Beaufort Sea because of the following reasons:

(1) It makes use of locally available material (sand and gravel),

(2) It requires short mobilization and construction time,

(3) It is suitable for subsequent island expansion or removal,

(4) It is of relatively low cost,

(5) It has prior construction experience in the Canadian Beaufort Sea (Prodanovic, 1979).

Because of the practical limitation of sandbag sizes, sandbag retained islands are generally regarded as temporal islands in relatively shallow water.

Analysis of matured breakwater profiles has shown that they assume a characteristic S-shape. Incorporation of this characteristic shape into the design of slopes protected with armor units may reduce the required weight of the slope protection unit. Furthermore, studies of wave runup on composite slope structures have shown that wave runup decreases as the width of a bench (or berm) is increased (Herbich, 1963). In addition, the bench slope is expected to reduce ice override by causing ice pile-up.

1.2 Objectives and Scope

The objectives of this study are to conduct experiments and quantify the effects of bench-type slopes on sandbag stability and wave runup as compared to uniform slopes and to develop preliminary design guidelines for use of a bench-type slope on sandbag retained islands.

Fig. 1 shows the bench slope configuration investigated in this study. The geometry of the bench slope may be characterized by the following parameters:

B = width of the bench

h_1 = bench depth at the shallowest point of the bench

h_2 = bench depth at the deepest point of the bench

ℓ = $[B^2 + (h_2-h_1)^2]^{1/2}$ = length of the bench

$\tan \theta_B = (h_2-h_1)/B$ = slope of the bench

$\tan \theta_1$ = slope of the landward portion of the bench slope

$\tan \theta_2$ = slope of the seaward portion of the bench slope

h = water depth on the horizontal seafloor

where all the depths are defined relative to the still water level (SWL).

For all the tests in this study the bench is located below SWL since the mild slope portion of the S-shape of matured breakwaters is located below SWL (Bruun and Johannesson, 1976). Furthermore, the present study is limited to the case where the water depth, h, is large relative to the height of incident regular waves, H, so that h has little effect on wave runup and sandbag stability. This condition is satisfied if the value of h/H is approximately greater than three (Gunbak and Bruun, 1979). Since the water depth, h, will not have very significant effects on the sandbag stability and wave runup unless incident regular waves break on the horizontal seafloor, the developed analysis procedure may be used for a preliminary design of the bench slope of a sandbag retained island located at a site where design incident waves are not limited by the design water depth at the site.

Since many parameters are involved in the problem investigated in this study, it was necessary to limit the tests to the cases of 1:3 uniform slopes ($\cot\theta = 3$ and $B = 0$) and the corresponding bench slopes with $\cot\theta_1 = \cot\theta_2 = 3$ and $\cot\theta_B = 6.1$. The bench width and the location of the bench relative to SWL together with the height and period of incident regular waves were changed systematically in the tests. Measurements were made of wave runup, wave rundown and critical wave heights for initiation of sandbag movement.

In order to generalize the test results obtained in this study, the uniform slope and bench slope test results were expressed in terms of important dimensionless parameters. Comparing the normalized results for the uniform slope and bench slope tests, a hypothesis of an equivalent uniform slope has been developed by modifying the method proposed by Saville (1958) for wave runup on composite slopes. This hypothesis enables us to predict the sandbag stability and wave runup on a bench slope with arbitrary configuration for given incident regular waves on the basis of the test results for the corresponding uniform slope. Using the hypothesis and the test results obtained in this study, a computer program has been developed so as to facilitate a preliminary design of a bench slope. Calculations are made for an example sandbag retained island with various bench configurations in the Southern Beaufort Sea.

1.3 Report Organization

The report contains six sections and six appendices.

Section 2 explains all the experimental procedures. The prototype conditions and appropriate scaling relationships are described, leading to the required model conditions. The laboratory equipment and instrumentation used in the tests are described including construction of the model sandbags. Both uniform and benched slope test procedures are discussed.

The results of the uniform slope tests are presented in Section 3. The normalized runup and rundown and the stability number are plotted as a function of the surf similarity parameter (Battjes, 1974) for different underlayers and placement methods. Most of the uniform slope tests were conducted for a single layer of sandbags placed end to end and side by side with the longitudinal axis of the bag parallel to the 1:3 uniform slope. The underlayer beneath the longitudinally-placed, single layer sandbag was comprised of quartz sand, pea gravel, impermeable backing or coconut hair. In addition, some of the uniform slope tests were conducted for the model sandbags placed in a 50% overlap fashion. This overlap placement requires approximately twice as many sandbags.

The results of the bench slope tests were analyzed using the hypothesis of an equivalent uniform slope and presented in Section 4. All the bench slope tests were conducted for the longitudinally-placed, single layer sandbag with a coconut hair underlayer. The coconut hair underlayer was found convenient for the speedy alteration of bench slope configurations. Comparison of the uniform and bench slope test results for the longitudinally-placed, single layer sandbag with the coconut hair underlayer indicates that the equivalent uniform slope hypothesis yields good agreement with the test results. This comparison may hence be regarded to be a justification of the hypothesis.

Section 5 presents an analysis procedure based on the uniform test results and the equivalent uniform slope hypothesis for a preliminary design of a bench slope with given underlayer material and sandbag placement. Considerations are also given to possible scale effects. Calculations for a typical sandbag retained island are made to illustrate the increase of sandbag stability and the decrease of wave runup resulting from various bench configurations.

The conclusions of this study and the recommendations of future studies are given in Section 6.

Appendix A explains the computer program developed for the analysis of irregular wave overtopping on gravel islands with uniform side slopes. This program is based on the mathematical model developed by Kobayashi and Reece (1983). Appendices B and C describe the computer programs for calculating armor unit stability under regular wave action. These programs are based on the mathematical model developed by Kobayashi and Jacobs (1983). Appendices A, B and C may not be directly related to the present study but may be useful for the design of gravel islands.

Appendix D presents a chronological listing of all the measured data including a description of test setups. The measured data may be used for a site-specific design of a bench slope if the prototype conditions are similar to the model conditions. Appendix E describes the data for 1:3 uniform slope tests with the 50% overlap placement of sandbags. Appendix F gives the computer program based on the equivalent uniform slope hypothesis discussed in Section 5.

2.0 EXPERIMENTAL PROCEDURES

2.1 Scale Relationships and Prototype Conditions

In modeling the effects of waves on coastal structures, the predominant forces to consider are inertia and gravity forces. Effects due to viscosity and surface tension are negligible as long as the model is not too small. Consequently, Froude similitude together with geometric and kinematic similitudes are usually employed for physical modeling of wave effects on coastal structures.

Geometric similitude requires

$$L_m = L_r L_p \tag{1}$$

where L is the characteristic length and the subscripts m and p indicate model and prototype values, respectively, and the subscript r indicates the model-to-prototype ratio. Kinematic similitude together with geometric similitude requires

$$T_m = T_r T_p \tag{2}$$

where T is the characteristic time. On the other hand, Froude similitude requires

$$T_r = \sqrt{L_r} \tag{3}$$

where $g_r = 1$ with g being the gravitational acceleration.

Modeling of the stability of sandbags requires that the ratio of the hydrodynamic force acting on a sandbag to the weight of a sandbag must be the same for the model and the prototype. The saturated surface dry weight of a sandbag is usually used for calculation of the required sandbag weight applying Hudson's formula (Prodanovic, 1979). This tacitly assumes that the sandbag dislodged under the wave action is fully submerged and saturated with water. The tests conducted in this study justify this assumption since the movement of sandbags generally occurred near the still water line below SWL. Use is hence made of the saturated surface dry weight of a sandbag, W. The unit weight of the sandbag, γ, is given by $\gamma = W/V$ where V is the volume of the sandbag. The specific weight of the sandbag may be defined as $s = \gamma/\gamma_w$ where γ_w is the unit weight of water. Modeling of the sandbag stability under the wave action requires that $s_r = s_m/s_p = 1$. Since model testing was performed in freshwater ($\gamma_w \simeq 62.4$ pcf) and the prototype bag system would be located in saltwater ($\gamma_w \simeq 64.0$ pcf), the following relationship between model and prototype sandbag unit weight was used;

$$\gamma_r = \frac{\gamma_m}{\gamma_p} = \frac{(\gamma_w)_m}{(\gamma_w)_p} = \frac{62.4}{64.0} = 0.975 \qquad (4)$$

Prototype sandbag sizes frequently used for slope protection of exploration islands include 2-cubic yard and 4-cubic yard sandbags. The length-to-width ratio of an unfilled bag is approximately 2 to 1. The unit weight of a prototype bag usually ranges from 112 pcf to 120 pcf.

Considering the similitude requirements and the capacity limitations of the laboratory facilities, the model-to-prototype length ratios of $L_r = 1/20$ and $L_r = 1/25$ were chosen to model 2-cubic yard and 4-cubic yard prototype sandbags, respectively. These scale relationships require a model sandbag whose volume is approximately 12-cubic inches. Using Eq. (3), the time ratio $T_r = T_m/T_p$ is $T_r = 1/4.5$ for $L_r = 1/20$ and $T_r = 1/5.0$ for $L_r = 1/25$. These scale relationships can be used to obtain the prototype conditions corresponding to the model conditions tested in this study. The model tests cover the range of the design conditions expected in the Southern Beaufort Sea.

2.2 Model Sandbags

In order to simulate the characteristics of the prototype sandbag, an attempt was made to fabricate the model bags from a material of similar quality as that used in the prototype. Using a polymide material donated by the Nicolon Corporation, ten model bags were constructed to see if the bag characteristics requirements were satisfied. It was found that the weave of the polymide material allowed leakage of the 0.1 mm to 0.2 mm sand used in the model bags. In addition, fabrication of the model bags proved to be time consuming as they had to be individually sewn. Alternatively, Hubco Protexo Oil Well Sand Sample Bags of size 3 1/2" x 5" were purchased. The Hubco Sample Bag is constructed of a fine weave cloth and allowed no leakage of the sand. Analysis of the filled Hubco model bags resulted in the model sandbags characterized by the average volume = 12 in^3 with the range in volume from 10.9 in^3 to 13.2 in^3 and the average unit weight = 119 pcf with the range in unit weight from 106 pcf to 122 pcf. Although the shape of the model sandbags is not exactly similar to that of the prototype, the model bags are believed to be similar enough to conduct a comparative study on the stability of sandbags on uniform and bench slopes.

2.3 Laboratory Equipment and Instrumentation

The tests were conducted in the University of Delaware's 80-feet by 2-feet by 4.5-feet wave flume located in the Ocean Engineering Laboratory. The waves were produced with a piston type wave paddle. The wave paddle was driven by a Reeves 7.5 H.P. constant speed motor with variable speed transmission. The amplitude of the paddle stroke was controlled by means of an adjustable eccentric cam. Wave heights were measured by means of a resistance wire wavestaff system and also by visual observation off the glass wall of the flume. Measurements of the incident waves were taken at three locations, at the toe of the structure and two locations offshore, in order to account for the effects of wave reflection from the test slope. The wave heights were recorded by means of a Hewlitt-Packard script chart recorder and reduced to voltages. Simultaneously, voltages were being recorded on a Fluke Digital Multimeter voltmeter. Wave runup and rundown were measured by visual observation off the glass wall of the tank. In this study, wave runup was defined as the vertical height above SWL reached by the uprushing body of water neglecting splash whereas wave rundown was defined as the uppermost vertical elevation relative to SWL reached by the downrushing body of water. The measurement of wave rundown was found difficult and less accurate than that of wave runup. The definition of the critical wave height for initiation of sandbag movement is given in Section 2.4.

2.4 Model Wave Periods and Heights

For each slope configuration, series of tests were run using seven model wave periods: 1.0 sec, 1.2 sec , 1.4 sec, 1.6 sec, 1.8 sec, 2.0 sec, and 2.2 sec. The wave periods were set by adjusting the variable speed pulley and checked by a digital stopwatch. For each wave period, several test runs were made beginning with small (less than 5 cm) wave heights until the incremental increase of wave heights resulted in removal of sandbag units from the primary protection layer. Wave heights were increased by increasing the eccentricity of the cam. The maximum wave height used in these tests was 19 cm.

Each test run was allowed to continue until the effects of re-reflected waves from the wavemaker became apparent at the test slope. The wave height, runup, rundown, and breaker type and location were measured for each run. Once movement of the sandbags became significant, a train of waves consisting of approximately 20 waves was sent in bursts in order to maintain uniformity in description of the critical condition and minimize effects of wave reflection from the wavemaker.

Initial movement of the sandbags appeared as vertical rocking (uplift) near the incipient breaking point of the incoming wave. The intensity of rocking (uplift) would increase with increasing wave height to a situation where the longitudinal axis of the bags would rotate from being parallel to the slope to being perpendicular to the slope. The wave height at which this bag rotation occurred is defined as the critical wave height for initiation of movement of sandbags in the primary protection layer. Further increase of wave height resulted in bags rolling downslope under the action of wave downrush.

2.5 Uniform Slope Tests

The base of the slope structure for all testing was a 1:3 plane wooden slope supported by a steel frame. The underlayer material and filter cloth were laid on this wooden slope and the sandbags were hand-placed in a single layer thickness with their longitudinal axis parallel to the slope (see photograph 1). The tank was then filled to a water depth of 36.6 cm.

Several test series were run on the uniform 1:3 slope using a variety of underlayer materials. Although it was not within the intent of this study to model permeability, it was found to have a significant effect on the response of the sandbag units. Initially 0.2 mm sand was used as underlayer material. However, piping of the sand along the glass wall occurred during the downrush of the larger waves and caused deformation of the slope. Instead, a layer of 1/4" pea gravel was used as the underlayer. This worked very well except that it was difficult to change slope configurations and maintain consistent underlayer thickness. In the course of a search for a better underlayer material, an impermeable backing was tried as this would require the minimum effort to change slope configurations. However, the bag response to the wave action was found to be different from that on a permeable slope. The sandbag movement was observed to be controlled by wave uprush instead of wave downrush and significantly larger wave heights, often larger than wavestaff recorder limits, were required to initiate the movement of sandbags on the impermeable slope. In an effort to find an underlayer material that was reasonably permeable yet easily workable, pressed coconut hair, often used as wave absorbers in flume studies, was tested. A layer of 2-inch thickness was used so that compression of the underlayer under the weight of the sandbags would be minimal. The bag response using the pressed coconut hair as the underlayer was found to be very similar to that associated with the sand and gravel underlayers. The coconut hair underlayer was used for the rest of the tests in this study.

In addition to the longitudinally-placed, single layer sandbag tests, 1:3 uniform slope tests were conducted with the model sandbags placed in a 50% overlap fashion. The 50% overlap placement of sandbags has been used as the slope protection system of a sandbag retained island in the Southern Beaufort Sea. This placement of sandbags is believed to increase the stability of sandbags under wave action although it requires more sandbags. An alternative to increase the stability of sandbags may be to use a bench slope. Site-specific considerations will be required to determine the best alternative.

2.6 Bench Slope Tests

The base of the bench slopes used in the model consisted of a series of wooden sections of 0.8-feet (3 bag length) by 2-feet, each being connected by hinges. The unit was attached at one end by a hinge to the 1:3 base slope used for the uniform slope tests at a 38.5 cm elevation above the bottom of the tank and extended down the flume according to the specified bench configuration. This made it easy to change bench length as well as bench slope. The bench unit was kept stable by means of threaded steel rods which screwed into each wooden section of the bench unit and firmly attached to the top of the wave flume.

Once the bench configuration was set, the pressed coconut hair was laid as the underlayer and the sandbags were hand-placed in a single layer with their longitudinal axis parallel to the slope (see photograph 3).

The depths h_1 and h_2 on the bench as shown in Fig. 1 were controlled by changing the water depth in the flume. In all, nine different bench configurations were tested. Three bench lengths, of three bag length, six bag length, and nine bag length, were tested in order to observe any trend with the bench length. For each bench length three water depths on the bench were tested in order to observe any trend with the bench depth. The depth h_1 ranged from 0 cm to 8 cm for each bench length and the depth h_2 ranged from 4 cm to 20 cm depending on the bench length. The bench slope, $\cot\theta_B$, was kept constant at $\cot\theta_B = 6.1$. A detailed description of bench slope configurations is given in Appendix D.

3.0 UNIFORM SLOPE TEST RESULTS

The uniform slope data on wave runup, wave rundown, sandbag stability tabulated in Appendix D is analyzed to establish a baseline to which the bench slope data will be compared in Section 4.

3.1 Wave Runup

A number of studies have shown that the surf similarity parameter, ξ, also called the Iribarren number, is a convenient dimensionless parameter for describing wave breaking phenomena and resulting wave action (Iribarren and Nogales, 1949; Bowen, Inman and Simmons, 1968; Battjes, 1974; and Ahrens and McCartney, 1975). The surf similarity parameter is defined by

$$\xi = \frac{\tan\theta}{\sqrt{H/L_o}} \tag{5}$$

in which $\tan\theta$ is the constant slope of a structure or a beach, H is the height of incoming waves at the toe of the structure, and L_o is the deep-water wave length given by

$$L_o = \frac{gT^2}{2\pi} \tag{6}$$

where T is the wave period and g is the gravitational acceleration.

Ahrens, et al. (1975), based on large scale tests on quarrystone riprap, proposed a runup relationship of the form

$$\frac{R_u}{H} = \frac{a_1\xi}{1 + b_1\xi} \tag{7}$$

where a_1 and b_1 are empirical coefficients, and R_u is the runup height measured vertically above SWL. Eq. (7) with $a_1 = 1.13$ and $b_1 = 0.506$ was found to fit the data well for quarrystone riprap.

Figs. 2 through 6 present the measured values of R_u/H as a function of the surf similarity parameter, ξ, for the different underlayer materials and placement methods used during the uniform slope testing. The runup relationship given by Eq. (7) with the coefficients a_1 and b_1 found by a curve-fitting analysis is also shown for each of the figures. R_u/H increases as ξ is increased. The values of a_1 and b_1 obtained for the different uniform slope setups are summarized in Table 1. Usage of Table 1 will be discussed in Section 5 which presents an analysis procedure based on the uniform slope test results and the equivalent uniform slope hypothesis for a preliminary design of a bench slope with given underlayer material and sandbag placement.

3.2 Wave Rundown

Wave rundown is defined as the uppermost vertical limit relative to SWL of the downrushing body of water. R_d denotes wave rundown and is positive if wave rundown is above SWL. The measured values of R_d/H are plotted in terms of the surf similarity parameter, ξ, in Figs. 7 through 11 for the different uniform slope setups. R_d/H decreases as ξ is increased. It should be mentioned that the measurement of wave rundown was difficult due to the outflow of water from the underlayer material during wave downrush. This may have caused some of the scatter of the rundown data in these figures.

3.3 Sandbag Stability

Hudson (1958), through an inspectional analysis, developed an empirical relationship for the stability of a primary armor unit on a slope under wave action. The relationship is still widely used for its convenience although it does not account for all the important factors involved in the stability of an armor unit (Shore Protection Manual, 1977). The present analysis follows the work by Ahrens (1975) who improved the relationship proposed by Hudson (1958).

The forces acting on an armor unit were analyzed by Kobayashi and Jacobs (1983). The wave forces acting on an armor unit may be separated into the drag, inertia and lift forces. The drag force is normally dominant and may be regarded as the dislodging force acting on the unit whereas the submerged weight of the unit resists the wave action. The ratio of the dislodging force to the submerged weight may be expressed in terms of the stability number defined by

$$N_s = \frac{H}{(W/\gamma)^{1/3}(s-1)} \tag{8}$$

where W and γ are the weight and the unit weight of the armor unit, respectively, and $s = \gamma/\gamma_w$ with γ_w being the unit weight of water. The value of N_s in Eq. (8) depends on the wave height measured for a specified criterion of armor movement.

The stability number N_s defined by Eq. (8) does not account for the slope effect on the stability of an armor unit. The stability coefficient, K_D, used in Hudson's formula (Shore Protection Manual, 1977) includes the slope effect and is defined by $K_D = N_s^3 \tan\theta$ where $\tan\theta$ is the constant slope of a structure. The values of K_D tabulated in the Shore Protection Manual are mainly based on small scale tests such as the quarrystone riprap tests conducted by Hudson and Jackson (1958). On the other hand, Ahrens (1975) conducted large scale tests on quarrystone riprap and obtained the relationship of $K_D = N_s^3(\tan\theta)^{2/3}$. This suggests that the functional form of the slope effect is not well established at present. In this study the stability coefficient is defined by

$$K_D = N_s^3(\tan\theta)^n \tag{9}$$

where n is an empirical constant. n = 1 corresponds to Hudson's formula whereas n = 2/3 for the tests by Ahrens. Since $\tan\theta = 1/3$ for all the uniform slope tests conducted in this study, it is not possible to establish the value of n from the uniform slope tests. The value of n will be determined in relation to the analysis of the bench slope tests.

For each of the test setups examined in this study, the critical wave height, H_c, was measured for given wave period. The critical wave height has been specified in Section 2.4 and is related to dislodgement of sandbags from the primary protection layer. The corresponding stability number is termed the critical stability number, N_{sc}, which is calculated from

$$N_{sc} = \frac{H_c}{(W/\gamma)^{1/3}(s-1)} \tag{10}$$

in which W = 0.82 lbs., γ = 120 pcf and s = 120/62.4 = 1.92 for the average model sandbag. The calculated value of N_{sc} is found to be dependent on the wave period in accordance with the large scale test results by Ahrens (1975).

Consequently, N_{sc} was plotted as a function of the surf similarity parameter defined by Eq. (5) which is proportional to the wave period. This showed the data following a parabolic trend which could be described by an equation of the form

$$N_{sc} = a_2\xi^2 + b_2\xi + c_2 \qquad (11)$$

where a_2, b_2, and c_2 are empirical constants and determined by a regression analysis.

Figs. 12 through 15 present the measured variation of critical stability numbers, N_{sc}, with respect to the surf similarity parameter, ξ, for each of the uniform slope setups. The data obtained for the test setup with the quartz sand underlayer is excluded because the data size is insufficient for the stability analysis. The relationship given by Eq. (11) is fitted using a regression analysis and also shown in the figures. Table 2 summarizes the values of a_2, b_2 and c_2 and the standard deviation of N_{sc} obtained from the regression analysis for each of the uniform slope setups.

The empirical relationships given by Eqs. (7) and (11) will be needed for the analysis procedure for a preliminary design of a bench slope presented in Section 5. For convenience, all the empirical coefficients obtained for the uniform slope tests are summarized in Tables 1 and 2.

4.0 BENCH SLOPE TEST RESULTS

All the bench slope tests in this study were conducted for the longitudinally-placed, single layer sandbag with a coconut hair underlayer as listed in Appendix D. Comparison with the corresponding uniform slope test results with the coconut hair underlayer is performed using the Saville's composite slope method for wave runup. This method is found to be insufficient for sandbag stability. A modified composite slope method is hence proposed and shown to yield good agreement with the test results.

4.1 Saville's Composite Slope Method

4.1.1 Method Description

Saville (1958) presented a method for determining runup on composite slopes using experimental results obtained for constant slopes. The method assumes that a composite slope can be replaced by a hypothetical, equivalent uniform slope running from the bottom, at the point where the incident wave breaks, up to the point of maximum wave uprush on the structure (Shore Protection Manual, 1977). A graphical representation of an equivalent slope is shown in Fig. 16 where θ_e = the angle of an equivalent uniform slope, R_u = the wave runup height above SWL, h_b = the water depth at the breaker point, and x_b = the horizontal distance from the still water line to the breaker point.

During the testing, an attempt was made to locate the breaker point for each run. However, the breaker point was difficult to identify consistently because the breaking process occurred over some distance along the slope.

Alternatively, a breaker index, α_b, defined by

$$\alpha_b = H/h_b \tag{12}$$

is used to identify the location of the breaker point in the following analysis. α_b may vary from $\alpha_b \simeq 0.8$ for mild beaches to $\alpha_b \simeq 1.2$ for steep beaches on the basis of previous studies by Iverson, 1952; Galvin, 1968; Bowen, et al., 1968; Jen and Lin, 1970; and Battjes, 1974, as summarized by Gunbak, 1976, and Weggel, 1972, as well as by Ostendorf and Madsen, 1979. Since the bench slopes tested in this study are steep relative to natural beaches, α_b may simply be taken as $\alpha_b \simeq 1.2$. The value of $\alpha_b \simeq 1.2$ is found to be approximately consistent with limited measurements made in this study.

The distance to the breaker point, x_b, located at the depth $h_b = H/\alpha_b$ can be calculated from

$$x_b = \begin{cases} h_1\cot\theta_1 + B + (h_b - h_2)\cot\theta_2 & (h_2 \le h_b \le h) \\ h_1\cot\theta_1 + (h_b - h_1)\cot\theta_B & (h_1 < h_b < h_2) \\ h_b\cot\theta_1 & (0 < h_b \le h_1) \end{cases} \tag{13}$$

where the variables are defined in Fig. 1. The equivalent uniform slope, $\tan\theta_e$, is given by

$$\tan\theta_e = \frac{R_u + h_b}{R_u\cot\theta_1 + x_b} \tag{14}$$

which implies that $\tan\theta_e = \tan\theta$ for a uniform slope as expected. Accordingly, the equivalent surf similarity parameter based on the Saville's composite slope method, ξ_s, may be defined by

$$\xi_s = \frac{\tan\theta_e}{\sqrt{H/L_o}} \tag{15}$$

where L_o is given by Eq. (6). The wave runup on a composite slope, R_u, may be predicted using the same runup relationship as that for the corresponding uniform slope

$$\frac{R_u}{H} = \frac{a_1\xi_s}{1 + b_1\xi_s} \tag{16}$$

where use may be made of the values of a_1 and b_1 obtained from the corresponding uniform slope tests.

Eqs. (12)-(16) may be solved using an iteration procedure to predict R_u for given incident wave characteristics (H and T) and composite slope (h_1, h_2, B, θ_1, and θ_2). An iteration procedure is required because the equivalent uniform slope $\tan\theta_e$ given by Eq. (14) depends on R_u. The iteration method used in the computer program given in Appendix F converged very rapidly. The major assumption of this method is that the runup relationship is the same for uniform and composite slopes provided that the equivalent uniform slope, $\tan\theta_e$, is to be used for the composite slope. This assumption is tested in the following by comparing the bench slope test results with the corresponding uniform slope test results.

4.1.2 Wave Runup and Rundown

Over 200 measurements of wave runup and rundown were made in the course of 63 test series on 9 different benches slope configurations.

For each run of the bench slope tests, the equivalent uniform slope given by Eq. (14) is calculated using the measured value of R_u. The equivalent surf similarity parameter ξ_s is then computed using Eq. (15) for each run. The measured value of R_u/H is plotted in terms of the computed value of ξ_s for each run in Fig. 17 which also shows the runup relationship given by Eq. (16) with a_1 and b_1 obtained from the corresponding uniform slope tests. $\alpha_b = 1.2$ is used but the results with $\alpha_b = 1.0$ are found to be almost the same as those shown in Fig. 17, indicating that the results are not sensitive to the value of α_b. For comparison, Fig. 17 includes the uniform slope test results with the coconut hair underlayer for which $\tan\theta = \tan\theta_e$ and hence $\xi = \xi_s$.

Fig. 17 shows a significant amount of scatter for the range of ξ_s greater than approximately two. This may be related to the breaker type observed for this range of ξ_s. Fig. 18 shows the observed breaker types in terms of ξ_s and B/L_o where B is the bench width and L_o is the deep-water wave length. $B = 0$ for the uniform slope tests. For the range of ξ_s greater than approximately 2.1, incident waves were observed to surge on the slope with little or no wave breaking. Consequently, the Saville's composite slope method based on the breaker point may not be strictly applicable for the range of $\xi_s \gtrsim 2.1$. In addition to the scatter of the data points, Fig. 17 indicates that the values of R_u/H for the composite slope tests tend to be slightly smaller than those for the uniform slope tests. This implies that the Saville's method will tend to underpredict wave runup on a bench slope in accordance with the findings by Battjes (1974) concerning wave runup on a concave slope.

As for the data on wave rundown, R_d, for the bench slope tests, the measured value of R_d/H for each run is plotted in terms of the value of ξ_s

calculated using the measured runup for the same run as shown in Fig. 19. For comparison, Fig. 19 also shows the uniform test results. The bench configuration reduced the wave rundown significantly. The wave rundown was always positive (i.e., above SWL) for $h_1 = 0$ and never fell below the depth h_1 for any case tested.

4.1.3 Sandbag Stability

The data on sandbag stability for the bench slope tests consists of the runs for which the critical wave height, H_c, for sandbag movement was measured. The critical stability number defined by Eq. (10) is calculated using the measured value of H_c. The corresponding value of ξ_s is computed from Eq. (15) with the predicted value of R_u using the Saville's composite slope method as outlined in Section 4.1.1. Fig. 20 shows the sandbag stability data for the bench slope tests expressed in the form of N_{sc} as a function of ξ_s. Fig. 20 also shows the uniform slope test data together with the empirical relationship given by Eq. (11) in which $\xi = \xi_s$ for the uniform slope. The bench slope data does not coincide with the uniform slope data.

The equivalent uniform slopes calculated for the bench slope tests are smaller than the 1:3 slope for the uniform slope tests. In order to account for the slope effect on the stability of sandbags, the stability coefficient defined by Eq. (9) is considered. The critical stability coefficient, K_{Dc}, may be defined by

$$K_{Dc} = N_{sc}^{\ 3}(\tan\theta_e)^n \tag{17}$$

in which N_{sc} is defined by Eq. (10) and the equivalent uniform slope, $\tan\theta_e$, is used for the bench slope tests. The value of n may be taken as n = 2/3 or 1. The measured values of $K_{Dc}^{1/3}$ for n = 2/3 are plotted in terms of ξ_s in Fig. 21. The curve shown in Fig. 21 is based on a regression analysis for the uniform slope data and given by

$$K_{Dc}^{1/3} = a_3 \xi_s^2 + b_3 \xi_s + c_3 \tag{18}$$

with

$$a_3 = (\tfrac{1}{3})^{2/9} a_2 \quad , \quad b_3 = (\tfrac{1}{3})^{2/9} b_2 \quad , \quad c_3 = (\tfrac{1}{3})^{2/9} c_2 \tag{19}$$

where $\tan\theta_e = 1/3$ for all the uniform slope data. Fig. 21 shows that the bench slope data does not coincide well with the uniform slope data for the case of n = 2/3. The same conclusion is also found for the case of n = 1.

These data anlayses indicate that the Saville's composite slope method does not make the bench slope data equivalent to the corresponding uniform slope data. Consequently, the Saville's method may not be applied for predicting the stability of sandbags on a bench slope on the basis of the corresponding uniform slope data. This conclusion could be anticipated since the method was originally developed for predicting wave runup on a composite slope. The shortcoming of the Saville's method is that it does not account for the actual slope configuration between the breaker point and the point of wave runup. The stability of armor units should be dependent on the slope configuration.

4.2 Modified Saville's Method

4.2.1 Method Description

The Saville's method described in Section 4.1 does not account for the slope configuration between the breaker point and the wave runup point as depicted in Fig. 16. One way to include the slope configuration effect is to consider the volume of water per unit slope width inside the breaker point below SWL. This volume of water is denoted by A_b for a bench slope and A_e for the corresponding equivalent uniform slope. The ratio of A_b to A_e may be shown to be given by

$$\frac{A_b}{A_e} = \begin{cases} \tan\theta_e [\cot\theta_2 + \left(\frac{h_2}{h_b}\right)^2 (\cot\theta_B - \cot\theta_2) - \left(\frac{h_1}{h_b}\right)^2 (\cot\theta_B - \cot\theta_1)] & (h_2 \leq h_b \leq h) \\ \tan\theta_e [\cot\theta_B - \left(\frac{h_1}{h_b}\right)^2 (\cot\theta_B - \cot\theta_1)] & (h_1 < h_b < h_2) \\ 1 & (0 < h_b \leq h_1) \end{cases} \tag{20}$$

where the variables are defined in Fig. 1 and the depth at the breaker point, h_b, may be estimated using Eq. (12), that is, $h_b = H/\alpha_b$. The stability of sandbags on a bench slope is expected to be greater or smaller than that on the corresponding equivalent uniform slope depending on whether the value of A_b/A_e is greater or smaller than unity. This is because the volume of water inside the breaker point may be considered to cushion the attack of breaking waves. Consequently, the equivalent wave height inside the breaker point, H_e, may be expressed in the form

$$H_e = H/(A_b/A_e)^m \tag{21}$$

where m is an empirical coefficient. The equivalent wave height may be regarded as the wave height seen by the equivalent uniform slope inside the breaker point, while the actual wave height, H, is associated with the actual bench slope.

Physical interpretations of Eq. (21) are made to obtain a rough estimate of the value of the coefficient m. If m = 1/2, Eq. (21) may be expressed as $H_e^2\sqrt{gh_b}/A_e = H^2\sqrt{gh_b}/A_b$ which may be interpreted such that the average rate of wave energy supplied to a unit volume of water inside the breaker point is the same for the bench slope and the equivalent uniform slope. On the other hand, if m = 2/3, Eq. (21) may be rewritten as $H_e\sqrt{gH_e}/A_e = H\sqrt{gH}/A_b$ which may be interpreted such that the rate of water volume supplied to a unit volume of water inside the breaker point at the moment of wave breaking is the same for the bench and equivalent uniform slopes. Admittedly, Eq. (21) may be interpreted in various ways but these qualitative analyses suggest that $m \simeq 1/2 \sim 2/3$. The actual value of m is recommended to be determined experimentally using these values of m as a guideline. It should be mentioned that the original Saville's method corresponds to the case of m = 0 because $H_e = H$ for m = 0.

The only modification required for the modified Saville's method is to use the equivalent wave height H_e in place of the actual wave height H. The distance to the breaker point, x_b, and the equivalent uniform slope, $\tan\theta_e$, are hence given by Eqs. (13) and (14), respectively. The equivalent surf similarity parameter based on H_e may be defined by

$$\xi_e = \frac{\tan\theta_e}{\sqrt{H_e/L_o}} \tag{22}$$

The wave runup on a bench slope may be predicted by

$$\frac{R_u}{H_e} = \frac{a_1\xi_e}{1 + b_1\xi_e} \tag{23}$$

where use may be made of the values of a_1 and b_1 obtained from the uniform slope tests because $H_e = H$, $\tan\theta_e = \tan\theta$ and $\xi_e = \xi$ for a uniform slope.

Eqs. (12), (13), (14), (20), (21), (22) and (23) may be solved using an iteration method to predict the wave runup R_u on a specified bench slope for given incident waves. The iteration method used in the computer program listed in Appendix F starts with the value of R_u estimated from Eq. (23) with $H_e = H$ and $\xi_e = \tan\theta_1/\sqrt{H/L_o}$. This iteration method is found to be rapidly convergent for the computation made in this study.

As for the stability of sandbags, the critical equivalent wave height, H_{ec}, may be defined by

$$H_{ec} = H_c/(A_b/A_e)^m \tag{24}$$

where H_c is the critical wave height for sandbag movement. The critical equivalent stability number, N_{ec}, may hence be defined by

$$N_{ec} = \frac{H_{ec}}{(W/\gamma)^{1/3}(s-1)} \tag{25}$$

Correspondingly, the critical equivalent stability coefficient, K_{ec}, may be expressed

$$K_{ec} = N_{ec}^{\ 3}(\tan\theta_e)^n \tag{26}$$

In order to predict the stability of sandbags using Eq. (25) or (26), the value of N_{ec} or K_{ec} must be estimated. This is investigated in Section 4.2.3 on the basis of the bench slope test results.

4.2.2 Wave Runup and Rundown

First, the wave runup data for the bench slope tests is used to check whether the empirical runup relationship given by Eq. (23) is valid. For each run of the bench slope tests, the values of H_e and ξ_e are calculated using the measured value of R_u. The value of R_u/H_e for each run is plotted in terms of the calculated value of ξ_e in Fig. 22 which also shows the curve predicted by Eq. (23) with the values of a_1 and b_1 obtained from the uniform slope tests with the coconut hair underlayer. For comparison, Fig. 22 includes the uniform slope data for which $H_e = H$ and $\xi_e = \xi$. The value of m in Eq. (21) is taken as $m = 1/2$ for Fig. 22. The results are not sensitive for the range of $m = 1/2 \sim 2/3$. Comparison of Fig. 22 with Fig. 17 indicates that the bench slope data based on the modified Saville's method falls more closely within the scatter of the uniform slope data than that based on the original Saville's method. Consequently, the modified Saville's method may be considered to yield slightly better agreement with the bench slope data than the original Saville's method.

The measured value of wave rundown, R_d, is normalized by the calculated value of H_e for each run of the bench slope tests. The value of R_d/H_e for each run is plotted with respect to the calculated value of ξ_e in Fig. 23 together with the uniform slope data. Fig. 23 is similar to Fig. 19 which is based on the original Saville's method.

4.2.3 Sandbag Stability

For each run of the bench slope tests in which the critical sandbag movement specified in Section 2.4 occurred, the critical equivalent wave height is calculated using Eq. (24) with the corresponding value of R_u predicted by Eq. (23). The values of $\tan\theta_e$ and ξ_e associated with each of these runs are also computed. The values of N_{ec} and K_{ec} are then computed using Eqs. (25) and (26), respectively. The value of n in Eq. (26) is taken as $n = 2/3$ which is found to give better agreement with the bench slope data than $n = 1$. The value of m in Eq. (21) is taken as $m = 1/2$.

Fig. 24 presents the bench slope data expressed in the form of N_{ec} versus ξ_e. Fig. 24 also shows the uniform slope data for which $H_{ec} = H_c$ and hence $N_{ec} = N_{sc}$. The curve shown in Fig. 24 is given by

$$N_{ec} = a_2\xi_e^2 + b_2\xi_e + c_2 \tag{27}$$

in which the values of a_2, b_2 and c_2 are the same as those in Eq. (11) obtained from the uniform slope data. The bench slope data in Fig. 24 appears to fit the uniform slope data much better than the data shown in Fig. 20 based on the original Saville's method.

Fig. 25 presents the bench slope data expressed in the form of K_{ec} versus ξ_e together with the uniform slope data for which K_{ec} is equal to K_{Dc} given by Eq. (17) with $\tan\theta_e = \tan\theta$. The curve shown in Fig. 25 corresponds to

$$K_{ec}^{1/3} = a_3\xi_e^2 + b_3\xi_e + c_3 \quad (28)$$

in which the values of a_3, b_3 and c_3 are calculated from Eq. (19) for n = 2/3 using the values of a_2, b_2 and c_2 obtained from the uniform slope data. The bench slope data in Fig. 25 coincides with the uniform slope data very well. The relationship given by Eq. (28) appears to be a good approximation since most of the bench slope data falls in the vicinity of the curve. It should be noted that for m = 2/3 the bench slope data tends to be shifted slightly downward in Fig. 25

Figs. 24 and 25 indicate that the modified Saville's method significantly improves our capability for predicting the stability of sandbags. Furthermore, the critical stability coefficient K_{ec} with n = 2/3 and m = 1/2 appears to be a better parameter than the critical equivalent stability number N_{ec} since K_{ec} includes the slope effect on the stability of sandbags. Consequently, K_{ec} is adopted in the analysis procedure for a preliminary design of a bench slope with given underlayer material and sandbag placement discussed in Section 5.

5.0 ANALYSIS PROCEDURE AND EXAMPLE COMPUTATION

5.1 Analysis Procedure

An analysis procedure is developed on the basis of the modified Saville's method to compute the required weight of a primary protection unit for given incident wave characteristics and geometry of a bench slope. The developed procedure can be executed using the computer program listed in Appendix F.

First, the following input parameters must be specified:

H = incident wave height at the toe of the bench slope

T = incident wave period at the toe of the bench slope

B = width of the bench

$\cot\theta_B$ = cotangent of the bench slope angle

h_1 = bench depth at the shallowest point of the bench

$\cot\theta_1$ = cotangent of the slope angle landward of the bench

$\cot\theta_2$ = cotangent of the slope angle seaward of the bench

γ = unit weight of a primary protection unit

where the definition sketch is given in Fig. 1. The bench depth at the deepest point of the bench, h_2, is $h_2 = h_1 + B \tan\theta_B$. The water depth on the horizontal seafloor, h, is assumed to be sufficiently large relative to H. Since only regular waves are considered in this study, design regular waves will have to be specified although actual wind-generated waves are irregular. For a preliminary design of a bench slope, H and T might be taken to be the significant wave height and associated period of a design sea state.

Second, the following empirical coefficients must be specified:

a_1, b_1 = runup coefficients in Eq. (23)

a_3, b_3, c_3 = coefficients related to K_{ec} in Eq. (28)

α_b = breaker index in Eq. (12)

m = coefficient related to H_e in Eq. (21)

n = slope effect coefficient in Eq. (26)

The values of a_1, b_1, a_3, b_3, and c_3 obtained from the uniform slope tests are summarized in Table 3 for different underlayer materials and sandbag placement methods. On the other hand, the analysis of the bench slope data in Section 4.2 has indicated that $\alpha_b \simeq 1.2$, $m \simeq 1/2$ and $n \simeq 2/3$. The values of the coefficients obtained in this study are based on the small scale tests with the length ratio $L_r = 1/20 \sim 1/25$. The effect of viscosity in these tests is expected to be greater than those in prototype conditions. The viscosity of water tends to reduce wave runup and sandbag stability. On the other hand, the hand-placed sandbags in the tests are believed to be more stable than the sandbags placed in the field. It is hence recommended to account for the scale effects in determining the values of the coefficients.

For given input parameters and coefficients the required weight of a primary protection unit on a bench slope can be computed as follows. The water depth at the breaker point, h_b, and the horizontal distance to the breaker point, x_b, can be calculated using Eqs. (12) and (13), respectively. Solving Eqs. (14), (20), (21), (22) and (23) by use of an iteration method, R_u, $\tan\theta_e$, H_e, ξ_e and A_b/A_e can be obtained where R_u = wave runup height above SWL, $\tan\theta_e$ = equivalent uniform slope, H_e = equivalent wave height inside the breaker point, ξ_e = equivalent surf similarity parameter, and A_b/A_e = ratio of the actual area A_b to the equivalent area A_e inside the breaker point. The equivalent stability coefficient for the critical movement of an armor unit, K_{ec}, may be estimated using Eq. (28). The weight of a protection unit corresponding to the critical movement of the armor unit may be calculated from

$$W_c = \frac{\gamma H_e^3}{K_{ec}(s-1)^3} (\tan\theta_e)^n \tag{29}$$

where W_c is the critical weight of the protection unit. The corresponding volume of the unit is $V_c = W_c/\gamma$. The critical movement of the protection units will occur if the actual weight W is less than W_c. Eq. (29) is obtained from Eqs. (25) and (26). It should be noted that for the model tests in this study the wave height H has been changed for given value of W, while for the design of a protection unit the critical weight W_c is found for given H. The definition of the critical movement of sandbags used in this study has been given in Section 2.4 and is related to dislodgement of sandbags from the primary protection layer. The required weight of the primary protection unit could be somewhat reduced if some damage on the primary protection layer is tolerable. It is, however, difficult to determine the tolerable damage without site-specific large-scale tests.

The analysis procedure may be used for a preliminary design of the bench configuration characterized by B, $\cot\theta_B$ and h_1. The critical weight W_c and the associated volume $V_c = W_c/\gamma$ can be computed and plotted in terms of B, $\cot\theta_B$ and h_1. The computed variations of W_c and V_c with respect to B, $\cot\theta_B$ and h_1 may enable us to determine the bench configuration. Conversely, the bench configuration required for given protection unit may be determined using the computed results. These are illustrated in Section 5.2.

5.2 Example Computation

An example computation for a hypothetical sandbag retained island is performed based on the analysis procedure presented in Section 5.1. The incident wave conditions for the computation were chosen to represent a possible design event characteristic to the Southern Beaufort Sea. The wave height is taken as $H = 12$ ft which may be regarded as the 25-year recurrance interval significant wave height inside the barrier islands (Heideman, 1979). The corresponding wave period may be taken as $T = 8$ sec. For the non-bench portions of the slope, $\cot\theta_1 = 3$ and $\cot\theta_2 = 3$ are assumed since typical sandbag retained islands have 1:3 uniform slopes. The sandbag unit weight is chosen as $\gamma =$ 120 pcf which is the value used in the analysis of the test data in Section 4. The specific weight of the sandbag, s, is calculated from $s = \gamma/\gamma_w$ where γ_w is the unit weight of sea water. The bench configuration parameters B, $\cot\theta_B$ and h_1 are treated as design variables.

The breaker index is simply chosen as $\alpha_b = 1.2$. The empirical runup coefficients, a_1 and b_1, and the stability curve coefficients, a_3, b_3 and c_3, used in the example computation are the values derived from the coconut hair underlayer tests as presented in Table 3. The slope effect coefficient, n, is taken as $n = 2/3$ on the basis of large scale tests on quarrystone riprap. The equivalent wave height coefficient, m, is taken as $m = 1/2$ from the present model tests. All the coefficients used in this example are listed in Table 4.

A bench configuration will be advantageous if the incident wave breaks on the water above the bench rather than directly on the structure slope. This would result in a decrease in the average wave energy dissipation per unit water volume (Dean, 1977). An effective bench configuration would hence be one that causes the incident wave to break in the vicinity of the deepest point of the bench located at the depth $h_2 = h_1 + B \tan\theta_B$. The volume of water inside the breaker point depends on the bench width, B, the bench slope, $\cot\theta_B$, and the depth at the shallowest point on the bench, h_1. The stability of sandbags and wave runup on the bench slope are hence affected by these bench configuration parameters.

Figs. 26 through 33 present two dimensional plots which illustrate the relationships among the bench configuration parameters and may be used in determining the bench configuration and the sandbag size for the specified wave conditions. In these figures, the water depth at the breaker point is $h_b = 10$ ft according to the simple breaking criterion adopted in this analysis procedure. Comparison of the values of h_b, h_1 and h_2 yields the location of wave breaking.

Fig. 26 shows the critical relationship of B and h_1 for given $\cot\theta_B$ for a bench slope protected with 4 cubic-yard sandbags. The critical movement of 4 cubic-yard sandbags will occur if the point corresponding to particular values of B and h_1 is located below the curve for given value of $\cot\theta_B$ in Fig. 26. The critical movement will not occur for the region above the curve. For example, for the case of $h_1 = 4$ ft and $\cot\theta_B = 7 \sim 17$, the critical movement will occur if B = 20 ft but will not occur if B = 40 ft. Likewise, Fig. 27 shows the critical relationship of B and h_1 for given $\cot\theta_B$ for the case of 2 cubic-yard sandbags.

Figs. 26 and 27 indicate that for given $\cot\theta_B$, the bench width corresponding to the critical sandbag movement decreases as h_1 is increased and becomes minimum when incident regular waves break at the seaward limit of the bench, that is, $h_b = h_2$ where $h_b = 10$ ft for this example computation and $h_2 = h_1 + B \tan\theta_B$. The sandbag stability is independent of B for the case of $h_2 > h_b$ according to this simple analysis procedure which considers only the region inside the breaker point. It should be noted that the present analysis procedure is applicable only if the bench width is sufficiently small relative to the incident wave length. This is because this procedure neglects wave transformation between the breaker point and the toe of the bench slope. The condition of $h_2 > h_b$ implies that incident waves break on the bench or on the 1:3 slope landward of the bench. Figs. 26 and 27 also show that the sandbag stability will not be sensitive to the bench slope for the value of $\cot\theta_B$ greater than approximately 9 if incident waves break seaward of the bench, that is, $h_2 < h_b$.

Figs. 26 and 27 may be used to estimate the required bench width for 4 or 2 cubic-yard sandbags. The bench slope may simply be taken as $\cot\theta_B = 9$ or greater. The depth h_1 may be chosen by considering the design water levels associated with easterly and westerly storms. The required bench width may then be estimated by requiring that the critical sandbag movement will not occur for the range of h_1 expected under design oceanographic conditions. For this example computation, it appears sufficient if B = 30 ~ 40 ft for 4 cubic-yard sandbags and B = 60 ~ 70 for 2 cubic-yard sandbags. However, Figs. 26 and 27 do not give any information regarding the degree of stability of these sandbags. Consequently, the calculated volume of a sandbag corresponding to the critical sandbag movement, V_c, is presented in terms of B, h_1 and $\cot\theta_B$ in the following.

Fig. 28 shows the critical sandbag volume, V_c, as a function of the bench width B for different values of h_1 for $\cot\theta_B = 9$ where H = 12 ft and

$T = 8$ sec for this example computation. $h_1 = 10$ ft corresponds to the situation where incident waves break at the toe of the 1:3 slope landward of the bench. V_c for given h_1 decreases as B is increased and becomes independent of B as B is increased further. The transition occurs at the value of B corresponding to breaking of incident waves at the seaward limit of the bench. For example, this value of B is 36 ft for $h_1 = 6$ ft so that $h_2 = h_1 + B \tan\theta_B$ is equal to $h_b = 10$ ft. Fig. 28 indicates that for B greater than about 40 ft, there is no or little reduction in the critical sandbag volume with increased bench width. On the other hand, V_c is plotted in Fig. 29 as a function of h_1 for given values of B where $\cot\theta_B = 9$ is the same as in Fig. 28. V_c for given B decreases and then increases as h_1 is increased. Since h_1 depends on the design water level which varies with storm surge and tides, the location of the bench relative to the normal water level should be designed such that the value of V_c for given B and $\cot\theta_B$ is not very sensitive for the range of h_1 expected at a particular site.

Figs. 30 and 31 show the critical sandbag volume, V_c, in terms of h_1 and $\cot\theta_B$ for the case of $B = 40$ ft. $\cot\theta_B = 3$ corresponds to a 1:3 uniform slope. Fig. 30 indicates that V_c is very sensitive to the value of h_1 as h_1 approaches $h_b = 10$ ft. Fig. 31 suggests that for $\cot\theta_B$ greater than approximately 9, there is no or little reduction in the value of V_c with the increase of $\cot\theta_B$. These figures also show that a properly designed bench slope will require much smaller sandbags for its slope protection than those required for the corresponding 1:3 uniform slope. Likewise, Figs. 32 and 33 show the critical sandbag volume, V_c, in terms of B and $\cot\theta_B$ for the case of $h_1 = 6$ ft.

Figs. 32 and 33 confirm the findings discussed in relation to Figs. 26 through 31. For this example computation, the optimal bench configuration for the stability of sandbags may be characterized by $B \simeq 40$ ft, $h_1 \simeq 2\text{-}7$ ft and $\cot\theta_B \gtrsim 9$ for 4 cubic-yard sandbags and $B \simeq 70$ ft, $h_1 \simeq 2\text{-}4$ ft and $\cot\theta_B \gtrsim 9$ for 2 cubic-yard sandbags. It should be mentioned that these bench configurations are based on the stability of the sandbags under the action of regular waves and intended to be preliminary design guidelines.

A bench slope not only increases the stability of sandbags but also reduces wave runup, R_u. Figs. 34, 35 and 36 show R_u as a function of the bench width B for different values of h_1 and $\cot\theta_B$ where H = 12 ft and T = 8 sec for this example computation. Fig. 34 indicates that for the case of $\cot\theta_B = 9$ wave runup on a bench slope with $B \gtrsim 40$ ft and $h_1 \simeq 2\text{-}6$ ft is approximately 40% less than that for the corresponding 1:3 uniform slope represented by the curve for $h_1 = 10$ ft. The effect of $\cot\theta_B$ on wave runup is shown in Figs. 35 and 36 for which $h_1 = 6$ ft and 2 ft, respectively. These figures indicate that wave runup is not very sensitive to $\cot\theta_B$ for the range of $\cot\theta_B \gtrsim 9$. Furthermore, it is apparent that wave runup on a bench slope is closely related to the stability of sandbags. The optimal bench configurations for the stability of the sandbags suggested in relation to Figs. 26 through 33 reduce wave runup significantly. As a result, a bench slope can be used to increase the sandbag stability as well as to reduce wave runup.

Actual formatted output from the computer program listed in Appendix F is presented in Table 5 for a uniform 1:3 slope and in Table 6 for a benched slope with B = 40 ft, $\cot\theta_B = 9$ and $h_1 = 6$ ft. The computer output shows a decrease in the critical sandbag size from 10.2 cubic-yards for the 1:3 uniform slope to 3.0 cubic-yards for the benched slope. Use of 4 cubic-yard sandbags on this benched slope would therefore be equivalent to incorporating a safety factor of 1.3 into the design. The stability coefficient for this uniform slope is found to be $K_D = 4.5$ which is slightly greater than that for randomly placed quarrystone given in the Shore Protection Manual (1977). The computer output shows that wave runup decreased from 12.9 ft for the uniform slope to 8.8 ft for the bench slope. It should be mentioned that Figs. 26 through 36 have been plotted using a subroutine with minor modifications of the computer program listed in Appendix F.

6.0 SUMMARY AND CONCLUSIONS

6.1 Summary

The objectives of this study are to investigate the sandbag stability and wave runup on a bench slope as compared to that on a uniform slope and to develop an analysis procedure for a preliminary design of a bench slope of a sandbag retained island.

First, a comprehensive series of two-dimensional hydraulic model tests using regular waves were performed such that the model-to-prototype length ratio would be 1:20 for 2 cubic-yard prototype sandbags and 1:25 for 4 cubic-yard prototype sandbags. In all, 107 separate test series were conducted and for each of the series the wave height was increased incrementally. The uniform slope tests consisted of 44 series on a uniform 1:3 slope using different underlayer materials and sandbag placement methods. The bench slope tests consisted of 63 series using nine different bench slope configurations. Seven different wave periods were used for each bench configuration to evaluate any effect due to wave period. A detailed description of the test setups and experimental procedures has been presented in Section 2.

The uniform slope test data was analyzed by use of the surf similarity parameter which was found to be convenient for describing the results concisely. The measured wave runup and rundown normalized by the wave height as well as the measured critical stability number were plotted as a function of the surf similarity parameter. Empirical relationships for the wave runup and critical sandbag movement were proposed on the basis of the uniform slope data and used for the analysis of the bench slope data. Description of the uniform slope test results has been included in Section 3.

The different bench slope configurations tested in this study were reduced to equivalent uniform slopes by applying the method presented by Saville (1958). The benched slope data was then analyzed using an equivalent surf similarity parameter based on the equivalent uniform slope found by the Saville's method. The Saville's method proved to be insufficient in describing the stability characteristics of the bench slope on the basis of the uniform slope data. Alternatively, an equivalent wave height was introduced to account for the difference of the volume of water inside the breaker point on a bench slope and that on the corresponding equivalent uniform slope. The bench test data was then analyzed using the equivalent wave height and the equivalent uniform slope. The bench slope data analyzed by the modified Saville's method was found to coincide with the corresponding uniform slope data. Consequently, the modified Saville's method may be used to predict the sandbag stability and wave runup on a bench slope on the basis of the corresponding uniform slope results. The bench slope test results including the modified Saville's method has been presented in Section 4.

A design methodology based on the test results and the modified Saville's method has been developed and presented in Section 5. The recommended methodology was incorporated into a computer program, and example computations were performed for hypothetical design wave conditions in the Southern Beaufort Sea. The bench slope configuration was systematically varied to illustrate the effects of the bench width, the bench slope and the water level on the runup and stability characteristics of a sandbag retained bench slope.

6.2 Conclusions

Since there are several parameters involved in the description of a bench-type slope configuration, a simple method to quantify the overall effects of these parameters on the stability characteristics of a bench slope is needed for a preliminary design of the bench slope. An investigation of various methods resulted in the modified equivalent slope method proposed in Section 4 which appears to be the best method available at present except for extensive model testing. This simple method enables us to examine various bench configurations with much less time and cost than extensive model testing. This method may hence be used to select a few alternative bench configurations for which site-specific, large scale model tests may be conducted.

The method makes use of the empirical runup and stability relationships which were originally proposed on the basis of large-scale model tests on quarrystone riprap. The empirical coefficients in these empirical relationships for sandbags obtained in this study are expected to include scale effects caused by viscosity, permeability, sandbag placement procedures and surface tension. It is hence recommended that the empirical coefficients in the runup and stability relationships be compared with those obtained from large-scale or field data. Furthermore, the simple criterion for wave breaking used in the modified equivalent slope method may be refined especially for waves surging on a bench slope. In practice, however, most of incident irregular waves will break in the form of plunging or collapsing. At this moment, the method is applicable to regular waves only. The method could be extended to irregular waves in the same manner as was done by Kobayashi et al. (1983) for predicting irregular wave runup and overtopping on a uniform slope. This would require considerable engineering efforts.

In spite of these shortcomings, the results of the present experiment compare reasonably well with the results of previous studies. During the testing, all the model sandbags were neatly hand-placed in order to maintain uniformity in the primary cover layer for each test. The stability coefficient, K_D, found from the uniform slope example computation is 4.5 which appears to be compatible with the values of K_D used for previous designs of sandbag retained uniform slopes.

The results of the example computation in Section 5 have indicated that a properly designed bench slope will significantly increase the stability of sandbags and reduce wave runup. The existing limit of 2 cubic-yard and 4 cubic-yard sandbags may hence be extended if a bench slope configuration is to be incorporated in the design of a gravel island. Application of a bench slope configuration appears to be promising for a gravel island which requires additional sandbag stability and reduction of wave runup.

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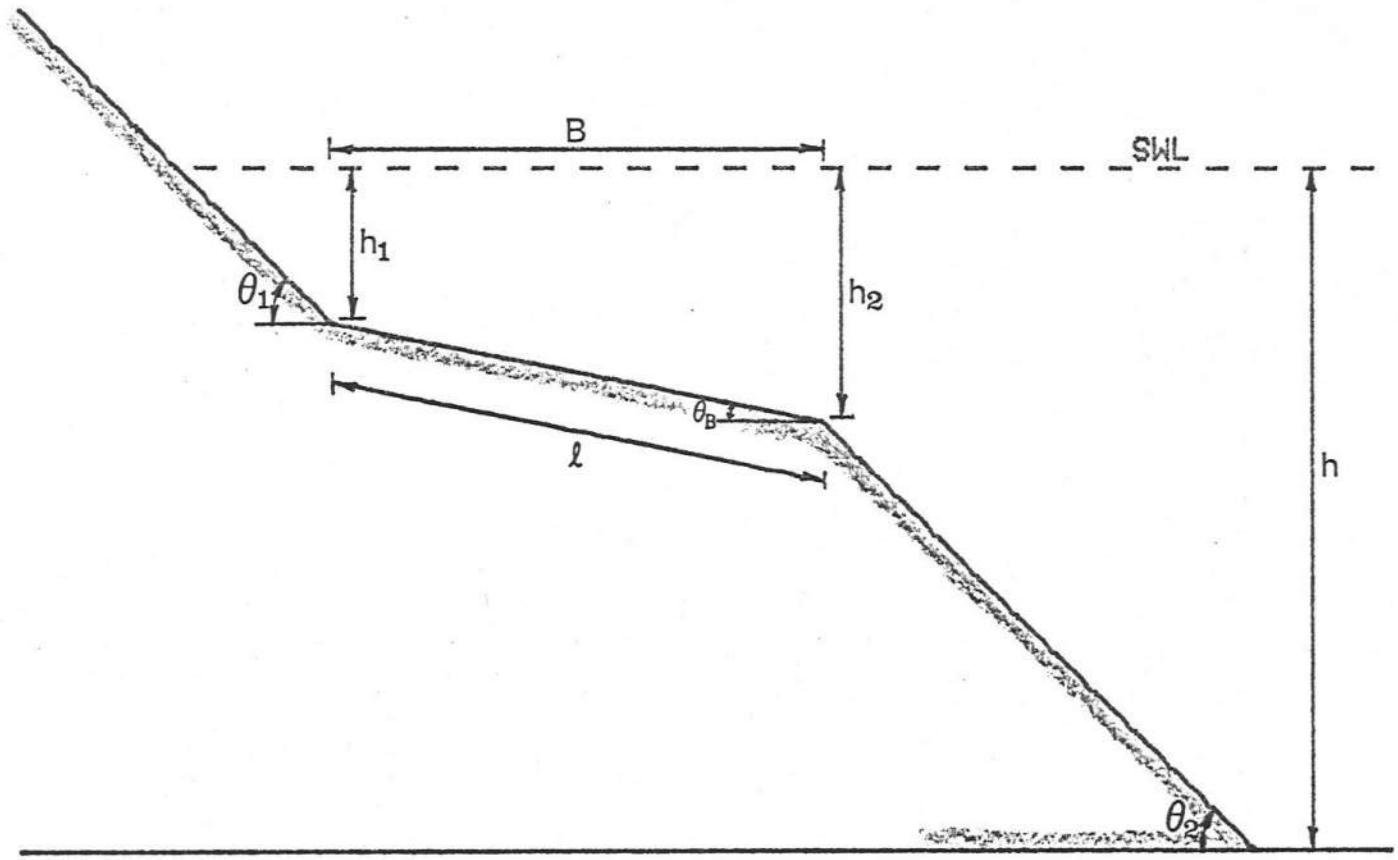

Figure 1. Graphical Representation of Bench Slope Configuration

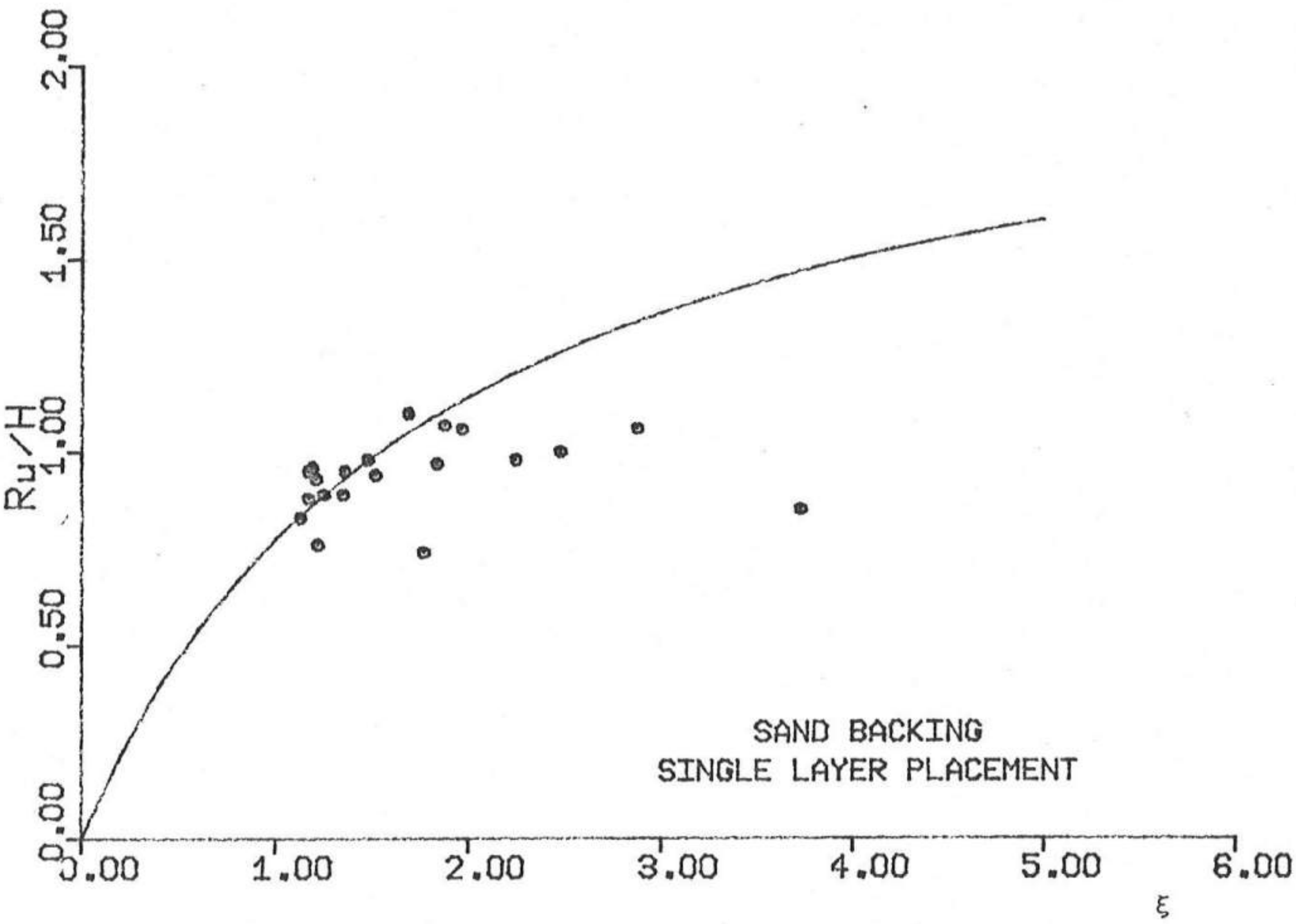

Figure 2. R_u/H vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Quartz Sand Backing

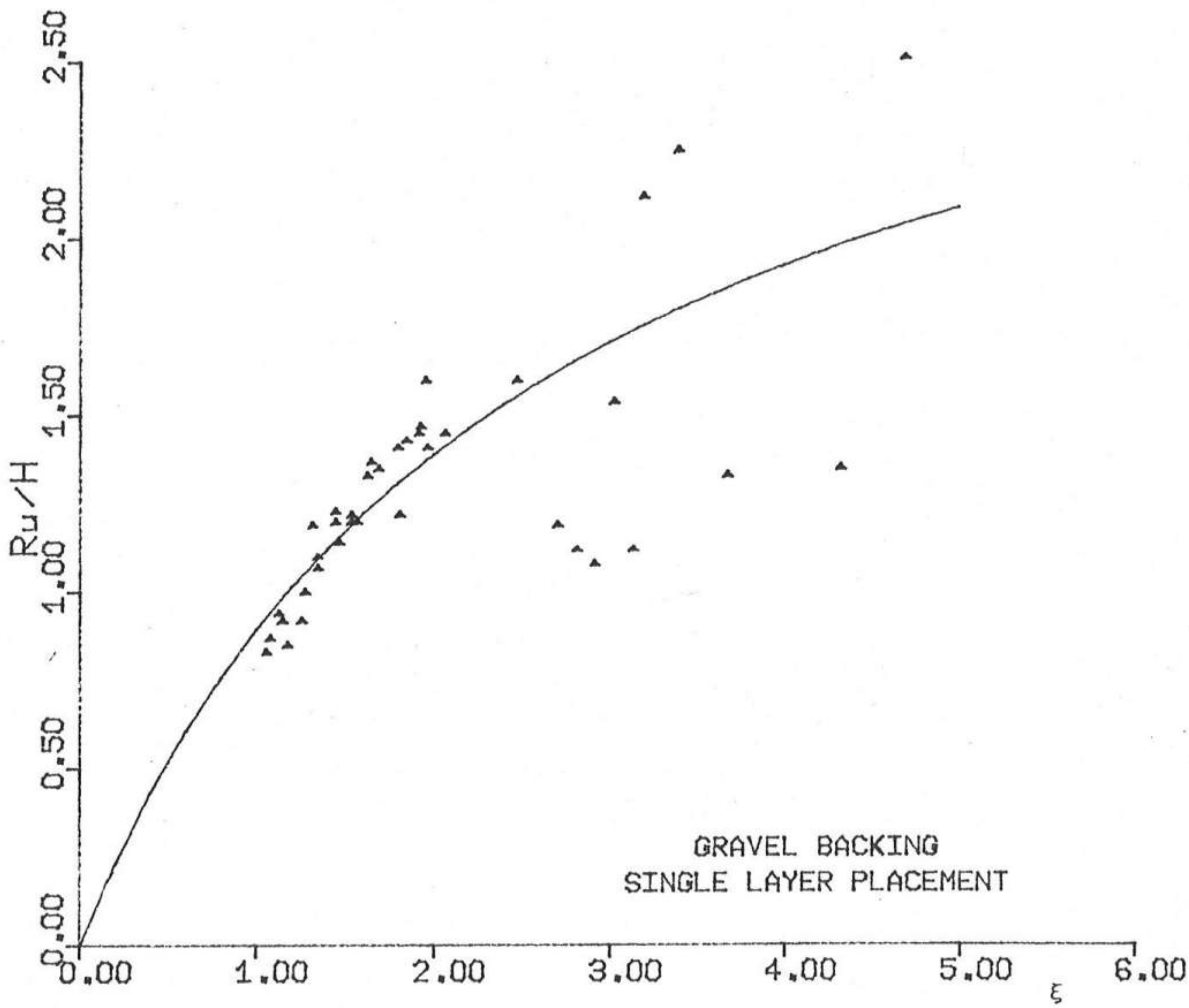

Figure 3. R_u/H vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Gravel Backing

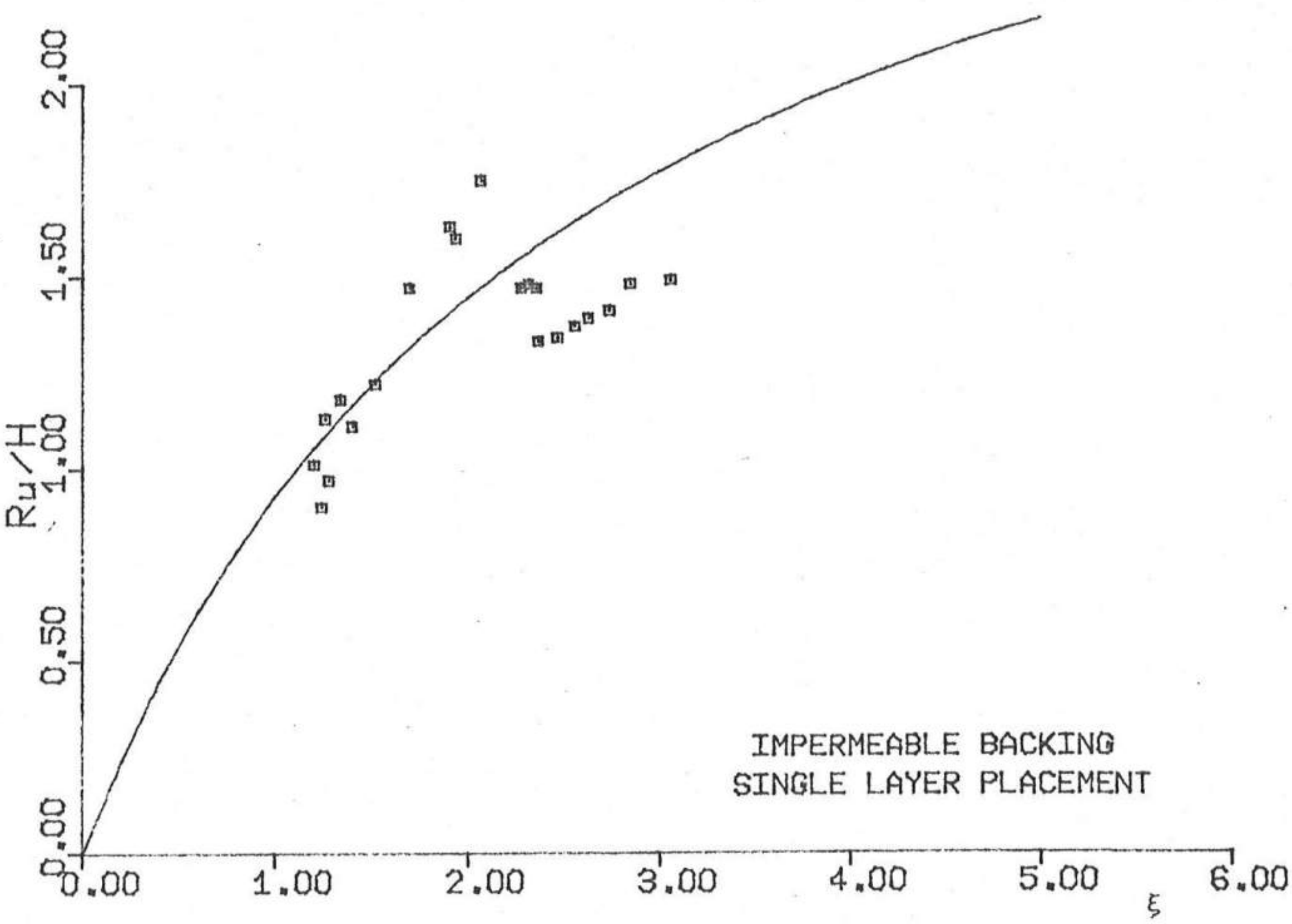

Figure 4. R_u/H vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Impermeable Backing

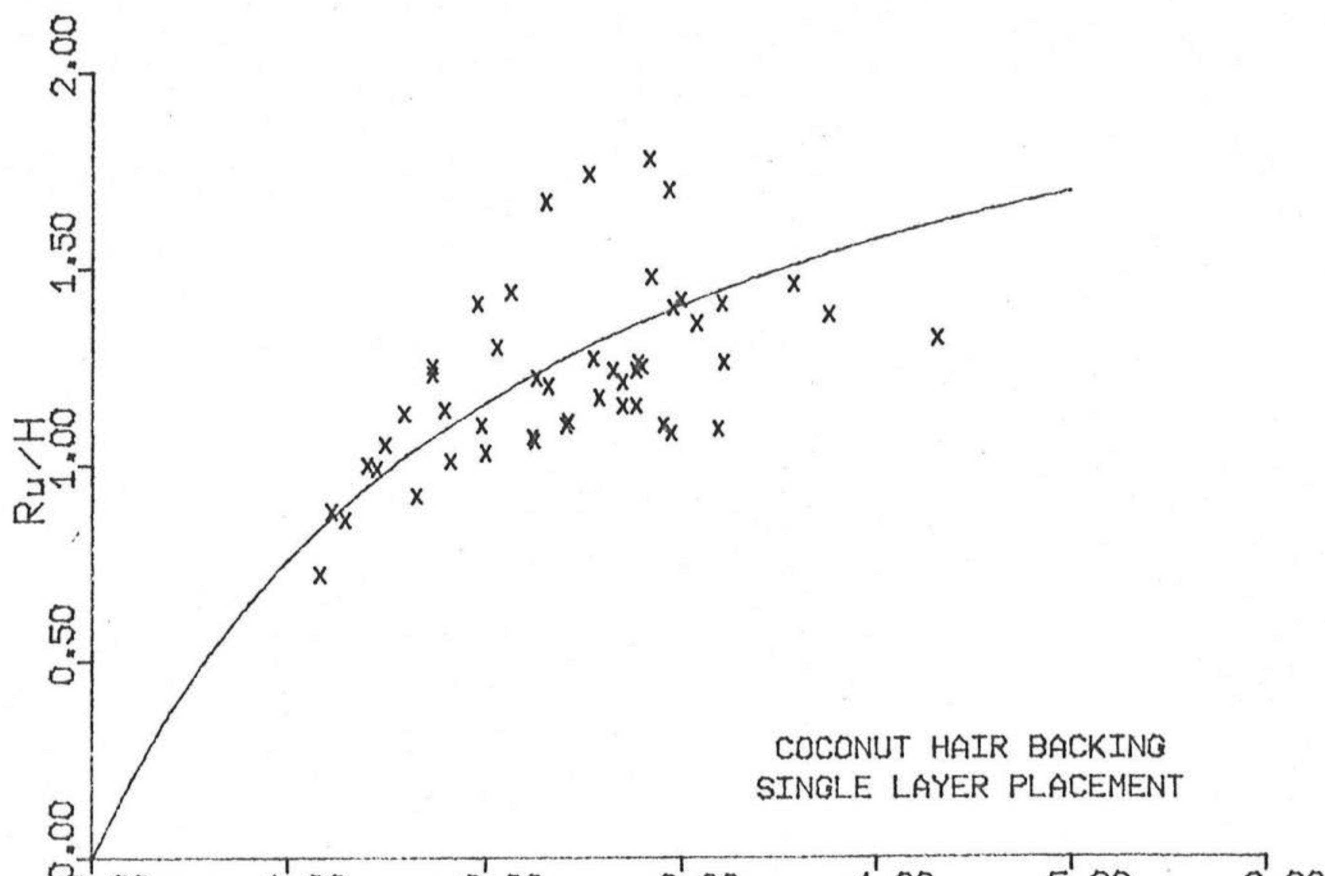

Figure 5. R_u/H vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Coconut Hair Backing

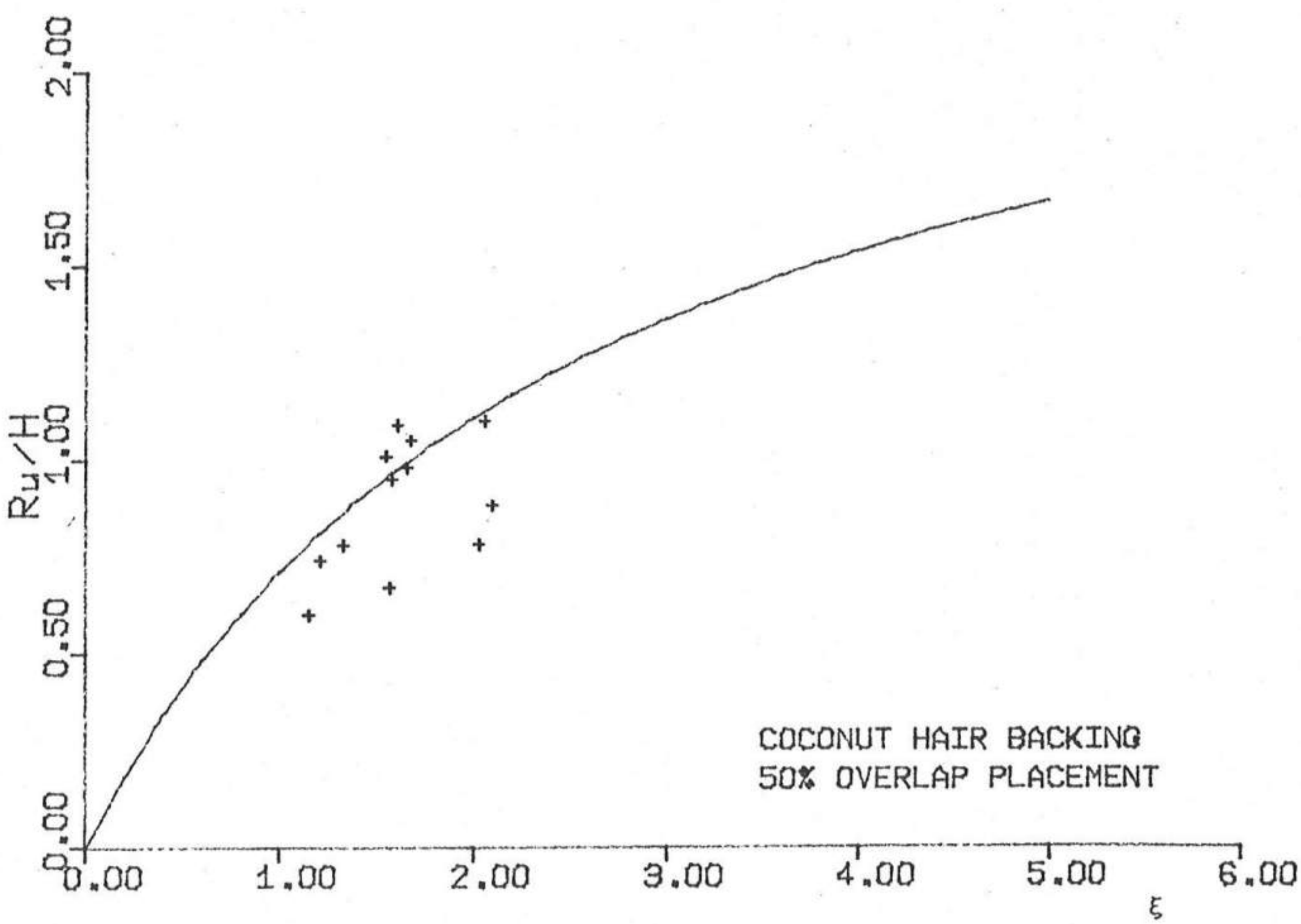

Figure 6. R_u/H vs. ξ for 50% Overlap Sandbag, Uniform 1:3 Slope with Coconut Hair Backing

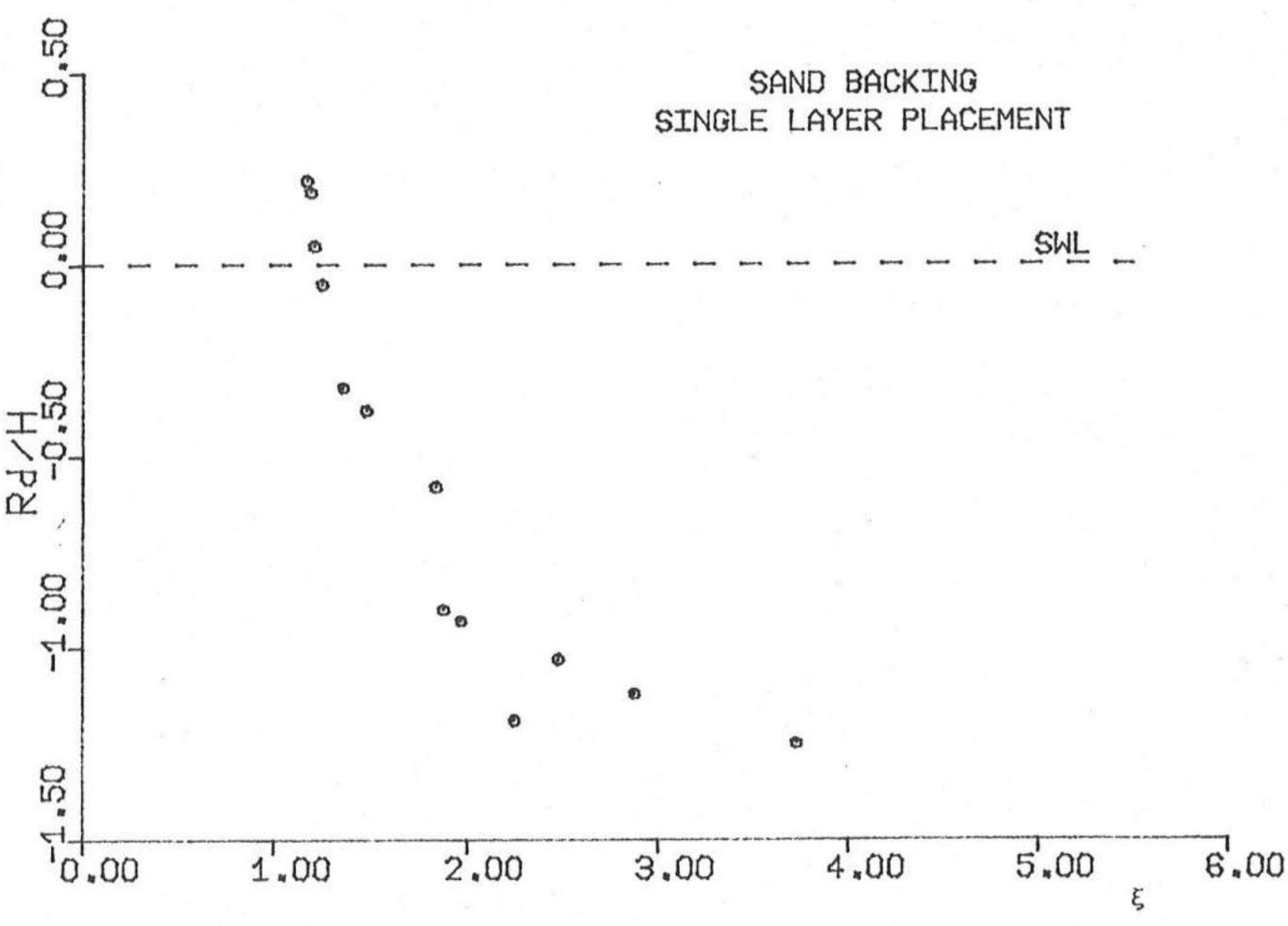

Figure 7. R_d/H vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Quartz Sand Backing

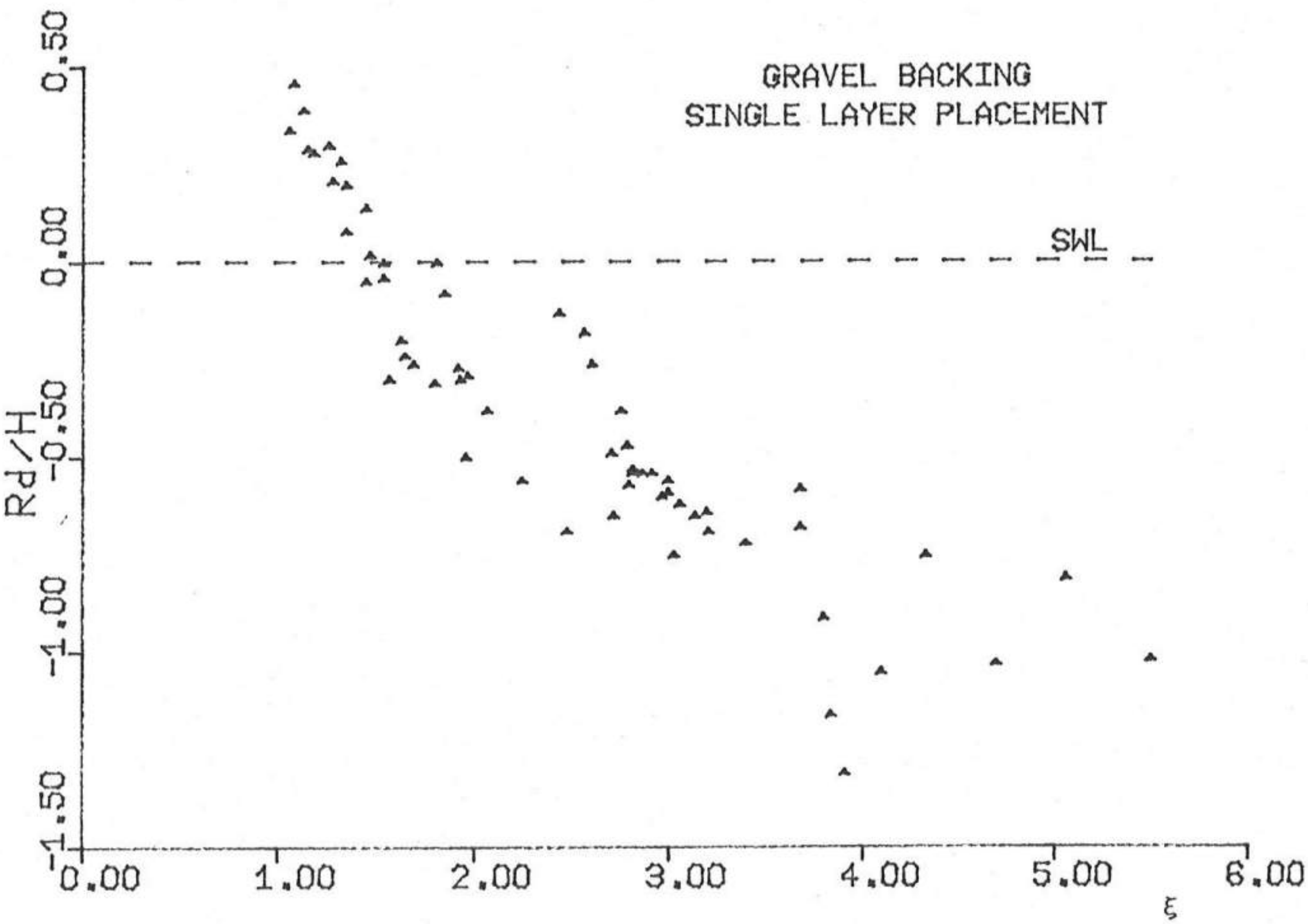

Figure 8. R_d/H vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Gravel Backing

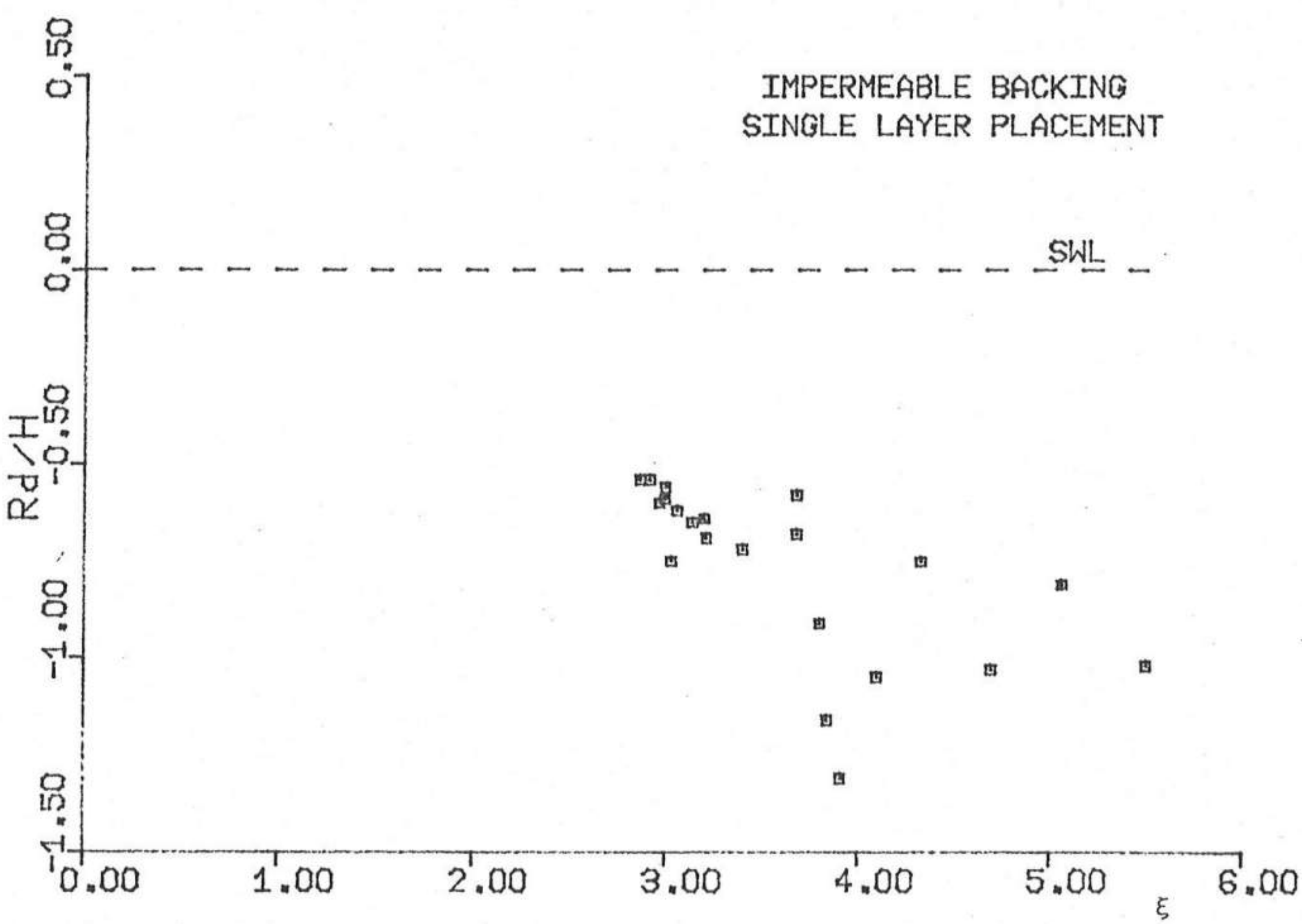

Figure 9. R_d/H vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Impermeable Backing

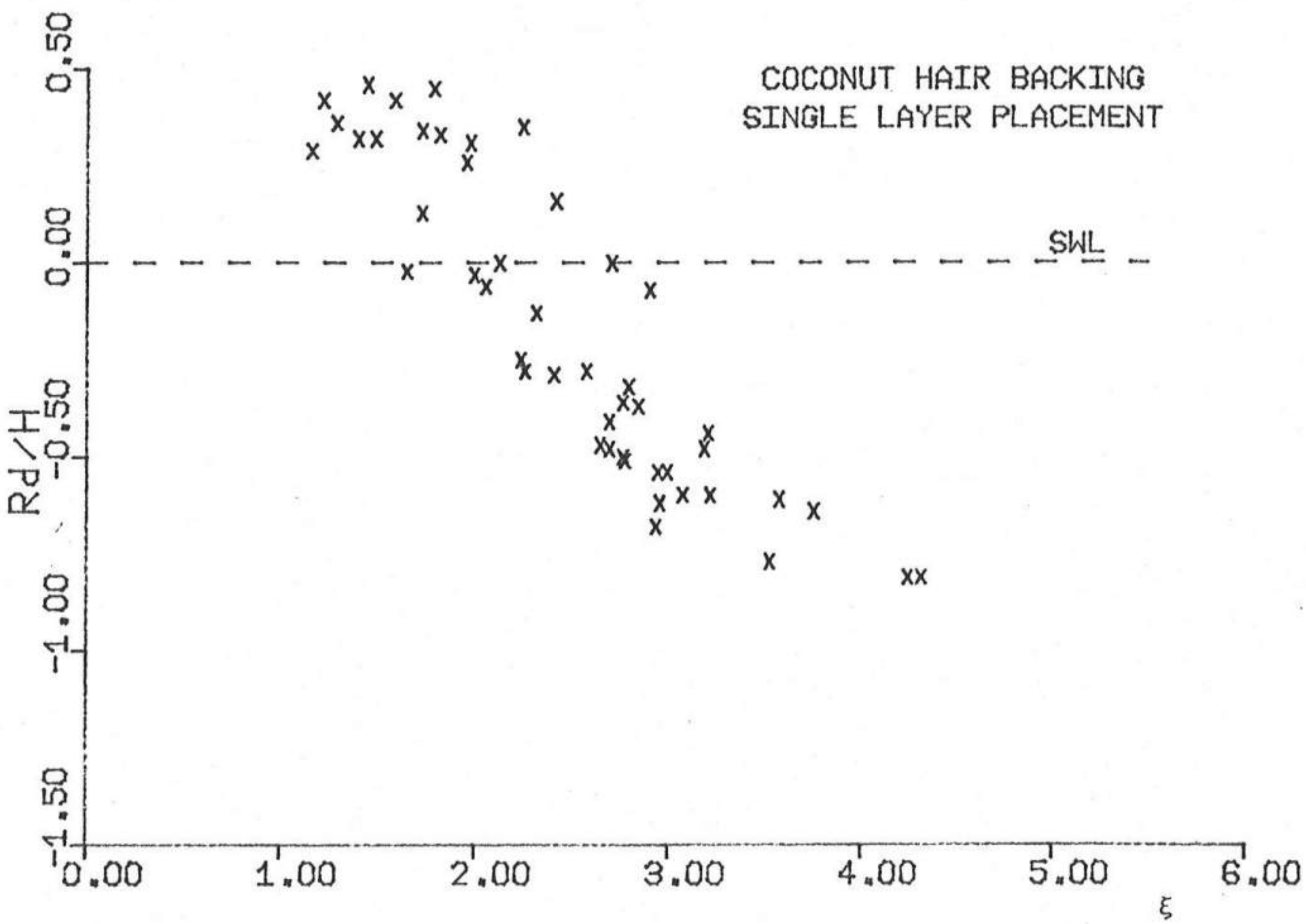

Figure 10. R_d/H vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Coconut Hair Backing

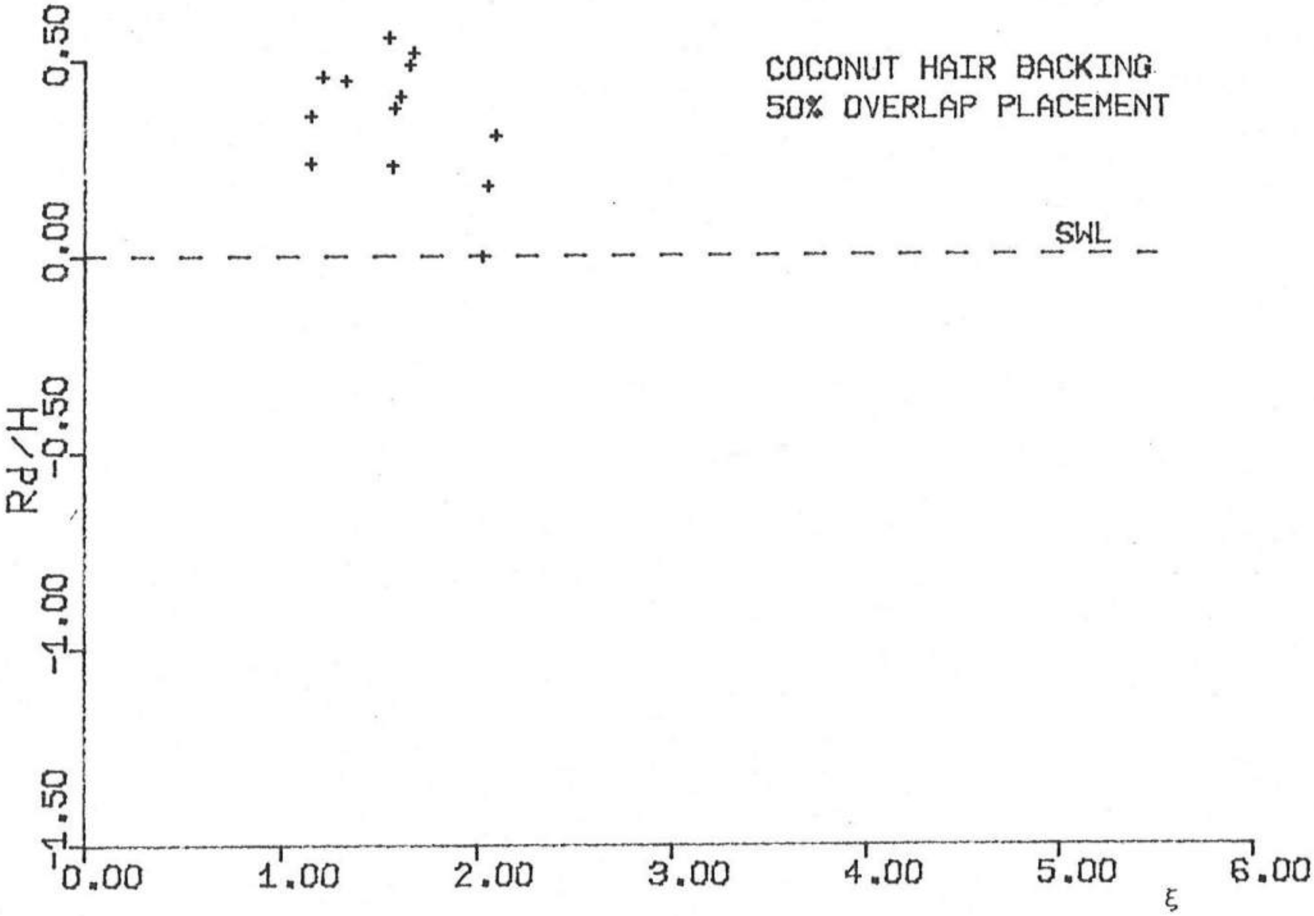

Figure 11. R_d/H vs. ξ for 50% Overlap Sandbag, Uniform 1:3 Slope with Coconut Hair Backing

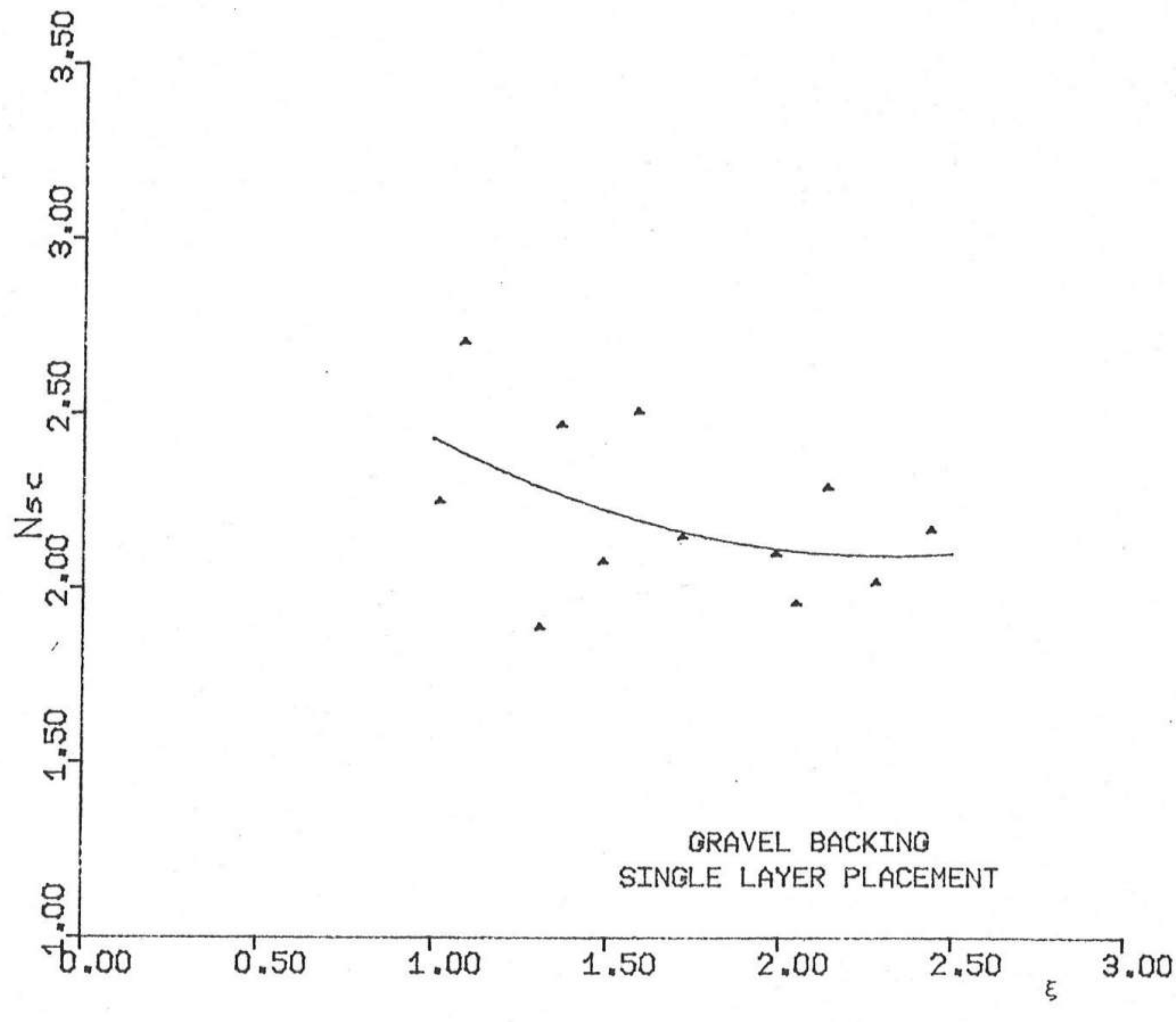

Figure 12. N_{sc} vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Gravel Backing

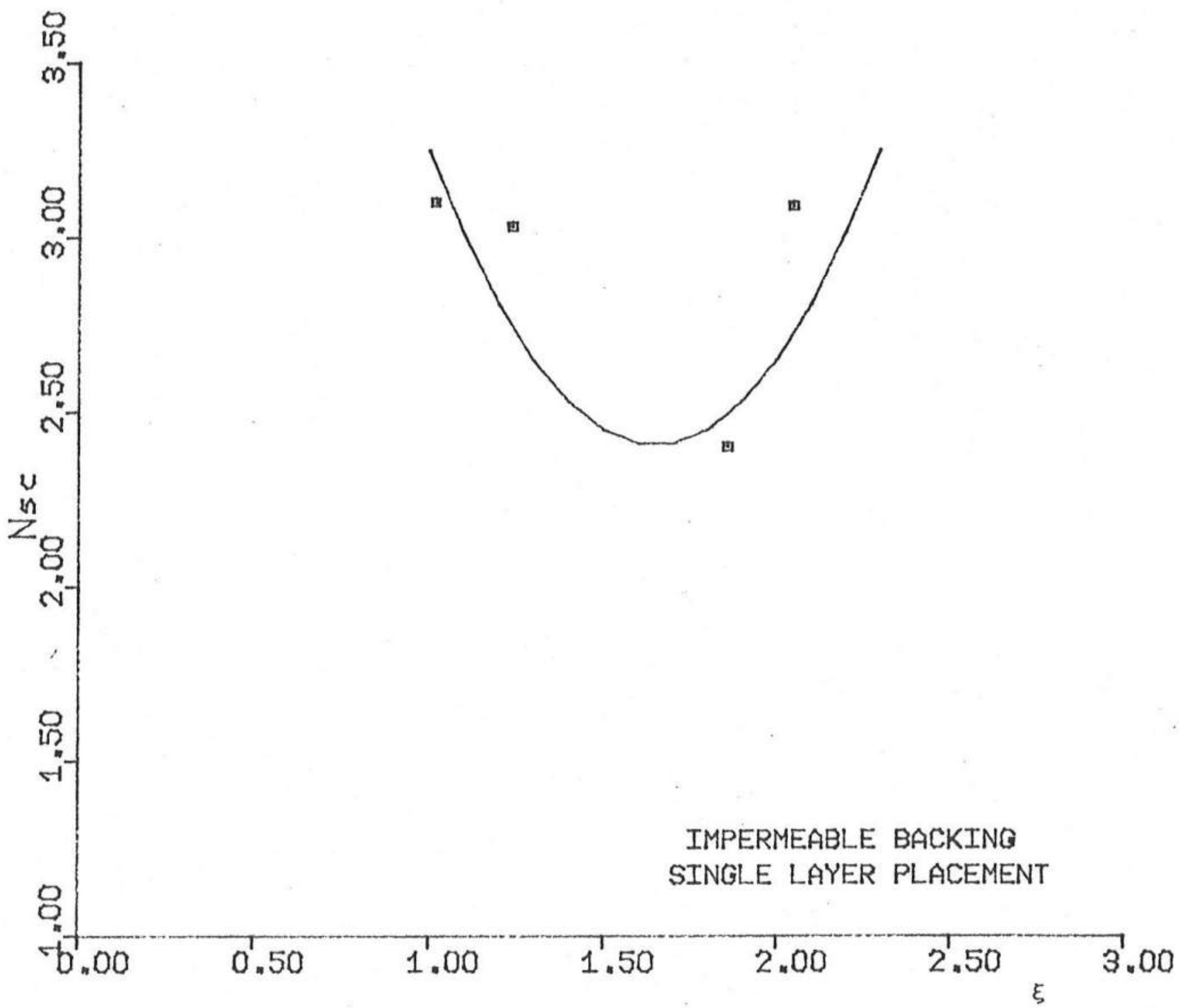

Figure 13. N_{sc} vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Impermeable Backing

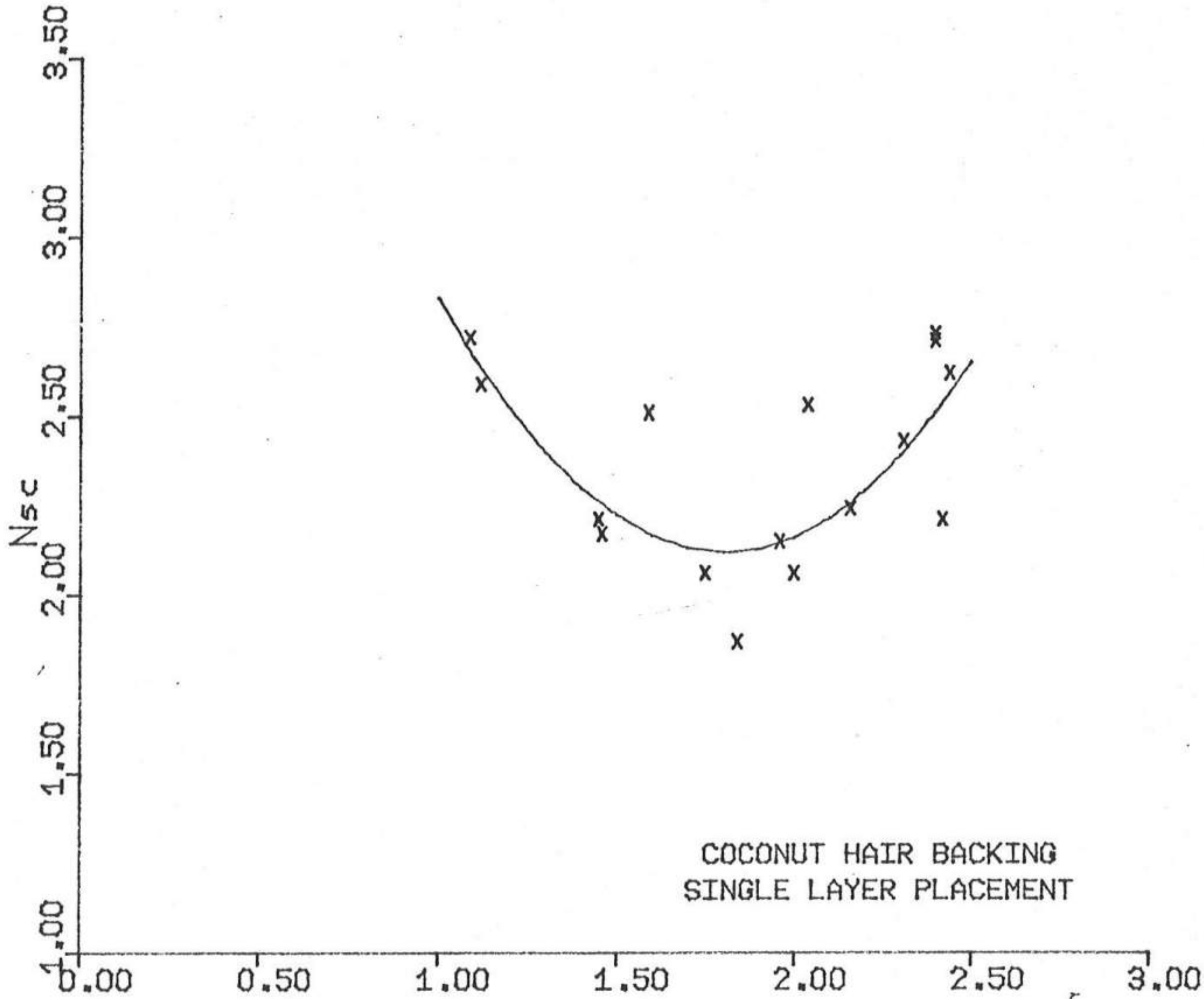

Figure 14. N_{sc} vs. ξ for Single Layer Sandbag, Uniform 1:3 Slope with Coconut Hair Backing

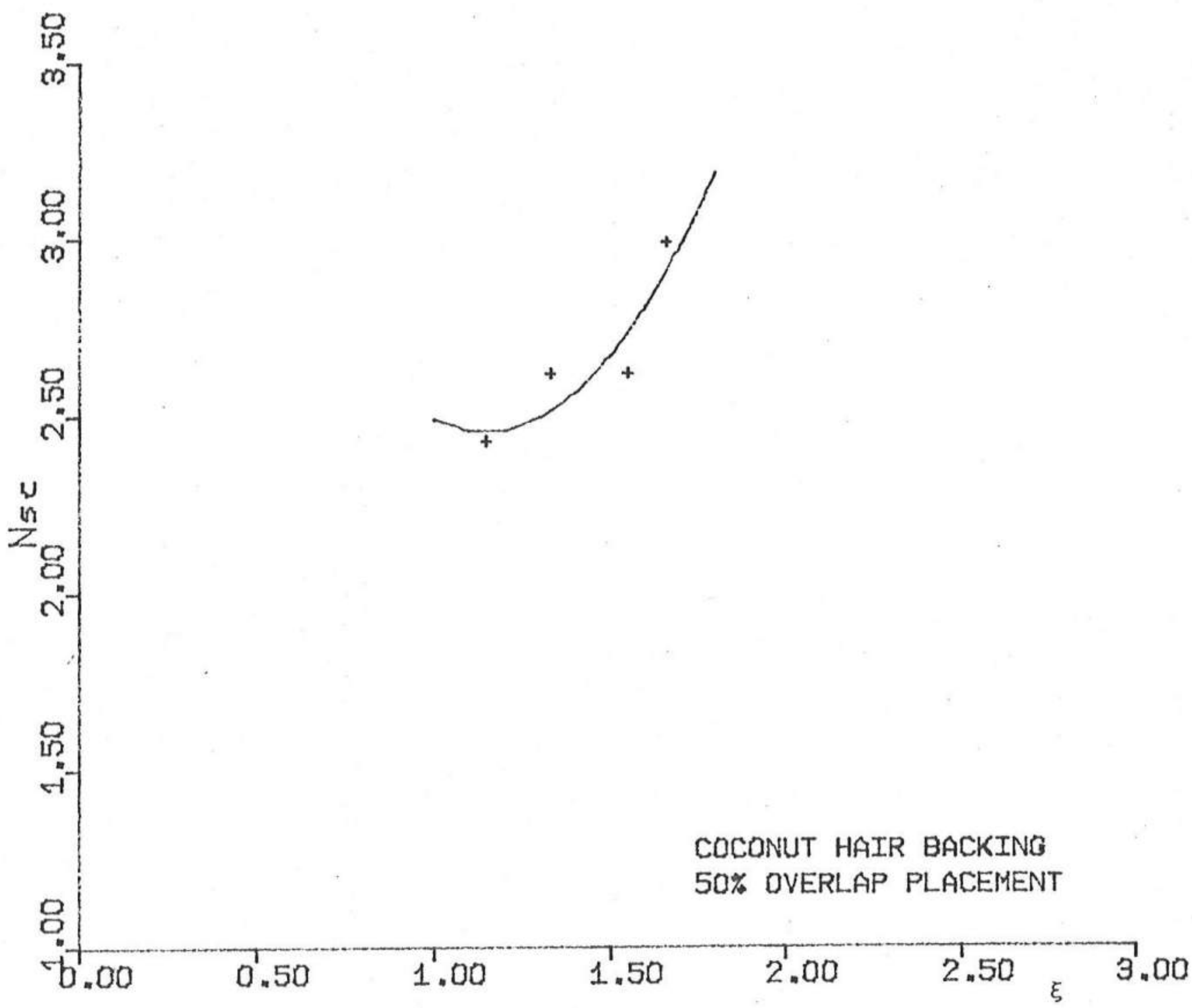

Figure 15. N_{sc} vs. ξ for 50% Overlap Sandbag, Uniform 1:3 Slope with Coconut Hair Backing

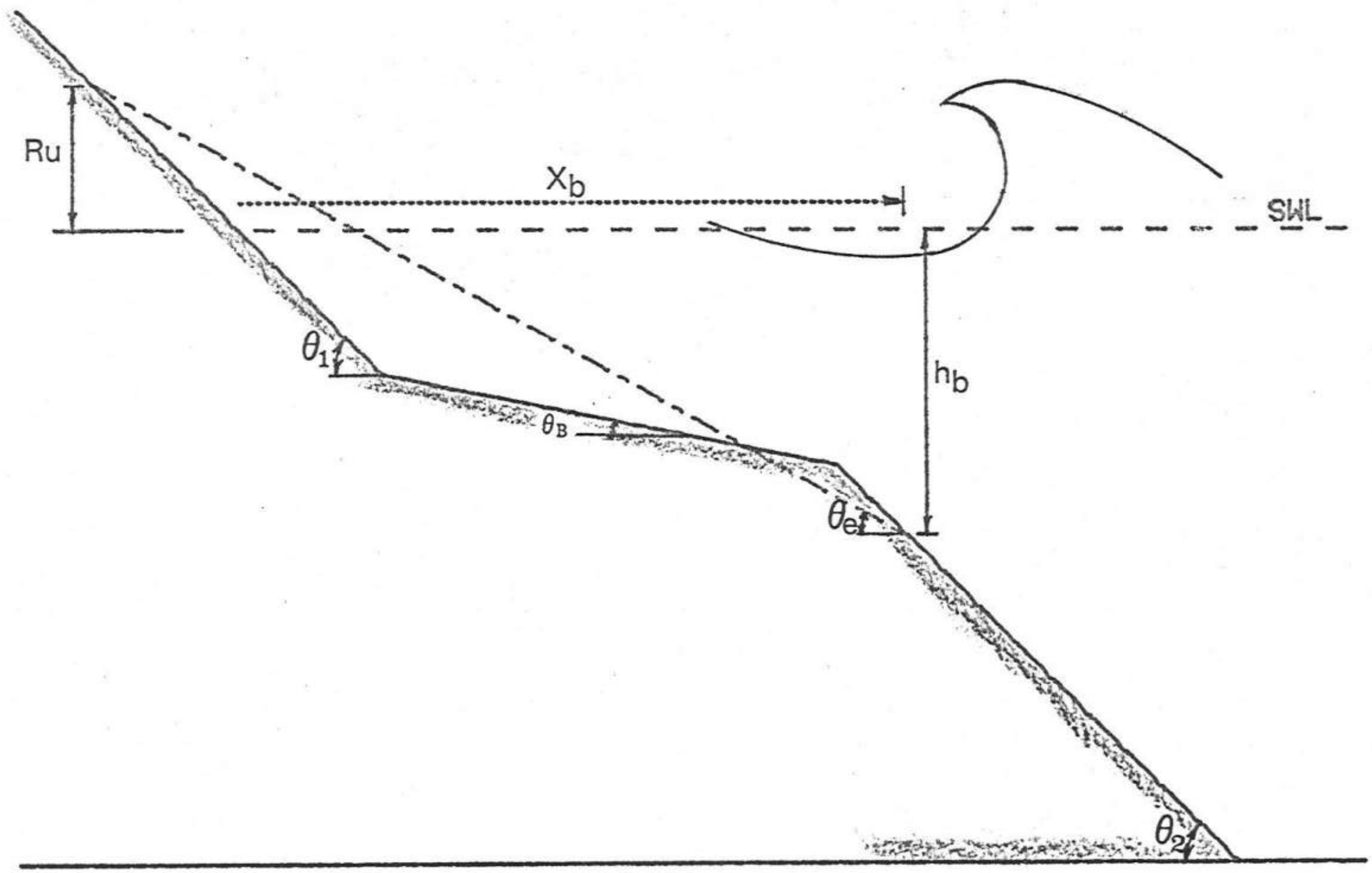

Figure 16. Graphical Representation of Saville's Composite Slope Method

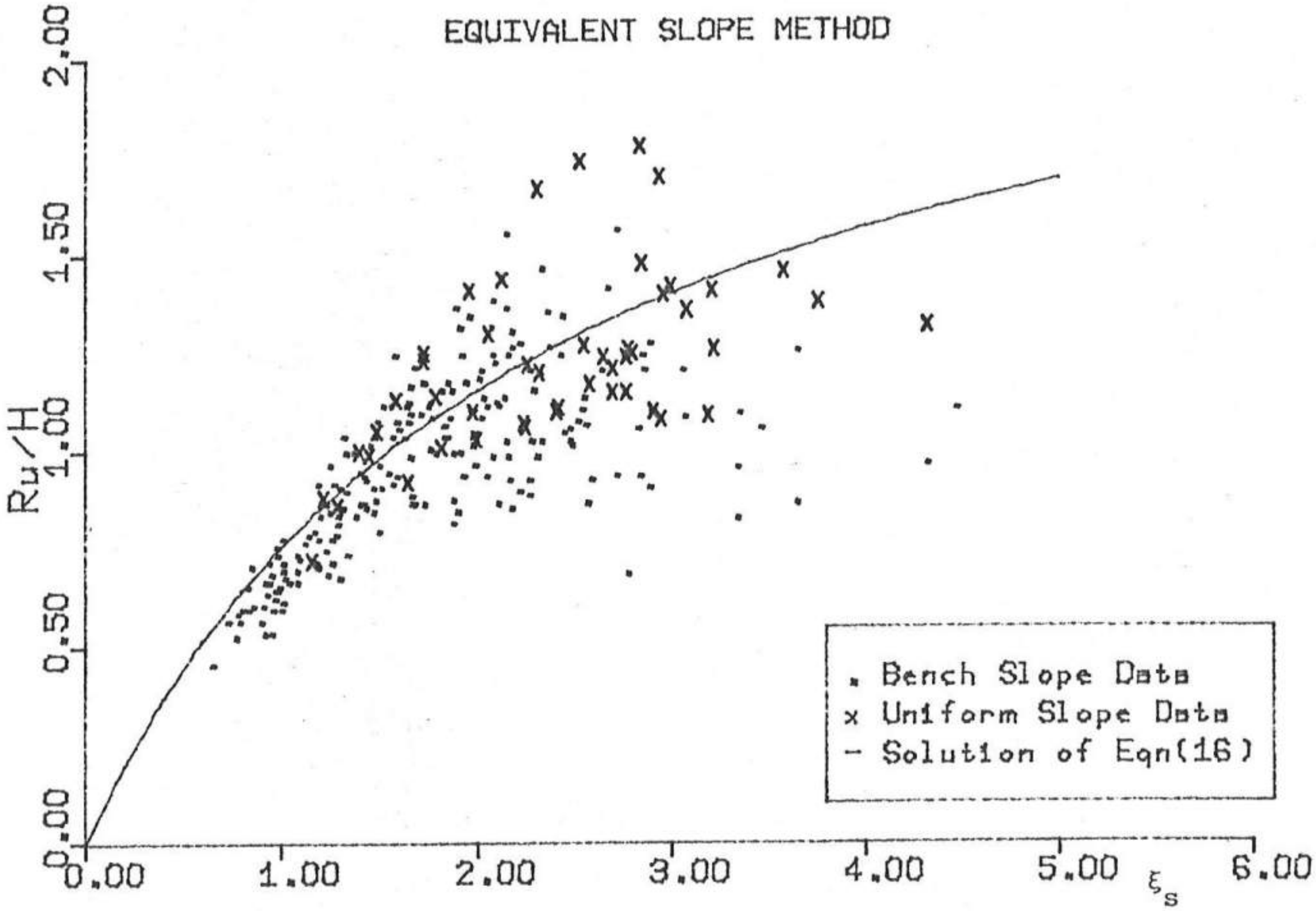

Figure 17. R_u/H vs. ξ_s for Bench Slope Tests (m = 0)

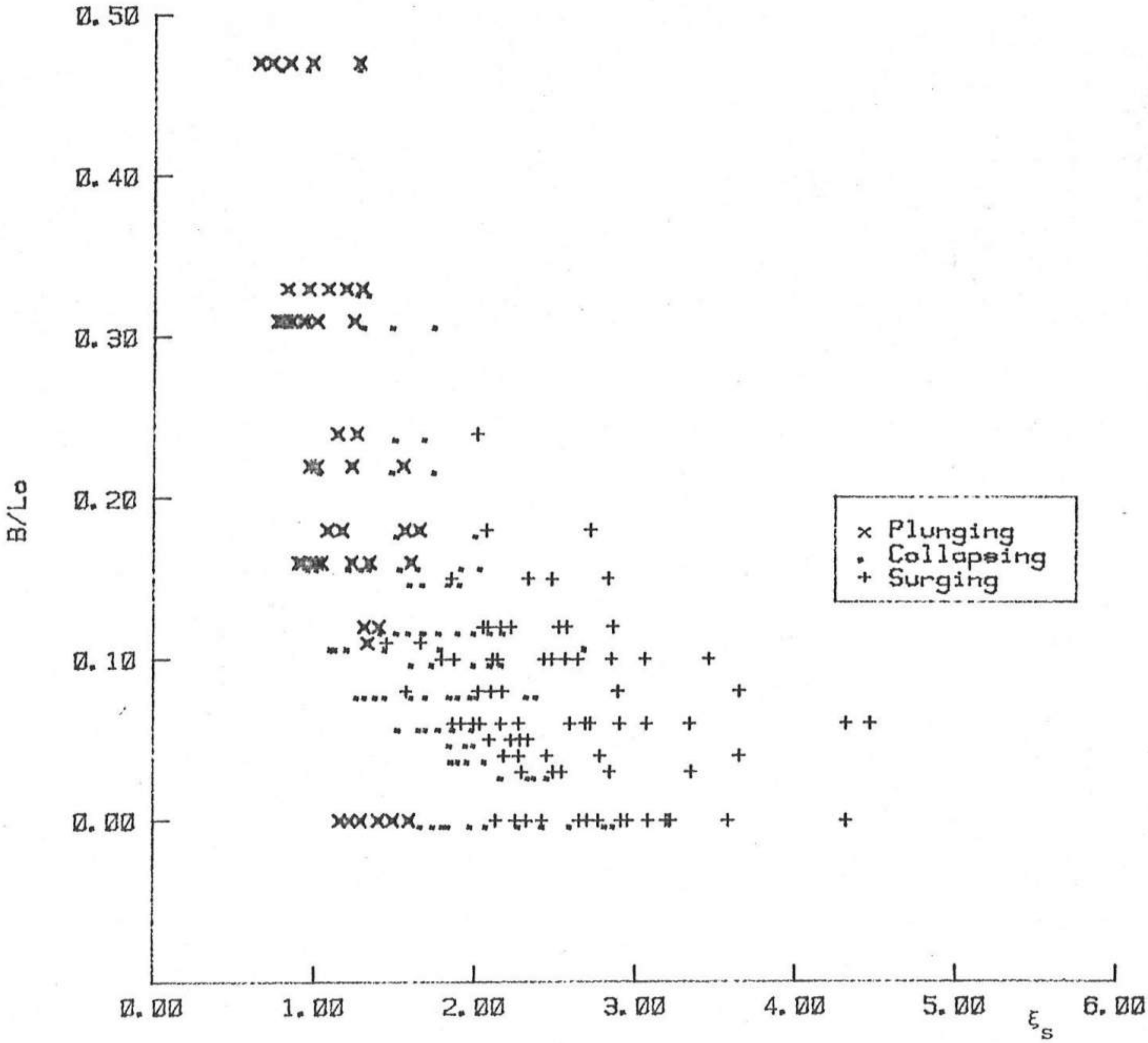

Figure 18. Observed Breaker Types in Terms of B/L_o and ξ_s

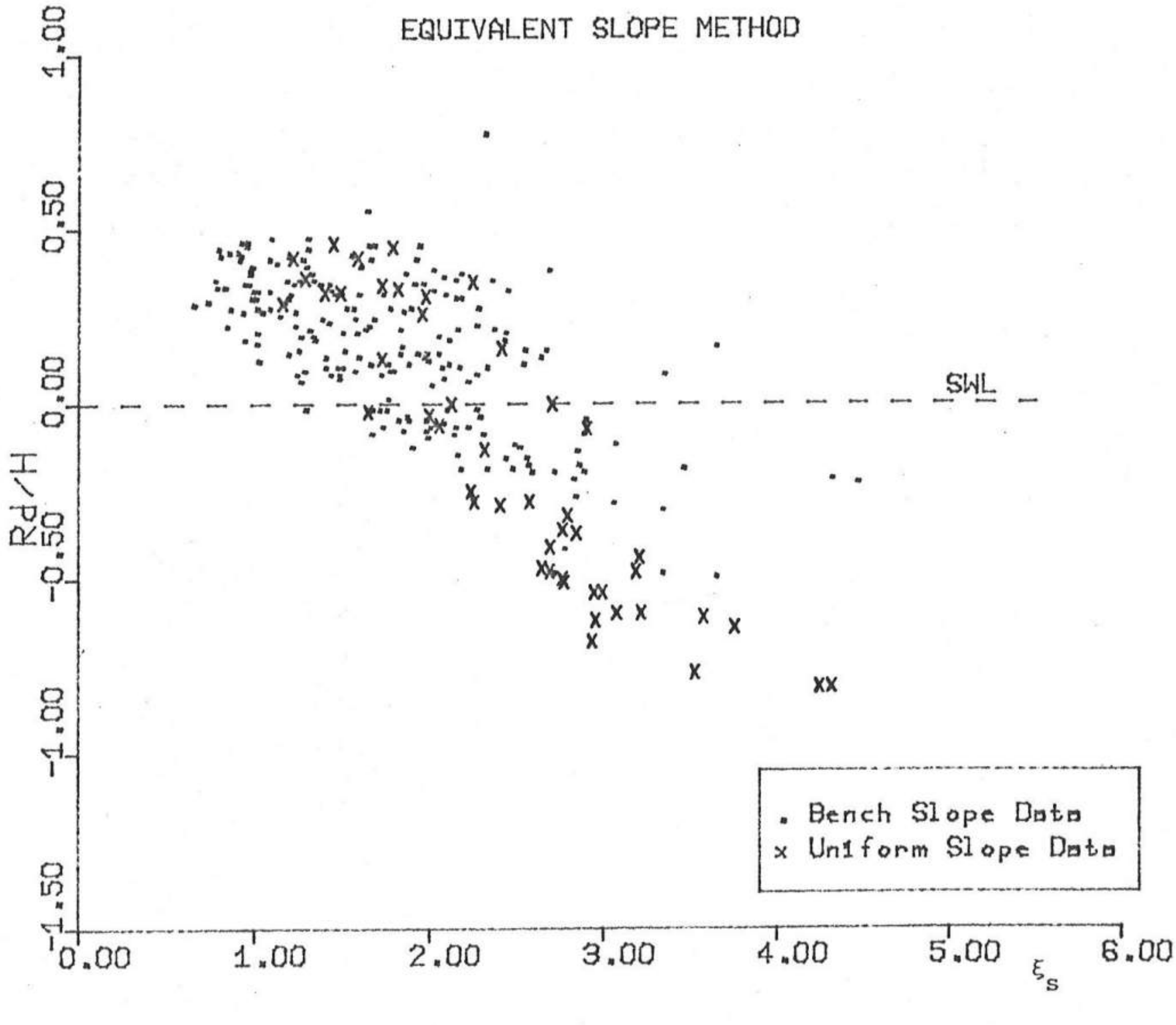

Figure 19. R_d/H vs. ξ_s for Bench Slope Tests (m = 0)

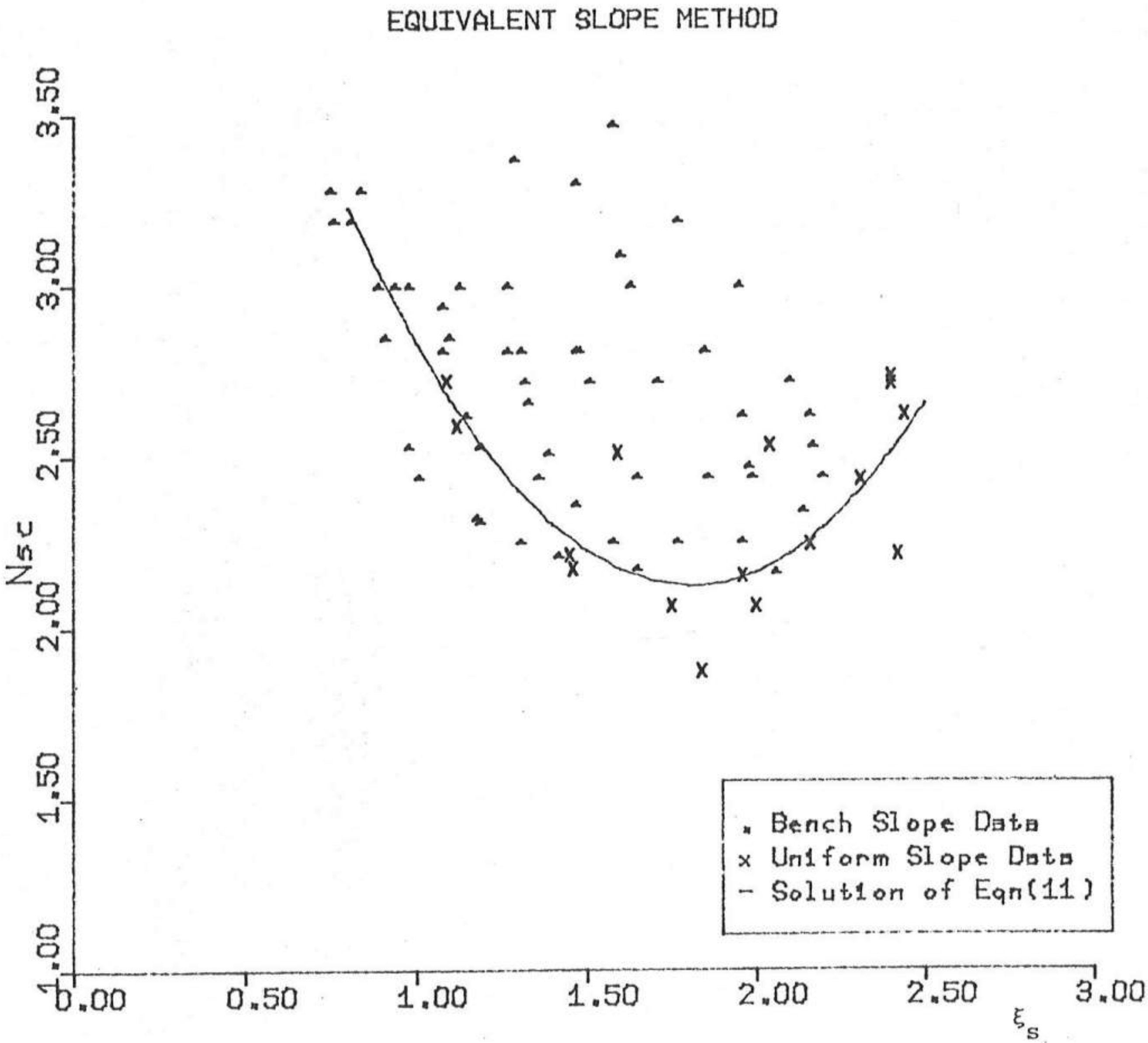

Figure 20. N_{sc} vs. ξ_s for Bench Slope Tests (m = 0)

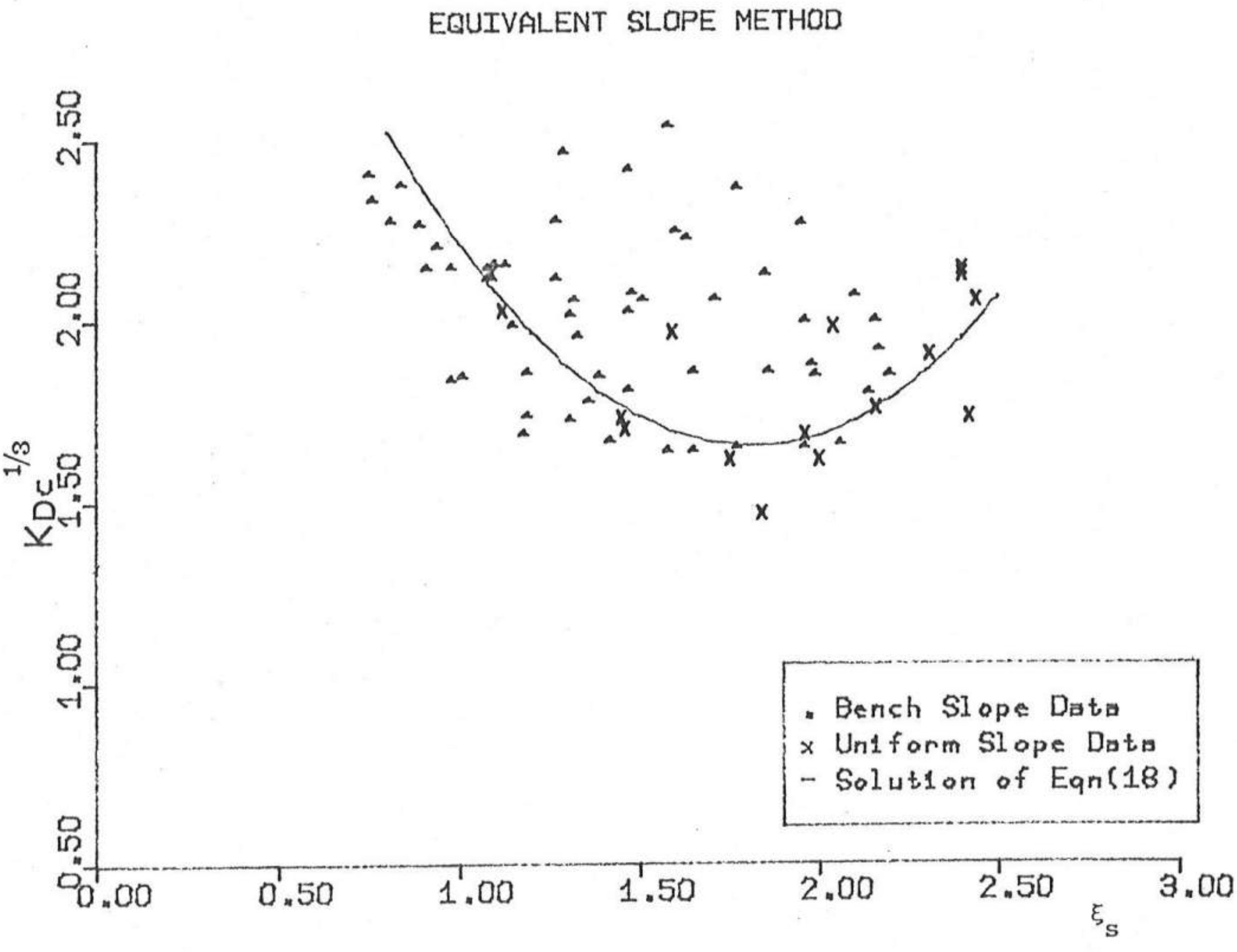

Figure 21. K_{Dc} vs. ξ_s for Bench Slope Tests (m = 0)

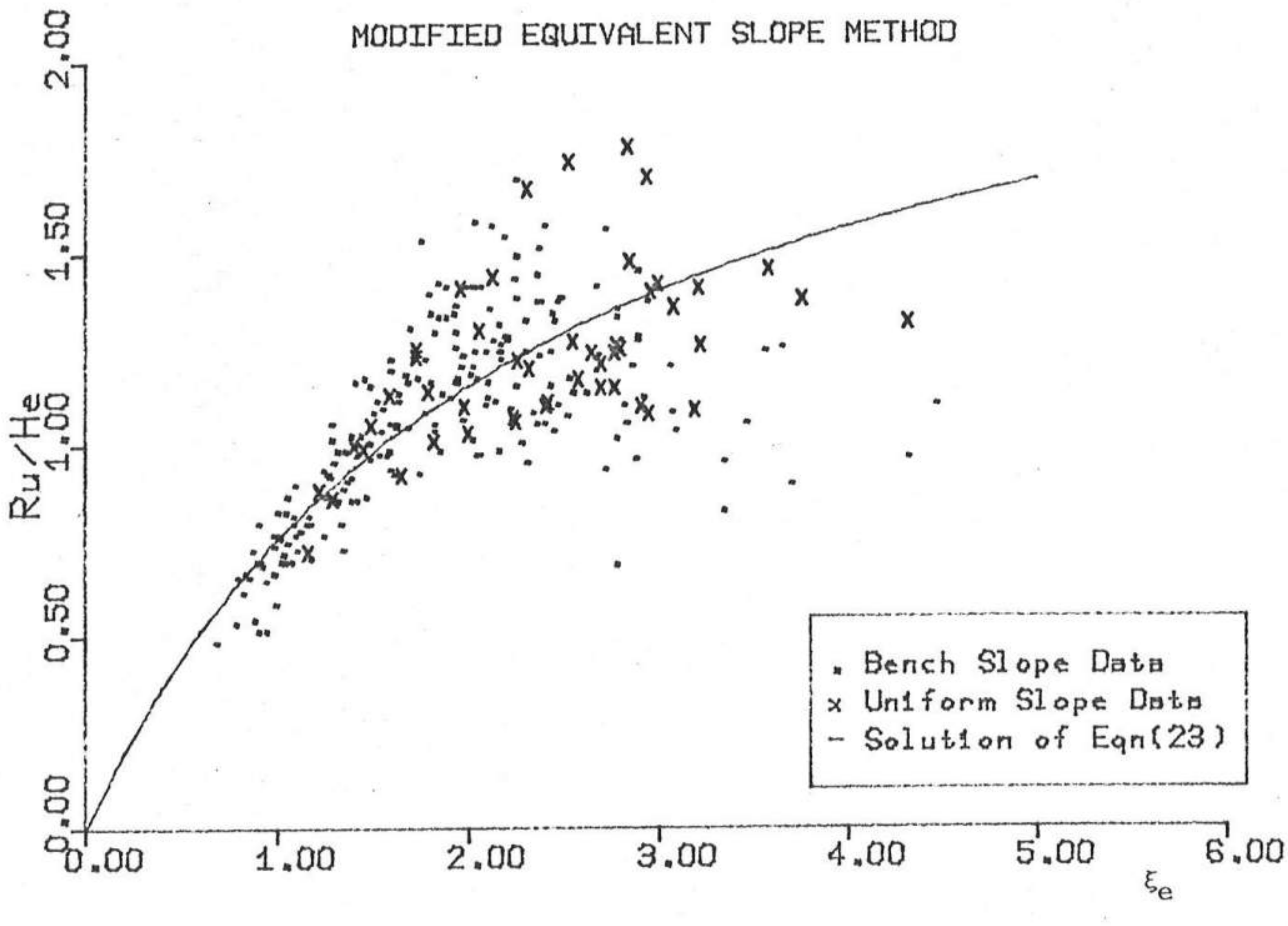

Figure 22. R_u/H_e vs. ξ_e for Bench Slope Tests (m = 1/2)

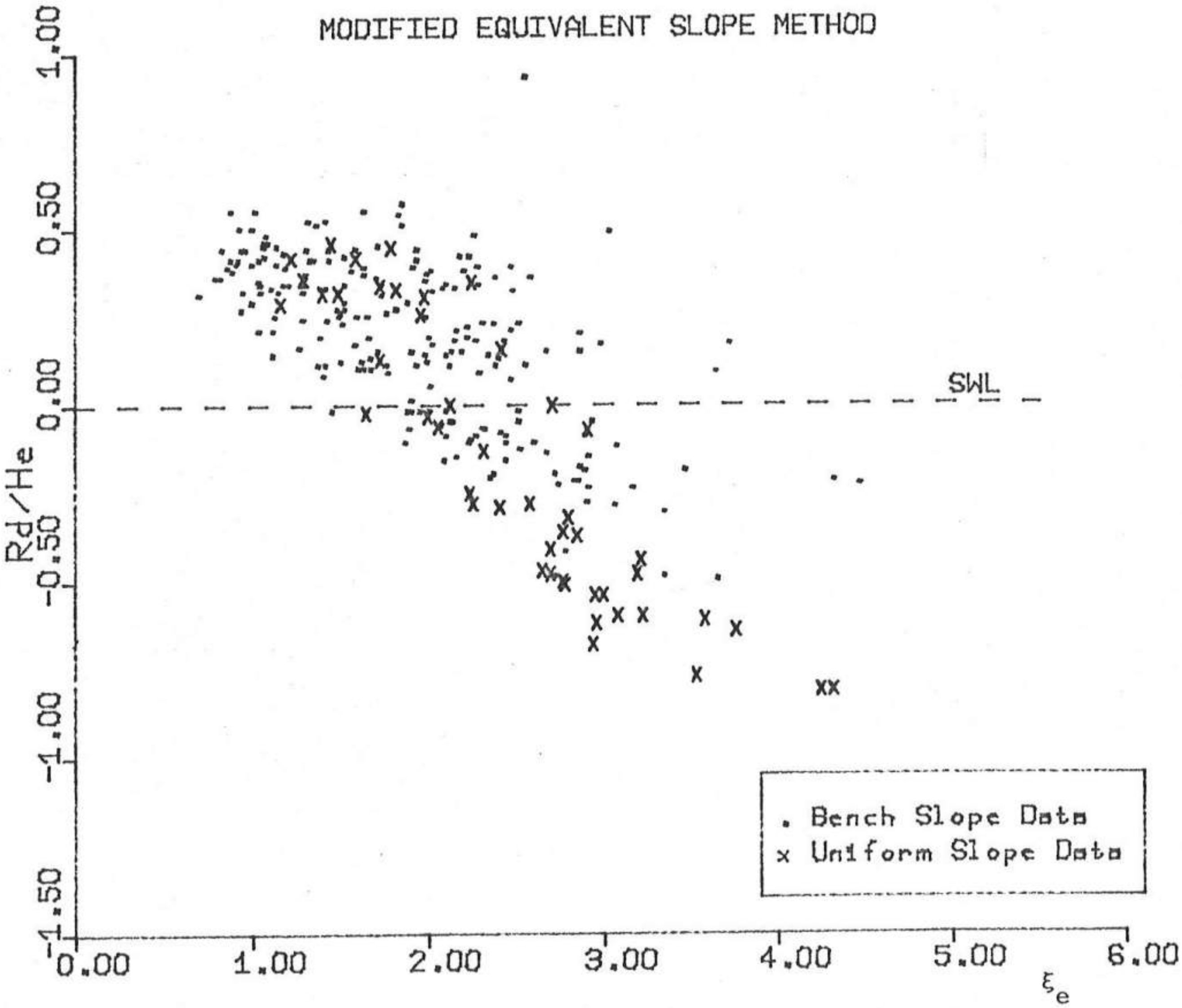

Figure 23. R_d/H_e vs. ξ_e for Bench Slope Tests (m = 1/2)

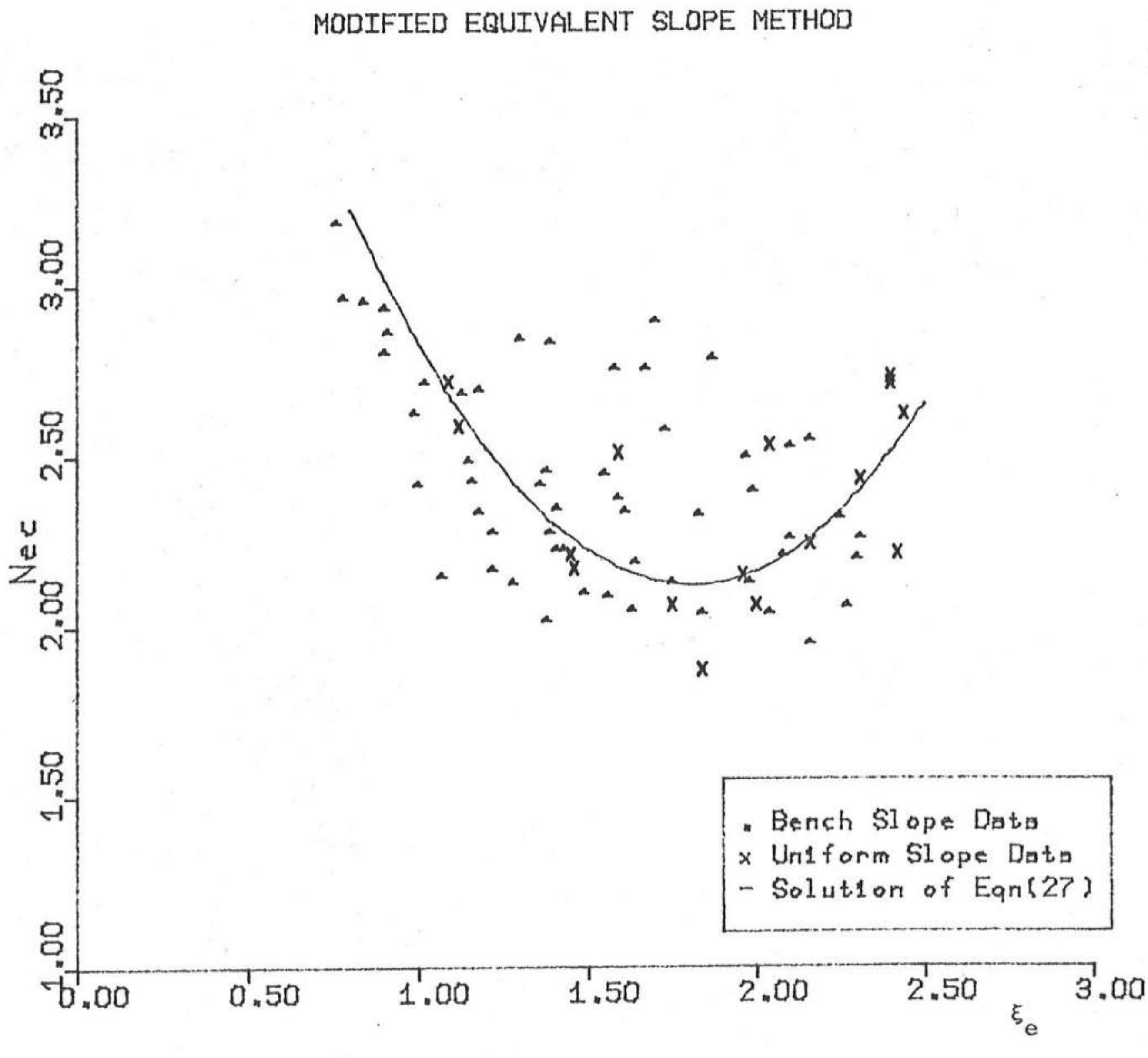

Figure 24. N_{ec} vs. ξ_e for Bench Slope Tests (m = 1/2)

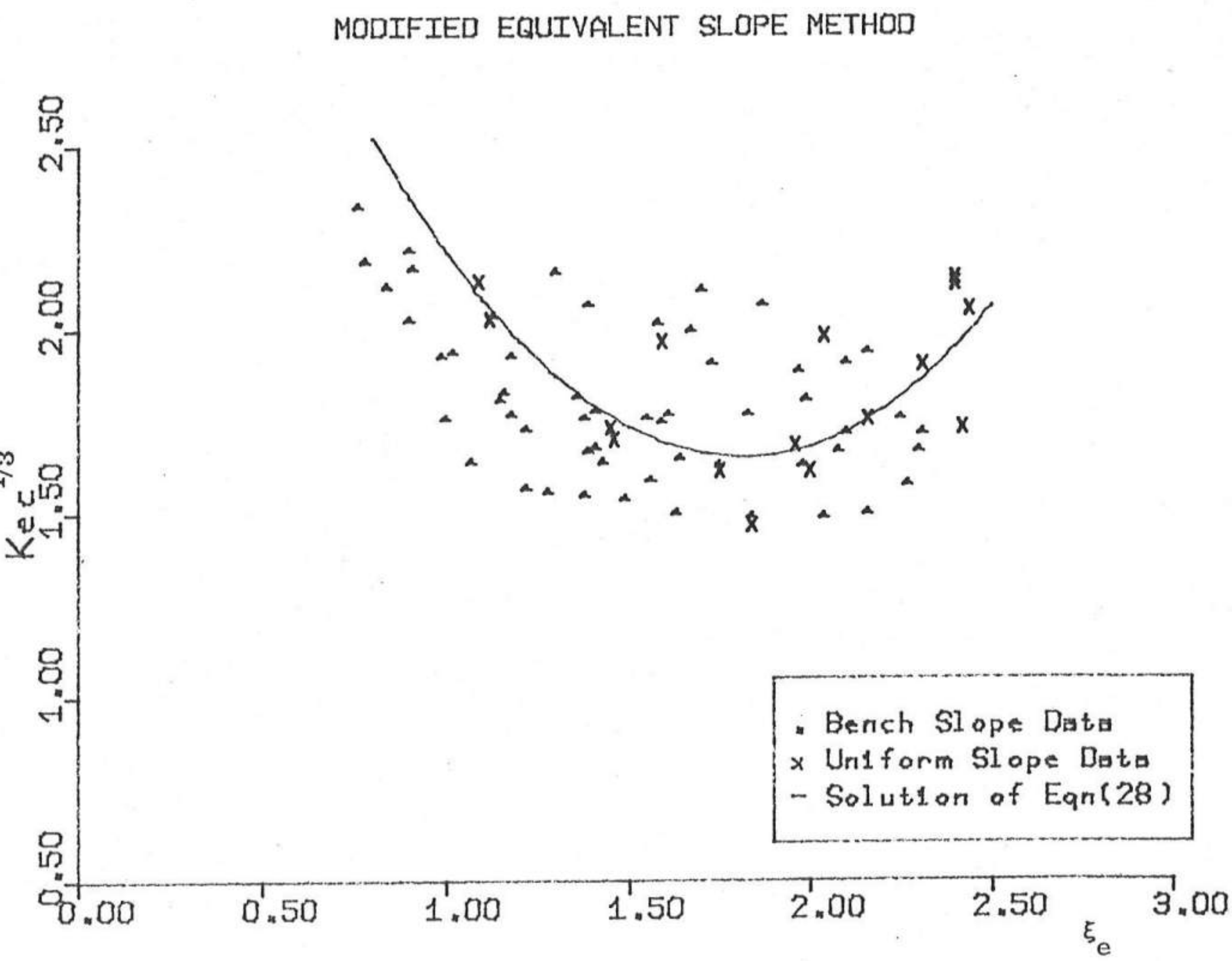

Figure 25. K_{ec} vs. ξ_e for Bench Slope Tests (m = 1/2)

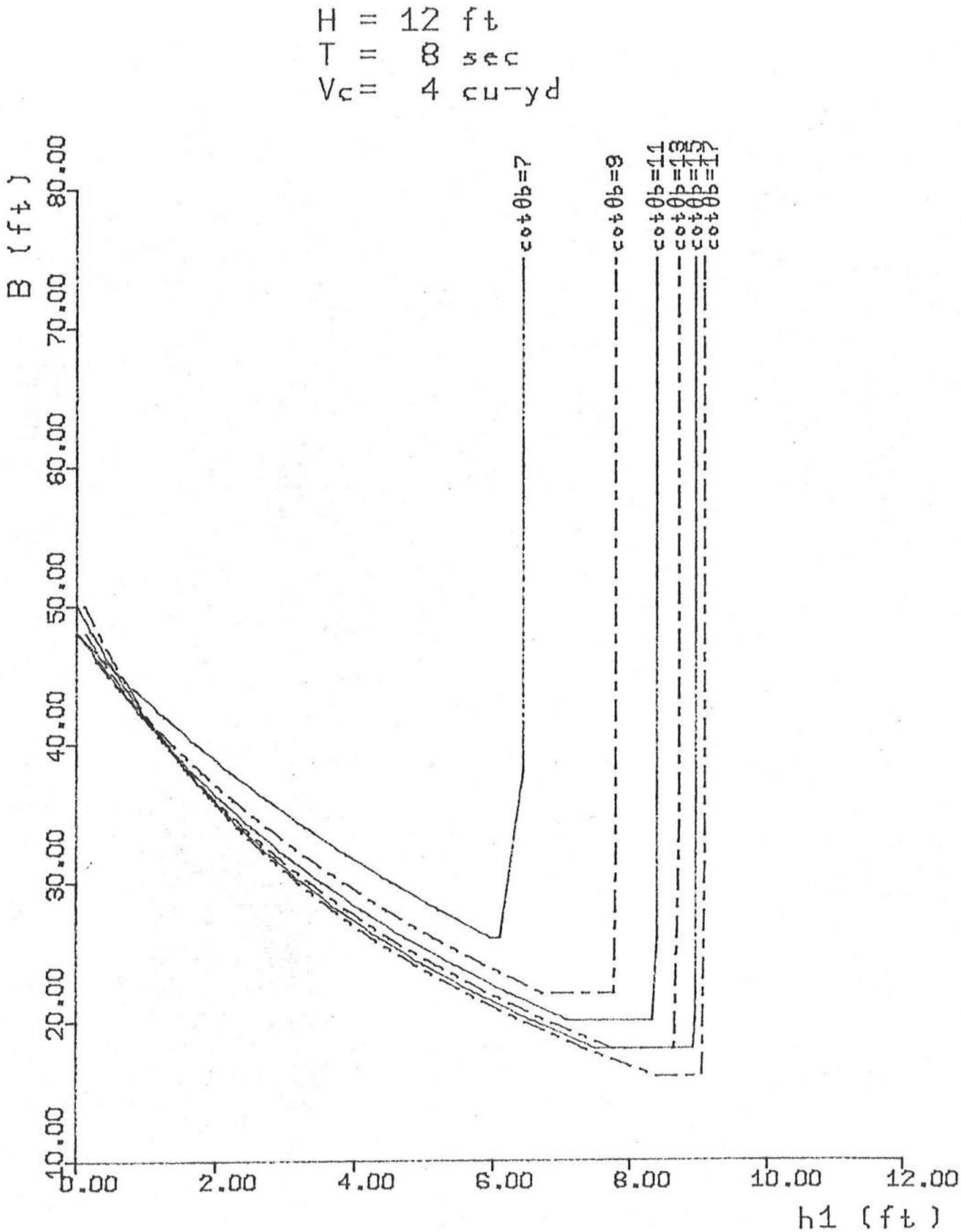

Figure 26. Critical Relationship of B, $\cot\theta_B$ and h_1 for $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, $V_c = 4\ yd^3$

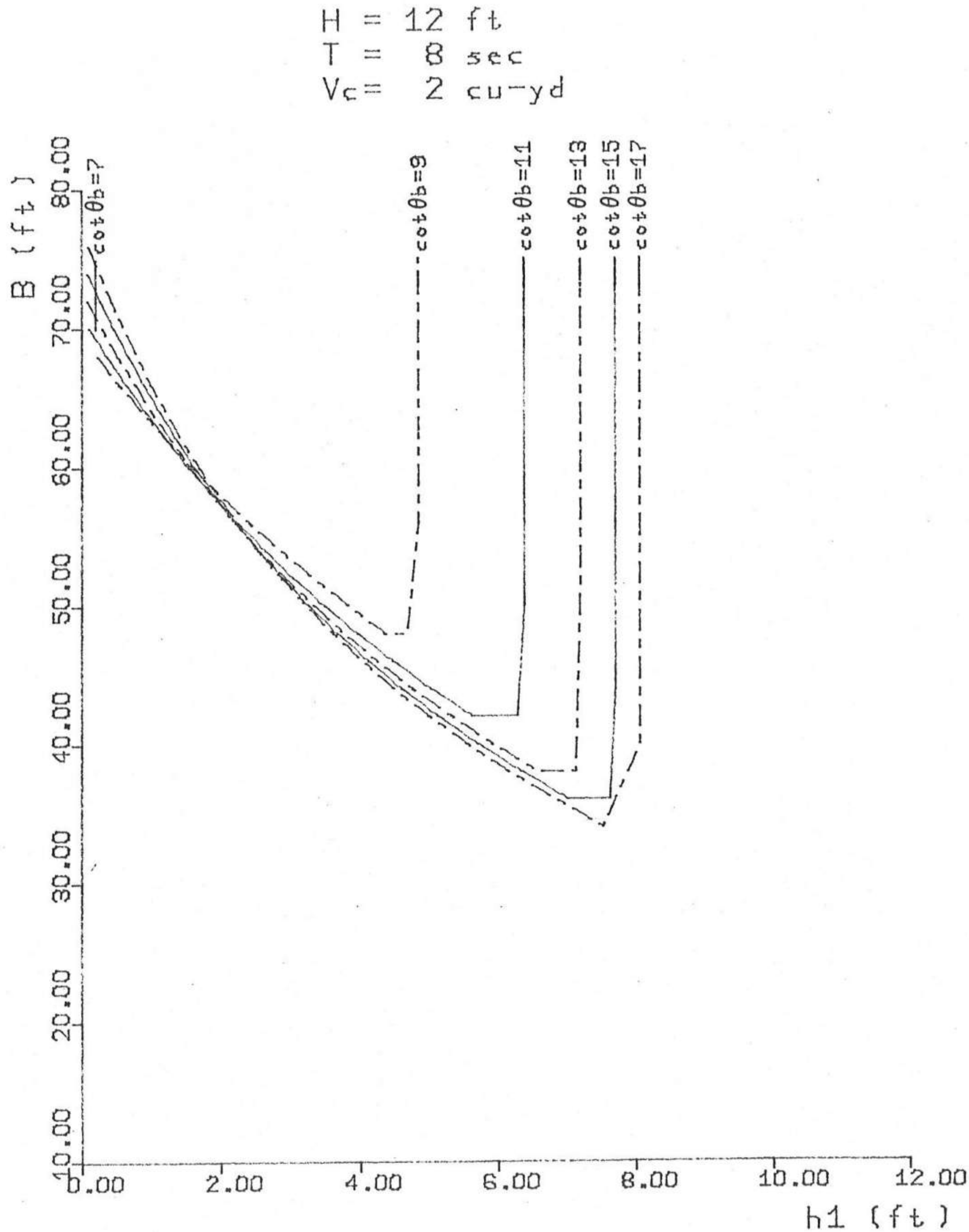

Figure 27. Critical Relationship of B, $\cot\theta_B$ and h_1 for $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, $V_c = 2\ yd^3$

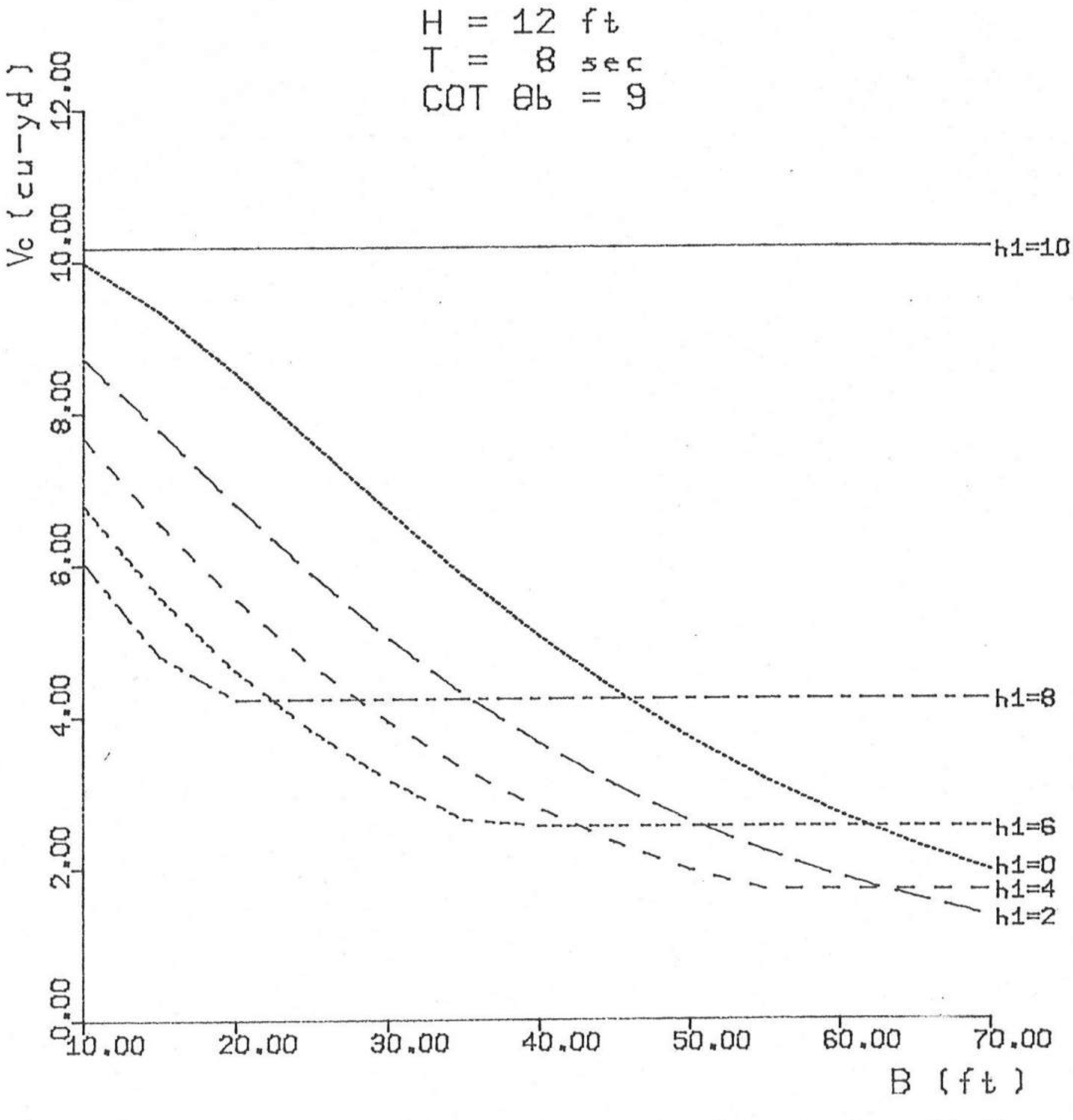

Figure 28. Relationship Between V_c and B for Different Values of h_1 in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, $\cot\theta_B = 9$

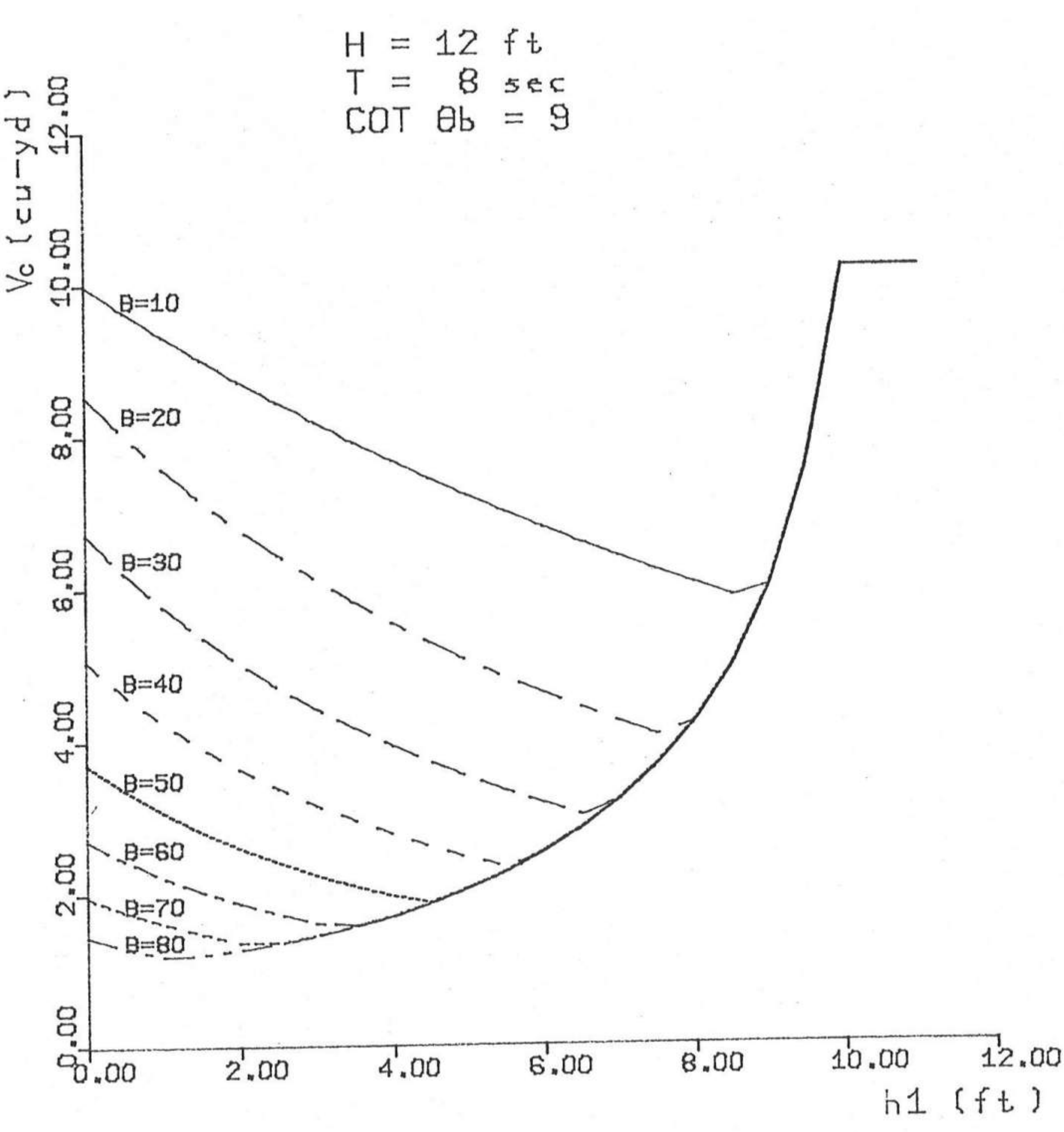

Figure 29. Relationship Between V_c and h_1 for Different Values of B in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, $\cot\theta_B = 9$

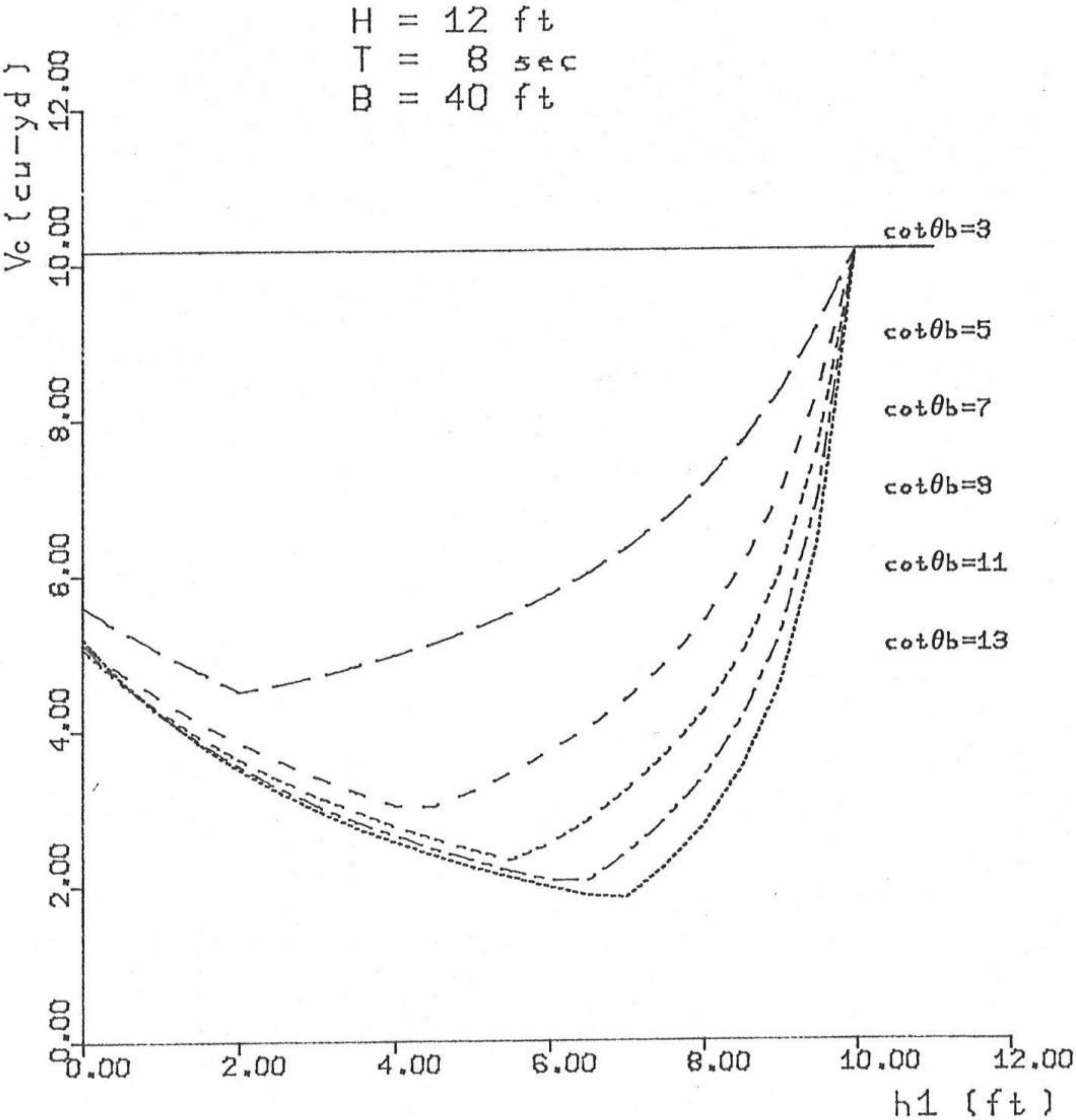

Figure 30. Relationship Between V_c and h_1 for Different Values of $\cot\theta_B$ in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, B = 40 ft

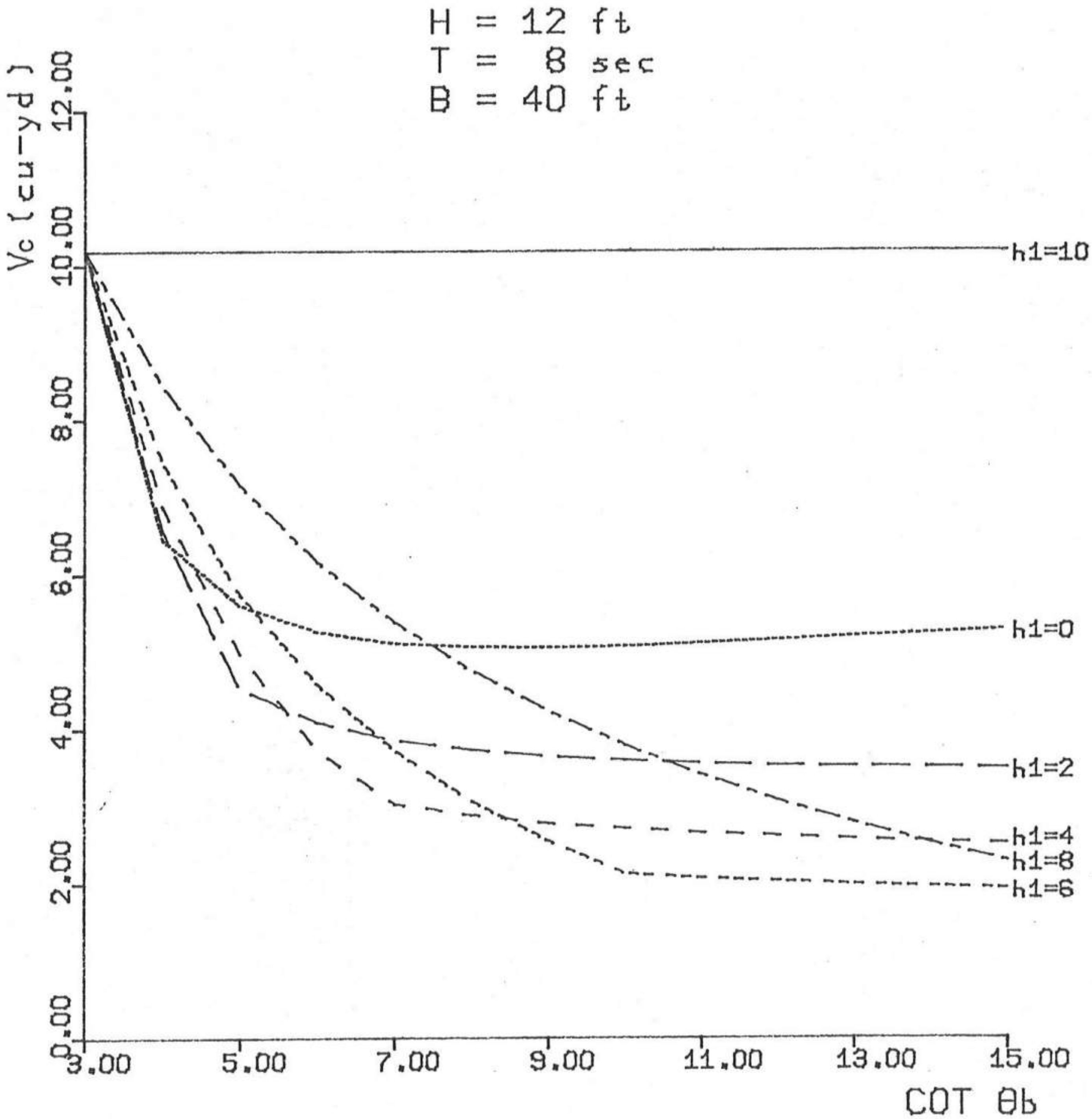

Figure 31. Relationship Between V_c and $\cot\theta_B$ for Different Values of h_1 in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, B = 40 ft

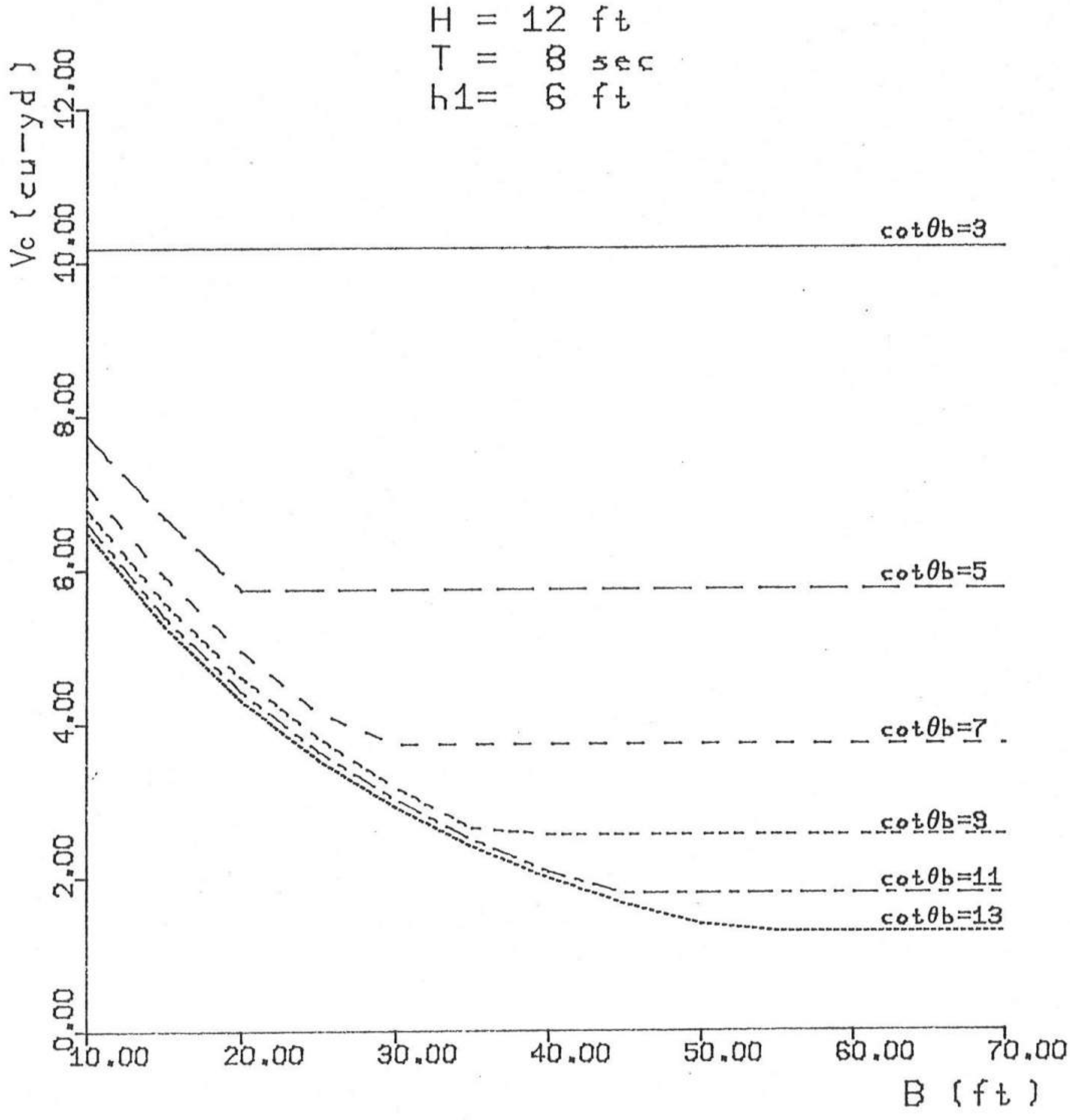

Figure 32. Relationship Between V_c and B for Different Values of $\cot\theta_B$ in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, h_1 = 6 ft

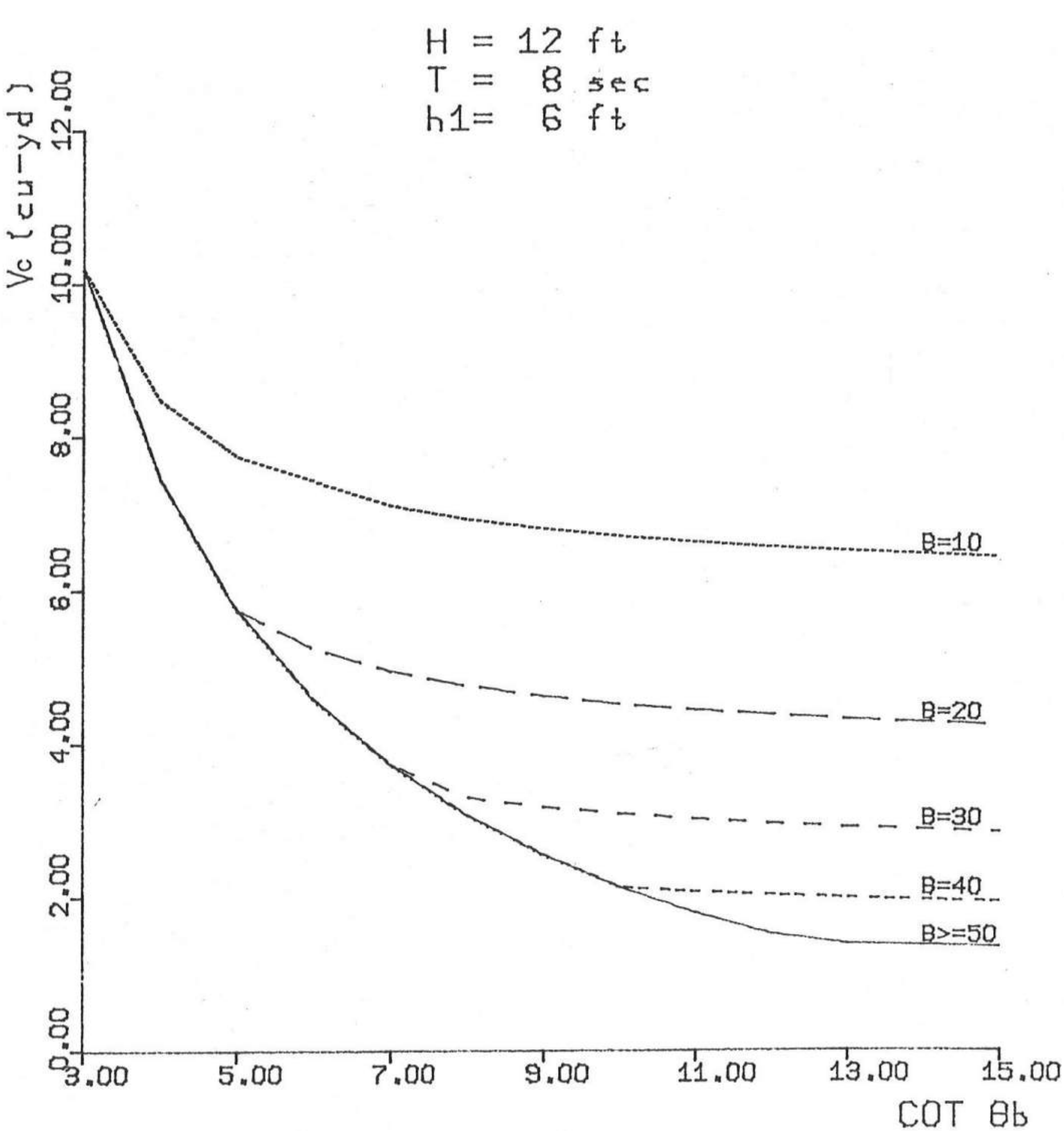

Figure 33. Relationship Between V_c and $\cot\theta_B$ for Different Values of B in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, h_1 = 6 ft

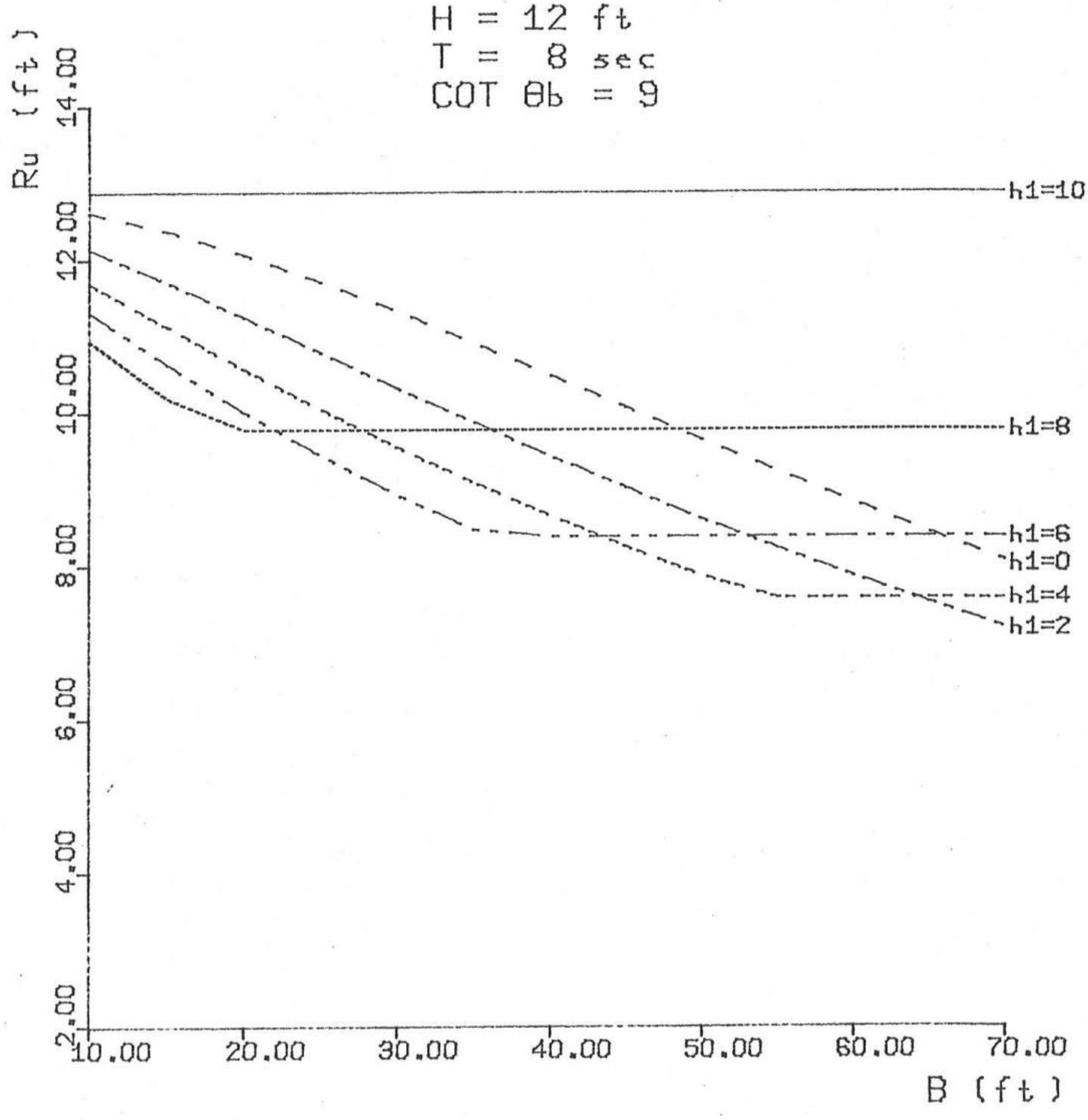

Figure 34. Relationship Between R_u and B for Different Values of h_1 in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, $\cot\theta_B = 9$

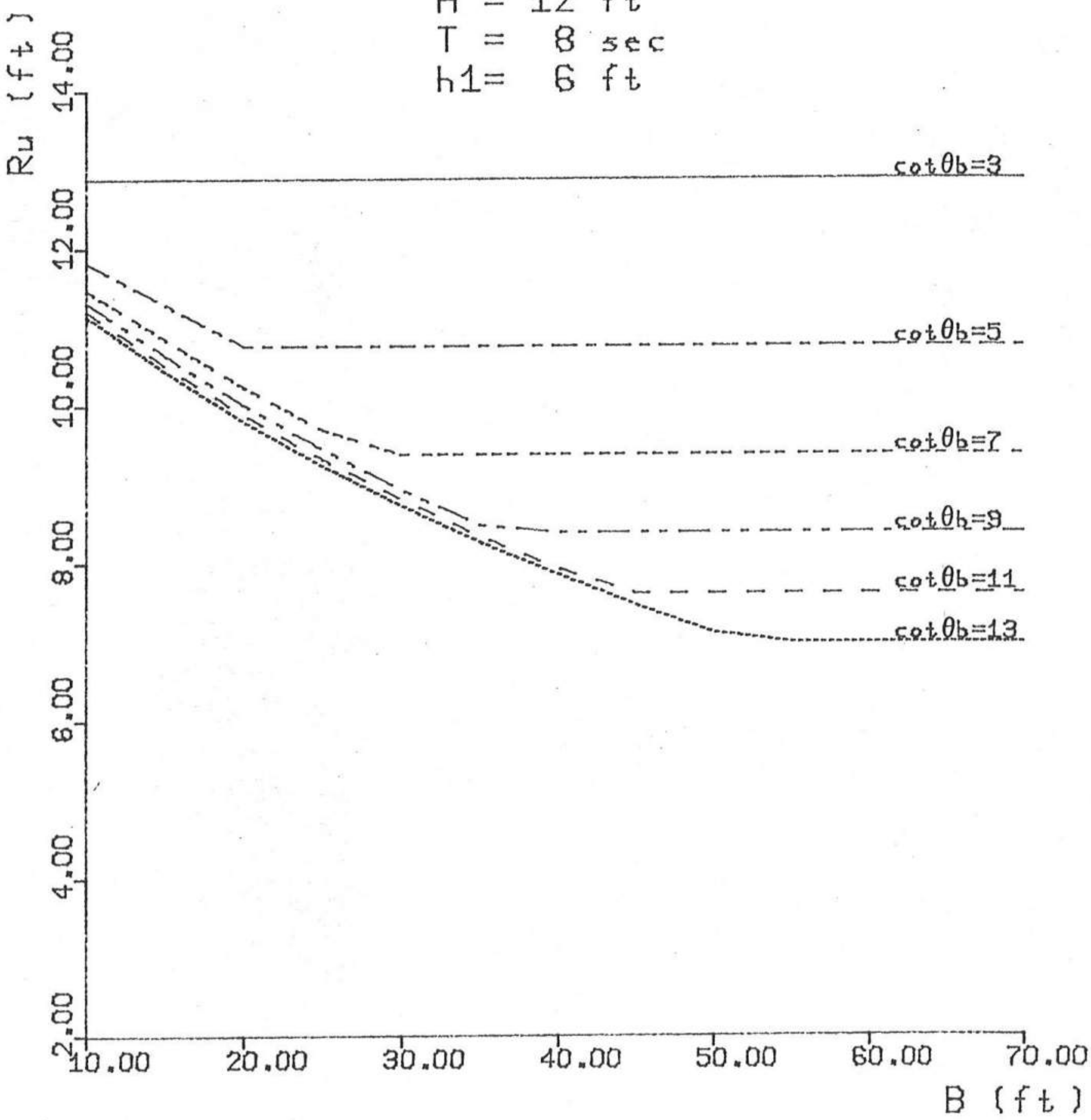

Figure 35. Relationship Between R_u and B for Different Values of $\cot\theta_B$ in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, h_1 = 6 ft

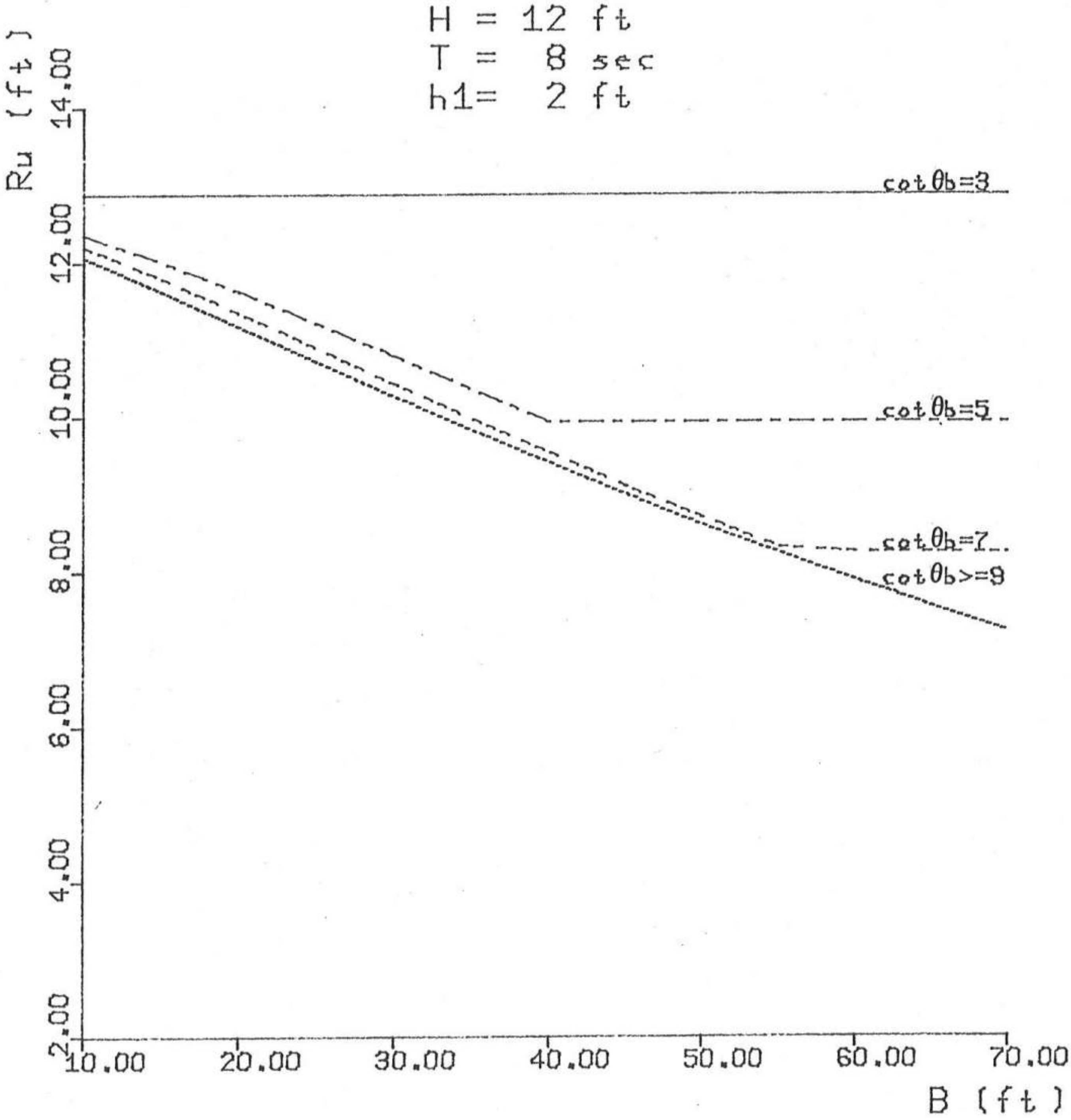

Figure 36. Relationship Between R_u and B for Different Values of $\cot\theta_B$ in Which $\cot\theta_1 = \cot\theta_2 = 3$, H = 12 ft, T = 8 sec, h_1 = 2 ft

Table 1. Empirical Runup Coefficients, a_1 and b_1, for the Different Underlayer Materials and Placement Methods from Uniform Slope Tests

Placement	Backing	a_1	b_1
single layer	quartz sand	1.2	0.55
single layer	gravel	1.25	0.40
single layer	impermeable	1.3	0.40
single layer	coconut hair	1.1	0.45
50% overlap	coconut hair	1.0	0.40

Table 2. Empirical coefficients, a_2, b_2 and c_2, Associated with Critical Stability Number N_{sc} for Different Underlayer Materials and Placement Methods from Uniform Slope Tests and Observed Standard Deviation of N_{sc}

Placement	Backing	a_2	b_2	c_2	Standard Deviation
single layer	gravel	0.20	-0.92	3.15	0.2408
single layer	impermeable	2.07	-6.63	7.85	0.4022
single layer	coconut hair	1.11	-3.97	5.69	0.1996
50% overlap	coconut hair	1.70	-3.89	4.68	0.1771

Table 3. Empirical Runup Coefficients, a_1 and b_1, and Stability Curve Coefficients, a_3, b_3, and c_3, for Different Underlayer Materials and Placement Methods from Uniform Slope Tests

Placement	Backing	a_1	b_1	a_3	b_3	c_3
single layer	gravel	1.25	0.40	0.15	-0.72	2.46
single layer	impermeable	1.30	0.40	1.62	-5.19	6.15
single layer	coconut hair	1.10	0.45	0.86	-3.11	4.46
50% overlap	coconut hair	1.00	0.40	1.33	-3.05	3.66

Table 4. Summary of Parameters and Coefficients Used in Example Computations

Parameter/ Coefficient	Uniform Slope Computation	Bench Slope Computation
H	12 ft	
T	8 sec	
a_1	1.1	
b_1	0.45	
a_3	0.86	
b_3	-3.11	
c_3	4.46	
$\cot\theta_1$	3	
$\cot\theta_2$	3	
B	0 ft	40 ft
$\cot\theta_B$	3	9
h_1	0 ft	6 ft
m	1/2	
n	2/3	
γ	120 pcf	
γ_w	64 pcf	
α_b	1.2	

Table 5. Input and Output of Example Uniform Slope Computation

WAVE RUNUP AND SANDBAG STABILITY ON BENCH SLOPES

DESIGN PARAMETERS

(INPUT)

Wave Height :	H =	12.00 ft
Wave Period :	T =	8.00 sec
Runup Coefficients :	a1 =	1.10
	b1 =	0.45
Stability Coefficients :	a3 =	0.86
	b3 =	-3.11
	c3 =	4.46
Slope Characteristics :	cot 01 =	3.00
	cot 02 =	3.00
	B =	0.00 ft
	cot 0b =	3.00
	h1 =	0.00 ft
Sandbag Characteristics :	Unit Wt. =	120.00 pcf
Breaker Index :	Alpha =	1.20

(OUTPUT)

Vertical Runup Height :	Ru =	12.89 ft
Required Weight of Sandbag :	Wc =	16.50 tons
Required Volume of Sandbag :	Vc =	10.19 cu-yd
Cotangent of Equiv. Slope :	cot 0e =	3.00

Table 6. Input and Output of Example Bench Slope Computation

WAVE RUNUP AND SANDBAG STABILITY ON BENCH SLOPES

DESIGN PARAMETERS

(INPUT)

Wave Height :	H =	12.00 ft
Wave Period :	T =	8.00 sec
Runup Coefficients :	a1 =	1.10
	b1 =	0.45
Stability Coefficients :	a3 =	0.86
	b3 =	-3.11
	c3 =	4.46
Slope Characteristics :	cot 01 =	3.00
	cot 02 =	3.00
	B =	40.00 ft
	cot 0b =	9.00
	h1 =	6.00 ft
Sandbag Characteristics :	Unit Wt. =	120.00 pcf
Breaker Index :	Alpha =	1.20

(OUTPUT)

Vertical Runup Height :	Ru =	8.87 ft
Required Weight of Sandbag :	Wc =	4.91 tons
Required Volume of Sandbag :	Vc =	3.03 cu-yd
Cotangent of Equiv. Slope :	cot 0e =	4.27

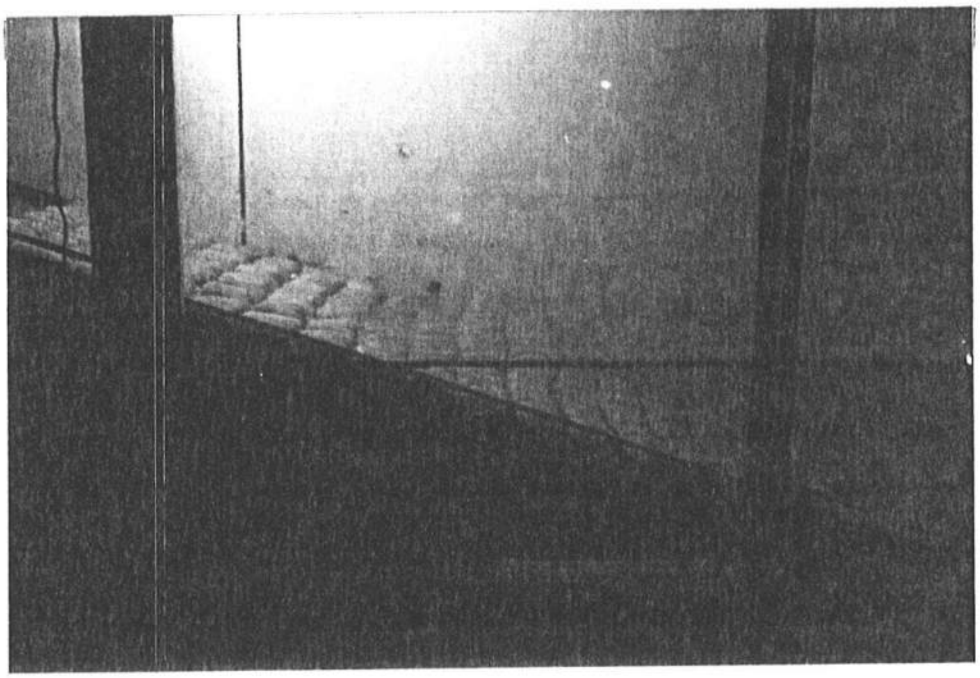

Photo 1. Uniform 1:3 Slope with Single Layer Sandbag Placement

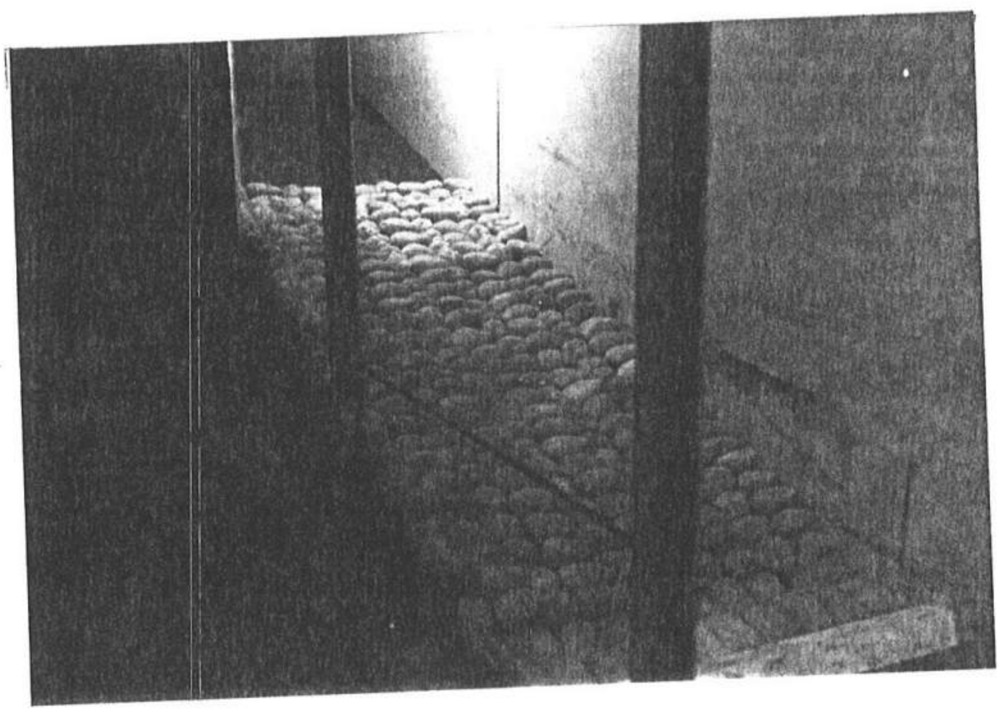

Photo 2. Uniform 1:3 Slope with 50% Overlap Sandbag Placement

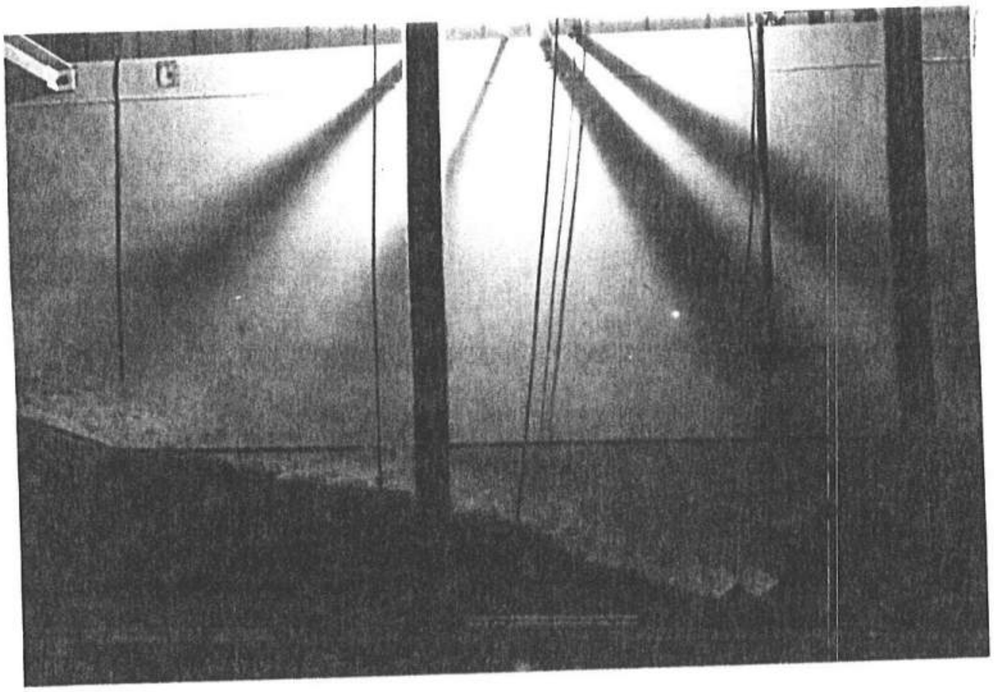

Photo 3. Benched Slope Configuration with Single Layer Sandbag Placement

APPENDIX A

IRREGULAR WAVE OVERTOPPING ON GRAVEL ISLANDS

Analysis procedures for statistical estimation of irregular wave runup and overtopping on gravel islands were developed by Kobayashi and Reece (1983). To facilitate the required computation, a computer program was developed by Seo Seung Nam, a graduate student in the Department of Civil Engineering, University of Delaware, under the supervision of Prof. Kobayashi. The basic flow diagram of the program is shown in Fig. A-1. The notations and equations used in the program are the same as those used in the original paper by Kobayashi and Reece (1983).

The set of input data required for the computation is composed of the following parameters:

D_T = top diameter of gravel island (ft)

$\tan\beta$ = side slope of gravel island

d_s = water depth below design water level (ft)

$\sqrt{8m_o}$ = root-mean-square wave height of incient irregular waves (ft)

$\overline{T}$ = mean zero up-crossing period of incident irregular waves (sec)

ε = spectral bandwidth parameter

$\overline{t}$ = mean value of normalized wave period ($\simeq 1$)

a = runup coefficient in Eq. (3) (Kobayashi and Reece, 1983)

b = runup coefficient in Eq. (3) (Kobayashi and Reece, 1983)

Q_* = wave overtopping coefficient in Eq. (22) (Kobayashi and Reece, 1983)

α_* = wave overtopping coefficient in Eq. (22) (Kobayashi and Reece, 1983)

C = parameter given in Figure 5 (Kobayashi and Reece, 1983)

These input data must be provided through a keyboard where the program is written for interactive computing rather than for batch processing. This program employs a external subroutine, corresponding to application programs in IMSL Library. The external subroutine computes the complementary error function.

The crest height of a gravel island above the design water level is a design variable and denoted by H_c. The range of the crest height and the increment of the crest height examined in the computation for each set of the input data are specified by the following input parameters:

HcMIN = minimum value of H_c(ft)

HcMAX = maximum value of H_c (ft)

HcINC = increment of H_c (ft)

For each value of the crest height, H_c (ft), computation is made of the following quantities:

$\mathrm{Prob}(R_o > H_c)$ = probability that wave runup exceeds the crest height

$E[v]$ = expected volume of overtopped water per wave (ft^3)

which decrease as the crest height, H_c, is increased.

The computer program is listed in Table A-1. The input and output of three example computations are shown in Tables A-2, A-3 and A-4. The three example computations correspond to the spectral bandwidth parameter ε = 0.5, 0.7 and 0.9, respectively, while the rest of input parameters are the same for the three example computations. The crest height, H_c, is varied from HcMIN = 10 ft to HcMAX = 23 ft by the increment HcINC = 0.5 ft.

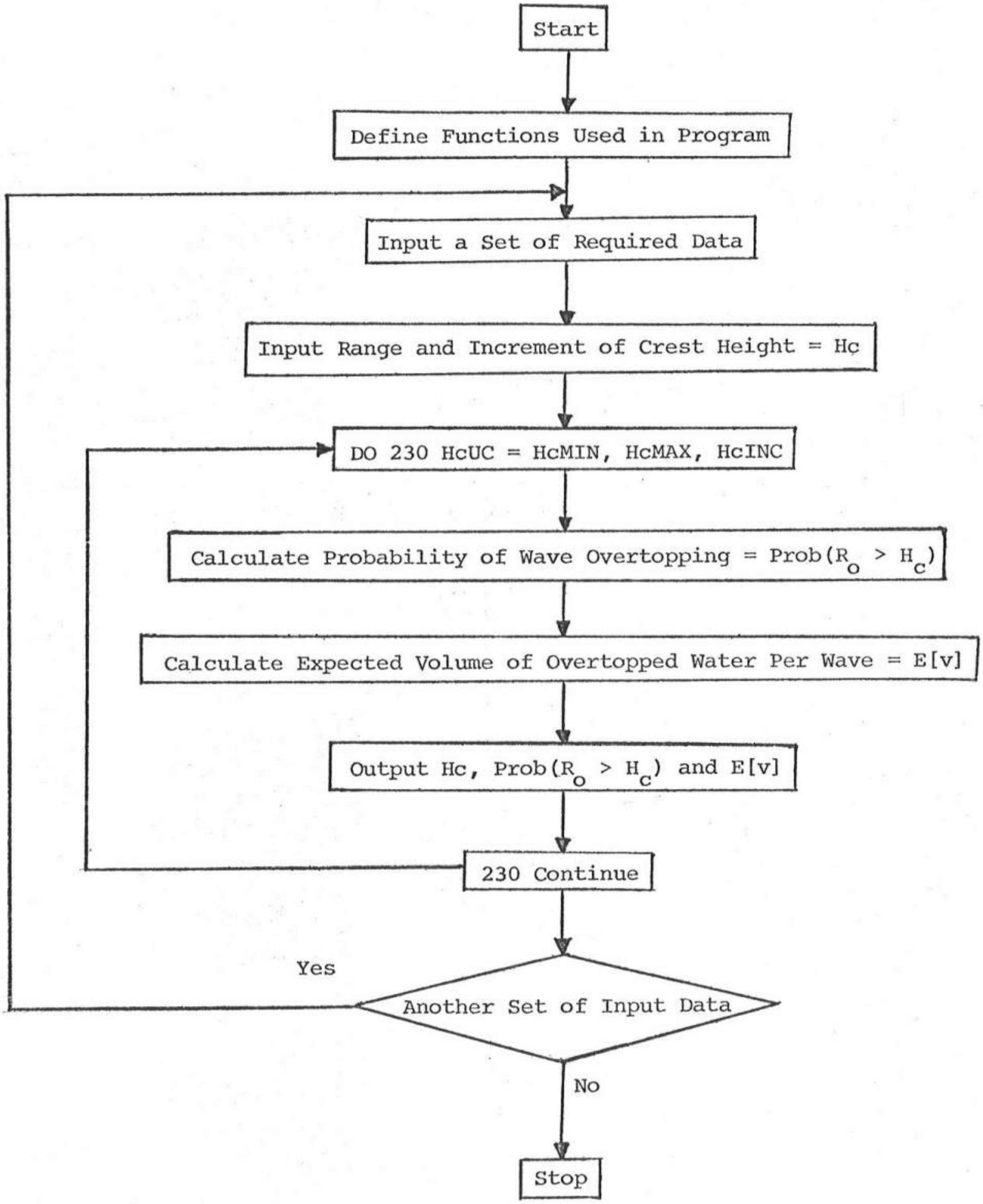

Fig. A-1. Flow Diagram of Program for Computing Irregular Wave Overtopping on Gravel Islands

Table A-1: Listing of Program for Irregular Wave Overtopping on Gravel Islands

```
C     ----------------------------------------------------------------
C      | ONE OF IMSL SUBROUTINES (MERRC, COMPLEMENTED ERROR FUNCTION) |
C      | IS INTRODUCED TO EVALUATE FUNCTION J(r).                     |
C     ----------------------------------------------------------------

          REAL LOWER,k,I,J

C+++++++EXPLANATION OF FUNCTIONS++++++++++++++++++++++++++++++++++++++++
C   u(r)      ; function defined by eq. (21)                           C
C   w(r)      ; function defined by eq. (26)                           C
C   J(r)      ; function defined by eq. (20)                           C
C   TEST(r)   ; function introduced to determine the upper limit of    C
C               eq. (23)                                               C
C   THETAo(r) ; function introduced to simplify the expression of      C
C               eq. (23)                                               C
C   H(r)      ; function intorduced to simplify the expression of      C
C               eq. (23)                                               C
C   I(r)      ; function defined by eq. (25)                           C
C   F(r)      ; integrand of eq. (23)                                  C

C+++++++DESIGNATION OF FUNCTIONS++++++++++++++++++++++++++++++++++++++++
          u(r)      = SIN(ATAN(SQRT(1.-Epsil**2)*(r/p-e**2/Epsil)/e**2))
          w(r)      = p*e**2*(Epsil*SQRT(1.-u(r)**2)/SQRT(1.-Epsil**2)
          1             -u(r))/Epsil
          J(r)      = EXP(r**2)*ERFC(r)
          THETAo(r) = SIN(AMIN1(ACOS(hc/r)/k,phi/2.))
          H(r)      = ((r-hc)/(r+hc))**astar
          TEST(r)   = EXP(-r**2)
          I(r)      = CONST*r**2*(1.-u(r)**2)**2*EXP(-r**2)*((u(r)*r)**2
          1             +1.+3.*w(r)*(u(r)*r+w(r))+SQRphi*w(r)*(1.5+w(r)**2)
          2             *J(u(r)*r))
          F(r)      = THETAo(r)*H(r)*I(r)


C+++++++INPUT DATA TO BE REQUIRED+++++++++++++++++++++++++++++++++++++++
10        TYPE 20
20        FORMAT(' Value of top diameter of gravel island   <DT> : ',$)
          ACCEPT *,DT
          TYPE 30
30        FORMAT(' Value of design water depth   <ds> : ',$)
          ACCEPT *,ds
          TYPE 40
40        FORMAT(' Value of side slope, i.e. 1:Slope   <Slope> : ',$)
          ACCEPT *,Slope
          TYPE 50
50        FORMAT(' Value of characteristic wave height   <RMSW> : ',$)
          ACCEPT *,RMSW
          TYPE 60
60        FORMAT(' Value of mean of normalized wave period  <tbar> : ',$)
          ACCEPT *,tbar
          TYPE 70
70        FORMAT(' Value of mean zero up-crossing period  <TUCbar> : ',$)
          ACCEPT *,TUCbar
          TYPE 80
80        FORMAT(' Value of spectral bandwidth parameter   <Epsil> : ',$)
          ACCEPT *,Epsil
90        TYPE 100
100       FORMAT(' Values of runup coefficient a,b   <a,b> : ',$)
          READ (5,*,ERR=90) a,b
```

```
110     TYPE 120
120     FORMAT(' Values of wave overtopping coefficient'/3X,'Q-star,
        1 Alpha-star   <Qstar,astar> : ',$)
        READ (5,*,ERR=110) Qstar,astar
        TYPE 130
130     FORMAT(' Value of parameter C   <C> : ',$)
        ACCEPT *,C


C+++++++FORMATS OF PRINTOUT++++++++++++++++++++++++++++++++++++++++++
        WRITE (13,140) DT,Slope,ds,RMSW,TUCbar,Epsil,tbar,a,b,Qstar,
        1              astar,C
140     FORMAT (1H1///
        1 ' **********************INPUT***************************'//
        2 3X,'Top diameter of gravel island, DT          : ',F5.0,' ft'/
        3 3X,'Side slope, tan(beta)                      : ',F6.5/
        4 3X,'Design water depth, ds                     : ',F4.0,' ft'/
        5 3X,'Characteristic wave height, RMSW           : ',F3.0,' ft'/
        6 3X,'Mean zero up-crossing period, T-bar        : ',F3.1,' sec'/
        7 3X,'Spectral bandwidth parameter, Epsilon      : ',F3.1/
        8 3X,'Mean of normalized wave period, t-bar      : ',F3.1/
        9 3X,'Runup coefficient, a                       : ',F3.1/
        1 3X,'Runup coefficient, b                       : ',F3.1/
        2 3X,'Wave overtopping coefficient, Q-star       : ',F6.5/
        3 3X,'Wave overtopping coefficient, Alpha-star : ',F3.1/
        4 3X,'Parameter C as a function of Alpha-star    : ',F3.2////)
        WRITE (13,150)
150     FORMAT (' **********************OUTPUT*********************'/
        1 /10X,'Hc',4X,'Prob(Ro>Hc)',8X,'E[v]'//)

C+++++++CONSTANTS++++++++++++++++++++++++++++++++++++++++++++++++++++
C   g ; gravitational acceleration in English units                 C
        g     = 32.2
        phi   = ACOS(-1.)
        Dphi  = 2.*phi    ;  SQRphi = SQRT(phi)

C+++++++EXPLANATION OF PARAMETERS USED IN THE PROGRAM+++++++++++++++++
C   HcUC  ; Berm height of gravel island above design water level   C
C   e     ; Parameter defined by eq. (3)                             C
C   Xistar; Parameter defined by eq. (15)                            C
C   p     ; Parameter defined by eq. (17)                            C
C   Rstar ; Parameter defined by eq. (17)                            C
C   DB    ; Base diametr of gravel island                            C
C   k     ; Parameter defined by eq. (5)                             C
C   CONST ; Parts independant of r in eq. (25)                       C

C+++++++SPECIFY THE RANGE AND INCREMENT OF ISLAND BERM HEIGHT (Hc)+++++
160     TYPE 170
170     FORMAT(' Values of the lower and upper limits'/3X,'<HcMIN,
        1 HcMAX> : ',$)
        READ (5,*,ERR=160) HcMIN,HcMAX
        TYPE 180
180     FORMAT(' Value of the increment of Hc : ',$)
        ACCEPT *,HcINC

        DO  230 HcUC = HcMIN,HcMAX,HcINC
        e = (1.+SQRT(1.-Epsil**2))/2.
        Xistar = Slope*TUCbar*SQRT(g/Dphi/RMSW)/tbar
        p = b*Xistar**2
        Rstar = Epsil*a*RMSW/b
```

```
      CONST = Epsil**2*(1.-Epsil**2)/SQRphi/p**3/e**5
      hc = HcUC/Rstar

C+++++++THE PROBABILITY THAT Ro IS GREATER THAN Hc+++++++++++++++++++
      FrC   = EXP(-hc**2)*(J(hc)-u(hc)*J(u(hc)*hc))/(2.*e)

      DB = DT+2.*(ds+HcUC)/Slope
      d = DB/DT
      k = 2.*ACOS(SQRT((d-1.)/(d+1.)))/phi

C+++++++INTEGRATION USING SIMPSON'S RULE FOR OVERTOPPED VOLUME+++++++++
      SIMPS = 0.
      LOWER = hc
      TIMES = 1.5
190   UPPER = hc*TIMES
      IF (TEST(UPPER) .LT. 1.E-20) GO TO 200
      TIMES = TIMES+.5
      GO TO 190

200   NPART = 300
      SIMPS = SIMPS+F(UPPER)+F(LOWER)
      DELTAR = (UPPER-LOWER)/FLOAT(NPART)
      r1 = LOWER+DELTAR
      r2 = r1+DELTAR
      NPART1 = NPART/2-1
      DO 210 IORDER=1,NPART1
        SIMPS = SIMPS+4.*F(r1)+2.*F(r2)
        r1 = r2+DELTAR
210   r2 = r1+DELTAR
      SIMPS = SIMPS+4.*F(r1)
      SIMPS = SIMPS/3.*DELTAR

      Vstar = C*SQRT(Qstar)*DT*g*(TUCbar/tbar)**2*RMSW

C+++++++EXPECTED VOLUME OF OVERTOPPED WATER PER WAVE+++++++++++++++++
      Evol = SIMPS*Vstar
      WRITE (13,220) HcUC,FrC,Evol
220   FORMAT (9X,F4.1,3X,E10.4,5X,E10.4)

230   CONTINUE
      TYPE 240
240   FORMAT(2X,'DO YOU WANT ANOTHER CALCULATION ?',
      1 /4X,'TYPE YES(Y) OR NO(RETURN) : ',$)
      ACCEPT 250,ANS
250   FORMAT(A1)
      IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') GO TO 10
      CALL EXIT
      END
```

Table A-2: Input and Output of Example Computation I ($\varepsilon = 0.5$)

**********************INPUT**************************

Top diameter of gravel island, DT	: 400. ft
Side slope, tan(beta)	: .33333
Design water depth, ds	: 30. ft
Characteristic wave height, RMSW	: 8. ft
Mean zero up-crossing period, T-bar	: 6.5 sec
Spectral bandwidth parameter, Epsilon	: .5
Mean of normalized wave period, t-bar	: 1.0
Runup coefficient, a	: 1.1
Runup coefficient, b	: .5
Wave overtopping coefficient, Q-star	: .00013
Wave overtopping coefficient, Alpha-star	: 1.7
Parameter C as a function of Alpha-star	: .57

**********************OUTPUT*********************

Hc	Prob(Ro>Hc)	E[v]
10.0	.3956E+00	.7760E+03
10.5	.3522E+00	.6098E+03
11.0	.3101E+00	.4742E+03
11.5	.2697E+00	.3646E+03
12.0	.2316E+00	.2772E+03
12.5	.1961E+00	.2082E+03
13.0	.1637E+00	.1545E+03
13.5	.1345E+00	.1132E+03
14.0	.1087E+00	.8180E+02
14.5	.8644E-01	.5835E+02
15.0	.6751E-01	.4107E+02
15.5	.5177E-01	.2853E+02
16.0	.3897E-01	.1955E+02
16.5	.2877E-01	.1322E+02
17.0	.2085E-01	.8835E+01
17.5	.1481E-01	.5832E+01
18.0	.1033E-01	.3807E+01
18.5	.7071E-02	.2459E+01
19.0	.4754E-02	.1574E+01
19.5	.3142E-02	.9989E+00
20.0	.2044E-02	.6296E+00
20.5	.1310E-02	.3944E+00
21.0	.8282E-03	.2459E+00
21.5	.5173E-03	.1527E+00
22.0	.3197E-03	.9452E-01
22.5	.1957E-03	.5838E-01
23.0	.1189E-03	.3601E-01

Table A-3: Input and Output of Example Computation II ($\varepsilon = 0.7$)

***********************INPUT***************************

Top diameter of gravel island, DT	: 400. ft
Side slope, tan(beta)	: .33333
Design water depth, ds	: 30. ft
Characteristic wave height, RMSW	: 8. ft
Mean zero up-crossing period, T-bar	: 6.5 sec
Spectral bandwidth parameter, Epsilon	: .7
Mean of normalized wave period, t-bar	: 1.0
Runup coefficient, a	: 1.1
Runup coefficient, b	: .5
Wave overtopping coefficient, Q-star	: .00013
Wave overtopping coefficient, Alpha-star	: 1.7
Parameter C as a function of Alpha-star	: .57

***********************OUTPUT**********************

Hc	Prob(Ro>Hc)	E[v]
10.0	.3585E+00	.1298E+04
10.5	.3231E+00	.1082E+04
11.0	.2893E+00	.8982E+03
11.5	.2573E+00	.7423E+03
12.0	.2271E+00	.6109E+03
12.5	.1990E+00	.5005E+03
13.0	.1731E+00	.4083E+03
13.5	.1495E+00	.3317E+03
14.0	.1281E+00	.2683E+03
14.5	.1089E+00	.2162E+03
15.0	.9195E-01	.1735E+03
15.5	.7704E-01	.1387E+03
16.0	.6407E-01	.1104E+03
16.5	.5290E-01	.8765E+02
17.0	.4336E-01	.6933E+02
17.5	.3530E-01	.5467E+02
18.0	.2855E-01	.4297E+02
18.5	.2294E-01	.3368E+02
19.0	.1832E-01	.2633E+02
19.5	.1455E-01	.2053E+02
20.0	.1149E-01	.1597E+02
20.5	.9021E-02	.1240E+02
21.0	.7049E-02	.9601E+01
21.5	.5483E-02	.7421E+01
22.0	.4246E-02	.5725E+01
22.5	.3274E-02	.4408E+01
23.0	.2516E-02	.3388E+01

Table A-4: Input and Output of Example Computation III ($\varepsilon = 0.9$)

**********************INPUT***************************

Top diameter of gravel island, DT	:	400. ft
Side slope, tan(beta)	:	.33333
Design water depth, ds	:	30. ft
Characteristic wave height, RMSW	:	8. ft
Mean zero up-crossing period, T-bar	:	6.5 sec
Spectral bandwidth parameter, Epsilon	:	.9
Mean of normalized wave period, t-bar	:	1.0
Runup coefficient, a	:	1.1
Runup coefficient, b	:	.5
Wave overtopping coefficient, Q-star	:	.00013
Wave overtopping coefficient, Alpha-star	:	1.7
Parameter C as a function of Alpha-star	:	.57

**********************OUTPUT*********************

Hc	Prob(Ro>Hc)	E[v]
10.0	.3249E+00	.2459E+04
10.5	.2969E+00	.2147E+04
11.0	.2703E+00	.1872E+04
11.5	.2453E+00	.1630E+04
12.0	.2218E+00	.1416E+04
12.5	.1998E+00	.1229E+04
13.0	.1794E+00	.1065E+04
13.5	.1605E+00	.9211E+03
14.0	.1432E+00	.7956E+03
14.5	.1272E+00	.6861E+03
15.0	.1127E+00	.5907E+03
15.5	.9949E-01	.5079E+03
16.0	.8755E-01	.4360E+03
16.5	.7681E-01	.3737E+03
17.0	.6717E-01	.3198E+03
17.5	.5857E-01	.2734E+03
18.0	.5092E-01	.2333E+03
18.5	.4414E-01	.1988E+03
19.0	.3816E-01	.1692E+03
19.5	.3290E-01	.1438E+03
20.0	.2829E-01	.1221E+03
20.5	.2426E-01	.1035E+03
21.0	.2076E-01	.8760E+02
21.5	.1772E-01	.7406E+02
22.0	.1508E-01	.6253E+02
22.5	.1281E-01	.5273E+02
23.0	.1086E-01	.4441E+02

APPENDIX B

COMPUTATION OF ARMOR UNIT STABILITY UNDER REGULAR WAVE ACTION

A mathematical model was developed by Kobayashi and Jacobs (1983) for predicting the flow characteristics in the downrush of regular waves and the critical condition for initiation of movement of armor units on a uniform slope. The model may be used to evaluate the variation of the degree of stability of armor units along the slope under the action of design incident waves. This information is needed for designing an efficient slope protection system for a gravel island. A computer program was developed to conduct the computations required for the mathematical model. The basic flow diagram of the program is shown in Fig. B-1. The framework of the computer program is explained following the basic flow diagram.

First, the set of input data required for the computation is composed of the following parameters:

ARMOR	= description of armor type
EPSMIN	= minimum value of nonlinearity parameter ε
EPSMAX	= maximum value of nonlinearity parameter ε
DELX	= increment of normalized horizontal coordinate x^*
DELT	= increment of normalized time t^*
DELEPS	= increment of nonlinearity parameter ε
COTTHE [$\cot\theta$]	= cotangent of structure slope
S [s]	= specific gravity of armor unit

CD $[C_D]$ = drag coefficient of armor unit

CL $[C_L]$ = lift coefficient of armor unit

CM $[C_M]$ = inertia coefficient of armor unit

TANPHI $[\tan\phi]$ = friction coefficient between armor units

AC [A] = coefficient associated with sliding stability

RA [a] = empirical runup coefficient

RB [b] = empirical runup coefficient

DTOH $[d_s/H]$ = water depth at toe of structure, d_s, normalized by incident wave height, H.

in which the variables in the square brackets are those used in the original paper by Kobayashi and Jacobs. This set of input data is to be incorporated into the program through READ statements for batch processing. The input file consists of nine lines whose order and format are shown in Table B-1.

The computation is made for each value of the nonlinearity parameter ε which is increased from EPSMIN to EPSMAX by the specified increment DELEPS. The dimensionless parameter ε is related to the surf similarity parameter and hence to the steepness of incident regular waves relative to the uniform slope of a structure. For each value of ε the following quantities are calculated:

T/TO $[\omega^{-1}]$ = characteristic time associated with wave downrush

SSP $[\xi]$ = surf similarity parameter

R/H [R/H] = runup height, R, normalized by incident wave height, H

TDS $[t_d{}^*]$ = normalized wave rundown time

XMAX $[\varepsilon d_s/R]$ = normalized horizontal coordinate x* of location of structure toe

For the specified value of ε, the normalized time t* is increased from zero to TDS by the specified increment DELT. The computation is limited to the period of wave downrush during which movement of armor units is more likely to be initiated than during wave uprush. The normalized time t* = 0 corresponds to the time when wave uprush is completed and wave rundown begins. Since the instantaneous waterline moves downward along the slope during wave downrush, it is required to compute XS $[x_w^*]$ = normalized location of instantaneous waterline so as to identify the segment of the slope exposed to the hydrodynamic action at the specified time t*.

For each value of t*, the normalized horizontal coordinate x* is varied from XS to XMAX by the specified increment DELX. The following quantities are then computed as a function of x*:

X [x] = linearized horizontal coordinate

T [t] = linearized time

U* [u*] = normalized horizontal velocity

N* $[\eta^*]$ = normalized free surface variation

EU2 $[\varepsilon(u^*)^2]$ = function required for computing N_R and N_L

EF $[\varepsilon F]$ = function required for computing N_R

NZS $[N_R]$ = function associated with stability against downward sliding or rolling

NZL $[N_L]$ = function associated with stability against upward lifting

The linearized variables were introduced to transform the nonlinear problem of wave downrush in terms of t* and x* into the corresponding linear problem in terms of t and x. The computation associated with this transformation requires an iterative procedure. The iteration procedure adopted in the program has been convergent for the range of ε up to $\varepsilon = 18.4$ within the number of iterations specified in the program, that is, NUM = 200. On the other hand, the value of N_R indicates the degree of stability of an armor unit located at x* against downward sliding or rolling, whereas the value of N_L indicates that against upward lifting. The larger N_R and N_L are, the more stable is the armor unit located at given x* for the specified time t*. In the program, the value 999 is used as the maximum printable value and appears wherever the values of N_R and N_L exceed 999. The location of x* corresponding to the minimum value of N_R and N_L is identified and the values of N_R and N_L at this location are stored.

After completing the required computation for each value of ε, the summary of the stability computation is printed. For each value of t*, the location of minimum stability and the corresponding values of N_R and N_L are listed. This summary may be used to evaluate the variation of the degree of stability of armor units along the slope during the period of wave downrush. The last output for each value of ε is the critical stability number for initiation of armor movement defined as the smallest value of N_R and N_L which vary along the slope during the downrush period. The critical stability number is related to the stability coefficient in Hudson's formula. The critical stability number depends on the nonlinearity parameter ε and hence the surf similarity parameter ξ. Consequently, the stability of armor units depends on the height and period of incident waves. It is noted that Hudson's formula neglects the wave period effect which was experimentally shown to be important by a number of investigators.

The program uses the following subroutines for given values of x^*, t^* and ε:

ITRATE: Compute the values of x, t, u^* and η^* using an iterative procedure.

FORCES: Compute the values of $\varepsilon(u^*)^2$ and εF required for calculating N_R and N_L.

STABIL: Compute the values of N_R and N_L and identify the location of minimum stability and the corresponding values of N_R and N_L for given values of t^* and ε.

The program also utilizes the following external subroutines from IMSL Library:

MMBSJN: IMSL Library subroutine to compute Bessel Functions of the first kind of n-th order.

ZREAL1: IMSL Library subroutine to compute the zeros of a real function.

The computer program is listed in Table B-2. An example computation is made using the following input data:

ARMOR = RIP RAP

EPSMIN = 4.0 , EPSMAX = 4.0

DELX = 0.5 , DELT = 0.5

DELEPS = 1.0

COTTHE = 3.5

S = 2.71 , CD = 0.5 , CL = 0.178

CM = 1.5 , TANPHI = 1.19 , AC = 10.8

RA = 1.13 , RB = 0.506

DTOH = 3.0

The output of this example computation is shown in Table B-3.

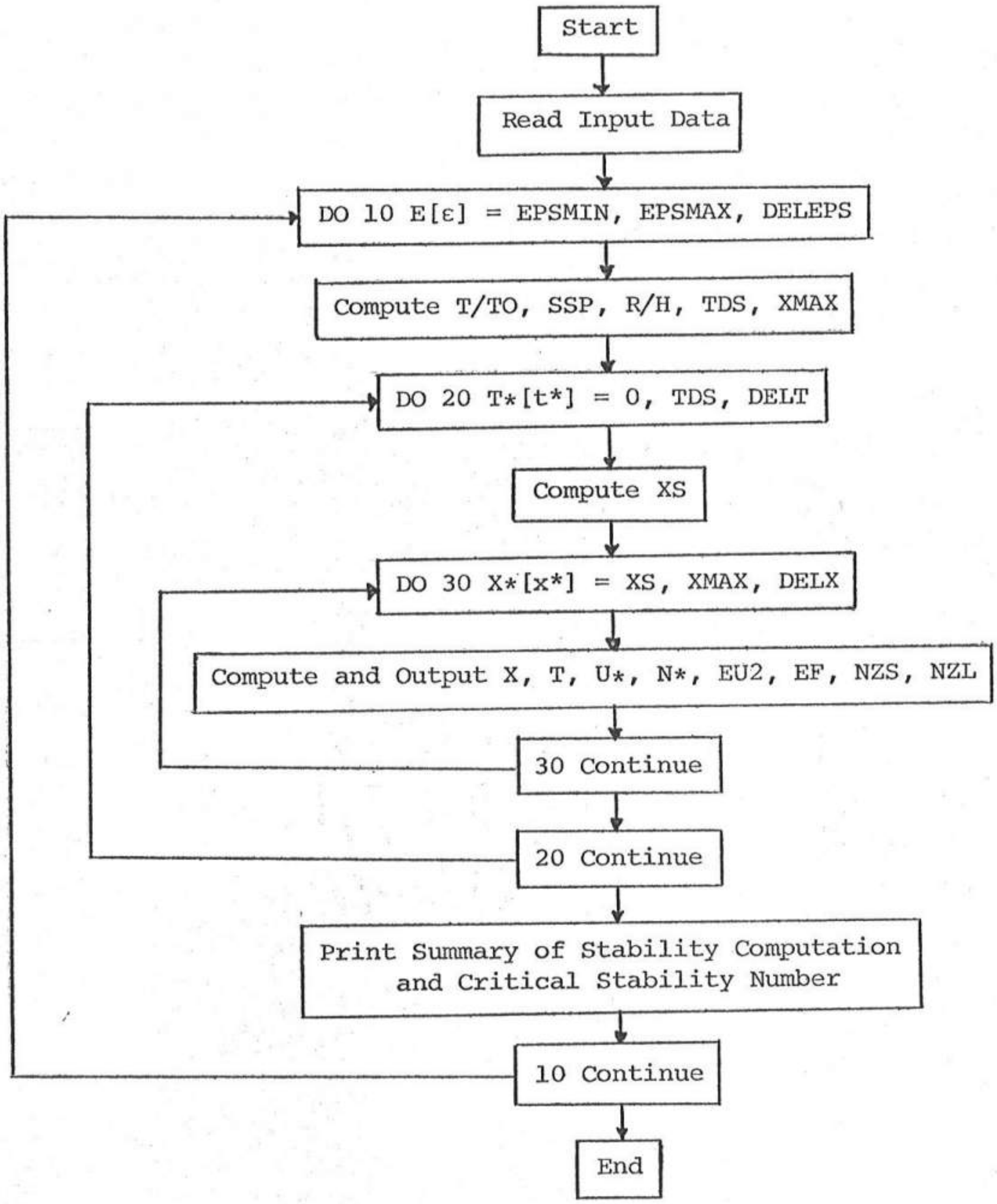

Fig. B-1. Flow Diagram of Program for Computing Armor Unit Stability under Regular Wave Action.

Table B-1. Required Input Parameters and Corresponding Format Statements

Input Parameter	Format
ARMOR	3A5
EPSMIN, EPSMAX	free format
DELX, DELT	free format
DELEPS	free format
COTTHE	free format
S, CD, CL	free format
CM, TANPHI, AC	free format
RA, RB	free format
DTOH	free format

```
00100  C
00200  C           Table B-2.  Listing of Program for Computation of Armor Unit
00300  C                       Stability
00400  C
00500  C     ******************************************************
00600  C     ******************************************************
00700  C     **                                                  **
00800  C     **                    SLOPE.FOR                     **
00900  C     **                                                  **
01000  C     **   A NUMERICAL MODEL TO PREDICT THE FLOW CHARA-   **
01100  C     **   CTERISTICS IN THE DOWNRUSH OF REGULAR WAVES     **
01200  C     **   AND THE CRITICAL CONDITION FOR INITIATION OF   **
01300  C     **   MOVEMENT  OF ARMOR UNITS  ON A UNIFORM SLOPE   **
01400  C     **                                                  **
01500  C     **                                                  **
01600  C     **   THE MODEL COMPUTES VELOCITIES ,WATER SURFACE   **
01700  C     **   ELEVATIONS,AND STABILITY AGAINST SLIDING AND   **
01800  C     **   LIFTING OF UNITS THROUGHOUT  THE  PERIOD  OF   **
01900  C     **   WAVE DOWNRUSH                                  **
02000  C     **                                                  **
02100  C     ******************************************************
02200  C     ******************************************************
02300  C
02400  C
02500  C
02600  C     *****            DECLARATION STATEMENTS            *****
02700  C
02800  C
02900           INTEGER IER,N,N1,N2,NSIG,ITMAX
03000           REAL F,EPS,EPS2,ETA,T(1),SSNM(50),SLNM(50),XXMN(50)
03100           DIMENSION ARMOR(3)
03200           EXTERNAL F
03300             COMMON /ONE/TS,EPSL
03400             COMMON/TWO/XDIF,TDIF
03500             COMMON/THREE/RTOH,SNCMIN,XMIN,J,SSNM,SLNM,XXMN,IJ
03600             COMMON/FOUR/AC,BC,COSTHE,TANPHI,TANTHE,CM,S,SNZMAX
03700             OPEN(UNIT=20,FILE='SLPOUT.DAT')
03800             OPEN(UNIT=21,DEVICE='DSK',FILE='SLOPIN.DAT')
03900  C
04000  C
04100  C
04200  C     THIS PROGRAM MAKES USE OF TWO IMSL LIBRARY SUBROUTINES:
04300  C
04400  C         ZREAL1  :  TO COMPUTE THE ZEROS OF A REAL FUNCTION
04500  C                    STATEMENT NUMBER 42900
04600  C         MMBSJN  :  TO COMPUTE THE BESSEL FUNCTIONS OF
04700  C                    THE FIRST KIND OF N-TH ORDER
04800  C                    STATEMENT NUMBER 51000
04900  C
05000  C
05100  C     *****     IMSL LIBRARY SUBROUTINE PARAMETERS        *****
05200  C
05300           EPS=0.00001
05400           EPS2=0.00001
05500           ETA=0.01
05600           NSIG=5
05700           N1=3
05800           N2=1
05900  C
06000  C
```

```
C
C     *****                 INPUT DATA                        *****
C
C
C                 VARIABLE DESCRIPTIONS
C                 -------- ------------
C
C                  ARMOR  : DESCRIPTION OF ARMOR TYPE
C                  EPSMIN : MINIMUM VALUE OF EPSILON FOR CALCULATIONS
C                  EPSMAX : MAXIMUM VALUE OF EPSILON FOR CALCULATIONS
C                  DELX   : SPACE INCREMENT ALONG SLOPE
C                  DELT   : TIME INCREMENT
C                  DELEPS : INCREMENT IN EPSILON BETWEEN EPSMAX-EPSMIN
C                  COTTHE : COTANGENT OF THE STRUCTURE SLOPE
C                  S      : SPECIFIC GRAVITY OF ARMOR UNIT
C                  CD     : DRAG COEFFICIENT
C                  CL     : LIFT COEFFICIENT
C                  CM     : INERTIA COEFFICIENT
C                  TANPHI : FRICTION FACTOR BETWEEN UNITS
C                  AC     : COEFFICIENT OF SLIDING STABILITY
C                  RA,RB  : EMPIRICAL RUNUP COEFFICIENTS
C                  DTOH   : RELATIVE DEPTH TO XMAX  D/H
C
C
C*****************************************************************
C*****************************************************************
C
C
C
C     ***********************************************************
C     ***********************************************************
C     **                                                       **
C     **     INPUT DESCRIPTION FOR PROGRAM SLOPE.FOR           **
C     **    TO CALCULATE VELOCITY,WATER SURFACE ELEV-          **
C     **    ATION,AND STABILITY ALONG A UNIFORM SLOPE          **
C     **        DURING THE PERIOD OF WAVE DOWNRUSH             **
C     **                                                       **
C     ***********************************************************
C     ***********************************************************
C
C
C            ***************************************
C            *                                     *
C            *       DESCRIPTION OF ARMOR TYPE     *
C            *    MUST BE LESS THAN 16 CHARACTERS  *
C            *                                     *
C ->
           READ(21,14) ARMOR
      14   FORMAT(3A5)
C ->
C            *                                     *
C            ***************************************
C
C
C             ***********************************
C             *                                 *
C             *   ALL DATA IS IN FREE FORMAT    *
C             *                                 *
C             ***********************************
C
```

```
C                                    (Continue)
C
C
C    ****************************************************
C    *                                                  *
C    *                RANGE OF EPSILON                  *
C    *   EPSILON IS PARAMETER OF WAVE CHARACTERISTICS   *
C    *                                                  *
C    *          EPSMIN                  EPSMAX          *
C    *          ------                  ------          *
C    *                                                  *
C ->
         READ(21,*) EPSMIN,EPSMAX
C ->
C    *                                                  *
C    *    EPSMAX MUST BE LESS THAN OR EQUAL TO 18.4     *
C    *                                                  *
C    ****************************************************
C
C
C
C            ********************************
C            *                              *
C            *   SPACE AND TIME INCREMENTS  *
C            *                              *
C            *        DELX        DELT      *
C            *        ----        ----      *
C            *                              *
C ->
         READ(21,*) DELX,DELT
C ->
C            *                              *
C            *------------------------------*
C            *                              *
C            *     INCREMENT OF EPSILON     *
C            *                              *
C            *           DELEPS             *
C            *           ------             *
C            *                              *
C ->
         READ(21,*) DELEPS
C ->
C            *                              *
C            ********************************
C
C
C
C                   **************
C                   *            *
C                   *   SLOPE    *
C                   *            *
C                   *   COTTHE   *
C                   *   ------   *
C                   *            *
C ->
         READ(21,*) COTTHE
C ->
C                   *            *
C                   **************
C
```

(Continue)

```
C
C
C  ***********************************************************
C  *                                                         *
C  *                ARMOR UNIT CHARACTERISTICS               *
C  *                                                         *
C  *   SPECIFIC GRAVITY    DRAG COEFF.    LIFT COEFF.        *
C  *          S                CD             CL             *
C  *          -                --             --             *
C  *                                                         *
C ->
        READ(21,*) S,CD,CL
C ->
C  *                                                         *
C  *---------------------------------------------------------*
C  *                                                         *
C  *    INERTIA COEFF.       FRICTION     SLIDING COEFF.     *
C  *        CM                TANPHI            AC           *
C  *        --                ------            --           *
C  *                                                         *
C ->
        READ(21,*) CM,TANPHI,AC
C ->
C  *                                                         *
C  ***********************************************************
C
C
C
C                   *************************
C                   *                       *
C                   *   RUN UP PARAMETERS   *
C                   *                       *
C                   *      RA         RB    *
C                   *      --         --    *
C                   *                       *
C ->
        READ(21,*) RA,RB
C ->
C                   *                       *
C                   *************************
C
C
C
C       ******************************************
C       *                                        *
C       *  RELATIVE DEPTH TO STRUCTURE TOE : D/H *
C       *                                        *
C       *               DTOH                     *
C       *               ----                     *
C       *                                        *
C     ->
        READ(21,*) DTOH
C     ->
C       *                                        *
C       ******************************************
C
C
C
C
C**************************************************************
```

```
C*************************************************************
C
C
C
C    *****             OUTPUT STATEMENTS                *****
C
C
C              OUTPUT VARIABLE DESCRIPTIONS
C              ------ -------- ------------
C
C               A       : COEFFICIENT OF SLIDING STABILITY
C               B       : COEFFICIENT OF LIFTING STABILITY
C               COT O   : COTANGENT OF THE STRUCTURE SLOPE
C               CD      : DRAG COEFFICIENT
C               CL      : LIFT COEFFICIENT
C               CM      : INERTIA COEFFICIENT
C               E       : NONLINEARITY PARAMETER-EPSILON
C               EU2     : RELATED TO DRAG FORCE
C               EF      : RELATED TO INERTIA FORCE
C               N*      : NORMALIZED WATER SURFACE VARIATION
C               NZS     : STABILITY NUMBER AGAINST SLIDING
C               NZL     : STABILITY NUMBER AGAINST LIFTING
C               R/H     : RELATIVE RUNUP
C               RA,RB   : EMPIRICAL RUNUP COEFFICIENTS
C               SG      : SPECIFIC GRAVITY OF ARMOR UNIT
C               SSP     : SURF SIMILARITY PARAMETER
C               T       : LINEARIZED TIME
C               T*      : NORMALIZED TIME
C               TAN O   : FRICTION FACTOR BETWEEN UNITS
C               T/TO    : CHARACTERISTIC RUNDOWN PERIOD
C               X       : LINEARIZED DISTANCE
C               X*      : NORMALIZED DISTANCE
C               U*      : NORMALIZED VELOCITY
C
C
   13 FORMAT(1H1,///////,15X,
     >'=====================================================',/,15X,
     >'=                                                   =',/,15X,
     >'=     OUTPUT FOR PROGRAM SLOPE.FOR TO PREDICT THE   =',/,15X,
     >'=     FLOW CHARACTERISTICS AND MINIMUM STABILITIES  =',/,15x,
     >'=     IN THE DOWNRUSH OF REGULAR WAVES ON A UNIFORM =',/,15x,
     >'=                      SLOPE                        =',/,15X,
     >'=                                                   =',/,15X,
     >'=====================================================',
     >//////,19X,'OUTPUT VARIABLE DESCRIPTIONS',///,16X,
     >'A      : SLIDING STABILITY COEFFICIENT',/,16X,
     >'B      : LIFTING STABILITY COEFFICIENT',/,16X,
     >'CD     : DRAG COEFFICIENT',/,16X,'CL     : LIFT COEFFICIENT',/,
     >16X,'CM     : INERTIA COEFFICIENT',/,16X,
     >'COT O : COTANGENT OF STRUCTURE SLOPE',/,16X,
     >'E      : EPSILON',/,16X,'EU2    : RELATED TO DRAG FORCE',/,16X,
     >'EF     : RELATED TO INERTIA FORCE',/,16X,
     >'N*     : NORMALIZED WATER SURFACE VARIATION',/,16X,
     >'NZS    : ZERO DAMAGE SLIDING STABILITY NUMBER',/,16X,
     >'NZL    : ZERO DAMAGE LIFTING STABILITY NUMBER',/,16X,
     >'R/H    : RELATIVE RUNUP',/,16X,
     >'RA,RB : EMPIRICAL RUNUP COEFFICIENTS',/,16X,
     >'SG     : SPECIFIC GRAVITY OF ARMOR UNIT',/,16X,
     >'SSP    : SURF SIMILARITY PARAMETER',/,16X,
     >'T      : LINEARIZED TIME',/,16X,'T*     : NORMALIZED TIME',
```

(Continue)

```
      >/,16X,'TAN O : FRICTION FACTOR BETWEEN UNITS',/,16X,
      >'T/TO  : CHARACTERISTIC RUNDOWN PERIOD',/,16X,
      >'X     : LINEARIZED DISTANCE',/,16X,
      >'X*    : NORMALIZED DISTANCE',/,16X,'U*    : NORMALIZED VELOCITY')
     1 FORMAT(1H1)
     2 FORMAT(1H/,50X,'ANALYSIS TO DETERMINE STABILITY OF A',/,56X,
      >3A5,1X,'PROTECTED SLOPE',///////////////,52X,'SLOPE',18X,
      >'COT O = ',F4.1,/,/,/,/,52X,'RUN UP PARAMETERS',9X,'RA = ',
      >F5.2,/,78X,'RB = ',F6.3,/,/,/,/,52X,'ARMOR UNIT PARAMETERS',5X,
      >'CD = ',F5.2,/,78X,'CL = ',F5.2,/,78X,'CM = ',F5.2,/,78X,'SG = ',
      >F5.2,/,75X,'TAN O = ',F5.2,/,79X,'A = ',F4.1,/,79X,'B = ',F4.1)
     3   FORMAT(1H1)
     4   FORMAT(1H2,47X,'NONLINEARITY PARAMETER ',8X,'E = ',
      >  F6.2,/,48X,'RELATIVE RUNDOWN PERIOD',5X,'T/TO = ',F6.2,
      >  /,48X,'SURF SIMILARITY PARAMETER',4X,'SSP = ',F6.2,/,48X,
      >  'RELATIVE RUNUP',15X,'R/H = ',F6.2)
     5     FORMAT(1H1,/,/,/,/,23X,'AT NORMALIZED TIME =',
      >    1X,F4.2,1X,//////////,15X,'X*',10X,'X',10X,'T',10X,'U*',
      >    10X,'N*',10X,'EU2',10X,'EF',10X,'NZS',10X,'NZL',/,15X,
      >    '--',10X,'-',10X,'-',10X,'--',10X,'--',10X,'---',10X,'--',
      >    10X,'---',10X,'---',/)
     6       FORMAT(11X,F7.3,5X,F6.3,6X,F6.3,6X,F6.3,6X,F6.3,
      >      6X,F6.3,6X,F6.3,7X,F7.3,6X,F7.3)
     7   FORMAT(1H1)
     8   FORMAT(1H3,20X,'SUMMARY OF MINIMUM STABILITIES FOR E ='F6.2,
      >  /,/,/,/,10X,'T*',15X,'X*',30X,'NZS',10X,'NZL',/,10X,'--',
      >  15X,'--',30X,'---',10X,'---',/,/,/)
     9     FORMAT(9X,F4.2,11X,F7.3,26X,F7.3,6X,F7.3)
    11   FORMAT(/,/,/,/,20X,'MINIMUM STABILITY NUMBER FOR E =',
      >  F6.2,1X,'IS  ',F7.3,/,/,20X,'MINIMUM OCCURS AT X* =',F7.3)
    12 FORMAT(10X,'CONVERGENCE NOT ACHIEVED',/,10X,'XDIFF = ',
      >F9.6,3X,'TDIFF = ',F8.5)
    16 FORMAT(1H1)
C
C
C
C    ******************************************************
C    *****                                            *****
C    *****         PROGRAM EXECUTION STATEMENTS       *****
C    *****                                            *****
C    ******************************************************
C
C
C
C    *****          DESCRIPTION OF VARIABLES          *****
C
C
C
C     ARG        : ARGUMENT OF THE BESSEL FUNCTION
C     AC         : SLIDING STABILITY COEFFICIENT
C     BC         : LIFTING STABILITY COEFFICIENT
C     COSTHE     : COSINE OF THE STRUCTURE SLOPE
C     EPSL       : NONLINEARITY PARAMETER-EPSILON
C     ETAL       : LINEAR NORMALIZED WATER SURFACE ELEVATION
C     ETAS       : NORMALIZED WATER SURFACE ELEVATION
C     F          : PARAMETER TO CALCULATE FI
C     FD         : DRAG FORCE AS DEVELOPED BY MORISON AND O'BRIEN
C     FI         : LIFT FORCE AS DEVELOPED BY MORISON AND O'BRIEN
C     ITMAX      : IMSL ROUTINE PARAMETER
C     PI         : CONSTANT=3.14159
```

```
C      PXM          : PARAMETER TO CALCULATE SSNZ
C      RTOH         : RELATIVE RUNUP    R/H
C      SLNZ         : STABILITY NUMBER FOR ZERO DAMAGE FROM LIFTING
C      SSNZ         : STABILITY NUMBER FOR ZERO DAMAGE FROM SIDING
C      SLNM(IJ)     : MINIMUM LIFTING STABILITY PER TIME INCREMENT
C      SSNM(IJ)     : MINIMUM SLIDING STABILITY PER TIME INCREMENT
C      SNZMIN       : MINIMUM STABILITY PER DOWNRUSH PERIOD
C      SNZMAX       : MAXIMUM PRINTABLE VALUE FOR STABILITY
C      SURFSP       : SURF SIMILARITY PARAMETER
C      TANTHE       : TANGENT OF THE STRUCTURE SLOPE
C      TDS          : NORMALIZED RUNDOWN TIME    TD*
C      T(1)         : LINEAR NORMALIZED RUNDOWN TIME    TD
C      TO           : RANGE OF ONE-TO-ONE MATCHUP BETWEEN T AND TD*
C      TOTO         : RELATIVE RUNDOWN PERIOD    T/TO
C      TRIGC        : PARAMETER TO CALCULATE SSNZ
C      TS           : NORMALIZED TIME    T*
C      VEL          : LINEARIZED VELOCITY
C      VELS         :  NORMALIZED VELOCITY
C      XM1          : FUNCTION OF FIRST-ORDER BESSEL FUNCTION
C      XM2          : FUNCTION OF SECOND-ORDER BESSEL FUNCTION
C      XMIN         : LOCATION OF MINIMUM STABILITY OVER DOWNRUSH
C      XMAX         : HORIZONTAL LIMIT OF CALCULATIONS
C      XS           : NORMALIZED DISTANCE    X*
C      XXMN(IJ)     : LOCATION OF MINIMUM STABILITY PER TIME INCREMENT
C
C
C
       BC=AC*((CD/CL)+TANPHI)
       TANTHE=1./COTTHE
       COSTHE=COS(ATAN(TANTHE))
       PI=4.*ATAN(1.)
       SNZMAX=999.
       WRITE(20,13)
       WRITE(20,1)
       WRITE(20,2) ARMOR,COTTHE,RA,RB,CD,CL,CM,S,TANPHI,AC,BC
       N=IFIX((EPSMAX-EPSMIN)/DELEPS)
       EPSL=EPSMIN
C
C   -> FOR EACH VALUE OF EPSILON <-
C
       DO 10 I=1,N
         TO=0.
         IF(EPSL.GE.4.) TO=ACOS(4./EPSL)
         TDS=PI+TO-TAN(TO)
         TOTO=(PI+TDS)/(2.*PI)
         SURFSP=(-EPSL+SQRT(EPSL**2+(100.53*RA*RB*EPSL*TOTO**2)))/
     >   (2.*RB*EPSL)
         RTOH=(RA*SURFSP)/(1.+(RB*SURFSP))
         XMAX=EPSL*DTOH/RTOH
         WRITE(20,3)
         WRITE(20,4) EPSL,TOTO,SURFSP,RTOH
         SNZMIN=SNZMAX
         M=IFIX(TDS/DELT)+1
C
C
C      PROCEDURE BEGINS FOR EACH EPSILON AT T*=0
C      WHICH IS TIME OF MAXIMUM RUNUP AND STEPS
C      TO TIME OF MAXIMUM RUNDOWN
C
C
```

```
          TS=0.0
C
C   -> FOR DIFFERENT NORMALIZED TIME  T* <-
C
          DO 20 J=1,M
            WRITE(20,5) TS
            T(1)=0.
            ITMAX=100
            CALL ZREAL1(F,EPS,EPS2,ETA,NSIG,N2,T,ITMAX,IER)
            SNCMIN=SNZMAX
            ETAL=COS(T(1))
            VEL=SIN(T(1))
            ETAS=ETAL-(EPSL/8.)*VEL**2
C
C
C     FOR EACH T* , THE DESIRED VALUES ARE CALCULATED
C     ALONG THE SLOPE FROM X*(MIN) TO XMAX
C
C
            XS=-EPSL*ETAS
            L=IFIX((XMAX-XS)/DELX)+1
C
C   -> FOR DIFFERENT NORMALIZED DISTANCE  X* <-
C
            DO 30 K=1,L
              CALL ITRATE(&40,N1,IER,EPSL,XS,TS,X2,T2,VELS,
     >        ETAS,FD,FI,SSNZ,SLNZ)
              WRITE(20,6) XS,X2,T2,VELS,ETAS,FD,FI,SSNZ,SLNZ
              XS=XS+DELX
   30       CONTINUE
C
C   -> COMPLETED FOR ALL POINTS ALONG SLOPE <-
C
            IF(SNCMIN.LT.SNZMIN)SNZMIN=SNCMIN
            IF(SNZMIN.EQ.SNCMIN)XMIN=XXMN(IJ)
            TS=TS+DELT
   20     CONTINUE
          WRITE(20,7)
C
C   -> COMPLETED FOR ALL TIMESTEPS DURING DOWNRUSH <-
C
          WRITE(20,8) EPSL
C
C
C     THE MINIMUM STABILITY NUMBERS AND THEIR
C     LOCATIONS ARE PRINTED FOR EACH TIMESTEP
C
C
          TS=0.
          DO 15 IJ=1,M
            WRITE(20,9) TS,XXMN(IJ),SSNM(IJ),SLNM(IJ)
            TS=TS+DELT
   15     CONTINUE
C
C
C     THE MINIMUM STABILITY COEFFICIENT AND ITS LOCATION
C                       IS PRINTED
C
C
          WRITE(20,11) EPSL,SNZMIN,XMIN
```

```
          EPSL=EPSL+DELEPS
   10 CONTINUE
C
C   -> COMPLETED FOR EACH VALUE OF EPSILON <-
C
      GO TO 50
  40  WRITE(20,12) XDIF,TDIF
   50 WRITE(20,16)
      STOP
      END
C
C
C
C
C   *****              SUBROUTINE ITRATE                  *****
C
C          THIS SUBROUTINE CALCULATES THE LINEARIZED
C          VALUES OF X AND T FOR SPECIFIED X* AND T*
C
        SUBROUTINE ITRATE(&,N1,IER,EPSL,XS,TS,X2,T2,
     >  VELS,ETAS,FD,FI,SSNZ,SLNZ)
        COMMON /TWO/XDIF,TDIF
       REAL*8 B(3),ARG
       NUM=200
       X1=ABS(XS)
       IF(XS.LT.0.)X1=0.
       T1=TS
       DO 15 I=1,NUM
            ARG=SQRT(X1)
            CALL MMBSJN(ARG,N1,B,IER)
            ETAL = B(1)*COS(T1)
            IF(ARG.NE.0.)GO TO 100
            XM1=1.
            XM2=0.
            GO TO 200
  100       XM1=2./ARG*B(2)
            XM2=2./ARG*B(3)
  200       VEL = XM1*SIN(T1)
            ETAS=ETAL-(EPSL/8.)*VEL**2
            VELS=VEL
            X2=XS+EPSL*ETAS
            T2=TS-(EPSL/4.)*VELS
C
C
C    IF CONVERGENCE OF THE ITERATION PROCESS TO MATCH
C    X TO X* AND T TO T* IS NOT ACHIEVED , THIS IS
C    PRINTED AND THE PROGRAM IS STOPPED
C
C
            XDIF=ABS(X2-X1)
            TDIF=ABS(T2-T1)
            IF(XDIF.LE.0.01.AND.TDIF.LE.0.01) GO TO 300
            X1=(X1+X2)/2.
            IF(X1.LE.0.) X1=0.
            T1=(T1+T2)/2.
  15   CONTINUE
       RETURN 1
 300   CALL FORCES(T2,EPSL,XM1,XM2,VEL,FD,FI,XS,SSNZ,SLNZ)
       RETURN
       END
```

```
C
C
C
C
C     *****               SUBROUTINE FORCES                    *****
C
C            THIS SUBROUTINE CALCULATES THE DRAG
C            AND INERTIA FORCES ON AN ARMOR UNIT
C
      SUBROUTINE FORCES(T2,EPSL,XM1,XM2,VEL,FD,FI,XS,SSNZ,SLNZ)
      PXM=XM1**2*COS(T2)**2-XM2**2*SIN(T2)**2
      F=(4.*XM1*COS(T2)+EPSL*PXM)/(16.+8.*EPSL*XM1*COS(T2)+EPSL**2*PXM)
      FD=EPSL*VEL**2
      FI=EPSL*F
       CALL STABIL(FD,FI,XS,SSNZ,SLNZ)
      RETURN
      END
C
C
C
C
C     *****               SUBROUTINE STABIL                    *****
C
C           THIS SUBROUTINE CALCULATES THE STABILITY
C           NUMBERS AGAINST SLIDING AND LIFT AND
C           SAVES THE MINIMUM  VALUE FOR EACH DURING
C           THE DOWNRUSH
C
       SUBROUTINE STABIL(FD,FI,XS,SSNZ,SLNZ)
       DIMENSION SSNM(50),SLNM(50),XXMN(50)
       COMMON/THREE/RTOH,SNCMIN,XMIN,J,SSNM,SLNM,XXMN,IJ
       COMMON/FOUR/AC,BC,COSTHE,TANPHI,TANTHE,CM,S,SNZMAX
       IJ=J
       TRIGC=COSTHE*(TANPHI-TANTHE)-(CM*TANTHE*FI/(S-1.))
       IF(FD.EQ.0.)GO TO 10
       SSNZ=AC*TRIGC/(RTOH*FD)
       SLNZ=BC*COSTHE/(RTOH*FD)
C
C
C    THE VALUE 999 IS PRINTED FOR STABILITY NUMBER
C    WHEN VELOCITY=0 , I.E., MAXIMUM RUNUP AND RUNDOWN
C
C
C    THE VALUE 999 IS PRINTED FOR STABILITY NUMBER
C    GREATER THAN OR EQUAL TO 999   (SNZMAX=999)
C
C
       IF(SSNZ.GT.SNZMAX)SSNZ=SNZMAX
       IF(SLNZ.GT.SNZMAX)SLNZ=SNZMAX
       GO TO 20
   10  SSNZ=SNZMAX
       SLNZ=SNZMAX
   20  IF(SSNZ.LT.SNCMIN)SNCMIN=SSNZ
       IF(SSNZ.EQ.SNCMIN)SSNM(IJ)=SSNZ
       IF(SSNZ.EQ.SNCMIN)SLNM(IJ)=SLNZ
       IF(SSNZ.EQ.SNCMIN)XXMN(IJ)=XS
       IF(SLNZ.LT.SNCMIN)SNCMIN=SLNZ
       IF(SLNZ.EQ.SNCMIN)SSNM(IJ)=SSNZ
       IF(SLNZ.EQ.SNCMIN)SLNM(IJ)=SLNZ
       IF(SLNZ.EQ.SNCMIN)XXMN(IJ)=XS
```

(Continue)

```
      RETURN
      END
C
C
C
C
C   *****                FUNCTION F(T)                    *****
C
C        OBJECT FUNCTION FOR IMSL ROUTINE  ZREAL1
C        TO FIND TD FOR SPECIFIED EPSILON AND TD*
C
      REAL FUNCTION F(T)
      COMMON/ONE/TS,EPSL
      REAL T
      F=(EPSL/4.)*SIN(T)+T-TS
      RETURN
      END
```

Table B-3. Out of Example Computation.

```
=====================================================
=                                                   =
=    OUTPUT FOR PROGRAM SLOPE.FOR TO PREDICT THE    =
=    FLOW CHARACTERISTICS AND MINIMUM STABILITIES   =
=    IN THE DOWNRUSH OF REGULAR WAVES ON A UNIFORM  =
=                      SLOPE                        =
=                                                   =
=====================================================
```

```
   OUTPUT VARIABLE DESCRIPTIONS

A      : SLIDING STABILITY COEFFICIENT
B      : LIFTING STABILITY COEFFICIENT
CD     : DRAG COEFFICIENT
CL     : LIFT COEFFICIENT
CM     : INERTIA COEFFICIENT
COT O  : COTANGENT OF STRUCTURE SLOPE
E      : EPSILON
EU2    : RELATED TO DRAG FORCE
EF     : RELATED TO INERTIA FORCE
N*     : NORMALIZED WATER SURFACE VARIATION
NZS    : ZERO DAMAGE SLIDING STABILITY NUMBER
NZL    : ZERO DAMAGE LIFTING STABILITY NUMBER
R/H    : RELATIVE RUNUP
RA,RB  : EMPIRICAL RUNUP COEFFICIENTS
SG     : SPECIFIC GRAVITY OF ARMOR UNIT
SSP    : SURF SIMILARITY PARAMETER
T      : LINEARIZED TIME
T*     : NORMALIZED TIME
TAN O  : FRICTION FACTOR BETWEEN UNITS
T/TO   : CHARACTERISTIC RUNDOWN PERIOD
X      : LINEARIZED DISTANCE
X*     : NORMALIZED DISTANCE
U*     : NORMALIZED VELOCITY
```

(Continue)

ANALYSIS TO DETERMINE STABILITY OF A
RIP RAP PROTECTED SLOPE

SLOPE	COT O =	3.5
RUN UP PARAMETERS	RA =	1.13
	RB =	0.506
ARMOR UNIT PARAMETERS	CD =	0.50
	CL =	0.18
	CM =	1.50
	SG =	2.71
	TAN O =	1.19
	A =	10.8
	B =	43.2

(Continue)

NONLINEARITY PARAMETER	E =	4.00
RELATIVE RUNDOWN PERIOD	T/TO =	1.00
SURF SIMILARITY PARAMETER	SSP =	2.89
RELATIVE RUNUP	R/H =	1.33

(Continue)

AT NORMALIZED TIME = .00

X*	X	T	U*	N*	EU2	EF	NZS	NZL
-4.000	0.000	0.000	0.000	1.000	0.000	0.500	999.000	999.000
-3.500	0.254	0.000	0.000	0.938	0.000	0.492	999.000	999.000
-3.000	0.508	0.000	0.000	0.877	0.000	0.484	999.000	999.000
-2.500	0.769	0.000	0.000	0.817	0.000	0.476	999.000	999.000
-2.000	1.034	0.000	0.000	0.759	0.000	0.467	999.000	999.000
-1.500	1.304	0.000	0.000	0.701	0.000	0.458	999.000	999.000
-1.000	1.575	0.000	0.000	0.644	0.000	0.449	999.000	999.000
-0.500	1.853	0.000	0.000	0.588	0.000	0.440	999.000	999.000
0.000	2.136	0.000	0.000	0.534	0.000	0.431	999.000	999.000
0.500	2.423	0.000	0.000	0.481	0.000	0.421	999.000	999.000
1.000	2.716	0.000	0.000	0.429	0.000	0.411	999.000	999.000
1.500	3.014	0.000	0.000	0.379	0.000	0.401	999.000	999.000
2.000	3.314	0.000	0.000	0.328	0.000	0.390	999.000	999.000
2.500	3.622	0.000	0.000	0.280	0.000	0.379	999.000	999.000
3.000	3.935	0.000	0.000	0.234	0.000	0.368	999.000	999.000
3.500	4.254	0.000	0.000	0.188	0.000	0.357	999.000	999.000
4.000	4.578	0.000	0.000	0.145	0.000	0.345	999.000	999.000
4.500	4.911	0.000	0.000	0.103	0.000	0.334	999.000	999.000
5.000	5.246	0.000	0.000	0.061	0.000	0.321	999.000	999.000
5.500	5.589	0.000	0.000	0.022	0.000	0.309	999.000	999.000
6.000	5.933	0.000	0.000	-0.017	0.000	0.296	999.000	999.000

(Continue)

AT NORMALIZED TIME = .50

X*	X	T	U*	N*	EU2	EF	NZS	NZL
-3.751	0.000	0.251	0.249	0.938	0.248	0.492	24.550	126.508
-3.251	0.254	0.256	0.244	0.876	0.239	0.483	25.562	131.347
-2.751	0.514	0.260	0.240	0.816	0.230	0.475	26.583	136.194
-2.251	0.780	0.265	0.235	0.758	0.222	0.466	27.665	141.318
-1.751	1.050	0.269	0.231	0.700	0.213	0.457	28.849	146.917
-1.251	1.324	0.274	0.226	0.644	0.205	0.447	30.149	153.056
-0.751	1.604	0.279	0.221	0.589	0.196	0.438	31.580	159.809
-0.251	1.889	0.284	0.216	0.535	0.187	0.428	33.160	167.258
0.249	2.180	0.289	0.211	0.483	0.179	0.417	34.865	175.268
0.749	2.470	0.292	0.208	0.430	0.172	0.407	36.307	181.890
1.249	2.770	0.298	0.202	0.380	0.164	0.396	38.329	191.344
1.749	3.075	0.303	0.197	0.331	0.155	0.385	40.566	201.783
2.249	3.386	0.308	0.192	0.284	0.147	0.374	43.050	213.351
2.749	3.702	0.314	0.186	0.238	0.138	0.362	45.821	226.226
3.249	4.025	0.320	0.180	0.194	0.130	0.350	48.926	240.627
3.749	4.353	0.325	0.175	0.151	0.122	0.338	52.425	256.821
4.249	4.687	0.331	0.169	0.109	0.114	0.325	56.391	275.142
4.749	5.028	0.337	0.163	0.070	0.106	0.312	60.916	296.004
5.249	5.374	0.344	0.156	0.031	0.098	0.299	66.116	319.927
5.749	5.728	0.349	0.151	-0.005	0.092	0.285	70.993	342.092

(Continue)

AT NORMALIZED TIME = 1.00

X*	X	T	U*	N*	EU2	EF	NZS	NZL
-3.011	-0.001	0.511	0.489	0.752	0.958	0.466	6.404	32.714
-2.511	0.268	0.521	0.479	0.695	0.918	0.455	6.704	34.122
-2.011	0.542	0.529	0.471	0.638	0.888	0.445	6.958	35.297
-1.511	0.821	0.538	0.462	0.583	0.853	0.434	7.271	36.750
-1.011	1.107	0.548	0.452	0.529	0.817	0.422	7.617	38.353
-0.511	1.401	0.558	0.442	0.478	0.782	0.411	7.991	40.080
-0.011	1.699	0.568	0.432	0.427	0.746	0.398	8.411	42.021
0.489	2.005	0.582	0.418	0.379	0.700	0.385	8.992	44.727
0.989	2.320	0.592	0.408	0.333	0.665	0.372	9.514	47.128
1.489	2.632	0.602	0.398	0.286	0.634	0.359	10.016	49.404
1.989	2.957	0.613	0.387	0.242	0.598	0.345	10.673	52.410
2.489	3.289	0.625	0.375	0.200	0.562	0.331	11.411	55.781
2.989	3.628	0.637	0.363	0.160	0.526	0.316	12.246	59.582
3.489	3.974	0.650	0.350	0.121	0.490	0.301	13.196	63.896
3.989	4.327	0.663	0.337	0.084	0.455	0.285	14.284	68.828
4.489	4.688	0.676	0.324	0.050	0.420	0.269	15.540	74.508
4.989	5.057	0.689	0.311	0.017	0.386	0.253	17.001	81.103
5.489	5.434	0.703	0.297	-0.014	0.353	0.237	18.717	88.827
5.989	5.819	0.716	0.284	-0.043	0.322	0.220	20.591	97.225

(Continue)

AT NORMALIZED TIME = 1.50

X*	X	T	U*	N*	EU2	EF	NZS	NZL
-1.807	-0.004	0.789	0.711	0.451	2.021	0.413	3.087	15.500
-1.307	0.302	0.808	0.692	0.402	1.916	0.397	3.274	16.351
-0.807	0.598	0.821	0.679	0.351	1.842	0.383	3.421	17.004
-0.307	0.910	0.838	0.662	0.304	1.752	0.366	3.616	17.879
0.193	1.231	0.856	0.644	0.260	1.661	0.349	3.836	18.863
0.693	1.564	0.874	0.626	0.218	1.569	0.331	4.083	19.962
1.193	1.903	0.893	0.607	0.177	1.476	0.312	4.367	21.223
1.693	2.251	0.913	0.587	0.140	1.380	0.292	4.700	22.699
2.193	2.617	0.934	0.566	0.106	1.282	0.272	5.093	24.433
2.693	2.987	0.954	0.546	0.074	1.191	0.251	5.518	26.304
3.193	3.363	0.975	0.525	0.043	1.102	0.229	6.007	28.439
3.693	3.754	0.997	0.503	0.015	1.011	0.206	6.593	31.001
4.193	4.157	1.020	0.480	-0.009	0.921	0.183	7.287	34.021
4.693	4.570	1.044	0.456	-0.031	0.833	0.160	8.115	37.619
5.193	4.996	1.068	0.432	-0.049	0.747	0.136	9.114	41.951
5.693	5.432	1.091	0.409	-0.065	0.668	0.113	10.261	46.908

(Continue)

AT NORMALIZED TIME = 2.00

X*	X	T	U*	N*	EU2	EF	NZS	NZL
-0.194	-0.006	1.106	0.894	0.047	3.200	0.310	2.016	9.790
0.306	0.366	1.137	0.863	0.015	2.979	0.280	2.187	10.518
0.806	0.713	1.162	0.838	-0.023	2.809	0.253	2.338	11.154
1.306	1.094	1.193	0.807	-0.053	2.608	0.221	2.544	12.014
1.806	1.495	1.225	0.775	-0.078	2.405	0.187	2.788	13.029
2.306	1.925	1.261	0.739	-0.095	2.182	0.147	3.109	14.358
2.806	2.361	1.296	0.704	-0.111	1.984	0.110	3.457	15.789
3.306	2.808	1.332	0.668	-0.124	1.785	0.070	3.889	17.552
3.806	3.282	1.370	0.630	-0.131	1.586	0.028	4.431	19.754
4.306	3.777	1.410	0.590	-0.132	1.391	-0.014	5.115	22.530
4.806	4.292	1.452	0.548	-0.128	1.201	-0.055	5.991	26.084
5.306	4.826	1.494	0.506	-0.120	1.023	-0.092	7.108	30.619
5.806	5.384	1.538	0.462	-0.105	0.852	-0.127	8.615	36.753

(Continue)

AT NORMALIZED TIME = 2.50

X*	X	T	U*	N*	EU2	EF	NZS	NZL
1.717	-0.009	1.502	0.998	-0.431	3.982	0.064	1.746	7.867
2.217	0.483	1.560	0.940	-0.434	3.534	-0.018	2.015	8.866
2.717	1.017	1.624	0.876	-0.425	3.070	-0.115	2.384	10.205
3.217	1.621	1.694	0.806	-0.399	2.598	-0.225	2.903	12.058
3.717	2.250	1.769	0.731	-0.367	2.136	-0.341	3.644	14.669
4.217	2.944	1.851	0.649	-0.318	1.685	-0.454	4.755	18.594
4.717	3.690	1.938	0.562	-0.257	1.264	-0.543	6.483	24.788
5.217	4.482	2.020	0.480	-0.184	0.923	-0.580	8.962	33.960
5.717	5.274	2.094	0.406	-0.111	0.660	-0.567	12.490	47.476

(Continue)

AT NORMALIZED TIME = 3.00

X*	X	T	U*	N*	EU2	EF	NZS	NZL
3.634	-0.008	2.183	0.817	-0.910	2.669	-1.352	3.688	11.738
4.134	1.636	2.562	0.438	-0.625	0.769	-2.967	17.102	40.765
4.634	3.300	2.769	0.231	-0.334	0.214	-1.733	49.659	146.457
5.134	4.498	2.846	0.154	-0.159	0.095	-1.137	99.159	330.241
5.634	5.485	2.889	0.111	-0.037	0.049	-0.830	177.507	633.389

(Continue)

SUMMARY OF MINIMUM STABILITIES FOR E = 4.00

T*	X*	NZS	NZL
.00	6.000	999.000	999.000
.50	-3.751	24.550	126.508
1.00	-3.011	6.404	32.714
1.50	-1.807	3.087	15.500
2.00	-0.194	2.016	9.790
2.50	1.717	1.746	7.867
3.00	3.634	3.688	11.738

MINIMUM STABILITY NUMBER FOR E = 4.00 IS 1.746

MINIMUM OCCURS AT X* = 1.717

APPENDIX C

COMPUTATION OF CRITICAL STABILITY NUMBER AS A FUNCTION OF SURF SIMILARITY PARAMETER

The computer program described in APPENDIX B computes the variations of the flow characteristics and the stability of armor units along a uniform flow during the period of regular wave downrush. This program may be used to evaluate the extent and type of slope protection measures which may vary along the slope of a gravel island. For a preliminary estimation of the required size of primary protection units, however, it would be more convenient if the critical stability number is to be computed as a function of the surf similarity parameter without calculating the detailed variation of the degree of stability along the slope during the period of wave downrush.

The analysis of stability of rip rap under regular wave action conducted by Kobayashi and Jacobs (1983) indicates that the instantaneous waterline is the point of the least stability during the downrush period if the inertia force acting on an armor unit is negligible compared with the drag force. For this case, computation of the critical number can be made by examining the stability of armor units at the instantaneous waterline only. The computer program described in the following assumes that the instantaneous waterline is the point of the least stability during the downrush period. The validity of this assumption for a specific problem may be checked using the computer program described in APPENDIX B.

Fig. C-1 shows the basic flow diagram of the computer program for calculating the critical stability number as a function of the surf similarity parameter which accounts for the effect of incident wave periods on the stability of armor units. The set of input data required for the computation is composed of the following parameters:

ARMOR	=	description of armor type
EPSMIN	=	minimum value of parameter ε
EPSMAX	=	maximum value of parameter ε
DELEPS	=	increment of parameter ε
COTTHE [$\cot\theta$]	=	cotangent of structure slope
S [s]	=	specific gravity of armor unit
CD [C_D]	=	drag coefficient of armor unit
CL [C_L]	=	lift coefficient of armor unit
CM [C_M]	=	inertia coefficient of armor unit
TANPHI [$\tan\phi$]	=	frictional coefficient between armor units
AC [A]	=	coefficient associated with sliding stability
RA [a]	=	empirical runup coefficient
RB [b]	=	empirical runup coefficient

in which the variables in the square brackets are those used in the original paper by Kobayashi and Jacobs. This set of input data is to be incorporated into the program through READ statements for batch processing. The input file consists of seven lines whose order and format are shown in Table C-1. The program uses an external subroutine, corresponding to an application program in IMSL Library. The external subroutine, ZREAL1, computes the zeros of a real function.

The computation is made for each value of the nonlinearity parameter ε which is decreased from EPSMAX to EPSMIN by the specified increment DELEPS. The parameter ε increases as the surf similarity parameter ξ is decreased. For each value of ε, the following quantities are computed:

SSP [ξ]	=	surf similarity parameter
TD [t_d]	=	linearized wave rundown time
TM [t_m]	=	linearized time at which N_{RW} is minimum if $t_d > t_m$
NZS [min N_{RW}]	=	minimum value of N_{RW}
NZL [min N_{LW}]	=	minimum value of N_{LW}

in which N_{RW} is the function associated with the stability against downward rolling or sliding evaluated at the instantaneous waterline, whereas N_{LW} is that against upward lifting at the instantaneous waterline. N_{RW} is minimum at the linearized time $t = t_m$ if $t_d > t_m$ and at $t = t_d$ if $t_d \leq t_m$. N_{LW} is minimum at $t = \pi/2$ if $t_d \geq \pi/2$ and $t = t_d$ if $t_d < \pi/2$. The condition that the stability of armor units is limited by the location of wave rundown is reached when $t_d = t_m$ for N_{RW} and when $t_d = \pi/2$ for N_{LW}. Comparison of the calculated values of NZS and NZL for each value of ε and hence ξ indicates a possible mode of armor movement. The critical stability number is the smaller of the calculated values of NZS and NZL.

The computer program is listed in Table C-2. An example computation is made using the following input data

ARMOR = RIP RAP

EPSMIN = 0.5 , EPSMAX = 18.0

DELEPS = 0.5

COTTHE = 3.5

S = 2.71 , CD = 0.5 , CL = 0.178

CM = 1.5 , TANPHI = 1.19 , AC = 10.8

RA = 1.13 , RB = 0.506

The output of this example computation is shown in Table B-3.

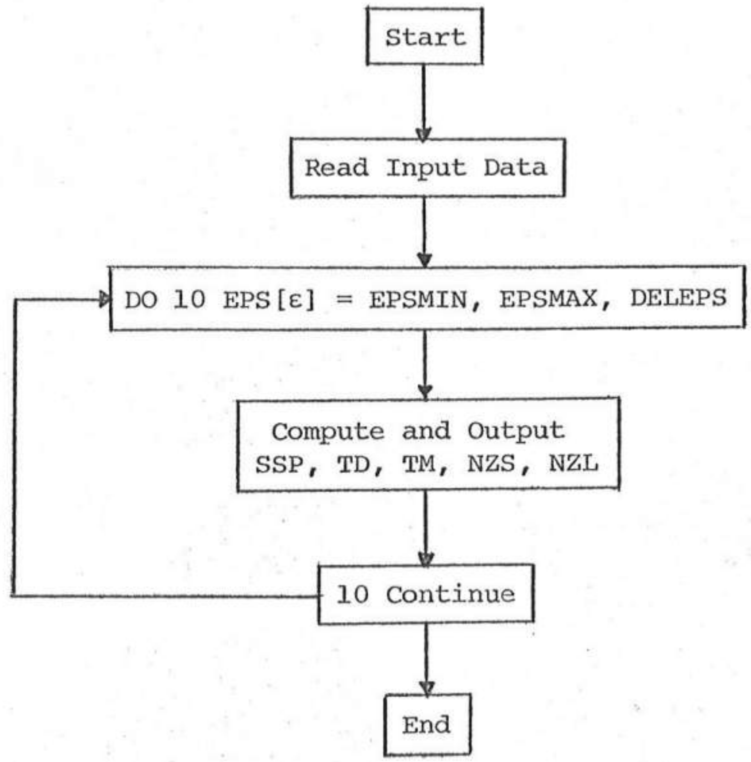

Fig. C-1. Flow Diagram of Program for Computing Critical Stability Number.

Table C-1. Required Input Parameters and Corresponding Format Statements.

Input Parameter	Format
ARMOR	3A5
EPSMIN, EPSMAX	free format
DELEPS	free format
COTTHE	free format
S, CD, CL	free format
CM, TANPHI, AC	free format
RA, RB	free format

Table C-2. Listing of Program for Computation of Critical Stability Number.

```
C    ****************************************************
C    *                                                  *
C    *                   STABLE.FOR                     *
C    *                                                  *
C    *   A NUMERICAL  MODEL TO CALCULATE  THE STABILITY *
C    *   NUMBERS AGAINST SLIDING AND LIFT AS A FUNCTION *
C    *             OF SURF SIMILARITY PARAMETER         *
C    *                                                  *
C    ****************************************************
C
C
C
C
C    *****           DECLARATION STATEMENTS         *****
C
C
      INTEGER IER,N,NSIG,ITMAX
      REAL F,U,EPS,EPS2,ETA,T(1),P(1)
      DIMENSION ARMOR(3)
      COMMON/ONE/TDS,EPSL,E
      EXTERNAL F
      EXTERNAL U
        OPEN(UNIT=20,FILE='STBOUT.DAT')
        OPEN(UNIT=21,DEVICE='DSK',FILE='STABL.DAT')
C
C
C
C     THIS PROGRAM MAKES USE OF IMSL LIBRARY ROUTINE:
C
C        ZREAL1 : TO COMPUTE THE ZEROS OF A REAL FUNCTION
C                 STATEMENT NUMBERS 32000 AND 32300
C
C
C    *****     IMSL LIBRARY SUBROUTINE PARAMETERS   *****
C
      EPS=0.00001
      EPS2=0.00001
      ETA=0.01
      NSIG=5
      N=1
C
C
C
C    *****                INPUT DATA                *****
C
C
C          VARIABLE DESCRIPTIONS
C          -------- ------------
C
C           ARMOR  : DESCRIPTION OF ARMOR TYPE
C           EPSMIN : MINIMUM VALUE OF EPSILON FOR CALCULATIONS
C           EPSMAX : MAXIMUM VALUE OF EPSILON FOR CALCULATIONS
C           DELEPS : INCREMENT IN EPSILON BETWEEN EPSMAX-EPSMIN
C           COTTHE : COTANGENT OF THE STRUCTURE SLOPE
C           S      : SPECIFIC GRAVITY OF ARMOR UNIT
C           CD     : DRAG COEFFICIENT
C           CL     : LIFT COEFFICIENT
C           CM     : INERTIA COEFFICIENT
C           TANPHI : FRICTION COEFFICIENT
C           AC     : COEFFICIENT OF SLIDING STABILITY
```

```
C              RA,RB  : EMPIRICAL RUNUP COEFFICIENTS
C
C
C*****************************************************************
C
C
C
C    ****************************************************
C    ****************************************************
C    **                                                **
C    **  INPUT DESCRIPTION FOR PROGRAM STABLE.FOR      **
C    **  TO CALCULATE THE MINIMUM STABILITY COEFF-     **
C    **  ICIENTS FOR EACH EPSILON OVER A SPECIFIED     **
C    **                   RANGE                        **
C    **                                                **
C    ****************************************************
C    ****************************************************
C
C
C         **************************************
C         *                                    *
C         *     DESCRIPTION OF ARMOR TYPE      *
C         *  MUST BE LESS THAN 16 CHARACTERS   *
C         *                                    *
C ->
        READ(21,14) ARMOR
     14 FORMAT(3A5)
C ->
C         *                                    *
C         **************************************
C
C
C            ********************************
C            *                              *
C            *  ALL DATA IS IN FREE FORMAT  *
C            *                              *
C            ********************************
C
C
C
C
C    *****************************************************
C    *                                                   *
C    *                RANGE OF EPSILON                   *
C    *   EPSILON IS PARAMETER OF WAVE CHARACTERISTICS    *
C    *                                                   *
C    *           EPSMIN               EPSMAX             *
C    *           ------               ------             *
C    *                                                   *
C ->
           READ(21,*) EPSMIN,EPSMAX
C ->
C    *                                                   *
C    *  EPSMAX MUST BE LESS THAN OR EQUAL TO 18.0        *
C    *                                                   *
C    *****************************************************
C
C
C
C            ********************************
```

(Continue)

```
C              *                             *
C              *      INCREMENT OF EPSILON   *
C              *                             *
C              *            DELEPS           *
C              *            ------           *
C              *                             *
C ->
         READ(21,*) DELEPS
C ->
C              *                             *
C              *******************************
C
C
C
C                      **************
C                      *            *
C                      *    SLOPE   *
C                      *            *
C                      *   COTTHE   *
C                      *   ------   *
C                      *            *
C ->
         READ(21,*) COTTHE
C ->
C                      *            *
C                      **************
C
C
C
C   *****************************************************
C   *                                                   *
C   *              ARMOR UNIT CHARACTERISTICS           *
C   *                                                   *
C   *   SPECIFIC GRAVITY   DRAG COEFF.   LIFT COEFF.    *
C   *          S               CD            CL         *
C   *          -               --            --         *
C   *                                                   *
C ->
         READ(21,*) S,CD,CL
C ->
C   *                                                   *
C   *---------------------------------------------------*
C   *                                                   *
C   *   INERTIA COEFF.     FRICTION    SLIDING COEFF.   *
C   *        CM             TANPHI          AC          *
C   *        --             ------          --          *
C   *                                                   *
C ->
         READ(21,*) CM,TANPHI,AC
C ->
C   *                                                   *
C   *****************************************************
C
C
C
C                  ***********************
C                  *                     *
C                  *  RUN UP PARAMETERS  *
C                  *                     *
C                  *     RA       RB     *
```

```
C                     *         --          --        *
C                     *                               *
C ->
         READ(21,*) RA,RB
C ->
C                     *                               *
C                     *****************************
C
C
C
C
C
C*************************************************************
C*************************************************************
C
C
C
C    *****            OUTPUT STATEMENTS            *****
C
C
C             OUTPUT VARIABLE DESCRIPTIONS
C             ------ -------- ------------
C
C               A       : COEFFICIENT OF SLIDING STABILITY
C               COT 0   : COTANGENT OF THE STRUCTURE SLOPE
C               EPS     : NONLINEARITY PARAMETER-EPSILON
C               SSP     : SURF SIMILARITY PARAMETER
C               TD      : LINEARIZED RUNDOWN TIME
C               TM      : IDEAL TIME OF MINIMUM SLIDING STABILITY
C               NZS     : SLIDING STABILITY COEFFICIENT
C               NZL     : LIFTING STABILITY COEFFICIENT
C
C
    1 FORMAT(1H1,///////,15X,
     >'==========================================================',/,15X,
     >'=                                                        =',/,15X,
     >'=    OUTPUT FOR PROGRAM STABLE.FOR TO CALCULATE THE      =',/,15X,
     >'=    MINIMUM STABILITIES ON A  UNIFORM SLOPE OVER A      =',/,15X,
     >'=                RANGE OF WAVE BREAKER TYPE              =',/,15X,
     >'=                                                        =',/,15X,
     >'==========================================================',
     >//////,19X,'OUTPUT VARIABLE DESCRIPTIONS',///,16X,
     >'EPS    : NONLINEARITY PARAMETER',/,16X,
     >'SSP    : SURF SIMILARITY PARAMETER',/,16X,
     >'TD     : LINEARIZED RUNDOWN TIME',/,16X,
     >'TM     : TIME OF MINIMUM SLIDING STABILITY (TM<TD)',/,16X,
     >'NZS    : ZERO DAMAGE SLIDING STABILITY NUMBER',/,16X,
     >'NZL    : ZERO DAMAGE LIFTING STABILITY NUMBER')
    2 FORMAT(1H1,//////////,19X,'INPUT DATA',////,
     >16X,'ARMOR  : ',3A5,/,16X,'COTTHE : ',F4.1,/,
     >16X,'S      : ',F5.2,/,16X,'CD     : ',F4.1,/,
     >16X,'CL     : ',F6.3,/,16X,'CM     : ',F4.1,/,
     >16X,'TANPHI : ',F5.2,/,16X,'AC     : ',F4.1,/,
     >16X,'RA     : ',F5.2,/,16X,'RB     : ',F6.3)
    3 FORMAT(1H1,
     >//////////,10X,'EPS',10X,'SSP',10X,'TD',10X,'TM',10X,'NZS',
     >10X,'NZL',/,10X,'---',10X,'---',10X,'--',10X,'--',
     >10X,'---',10X,'---',//)
    4 FORMAT(9X,F5.2,8X,F4.2,9X,F4.2,8X,F4.2,8X,F6.2,7X,F6.2)
C
```

```
C
C
C     *****************************************************
C     *****                                           *****
C     *****        PROGRAM EXECUTION STATEMENTS       *****
C     *****                                           *****
C     *****************************************************
C
C
C
C     *****          DESCRIPTION OF VARIABLES         *****
C
C
C
C      AC       : SLIDING STABILITY COEFFICIENT
C      BC       : LIFTING STABILITY COEFFICIENT
C      COSTHE   : COSINE OF THE STRUCTURE SLOPE
C      EPSL     : NONLINEARITY PARAMETER-EPSILON
C      E        : PARAMETER TO CALCULATE P(1)
C      ITMAX    : IMSL ROUTINE PARAMETER
C      P(1)     : PARAMETER TO CALCULATE TM
C      PI       : THE CONSTANT 3.14159
C      PIOT     : PI/2
C      PXM      : PARAMETER TO CALCULATE SSNZ
C      RTOH     : RELATIVE RUNUP    R/H
C      SLNZ     : STABILIY NUMBER FOR ZERO DAMAGE FROM LIFTING
C      SSNZ     : STABILITY NUMBER FOR ZERO DAMAGE FROM SIDING
C      SNZMAX   : MAXIMUM PRINTABLE STABILITY COEFFICIENT
C      SURFSP   : SURF SIMILARITY PARAMETER
C      TANTHE   : TANGENT OF THE STRUCTURE SLOPE
C      TDS      : NORMALIZED RUNDOWN TIME        TD*
C      T(1)     : LINEAR NORMALIZED RUNDOWN TIME      TD
C      TO       : PARAMETER TO CALCULATE RUNDOWN TIME TD*
C      TOTO     : RELATIVE RUNDOWN PERIOD        T/TO
C      TM       : IDEAL TIME OF MINIMUM SLIDING STABILITY
C      TS       : TIME OF MINIMUM SLIDING STABILITY (=TM,TM<TD)
C
C
C
        WRITE(20,1)
        WRITE(20,2) ARMOR,COTTHE,S,CD,CL,CM,TANPHI,AC,RA,RB
        BC=AC*((CD/CL)+TANPHI)
        TANTHE=1./COTTHE
        COSTHE=COS(ATAN(TANTHE))
        PI=4.*ATAN(1.)
        E=(CM*TANTHE)/(COSTHE*(S-1.)*(TANPHI-TANTHE))
        SNZMAX=999.
        WRITE(20,3)
C
C
C     THE PROCEDURE BEGINS AT EPSILON = EPSMAX
C     CALCULATES SSP,TD,TM,AND SLIDING AND LIFT
C     COEFFICIENTS FOR THE RANGE OF EPSILON TO
C                      EPSMIN
C
C
        EPSL=EPSMAX
        M=IFIX((EPSMAX-EPSMIN)/DELEPS)+1
C
C   -> FOR EACH VALUE OF EPSILON <-
```

```
C
      DO 10 I=1,M
      TO=0.
      IF(EPSL.GE.4.) TO=ACOS(4./EPSL)
      TDS=PI+TO-TAN(TO)
      TOTO=(PI+TDS)/(2*PI)
      SURFSP=(-EPSL+SQRT(EPSL**2+100.53*RA*RB*EPSL*TOTO**2))/
     >(2.*RB*EPSL)
      RTOH=(RA*SURFSP)/(1.+RB*SURFSP)
      T(1)=PI
C
C
C     TD = PI FOR EPSILON < 4
C     TD < PI FOR EPSILON > 4
C
C
      IF(EPSL.LT.4.) GO TO 100
      ITMAX=100
      T(1)=0.
      CALL ZREAL1(F,EPS,EPS2,ETA,NSIG,N,T,ITMAX,IER)
  100 P(1)=1.
      ITMAX=100
      CALL ZREAL1(U,EPS,EPS2,ETA,NSIG,N,P,ITMAX,IER)
      TM=ACOS(P(1))
      SLNZ=(BC*COSTHE)/(RTOH*EPSL)
      PIOT=PI/2.
      IF(T(1).LT.PIOT) SLNZ=SLNZ/SIN(T(1))**2
      TS=T(1)
C
C
C     MINIMUM SLIDING STABILITY IS CALCULATED AT TM FOR TD>TM
C
C
      IF(T(1).GE.TM) TS=TM
      PXM=(1./SIN(TS)**2)*(1.-(EPSL*E*COS(TS)/(4.+EPSL*COS(TS))))
      SSNZ=(AC/RTOH)*(COSTHE*(TANPHI-TANTHE)/EPSL)*PXM
      IF(SLNZ.GT.SNZMAX) SLNZ=SNZMAX
      IF(SSNZ.GT.SNZMAX) SSNZ=SNZMAX
      WRITE(20,4) EPSL,SURFSP,T(1),TM,SSNZ,SLNZ
      EPSL=EPSL-DELEPS
   10 CONTINUE
C
C   -> OUTPUT FOR EACH EPSILON <-
C
      STOP
      END
C
C
C
C
C    *****               FUNCTION F(T)                *****
C
C          OBJECT FUNCTION FOR IMSL ROUTINE  ZREAL1
C          TO FIND TD FOR SPECIFIED EPSILON AND TD*
C
      REAL FUNCTION F(T)
      COMMON/ONE/TDS,EPSL,E
      REAL T
      F=(EPSL/4.)*SIN(T)+T-TDS
      RETURN
```

```
      END
C
C
C
C
C *****                  FUNCTION U(P)                        *****
C
C          OBJECT FUNCTION FOR IMSL ROUTINE  ZREAL1
C          TO FIND P(1) FOR SPECIFIED EPSILON AND E
C
      REAL FUNCTION U(P)
      COMMON/ONE/TDS,EPSL,E
      REAL P
      U=EPSL**2*(1.-E)*P**3+2.*EPSL*(4.-E)*P**2+16.*P-2.*E*EPSL
      RETURN
      END
```

1

Table C-3. Output of Example Computation.

```
=====================================================================
=                                                                   =
=    OUTPUT FOR PROGRAM STABLE.FOR TO CALCULATE THE                 =
=    MINIMUM STABILITIES ON A  UNIFORM SLOPE OVER A                 =
=                RANGE OF WAVE BREAKER TYPE                         =
=                                                                   =
=====================================================================
```

```
   OUTPUT VARIABLE DESCRIPTIONS

EPS    : NONLINEARITY PARAMETER
SSP    : SURF SIMILARITY PARAMETER
TD     : LINEARIZED RUNDOWN TIME
TM     : TIME OF MINIMUM SLIDING STABILITY (TM<TD)
NZS    : ZERO DAMAGE SLIDING STABILITY NUMBER
NZL    : ZERO DAMAGE LIFTING STABILITY NUMBER
```

1

```
   INPUT DATA

ARMOR  :  RIP RAP
COTTHE :  3.5
S      :  2.71
CD     :  0.5
CL     :  0.178
CM     :  1.5
TANPHI :  1.19
AC     : 10.8
RA     :  1.13
RB     :  0.506
```

1

EPS	SSP	TD	TM	NZS	NZL
18.00	.36	.02	1.37	999.00	999.00
17.50	.39	.04	1.37	652.44	999.00
17.00	.42	.07	1.37	250.14	999.00
16.50	.46	.09	1.37	125.67	723.48
16.00	.50	.12	1.37	72.94	419.08
15.50	.54	.15	1.37	46.34	265.69
15.00	.58	.18	1.37	31.34	179.25
14.50	.63	.21	1.37	22.19	126.60
14.00	.68	.24	1.38	16.28	92.61
13.50	.73	.27	1.38	12.28	69.67
13.00	.78	.31	1.38	9.49	53.63
12.50	.84	.35	1.38	7.47	42.09
12.00	.90	.39	1.38	5.99	33.59
11.50	.97	.44	1.38	4.87	27.19
11.00	1.04	.49	1.38	4.01	22.30
10.50	1.11	.54	1.39	3.35	18.51
10.00	1.19	.60	1.39	2.83	15.54
9.50	1.28	.66	1.39	2.42	13.19
9.00	1.37	.73	1.39	2.10	11.31
8.50	1.46	.81	1.40	1.84	9.81
8.00	1.57	.90	1.40	1.64	8.62
7.50	1.69	.99	1.41	1.48	7.68
7.00	1.81	1.10	1.41	1.37	6.96
6.50	1.95	1.23	1.42	1.32	6.47
6.00	2.10	1.39	1.42	1.32	6.22
5.50	2.26	1.58	1.43	1.39	6.33
5.00	2.45	1.83	1.44	1.48	6.72
4.50	2.66	2.18	1.44	1.60	7.21
4.00	2.89	3.15	1.45	1.74	7.83
3.50	3.14	3.14	1.46	1.93	8.66
3.00	3.45	3.14	1.48	2.18	9.75
2.50	3.85	3.14	1.49	2.53	11.25
2.00	4.40	3.14	1.50	3.03	13.47
1.50	5.21	3.14	1.52	3.86	17.10
1.00	6.57	3.14	1.54	5.46	24.19
0.50	9.65	3.14	1.55	10.13	44.81

APPENDIX D

CHRONOLOGICAL LISTING OF SINGLE LAYER SANDBAG TESTS

The results of single layer sandbag tests conducted in this study are listed in the following. Sandbags were placed longitudinally in all the tests listed in APPENDIX D. The experimental results are summarized in Tables D-1 and D-2 for uniform slope and bench slope tests, respectively. Some of the tests conducted to pinpoint the critical sandbag movement are not listed.

Uniform Slope Tests

Uniform slope tests were conducted using four different underlayers as listed below:

Setup No. 1: single layer sandbag - longitudinal placement
1:3 slope
quartz sand underlayer
water depth = 36.6 cm

Setup No. 2: single layer sandbag - longitudinal placement
1:3 slope
pea gravel (1/4") underlayer
water depth = 36.6 cm

Setpup No. 3: single layer sandbag - longitudinal placement
1:3 slope
impermeable backing
water depth = 36.6 cm

Setup No. 4: single layer sandbag - longitudinal placement

1:3 slope

coconut hair underlayer

water depth = 36.6 cm

The uniform slope test results are listed in Table D-1 where the following notations are used:

T = wave period (sec)

H = wave height (cm)

R_u = wave runup measured vertically upward above SWL (still water level) (cm)

R_d = wave rundown measured vertically upward above SWL (cm)

The negative value of R_d implies that the wave rundown is below SWL.

Bench Slope Tests

Bench slope tests were conducted using nine different bench configurations as listed below:

Setup No. 5: single layer sandbag - longitudinal placement

h_1 = 0 cm

h_2 = 4 cm

ℓ = 24.7 cm (3 bags)

bench slope = 1:6

slope above and below the bench = 1:3

coconut hair underlayer

water depth = 38.5 cm

Setup No. 6: single layer sandbag - longitudinal placement

$h_1 = 4$ cm

$h_2 = 8$ cm

$\ell = 24.7$ cm (3 bags)

bench slope = 1:6

slope above and below the bench = 1:3

coconut hair underlayer

water depth = 42.5 cm

Setup No. 7: single layer sandbag - longitudinal placement

$h_1 = 8$ cm

$h_2 = 12$ cm

$\ell = 24.7$ cm (3 bags)

bench slope = 1:6

slope above and below the bench = 1:3

coconut hair underlayer

water depth = 46.5 cm

Setup No. 8: single layer sandbag - longitudinal placement

$h_1 = 0$ cm

$h_2 = 8$ cm

$\ell = 49.5$ cm (6 bags)

bench slope = 1:6

slope above and below the bench = 1:3

coconut hair underlayer

water depth = 38.5 cm

Setup No. 9: single layer sandbag - longitudinal placement

h_1 = 4 cm

h_2 = 12 cm

ℓ = 49.5 cm (6 bags)

bench slope = 1:6

slope above and below the bench = 1:3

coconut hair underlayer

water depth = 42.5 cm

Setup No. 10: single layer sandbag - longitudinal placement

h_1 = 8 cm

h_2 = 16 cm

ℓ = 49.5 cm (6 bags)

bench slope = 1:6

slope above and below the slope = 1:3

coconut hair underlayer

water depth = 46.5 cm

Setup No. 11: single layer sandbag - longitudinal placement

h_1 = 0 cm

h_2 = 12 cm

ℓ = 74.3 cm (9 bags)

bench slope = 1:6

slope above and below the bench = 1:3

coconut hair underlayer

water depth = 38.5 cm

Setup No. 12: single layer sandbag - longitudinal placement

h_1 = 4 cm

h_2 = 16 cm

ℓ = 74.3 (9 bags)

bench slope = 1:6

slope above and below the bench = 1:3

coconut hair underlayer

water depth = 42.5 cm

Setup No. 13: single layer sandbag - longitudinal placement

h_1 = 8 cm

h_2 = 20 cm

ℓ = 74.3 cm (9 bags)

bench slope = 1:6

slope above and below the bench = 1:3

coconut hair underlayer

water depth = 42.5 cm

In these experimental setups the following notations are used:

h_1 = the shallowest depth above the bench (cm)

h_2 = the deepest depth above the bench (cm)

ℓ = the length of the bench (cm)

The definition sketch is given in Fig. 1.

The bench slope test results are listed in Table D-2 where the notations are the same as those in Table D-1.

Table D-1. Listing of Uniform Slope Tests

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
2	1.0	1	1	5.5	4.1	-	+c: no movement
		2	1	6.0	6.6	-	c: no movement
		3	1	7.5	7.1	-	c: no movement
		4	1	9.5	8.5	-	c/p: small movement
		5	1	11.5	8.8	-	p: small movement
		6	1	12.5	11.0	-	p: significant movement
		* 7	1	13.5	11.2	-	p: rotation at x = 31 cm
3	1.0	1	1	3.1	5.0	-3.0	s/c: no movement
		2	1	6.0	7.7	-3.0	c: no movement
		3	1	7.5	8.8	-3.0	c/p: no movement
		4	1	9.7	9.8	-0.6	p: small movement
		5	1	11.0	11.0	0.6	p: small movement
		6	1	12.0	11.7	2.4	p: small movement
		7	1	12.5	12.0	2.8	p: small movement
		* 8	1	13.4	-	-	p: rotation at x = 7 cm
4	disregarded due to instrumentation maladjustment						
5	1.0	1	2	3.7	7.4	-2.2	c: no movement
		2	2	6.0	8.2	-1.9	c: no movement
		3	2	7.2	10.1	1.2	c/p: no movement
		4	2	8.5	10.4	1.9	c/p: movement
		* 5	2	10.5	10.7	2.2	p: rotation at x = 19 cm
6	2.0	1	2	3.7	5.0	-	s: no movement
		2	2	5.1	6.8	-	s: no movement
		3	2	7.0	7.9	-	s: no movement
		4	2	8.1	8.8	-	c: movement
		5	2	8.7	9.8	-	c: significant movement
		6	2	9.4	11.2	-	c: significant movement
		* 7	2	11.6	-	-	c: rotation at x = 36 cm
7	1.2	1	2	7.7	10.9	-2.4	c: no movement
		2	2	8.7	11.8	-2.3	c/p: no movement
		3	2	9.4	12.5	-1.9	c/p: no movement
		4	2	10.5	12.6	-0.5	c/p: small movement
		5	2	10.5	12.9	0	p: small movement
		* 6	2	11.5	13.1	0.2	p: rotation at x = 22 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type

s = surging
c = collapsing
p = plunging

Table D-1 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
8	1.4	1	2	3.7	5.7	-2.8	+s: no movement
		2	2	5.5	8.8	-3.8	s/c: no movement
		3	2	7.9	11.5	-3.0	s/c: no movement
		4	2	9.1	13.4	-2.8	c: no movement
		5	2	10.3	12.6	0	c/p: movement
		* 6	2	11.5	-	-	p: rotation x = 18-36 cm
9	0.85	1	2	4.6	6.3	-1.1	c: no movement
		2	2	7.1	8.5	1.9	p: no movement
		3	2	9.4	8.7	2.8	p: no movement
		4	2	10.6	9.3	4.9	p: no movement
		5	2	12.0	-	-	p: small move, no failure
10	1.6	1	2	3.0	9.5	-3.5	s: no movement
		2	2	5.8	13.3	-2.2	c: movement under breaker
		3	2	6.7	13.9	-1.2	c: movement under breaker
		4	2	8.0	-	-	p: significant movement
		* 5	2	10.8	-	-	p: rotation at x = 25 cm
11	1.8	1	2	2.4	6.1	-2.5	s: no movement
		2	2	6.8	10.7	-2.5	s/c: no movement
		3	2	7.5	11.5	-2.5	s/c: no movement
		4	2	10.0	-	-	c: movement under breaker
		* 5	2	10.9	-	-	c: rotation at x = 25 cm
12	1.0	1	2	8.2	-	-	p: no movement
		2	2	10.0	-	-	p: no movement
		3	2	11.0	-	-	p: small movement
		4	2	13.2	-	-	p: significant movement
		* 5	2	14.5	-	-	p: rotation
13	1.2	1	2	8.6	-	-	no movement
		2	2	11.0	-	-	small movement
		* 3	2	13.0	-	-	rotation
14	1.4	1	2	6.4	-	-	no movement
		2	2	9.1	-	-	no movement
		3	2	9.9	-	-	no movement
		4	2	10.5	-	-	no movement
		5	2	12.0	-	-	movement under breaker
		* 6	2	13.4	-	-	rotation

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
s = surging
c = collapsing
p = plunging

Table D-1 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
15	1.6	1	2	5.5	-	-	no movement
		2	2	7.0	-	-	no movement
		3	2	8.0	-	-	movement
		4	2	9.0	-	-	movement
		5	2	9.5	-	-	significant movement
		* 6	2	11.2	-	-	rotation
16	1.8	* 1	2	12.2	-	-	rotation
17	2.0	1	2	9.3	-	-	-
		2	2	11.0	-	-	-
		3	2	11.7	-	-	-
		4	2	13.3	-	-	-
		* 5	2	14.8	-	-	critical wave height
18	1.0	1	3	8.8	9.8	2.5	+p: no movement
		2	3	9.6	11.4	3.0	p: no movement
		3	3	10.9	12.3	4.1	p: no movement
		4	3	11.9	12.0	4.7	p: no movement
		5	3	12.7	-	-	p: small movement
		* 6	3	14.5	-	-	p: rotation x = 14 cm
19	1.2	1	3	6.6	10.6	-0.3	no movement
		2	3	8.6	12.6	2.2	no movement
		3	3	10.7	13.1	4.4	no movement
		4	3	15.1	14.7	4.9	small movement
		* 5	3	16.2	14.7	5.0	rotation at x = 26 cm
20	1.6	1	3	10.3	18.0	1.7	no movement
		* 2	3	12.5	19.7	3.9	rotation at x = 25 cm
21	2.0	1	3	7.4	11.0	-3.1	s: no movement
		2	3	8.5	12.6	-3.4	s: no movement
		3	3	9.2	12.9	-4.4	s/c: no movement
		4	3	10.0	13.9	-3.8	s/c: no movement
		5	3	11.3	15.2	-2.0	c: small movement
		6	3	12.4	18.3	-1.1	c: small movement
		7	3	13.3	19.6	0.5	c: small movement
		8	3	15.5	-	-	c: no failure

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type

s = surging
c = collapsing
p = plunging

Table D-1 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
22	1.0	1	4	3.8	5.5	0	+s: no movement
		2	4	5.8	7.3	0.8	s/c: no movement
		3	4	7.8	8.2	2.5	c: no movement
		4	4	10.3	8.8	3.8	p: no movement
		5	4	12.9	9.3	3.8	p: small movement
		* 6	4	13.8	-	-	p: rotation at x = 15 cm
23	1.2	1	4	3.4	2.8	0	s: no movement
		2	4	4.9	5.2	1.7	s: no movement
		3	4	7.5	7.5	2.5	c/p: small movement
		* 4	4	11.8	11.7	5.5	p: rotation at x = 7 cm
24	1.4	1	4	4.0	4.4	-0.3	s: no movement
		2	4	5.8	6.5	0.9	s: no movement
		3	4	8.6	9.5	2.7	c: no movement
		4	4	10.5	12.0	4.7	c: small movement
		* 5	4	13.4	15.1	5.7	c/p rotation at x = 15 cm
25 & 26	disregarded due to instrumentation maladjustment						
27	2.0	1	4	4.9	6.8	-3.1	s: no movement
		2	4	6.7	9.5	-3.0	s: no movement
		3	4	8.8	11.0	-2.8	c: no movement
		4	4	10.4	12.2	-3.0	c: movement
		* 5	4	11.8	-	-	c: rotation at x = 28 cm
28	2.2	1	4	8.1	10.2	-4.9	s: no movement
		2	4	9.3	13.3	-5.0	s: no movement
		3	4	10.8	13.6	-5.5	s: no movement
		4	4	11.5	13.9	-5.5	s/c: small movement
		* 5	4	14.0	-	-	c: rotation at x = 22 cm
29	2.2	1	4	9.6	10.4	-5.2	s: no movement
		2	4	10.9	13.6	-5.5	s: no movement
		3	4	11.9	14.8	-5.7	s: no movement
		4	4	12.9	16.4	-	s: small movement
		* 5	4	14.5	-	-	s/c: rotation at x = 25 c

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
s = surging
c = collapsing
p = plunging

Table D-1 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
30	2.0	1	4	3.7	4.9	-3.0	s[+]: no movement
		2	4	5.4	7.9	-3.3	s: no movement
		3	4	7.3	9.9	-4.4	s: no movement
		4	4	7.9	11.0	-4.9	s/c: small movement
		5	4	8.5	12.6	-3.1	c: small movement
		* 6	4	13.0	-	-	c: rotation at x = 25 cm
31	1.8	1	4	5.5	6.0	-2.6	s: no movement
		2	4	7.7	8.8	-3.1	s: no movement
		3	4	9.6	10.6	-2.8	s/c: movement
		* 4	4	12.0	-	-	c: rotation at x = 21 cm
32	1.6	1	4	8.8	9.5	-2.2	s/c: movement under breaker
		* 2	4	11.0	11.4	-0.3	c/p: rotation at x = 21 cm
33	1.4	1	4	4.4	5.0	-1.5	s: no movement
		2	4	6.6	8.0	-1.9	c: no movement
		3	4	8.0	10.4	-0.5	c: no movement
		* 4	4	10.0	-	-	c: rotation at x = 23 cm
34	1.2	1	4	4.6	5.5	-0.6	s/c: no movement
		2	4	6.5	9.1	1.7	c: no movement
		3	4	8.3	10.3	2.8	c/p: no movement
		* 4	4	11.6	-	-	p: rotation at x = 5 cm
35	1.0	1	4	6.3	5.8	-0.1	c/p: no movement
		2	4	8.8	8.8	2.8	p: no movement
		3	4	11.5	10.1	4.9	p: no movement
		4	4	12.5	-	-	p: movement
		* 5	4	14.5	-	-	p: rotation
36	1.2	* 2	4	10.5	-	-	p: rotation at x = 8 cm
37	1.4	* 3	4	11.0	-	-	c: rotation at x = 8 cm
38	1.6	* 2	4	11.5	-	-	c: rotation at x = 16 cm
39	1.8	* 4	4	13.5	-	-	c: rotation at x = 23 cm
40	2.2	* 4	4	14.5	-	-	c: rotation at x = 23 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
s = surging
c = collapsing
p = plunging

Table D-2. Listing of Bench Slope Tests

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
41	1.0	1	5	5.7	4.1	0.9	+s: no movement
		2	5	10.8	6.6	3.5	c: no movement
		3	5	12.5	6.9	6.0	c/p: no movement
		4	5	13.8	7.6	6.1	p: small movement
		* 5	5	15.2	8.8	6.9	p: rotation at x = 34 cm
42	1.2	1	5	4.2	4.2	1.8	s: no movement
		2	5	6.7	6.9	2.2	s/c: no movement
		* 3	5	12.0	8.8	4.4	c: rotation at x = 34 cm
		4	5	15.5	11.4	7.6	p: removed at x = 34-40 cm
43	1.4	1	5	4.0	4.4	1.6	s: no movement
		2	5	8.5	7.9	2.2	s/c: small movement
		* 3	5	11.5	10.1	4.1	c: rotation at x = 34 cm
44	1.6	1	5	3.0	3.5	1.2	s: no movement
		2	5	7.0	7.1	2.5	s/c: no movement
		3	5	8.0	8.8	3.1	c: small movement
		* 4	5	12.0	13.6	6.9	c/p: rotation at x=34-42 cm
45	1.8	1	5	5.5	5.7	1.6	s: no movement
		2	5	8.4	10.4	2.8	s/c: no movement
		* 3	5	11.0	13.9	4.7	c: rotation at x = 34-42 cm
46	2.0	1	5	6.5	6.9	2.2	s: no movement
		2	5	9.0	11.0	2.2	s: no movement
		3	5	10.4	13.3	4.1	s/c: movement
		4	5	14.0	16.7	6.6	c: *H_c = 13.2 cm
47	2.2	1	5	11.0	15.1	4.1	c: significant movement
		2	5	10.0	13.6	2.2	c: significant movement
		* 3	5	13.5	-	-	c: rotation at x=26-34 cm
48	1.0	1	6	7.5	6.0	0.8	c: no movement
		2	6	10.0	6.8	2.8	p: no movement
		3	6	12.0	7.9	3.8	p: small movement
		4	6	14.6	9.1	6.3	p: small movement
		* 5	6	16.0	-	-	p: rotation at x = 24 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
- s = surging
- c = collapsing
- p = plunging

Table D-2 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
49	1.2	1	6	3.5	5.0	0.6	+c: no movement
		2	6	8.4	7.9	0.8	c: no movement
		3	6	12.0	9.5	3.8	c: no movement
		4	6	14.4	11.2	6.0	c/p: movement under breaker
		* 5	6	15.2	–	–	P: rotation at x = 47 cm
50	1.4	1	6	7.0	9.5	2.5	c: no movement
		2	6	11.2	9.8	3.8	c: no movement
		3	6	14.2	9.8	6.9	c: small movement
		4	6	17.0	16.7	6.3	c/p: $*H_c$ = 16 cm
51	1.6	1	6	9.0	10.7	2.5	c: movement
		* 2	6	11.5	14.2	5.4	c: rotation at x = 30 cm
52	1.8	1	6	8.0	7.3	0.6	s: no movement
		2	6	12.0	12.6	2.8	c: removed at x = 30 cm
		* 3	6	10.0	9.5	1.6	s/c: rotation at x=30 cm
53	2.0	1	6	5.0	4.4	0.9	s: no movement
		2	6	9.0	8.5	0.9	s/c: no movement
		3	6	12.0	13.6	2.5	c/p: significant movement
		4	6	15.0	19.9	5.4	p: $*H_c$ = 13 cm
54	2.2	1	6	6.2	6.9	0.6	s: no movement
		2	6	9.0	10.1	1.2	s: no movement
		3	6	11.2	13.6	8.8	c: significant movement
		4	6	14.5	22.7	5.3	c/p: $*H_c$ = 13 cm
55	1.0	1	7	7.5	8.5	2.2	c/p: no movement
		2	7	10.5	9.2	2.5	p: small movement
		* 3	7	13.0	9.5	3.8	p: rotation at x = 16 cm
56	1.2	1	7	8.0	8.8	0.9	c: no movement
		2	7	11.0	10.4	2.8	c/p: significant movement
		* 3	7	11.8	10.7	4.4	p: rotation at x = 7-16 cm
57	1.4	1	7	7.7	8.8	0	s/c: no movement
		2	7	10.8	9.5	2.8	c: no movement
		3	7	11.6	12.6	3.8	c/p: no movement
		4	7	13.8	13.9	5.0	c/p: significant movement
		* 5	7	14.5	–	–	p: rotation at x = 10 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
- s = surging
- c = collapsing
- p = plunging

Table D-2 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
58	1.6	1	7	6.0	5.7	-2.8	+s: no movement
		2	7	9.5	9.5	-1.2	s/c: no movement
		3	7	12.0	12.3	0.3	c: no movement
		4	7	14.5	13.3	2.5	c: small movement
		* 5	7	16.0	-	-	c: rotation at x = 55 cm
59	1.8	1	7	10.0	10.4	-1.7	s: no movement
		2	7	12.0	12.6	-0.3	c: significant movement
		* 3	7	13.0	-	-	c: rotation at x=40-50 cm
60	2.0	1	7	9.0	6.3	-3.6	s: no movement
		2	7	12.0	10.4	-2.0	s/c: small movement
		* 3	7	14.5	12.9	-0.5	c: rotation at x = 65 cm
		4	7	16.0	17.2	2.8	c: bags removed
		5	7	15.0	-	-	c: bags removed
61	2.2	1	7	7.5	6.3	-3.5	s: no movement
		2	7	10.0	9.5	-2.5	s: no movement
		3	7	11.6	12.0	-1.2	s/c: no movement
		4	7	13.0	15.2	-0.3	s/c: significant movement
		* 5	7	14.0	-	-	s/c: rotation at x = 50 cm
62	1.0	1	8	3.6	3.3	1.2	c: no movement
		2	8	7.2	5.7	1.6	p: no movement
		3	8	10.5	7.6	4.7	p: small movement
		4	8	13.0	7.9	5.7	p: small movement
		5	8	14.5	7.9	5.4	p: small movement
63	1.2	1	8	5.1	4.4	0.6	c: no movement
		2	8	10.0	6.9	1.4	c: no movement
		3	8	12.0	8.0	4.1	c/p: small movement
		4	8	13.4	8.8	5.4	p: significant movement
		* 5	8	13.5	-	-	p: rotation at x = 60 cm
64	1.4	1	8	6.0	6.3	1.4	c: no movement
		2	8	8.9	9.0	1.9	c: no movement
		3	8	11.5	9.8	3.8	c: movement
		* 4	8	12.4	-	-	c: rotation at x = 60 cm
65	1.6	1	8	9.0	8.8	1.1	c: no movement
		2	8	11.5	11.0	1.4	c: small movement
		* 3	8	13.0	-	-	c: rotation at x = 60 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
s = surging; c = collapsing; p = plunging

Table D-2 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
66	1.8	1	8	4.0	4.9	0.6	+s: no movement
		2	8	6.1	6.9	1.2	s: no movement
		3	8	11.0	10.4	1.6	c: small movement
		* 4	8	12.4	-	-	c: rotation at x=50-60 cm
67	2.0	1	8	6.7	6.3	0.8	s: no movement
		2	8	9.1	9.2	1.2	c: small movement
		3	8	10.2	11.0	1.6	c: small movement
		* 4	8	12.0	-	-	c: rotation at x = 60 cm
68	2.2	1	8	7.3	6.6	0	s: no movement
		2	8	10.0	9.8	1.4	s/c: no movement
		3	8	11.5	12.9	1.7	s/c: *H_c = 12 cm
69	1.0	1	9	7.7	5.4	0.8	p: no movement
		2	9	11.2	7.3	3.1	p: no movement
		3	9	13.5	8.2	4.7	p: no movement
		4	9	14.2	8.2	6.6	p: small movement
		5	9	16.0	-	-	p: small movement
70	1.2	1	9	6.5	5.7	-0.3	c/p: no movement
		2	9	10.0	7.6	2.8	p: no movement
		3	9	13.0	8.2	4.4	p: small movement
		4	9	14.0	9.0	5.4	p: small movement
		* 5	9	16.0	-	-	p: rotation at x = 30 cm
71	1.4	1	9	7.0	6.0	-0.8	c: no movement
		2	9	11.0	8.2	2.2	P: no movement
		* 3	9	13.5	-	-	p: rotation at x = 30 cm
72	1.6	1	9	7.5	7.5	-0.3	s: no movement
		2	9	10.0	8.8	0	c: small movement
		3	9	12.0	10.7	1.1	c/p: small movement
		4	9	13.0	11.4	1.9	p: small movement
		* 5	9	14.5	12.6	3.3	p: rotation at x = 30 cm
		6	9	15.0	-	-	p: bags removed at x=30 cm
73	1.8	1	9	7.0	7.3	-1.2	s: no movement
		2	9	9.5	9.8	-0.6	c: no movement
		3	9	12.0	13.3	0	c: no movement
		* 4	9	15.0	-	-	c: rotation at x = 48 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
s = surging; c = collapsing; p = plunging

Table D-2 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
74	2.0	1	9	6.5	6.0	-1.2	+s: no movement
		2	9	8.8	8.8	-0.6	c: no movement
		3	9	11.0	11.7	-0.6	c: no movement
		* 4	9	16.0	-	-	c: rotation at x = 62 cm
75	2.2	1	9	4.5	4.4	-0.9	s: no movement
		2	9	8.5	8.0	-1.5	s: no movement
		3	9	11.3	11.7	-0.6	s: no movement
		4	9	12.6	14.5	-0.5	s/c: no movement
		5	9	17.0	-	-	c: significant movement
		6	9	13.3	-	-	c: no movement
		7	9	16.0	-	-	c: movement
		* 8	9	17.5	-	-	c: rotation at x = 62 cm
76	1.0	1	10	5.8	6.9	1.9	c: no movement
		2	10	10.0	8.5	4.1	c/p: no movement
		3	10	14.0	9.5	5.0	p: small movement
		4	10	14.5	9.8	6.9	p: small movement
77	1.2	1	10	10.0	9.6	4.4	p: no movement
		2	10	13.0	11.4	4.7	p: small movement
		* 3	10	15.0	-	-	p: rotation at x=8-12 cm
78	1.4	1	10	8.3	10.1	2.8	c/p: no movement
		2	10	11.5	12.3	4.7	p: movement
		* 3	10	12.6	-	-	p: rotation at x = 15 cm
79	1.6	1	10	7.0	7.6	-0.8	s/c: no movement
		2	10	9.5	12.0	2.2	c: no movement
		* 3	10	13.0	-	-	c: rotation at x=8-12 cm
80	1.8	1	10	6.0	7.3	-1.6	s: no movement
		2	10	9.5	12.0	1.9	s/c: no movement
		3	10	11.0	15.2	3.5	c: significant movement
		* 4	10	11.5	16.1	4.4	c/p: rotation at x = 15 cm
81	2.0	1	10	5.2	6.6	-2.5	s: no movement
		2	10	8.3	10.7	-0.6	s/c: no movement
		3	10	11.1	14.2	2.5	c: small movement
		* 4	10	12.5	-	-	c/p: rotation at x = 15 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaking Type
s = surging; c = collapsing; p = plunging

Table D-2 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
82	2.2	1	10	4.2	4.7	-0.9	+s: no movement
		2	10	7.5	7.3	-2.2	s: no movement
		3	10	8.9	9.8	-0.9	s/c: small movement
		4	10	9.8	11.0	-0.3	s/c: small movement
		* 5	10	14.5	-	-	c: rotation at x = 15 cm
83	1.0	1	11	8.2	6.0	1.6	c: no movement
		2	11	11.0	6.6	3.8	c/p: no movement
		3	11	15.8	7.4	4.7	p: no movement
84	1.2	1	11	7.0	6.0	1.2	c/p: no movement
		2	11	10.0	7.1	1.9	p: no movement
		3	11	13.2	8.2	3.8	p: small movement
		4	11	15.6	10.4	5.4	p: small movement
		* 5	11	17.0	-	-	p: rotation at x = 35 cm
85	1.4	1	11	7.8	6.6	2.0	no movement
		2	11	12.0	8.5	4.1	no movement
		3	11	15.3	11.4	6.3	small movement
		4	11	18.0	12.6	8.5	$*H_c$ = 16 cm
86	1.6	1	11	8.5	6.9	1.9	c: no movement
		2	11	14.0	11.4	4.4	c/p: no movement
		3	11	19.0	14.2	8.2	p: $*H_c$ = 16 cm
87	1.8	1	11	6.0	7.9	1.9	no movement
		2	11	8.6	9.5	2.5	no movement
		3	11	10.0	11.4	4.7	no movement
		4	11	16.0	14.8	7.3	$*H_c$ = 15 cm
88	2.0	1	11	5.2	6.0	0.9	s: no movement
		2	11	7.5	7.1	1.2	s/c: no movement
		3	11	8.5	9.5	1.4	s/c: no movement
		4	11	10.8	12.3	1.4	c: no movement
		5	11	13.2	13.9	1.4	c: small movement
		* 6	11	15.4	16.1	1.5	c: rotation at x = 60 cm
89	2.2	1	11	8.3	7.3	1.1	s: no movement
		2	11	12.2	12.3	1.4	s/c: no movement
		3	11	14.0	16.7	1.4	c: small movement
		4	11	14.6	-	-	c: small movement
		* 5	11	16.5	-	-	c: rotation at x = 60 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
s = surging; c = collapsing; p = plunging

Table D-2 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
90	1.0	1	12	7.6	6.0	0.6	+c/p: no movement
		2	12	13.0	7.9	3.1	p: no movement
		3	12	16.0	9.2	5.0	p: no movement
91	1.2	1	12	9.5	7.9	0	p: no movement
		2	12	12.0	8.2	3.5	p: no movement
		3	12	14.0	8.5	5.0	p: small movement
		4	12	15.5	-	-	p: small movement
		* 5	12	17.8	-	-	p: rotation at x = 30 cm
92	1.4	1	12	8.3	7.5	-0.6	c/p: no movement
		2	12	12.0	8.8	2.5	p: no movement
		3	12	14.3	11.4	3.8	p: small movement
		* 4	12	15.7	-	-	p: rotation at x = 30 cm
93	1.6	1	12	8.0	8.5	-0.6	c: no movement
		2	12	10.5	11.4	2.5	p: no movement
		* 3	12	13.8	12.6	-	p: rotation at x = 30 cm
94	1.8	1	12	7.0	7.5	-1.2	s: no movement
		2	12	10.5	11.0	-0.6	s/c: no movement
		3	12	11.0	12.9	-0.3	c: no movement
		4	12	12.5	13.9	0	c: no movement
		5	12	14.0	17.7	3.1	c: small movement
		* 6	12	18.0	-	-	c/p: rotation at x = 48 cm
95	2.0	1	12	7.5	6.6	-1.2	s: no movement
		2	12	11.5	9.5	-0.3	c: no movement
		3	12	13.7	15.5	0	c: no movement
		4	12	15.0	17.7	1.9	c: no movement
		* 5	12	17.6	-	-	c: rotation at x = 55 cm
96	2.2	1	12	8.8	9.5	-1.2	s: no movement
		2	12	11.6	13.3	-0.8	s: no movement
		3	12	14.5	17.0	-0.3	s/c: no movement
		* 4	12	18.5	-	-	c: rotation at x = 46 cm
97	1.0	1	13	10.2	9.5	4.4	p: no movement
		2	13	13.5	10.4	5.6	p: no movement
98	1.2	1	13	4.2	5.7	-0.6	s: no movement
		2	13	12.0	12.6	4.7	c/p: small movement
		3	13	13.5	12.6	6.0	p: *H_c = 14 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
s = surging; c = collapsing; p = plunging

Table D-2 (Cont'd)

Series	T (sec)	Run No.	Setup No.	H (cm)	R_u (cm)	R_d (cm)	Description of Results
99	1.4	1	13	8.4	10.1	0.6	+c: no movement
		2	13	12.5	13.6	4.1	c/p: small movement
		* 3	13	15.0	–	–	p: rotation at x = 15 cm
100	1.6	1	13	6.0	9.5	-1.1	s: no movement
		2	13	10.0	13.3	1.2	s/c: no movement
		3	13	14.0	15.8	4.1	p: significant movement
		* 4	13	14.5	–	–	p: rotation at x = 8 cm
101	1.8	1	13	7.0	7.5	-1.4	s: no movement
		2	13	10.0	14.8	1.2	s/c: no movement
		3	13	13.0	18.0	3.8	c: small movement
		* 4	13	14.5	–	–	c/p: rotation at x = 30 cm
102	2.0	1	13	8.5	10.4	-1.4	s: no movement
		2	13	12.0	15.5	-0.6	s/c: small movement
		3	13	13.0	16.4	1.2	c: small movement
		* 4	13	15.0	–	–	c/p: rotation at x = 40 cm
103	2.2	1	13	7.0	7.5	-1.2	s: no movement
		2	13	10.0	12.6	-1.2	s: no movement
		* 3	13	16.0	–	–	s/c: rotation at x = 30 cm

*: test run in which critical sandbag movement occurred

+: Observed Breaker Type
s = surging
s = collapsing
p = plunging

APPENDIX E

LISTING OF 50% OVERLAP SANDBAG TESTS

At the conclusion of the benched slope testing, the model setup was converted back to a uniform slope with the model sandbags placed in a 50% overlap fashion. Pressed coconut hair was used as the underlayer material. An overlap sandbag placement configuration is expected to result in increased stability of the sandbag system as compared to a longitudinally-placed single layer sandbag system, although it requires nearly twice as many sandbags.

The laboratory setup and testing procedure was identical to that described in Section 2.4 and 2.5. A picture of the 50% overlap sandbag placement is shown in Photograph 2. Unfortunately, due to time limitations for this project it was not possible to complete the test series using the entire range of wave periods. The tests were run for wave periods T = 1.0 sec, 1.2 sec, 1.4 sec, and 1.6 sec. The measured wave heights, runup, rundown, and critical wave heights are presented in Table E-1.

TABLE E-1. Listing of 50% Overlap Tests

Series	T (sec)	Run No.	H (cm)	R_u (cm)	R_d (cm)
E-1	1.0	1	13.0	7.9	3.1
		* 2	13.0	7.9	4.7
		3	7.0	4.7	1.6
E-2	1.2	1	6.0	4.7	0
		2	10.0	9.5	3.8
		* 3	14.0	11.0	6.3
		4	17.0	12.6	7.9
E-3	1.4	1	8.0	8.8	1.5
		2	12.0	12.6	6.3
		* 3	14.0	14.2	7.9
		4	13.0	14.2	5.4
E-4	1.6	1	10.0	8.8	3.2
		* 2	16.0	15.8	7.9

*: test run in which critical sandbag movement occurred

APPENDIX F

COMPUTER PROGRAM FOR MODIFIED SAVILLE'S METHOD

An analysis procedure to determine the required sandbag volume for stability of a benched slope has been introduced in Section 4 and described in Section 5 of this report. This analysis procedure is based on the analysis of sandbag model tests performed at the Ocean Engineering Laboratory, the University of Delaware. A computer program has been developed to facilitate the required computation and is presented here. Figs. 26 through 36 of this report have been generated using this computer program by incrementally changing some of the input variables.

The set of input data required for the computation is as follows:

H = design wave height (ft)

T = design wave period (sec)

a_1, b_1 = empirical runup coefficients from Eq. (23)

a_3, b_3, c_3 = stability curve coefficients from Eq. (28)

$\cot\theta_1$ = cotangent of slope angle landward of bench

$\cot\theta_2$ = cotangent of slope angle seaward of bench

B = bench width (ft)

$\cot\theta_B$ = cotangent of bench slope angle

h_1 = depth of shallowest point of bench (ft)

γ = unit weight of armor unit (pcf)

α_b = breaker index from Eq. (12)

The values of the input data are read into the program from a data file. For convenience, the cotangents of the slopes are specified.

The following parameters are specified and held constant in the program:

$m = 1/2$ = coefficient related to H_e in Eq. (21)

$n = 2/3$ = slope effect coefficient in Eq. (26)

$\gamma_w = 64$ (pcf) = unit weight of seawater

$g = 32.2$ (ft/sec^2) = gravitational acceleration

A listing of the computer program is presented in Table F-1. Examples of the model output are shown in Tables 4 and 5.

Table F-1. Required Input Parameters and Corresponding Format Statements

Input Parameters	Format
H, T	unformatted
A1, B1	unformatted
A3, B3, C3	unformatted
COTθ1, COTθ2, B, COTθB, H1	unformatted
GA	unformatted
BI	unformatted

Table F-2. Listing of Computer Program to Calculate Critical Sandbag Volume Using Modified Saville's Method.

```
      OPEN(UNIT=2,DEVICE='DSK',FILE='COMPOS.DAT')
C   Read Wave Height and Wave Period
      READ(2,*) H,T
C   Read Runup Coefficients
      READ(2,*) A1,B1
C   Read  Stability Curve Coefficients
      READ(2,*) A3,B3,C3
C . Read Slope Characteristics
      READ(2,*) COTO1,COTO2,B,COTOB,H1
C   Read Unit Weight of Armor Unit
      READ(2,*) GA
C   Read Breaker Index
      READ(2,*) BI
      WRITE(5,2) H,T,A1,B1,A3,B3,C3,COTO1,COTO2,B,COTOB,H1,GA,BI
    2 FORMAT(1H1,//,16X,
     > 'WAVE RUNUP AND SANDBAG STABILITY ON BENCH SLOPES',
     > ///,31X,'DESIGN PARAMETERS',////,36X,'(INPUT)',
     > //,15X,'Wave Height :',23x,'H = ',f6.2,' ft',//,15x,
     > 'Wave Period :',23x,'T = ',f6.2,' sec',//,15x,
     > 'Runup Coefficients :',15x,'a1 = ',f6.2,/,50x,'b1 = ',f6.2,
     > //,15x,'Stability Coefficients :',11x,'a3 = ',f6.2,/,50x,
     > 'b3 = ',f6.2,/,50x,'c3 = ',f6.2,//,15x,
     > 'Slope Characteristics :',8x,'cot O1 = ',f6.2,/,46x,
     > 'cot O2 = ',f6.2,/,51X,'B = ',f6.2,' ft',/,46X,'cot Ob = ',
     > f6.2,/,50x,'h1 = ',f6.2,' ft',//,
     > 15x,'Sandbag Characteristics :    Unit Wt. = ',f6.2,' pcf',//,
     > 15x,'Breaker Index :',17x,'Alpha = ',f6.2)
C   Coefficient m (CM) related to He
      CM=1./2.
C   Slope effect coefficient n (CN) related to Kd
      CN=2./3.
C   Gravitational acceleration G = 32.2 fss
      G=32.2
C   Unit Weight of Sea Water GW = 64 pcf
      GW=64.
C   SG = Specific Weight of Sandbag
      SG=GA/GW
C   XLO = Deep water wave length
      XLO=G*T**2/6.2832
C   HB = Depth at breaker point
      HB=H/BI
C   H2 = Depth of deepest part of bench
      H2=H1+(B/COTOB)
C   XB = Horizontal distance to breaker point
      IF(HB.GE.H2) XB=H1*COTO1+B+(HB-H2)*COTO2
      IF(HB.LT.H2) XB=H1*COTO1+(HB-H1)*COTOB
      IF(HB.LE.H1) XB=HB*COTO1
C  ITERATIVE PROCEDURE
C   TANOE = Equivalent slope tan Oe
C   ARAT = Ratio Ab/Ae
      TANEQ=1./COTO1
      ARATI=1.
      DO 20 J=1,30
      HEI=H/ARATI**CM
      SSPEI=TANEQ/SQRT(HEI/XLO)
      RI=HEI*(A1*SSPEI)/(1.+B1*SSPEI)
      TANOE=(RI+HB)/(RI*COTO1+XB)
      IF(HB.GE.H2) ARAT=TANOE*(COTO2+(H2/HB)**2*(COTOB-COTO2)-
     > (H1/HB)**2*(COTOB-COTO1))
      IF(HB.LT.H2) ARAT=TANOE*(COTOB-(H1/HB)**2*(COTOB-COTO1))
```

continue

```
          IF(HB.LE.H1) ARAT=1.
          HE=H/ARAT**CM
          SSPE=TANOE/SQRT(HE/XLO)
          R=HE*(A1*SSPE)/(1.+B1*SSPE)
          RDIF=ABS(R-RI)
          IF(RDIF.LE.0.1) GO TO 30
          TANEQ=TANOE
          ARATI=ARAT
   20     CONTINUE
          IF(RDIF.GT.0.1) STOP
   30     COTOE=1./TANOE
C     SKEC = Kec from stability curve
          SKEC=(A3*SSPE**2+B3*SSPE+C3)**3
C     Hudson's equation
          W=(GA*HE**3)/(SKEC*(SG-1.)**3*COTOE**CN)
          VOL=W/(GA*27.)
          TW=W/2000.
          WRITE(5,3) R,TW,VOL,COTOE
    3     FORMAT(////,35X,'(OUTPUT)',///,15X,
     >    'Vertical Runup Height :',12x,'Ru = ',f6.2,' ft',//,15x,
     >    'Required Weight of Sandbag :',7x,'Wc = ',f6.2,' tons',//,15x,
     >    'Required Volume of Sandbag :',7x,'Vc = ',f6.2,' cu-yd',//,15x,
     >    'Cotangent of Equiv. Slope :     cot 0e = ',f6.2)
          STOP
          END
```