United States
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Soil
Conservation
Service

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TECHNICAL RELEASE NO. 69
210-VI

SUBJECT: ENG - RIPRAP FOR SLOPE PROTECTION AGAINST WAVE ACTION

Purpose. To distribute Technical Release No. 69, Riprap for Slope Protection Against Wave Action.

Effective Date. Effective when received.

This technical release (TR) presents recommended design procedures and criteria for rock used to protect slopes against erosion from deep-water wave action. The TR consolidates in one document, for convenient use by SCS personnel, a design procedure developed by the West National Technical Center.

The riprap design for slope protection is applicable to dam faces and other reservoir shorelines. When the slope cannot be adequately protected by vegetation, using procedures outlined in TR-56, riprap or other comparable types of structural protection should be used.

Filing Instruction. File with other Engineering Technical Releases.

Distribution. The technical release distribution made (shown on reverse side) provides enough copies so that each practicing professional engineer may have one as a reference copy. Additional copies may be obtained from Central Supply by ordering Item No. TR-69.

Paul M. Howard

PAUL M. HOWARD
Deputy Chief for Technology
Development and Application

Enclosure

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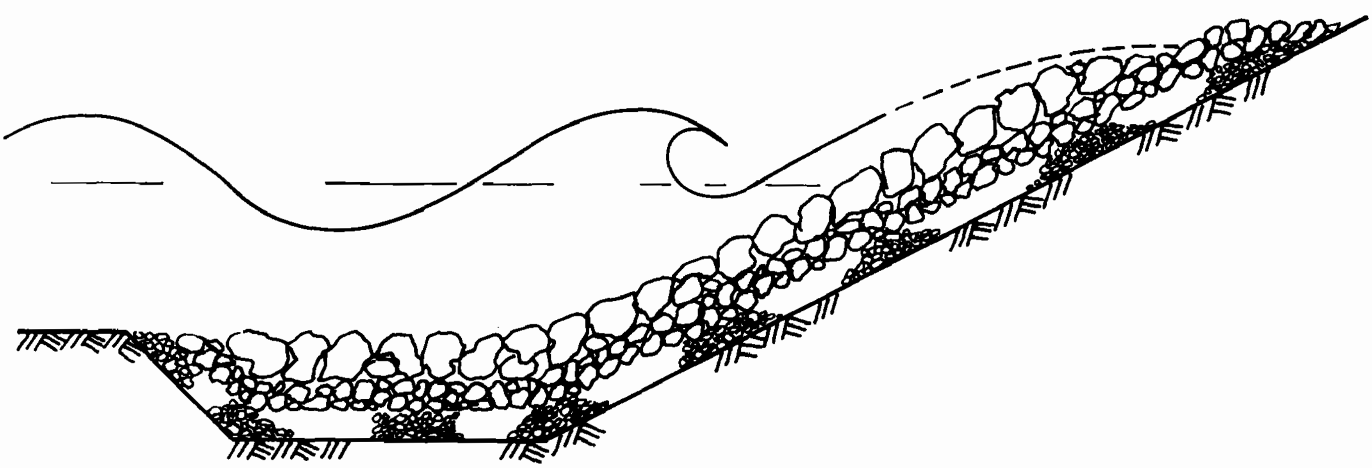
RIPRAP FOR SLOPE PROTECTION AGAINST WAVE ACTION



PREFACE

In late 1971, a need was recognized for design procedures for riprap protection of slopes. At the 1975 National Design Engineers Conference, Portland, Oregon, members discussed their most urgent needs and, in the interest of national benefit, decided that the Engineering and Watershed Planning units and Engineering Division would make a coordinated effort to develop the needed riprap design procedures. Preparation of a technical release (TR) was assigned to the West National Technical Center (NTC).

The Engineering Division distributed a draft of the TR to other NTC's during 1978 for review and comments. The late Harry W. Firman was instrumental in developing the technical information. Others who assisted substantially in preparing the TR were Gary Margheim, Charles Houston, Jack Stevenson, Harold Honeyfield, Jack Land, and James Dunlap.

The procedures presented herein should be useful to both planning and design engineers in determining preliminary or detailed design values for riprap protection of slopes.

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RIPRAP DESIGN FOR PROTECTING SLOPES AGAINST WAVE ACTION

CONTENTS

LIST OF FIGURES

NOMENCLATURE

$A = \frac{2\gamma^2\rho'}{\rho} = 6.28 \times 10^{-6}$ at 20°C., dimensionless

a = wave amplitude, feet

C = wave velocity, feet/second

= velocity of water flowing around or impinging on the rock, feet/second

C_d = drag coefficient, dimensionless

C_m = virtual mass coefficient, dimensionless

C_q = total coefficient, dimensionless

D = least dimension of a given geometric shape measured along one of the principal axis, feet

D_{50} = diameter of median rock size, feet

E = mean energy of wave per unit area $\frac{\text{foot-pound}}{\text{feet}^2}$

F = fetch, mile

F_d = drag force, pound

F_e = effective fetch, mile

F_p = fetch, longest reach of open water to dam, mile

F_m = inertial force, pound

F_q = total force, pound

g = acceleration of gravity, 32.16 feet/second²

G_s = specific gravity of rock, dimensionless - bulk, saturated surface dry, See ASTM C-127.

h = depth of water, feet

H = wave height from trough to crest, feet

H_s = significant wave height (average height of the highest one-third of the waves for a specified period of time), feet

$k = 2\pi/L$ feet^{-1}

k_s = stability coefficient, dimensionless

K = ratio of rock size related to the D_{50} size or (W_{50}) weight in a rock gradation curve.

K_a = coefficient of effective rock area constant such that $K_a \ell^2$ equals the projected area of a rock perpendicular to the velocity, dimensionless

K_v = coefficient of effective rock volume constant such that $K_v \ell^3$ equals the volume of rock, dimensionless

$K_\Delta = K_s^3$, dimensionless

ℓ = characteristic linear dimension of a rock, feet

L = wave length in deep water (distance between two successive crests in the direction of propagation), feet

r = 0.580 = coefficient of energy partition, dimensionless

R = wave runup (vertical distance above storm water surface to which a wave will run up on a given structure), feet

R_m = mean rate of energy transfer to wave from normal wind pressure, $\frac{\text{foot-pound}}{\text{feet}^2\text{-second}}$

R_T = mean rate of energy transfer to wave from tangential wind stress, $\frac{\text{foot-pound}}{\text{feet}^2\text{-second}}$

R_μ = mean rate of energy dissipation from viscosity, $\frac{\text{foot-pound}}{\text{feet}^2\text{-second}}$

s = 0.013 = coefficient of proportionality, dimensionless

S = wind set-up (the increase in water level above stillwater elevation in a reservoir from shear forces of the wind), feet

t = time, second

t_B = thickness, bedding, feet

t_f = thickness, filter, feet

t_r = thickness, riprap, feet

T' = thickness of riprap layer, inches

T = wave period, second

T_d = minimum wind duration required for generation of wave heights for a corresponding effective fetch distance and wind velocity, minute

U = wind velocity 30 ft above water surface, feet/second

U_d = design wind volocity, mile/hour

U_L = overland wind velocity, mile/hour

U_w = overwater wind velocity, mile/hour

W_{50} = weight of median size rock, pound

W_r = dry weight of rock, pound

W'_r = buoyant weight of rock, pound

Xi = radial distance over open water, pound

Z = cotangent of slope angle α, dimensionless

$\alpha = S/2\Upsilon^2 = 2.5$, or embankment slope angle from horizontal, dimensionless

β = wave age = C/U, dimensionless

$\beta' = 0.350$, dimensionless

$\Upsilon^2 = 2.6 \times 10^{-3}$ = wind resistance coefficient, dimensionless

Υ_r = specific unit weight of the rock, pound/feet^3

Υ_w = specific unit weight of water, pound/feet^3

δ = wave steepness = H/L, dimensionless

$\mu = 2.089 \times 10^{-5} \frac{\text{lb-sec}}{\text{ft}^2}$ = absolute viscosity of water)

$\rho = 1.937 \frac{\text{lb-sec}^2}{\text{ft}^4}$ = mass density of water) at 20°C

$\rho' = 2.340 \times 10^{-3} \frac{\text{lb-sec}^2}{\text{ft}^4}$ = mass density of air)

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RIPRAP DESIGN FOR PROTECTING SLOPES AGAINST WAVE ACTION

Scope

These design procedures and criteria are recommended for rock used as riprap protection against deep-water wave action. They are intended for use with dams and reservoirs receiving Soil Conservation Service (SCS) technical assistance. Generally, these have an effective fetch less than 10 miles and significant wave height less than 5 feet. Where site conditions present values greater than these, refer to the publications (1, 2, 3, 4, 5) listed in the Bibliography.

Introduction

Earth structures retaining a reservoir are subject to erosion by wave attack. It is often necessary to prevent the erosion by protecting the surface with riprap (6).

These design procedures are limited to rock used as riprap protection against wave action. Riprap protection against wave action is generally satisfactory for protecting the slope from other attacks.

Properly sized and graded rock overlying a suitable bedding, filter, or both has provided adequate slope protection (1). Evaluate the performance of all satisfactory slope-protection alternatives before selecting one for use.

For successful performance, a riprap layer must be designed to:

1. Protect the individual rock particles from displacement by the wave force, and

2. Keep the protected earth, filter, and bedding underlying the riprap from washing out through the voids.

Factors To Be Considered in Riprap Design

The Attack

The principal factor affecting the design for slope protection is wave action. The mechanics of wave generation are extremely complex, and the forces causing erosion during wave attack on an earth slope are both varied and complex. The described ranges of riprap design assume that the wave height is a direct measure of the erosiveness of the wave attack (7). See Figure 1.

To evaluate wave height, the following factors that create waves in open water must be analyzed:

1. Design wind direction

2. Effective fetch

3. Wind velocity and duration

The Resistance

The principal influence on the resistance provided by durable riprap is the size of rock. for successful performance, the riprap must be placed so that individual rock particles will not be displaced by the forces of waves or by outwash of underlying bedding, filter, or embankment materials.

The factors determining the rock size for a satisfactory riprap installation are:

1. Weight of rock

2. Gradation of riprap

3. Thickness of riprap layer

4. Roughness of riprap surface

5. Slope of the embankment face

6. Conditions of filter, bedding, or both

Design Procedure

I. Determination of Significant Wave Height

For many years wave height has been estimated by the empirical formulas of Stephenson, Molitor, Creager, and others. In recent years more exact methods have been developed by theoretical and experimental analysis. Figure 2 presents the generalized correlations of significant wave height (H_s) and wind duration (T_d) with design wind velocity (U_d) and effective fetch (F_e). This figure is based on relationships developed by Saville, McClendon, and Cochran in their study of freeboard allowances for waves on inland reservoirs (2, 8). The relationships are based on the Sverdrup-Muck theory (9) as modified by Bretschneider (10) and are considered accurate and reliable enough for riprap design. The analytical development of these relationships is shown in Appendix A.

Figure 2 is based on so-called "deep-water waves," which are defined as waves having lengths equal to or less than twice the depth of water. In most instances, deep-water waves are generated in front of an embankment

(11). Where shallow-water waves develop, estimates based on deep-water conditions give conservative wave-height predictions.

Figure 2 can be used to estimate the significant wave height that may develop within a reservoir after the following have been determined.

(a) the design wind direction, (b) the effective fetch, (c) the design wind velocity over water, and (d) the minimum wind duration.

A. Design Wind Direction

Considerable judgment must be used in determining the design wind direction. The determination can be made from (a) Weather Service climatological data or (b) site orientation.

Method 1 - Use of Climatological Data

The U.S. Weather Service publishes, in annual climatological-data summaries, tables of "Normals, Means, and Extremes" that include wind data for local areas. To obtain Local Climatological Data--Annual Summaries, get in touch with the National Climatic Center, Asheville, NC, FTS 672-0683. Another reference is Climatic Atlas of The United States, U.S. Department of Commerce. Effective use of this information requires an awareness of two potential problems: (a) an average or weighted average wind direction may be a wind direction infrequent in the area under consideration, and (b) in some areas of the United States, prevailing winds during the winter months (reservoir frozen) are considerably different from prevailing winds during the period when the reservoir has open water.

The procedure for determining the wind direction from climatological data is:

1. Using the climatological data tables, "Normals, Means, and Extremes," for the local area of concern, obtain the speed and direction for the fastest mile for each month.

2. Multiply the azimuth of the wind by the appropriate wind velocity for each month.

3. Divide the sum of the values determined in step 2 by the sum of the wind velocities to obtain the design wind direction. Note: Apply Method 2 if the computed design wind direction is away from the dam.

WIND DIRECTION

1 Month	2 Speed (mph)	3 Direction	4 Azimuth	5 Col. 2 X Col. 4
January				
February				
March				
April				
May				
June				
July				
August				
September				
October				
November				
December				
	Σ(2)		Σ(4)	Σ(5)

$$\text{Wind Direction} = \frac{\Sigma(5)}{\Sigma(2)} = \_\_\_\_\_\_\_\_$$

Check for comparison: $$\text{Wind Direction} = \frac{\Sigma(4)}{12} = \_\_\_\_\_\_\_\_$$

Method 2 - Use of Site Conditions

Wind direction can be obtained by determining the point on the shoreline over the longest stretch of open water from the dam. This direction should be weighed with other topographic conditions or climatic information.

B. Effective Fetch

Early studies of wind and wave development generally assumed the fetch to be the greatest straight-line distance over open water. Subsequent studies by Saville (12) showed that the shape of an open water area affects the fetch. Saville's method is based on the concept that the width of the fetch on inland reservoirs normally places a definite restriction on the length of effective fetch; the smaller the width-to-length ratio, the shorter the effective fetch.

Method 1 - Use of Climatological Data

Using a topographic map of the site, lay out seven radial lines at 6-degree intervals on each side of a central radial. Draw the central radial from a point on the face of the dam to a point on the opposite shoreline over the longest distance of open water in the direction of the "wind direction" as determined by Method 1 outlined above in paragraph A. Refer to Figure 3.

Method 2 - Use of Site Conditions

Using a topographic map, lay out seven radial lines at 6-degree intervals on each side of a central radial. Draw the central radial from a point on the face of the dam to a point on the opposite shoreline in the direction to yield the longest distance over open water.

Procedure for Methods 1 and 2:

1. Multiply the scaled length of each radial by the square of the cosine of its angle with the central radial.

2. Divide the sum of the radial values found in 1 by the sum of the cosines to obtain the effective fetch.

EFFECTIVE FETCH

1	2	3	4	5	6
No.	α	cos α	$\cos^2 \alpha$	Xi scale distance (Ft.)	col. 4 X col. 5
1	42	0.743	0.552		
2	36	0.809	0.654		
3	30	0.866	0.750		
4	24	0.914	0.835		
5	18	0.951	0.904		
6	12	0.978	0.956		
7	6	0.995	0.990		
8	0	1.000	1.000		
9	6	0.995	0.990		
10	12	0.978	0.956		
11	18	0.951	0.904		
12	24	0.914	0.835		
13	30	0.866	0.750		
14	36	0.809	0.654		
15	42	0.743	0.552		
		$\Sigma(3) = 13.512$		$\Sigma(5) =$	$\Sigma(6) =$

$$\text{Effective Fetch } (F_e) = \frac{\Sigma(6)}{\Sigma(3)} = \frac{\_\_\_\_\_\_}{13.512} \text{ ft.}$$

$$\_\_\_\_\text{ ft.} \div 5{,}280 \text{ ft/mi} = \_\_\_\_\_\_ \text{ mi.}$$

$$\text{Check: } F_e = \frac{\Sigma(5)}{15(5{,}280)} = \_\_\_\_\_\_ \text{ mi.}$$

C. Design Wind Velocity and Duration

Obtaining a reliable estimate of the maximum wind velocity that would exist over a length of time at a given site is practically impossible. The procedure is to obtain a value for wind velocity overland and then adjust it to represent the overwater conditioin. There are three methods of estimating maximum overland wind velocities.

1. Overland Wind Velocity (U_L)

Method 1 - Use of Climatological Data

The local climatological data bulletin lists the wind speed for the fastest mile by months, under the section "Normals, Means, and Extremes." List the 12 speeds given and obtain an average. The average represents the overland wind velocity.

Method 2 - Use of Generalized Data

A value for wind velocity can be obtained from Figure 4, which is a map of isolines showing the maximum wind velocity 30 feet above ground, for a 50-year period of recurrence. The contour lines were developed in part by H.C.S. Thom (13) and in part from U.S. Weather Service records at 141 stations throughout the United States. Judgment must be used with Figure 4, since wind velocity can change sharply in short distances, particularly in mountainous areas. These velocity changes are due to differences in altitude, slope of land, sheltered areas, and other topographical features.

Method 3 - Use of Maximum Speed of Record

The local climatological data bulletin lists the fastest mile of record under the section "Normals, Means, and Extremes." This value can be adjusted for duration and effective fetch in three steps:

a. Obtain the maximum wind velocity (fastest mile of record) for the area being studied.

b. Plot wind velocity (U_L) versus wind duration (T_d) from Figure 5 for the maximum wind velocity obtained in step a. above.

c. As in Figure 6, on the same graph plot wind velocity versus wind duration (T_d) from Figure 2 for the effective fetch (F_e) determined for the site.

The graph plotted should be similar to Figure 6. The value of wind velocity where the two curves intersect is the overland wind velocity for the site.

2. Overwater Wind Velocities (U_w)

Overland wind velocities must be adjusted to reflect overwater velocities, because the latter velocities are higher. Although the ratio of values for overland versus overwater for individual sites may vary considerably, the average observed values for this relationship are shown in Figure 7 (2). The ratio can be obtained from Figure 7 for the effective fetch determined for the site. The overwater velocity can be determined for the overland wind velocity by applying the ratio. The computed overwater velocity becomes the "design wind velocity (U_d)" for the site.

$$U_d = U_w$$

D. Significant Wave Height

The highest waves are energized by wind over long reaches of open water. Both methods used to obtain significant wave height (H_s) for a site require prior determination of wind velocity and effective fetch. Use Method 2 only when no climatic data are available.

Method 1 - Use of Prescribed Data

When site data have been developed by procedures described in this Technical Release, the significant wave height (H_s) can be determined from Figure 2 by use of the computed design wind velocity (U_d) and the effective fetch (F_e).

Method 2 - Use of Limited Data

The significant wave height (H_s) can be determined from Figure 2, entering with a wind velocity of 50 mph blowing toward the upstream face of the dam over the longest reach of open water (F_p) (14).

II. Design of Riprap Protection for Slopes (3, 4, 5, 15)

Flow charts contained in Appendix B indicate the steps to be followed during the design of riprap. The chart on page B1 is used for ponds. The charts on pages B2 and B3 are used for planning and design respectively.

Appendix C contains an example problem illustrating the design procedure. Appendix D contains some worksheets that may be used to record design data.

A. Rock Size

The size of rock is determined from relationships of wave heights, wave velocities, and drag on the rock relative to the stable size of rock needed to resist these forces for a given embankment. For a given site condition with significant wave height (H_s) and embankment slope known, determine proper rock size (W_{50} weight) from Figure 8. The design size relationship presented in Figure 8 is based on the results of a laboratory investigation (16, 17, 18, 19).

The analytical development of the equation in Figure 8 is given in Appendix E.

B. Gradation and Thickness of Rock

The recommended gradation and thickness of rock depends somewhat on the rock available and the base material. It is, therefore, necessary to recognize more than one gradation as satisfactory for embankment protection. Riprap consisting of well-graded mixtures of rock smaller than the D_{50} size and uniform mixtures of rock larger than the D_{50} size are as effective as riprap consisting of uniformly sized material. The advantage of uniform riprap is that it does not segregate during placement. Riprap with broadly graded minus-D_{50} material is more effective than uniformly graded rock in preventing leaching of the underlying material.

There are two types of rock placement:

1. Type 1 - Dumped (Equipment-Placed) Rock: The larger rocks are uniformly distributed and firmly in contact with one another, and the smaller rocks fill the voids among the larger ones. Equipment-placed rock is superior to hand-placed rock because of historically low maintenance costs (3).

The W_{50} weight of rock, as determined from Figure 8, can be converted to rock size (dimension in feet) from the relationship given by Figure 9. The recommended gradation limits (K ratio) for rock riprap are shown in Figure 10. The minimum thickness of a rock riprap layer is two times the D_{50} size of rock.

2. Type 2 - Hand-Placed Rock: Riprap that is hand-placed consists of rocks of uniform size carefully placed by hand in a definite pattern with minimum voids. The concept calls for angular rock.

The rock W_{50} weight, determined from Figure 8, is to be converted to size by Figure 9. The dimension as given by Figure 9 is then to be used as the minimum size (D_{min}) for hand-placed riprap. The maximum size (D_{max}) should be equal to or less than 1.5 times the D_{min} size.

It probably will be necessary to design a well-graded filter material for placement under hand-placed riprap to protect against the outwash of embankment. The minimum thickness of the hand-placed riprap layer should be D_{min}.

C. Beddings and Filters

The finer material underlying the riprap is picked up and carried away by turbulent eddies and jets that penetrate the riprap blanket through the interstices of the rock particles (leaching). Leaching may be prevented by (a) increasing the thickness of the riprap, (b) closing or reducing the size of the interstices, or (c) providing a bedding of finer rock.

Leaching can be prevented most effectively by placing progressively finer layers of bedding and filter under riprap until the base material is contained.

The drawdown of water after each cycle of runup from wave action forms a hydrostatic pore pressure. Filter material may be needed to prevent the outwash of embankment fill material during this process. Soil Mechanics Note No. 1, "Tentative Guides for Determining the Gradation of Filter Materials," has design guidelines for gradation of the filter and bedding materials. The filter and bedding layers should each be a minimum of 9 inches thick.

D. Slope Protection Layout

1. Lower Limit - The lower limit of the riprap should be set 1.5 times the significant wave height (H_s) below (a) the normal water elevation for the lowest ungated opening, or (b) the lowest controlled outlet. See Technical Release No. 60 and Design Note No. 3.

2. Upper Limit - Set the upper limit of the riprap at a minimum vertical distance above the normal pool still-water level equal to the sum of the wave runup (R) and wind set-up (S). Wave runup (R) can be obtained from information provided by Figures 11 and 12[1]. The designer can adjust the value of R according to the surface roughness assumed for the available material and the method of placement. Blocky or flat rock placed to create a smooth surface can increase the R value by a factor of 1.2 over that with a rough surface of angular rock. The wind setup (S) may be taken as 0.1 times the significant wave height (H_s) to a maximum of 0.5 foot, or may be taken from Figure 13. See Figure 14 for a sketch of the dimensions described.

3. Layout for Installation - The base of the riprap should be placed on and supported by a level berm. The use of a berm facilitates placement. Place rock bedding, and filters on the surface of the embankment slope as shown in Figure 15.

E. Construction Specifications

The rock and filter material shall be installed in accordance with the SCS National Engineering Handbook, Section 20, Specifications 24, Drain Fill; 61, Loose Rock Riprap; 521, Aggregates for Drain Fill and Filters; and 523, Rock for Riprap.

1/ The values of "R," as determined by references (2) and (20), have been modified to yield values for aged riprap with roughness with compatible with that of riprap installed by SCS.

Alternative (Short-Cut) Design Procedure

The relation between the rock size, D_{50}, and the longest fetch, F_p, can, by use of some reasonably conservative assumptions, be reduced to:

$$D_{50} = 0.85 \sqrt{F_p} \qquad (1)$$

This relation should not be used when actual site conditions depart markedly from the assumptions. The assumptions are:

1. F_e equals F_p.
2. Design wind velocity is 50 mph.
3. K_Δ equals 2.5.
4. G_s equals 2.6.
5. Cot α equals 2.5.
6. The rock shape is between a cube and a sphere.

The development of the above relation follows.

Introduction of assumptions 1 and 2 in Equation A19 yields:

$$H_s = 2.3\, F_p^{0.47} \qquad (2)$$

Use of assumptions 3, 4, and 5 in Equation E14 yields:

$$W_{50} = 6.29\, H_s^{3} \qquad (3)$$

Then, substituting from equation 2, obtain:

$$W_{50} = 76.53\, F_p^{1.41} \qquad (4)$$

Using assumption 6 with a shape constant of 1.1, the equation for D on Figure 9 becomes:

$$D_{50} = 1.1 \left(\frac{W_{50}}{62.4\, G_s} \right)^{1/3} = 1.1 \left(\frac{W_{50}}{162.2} \right)^{1/3} = 0.2\, W_{50}^{1/3} \qquad (5)$$

and using equation 4:

$$D_{50} = 0.85\, F_p^{0.47} \qquad (6)$$

The exponent may as well be taken as 0.5, giving equation 1 again as

$$D_{50} = 0.85 \sqrt{F_p} \qquad (1)$$

Equation 1 is a condensation of the theoretical and empirical relationship that constitutes the framework of the formal procedures. Its derivation is based on substitution of predetermined and rather conservative constants. Thus, the equation can be used to obtain quick, approximate but generally conservative estimates of required rock size.

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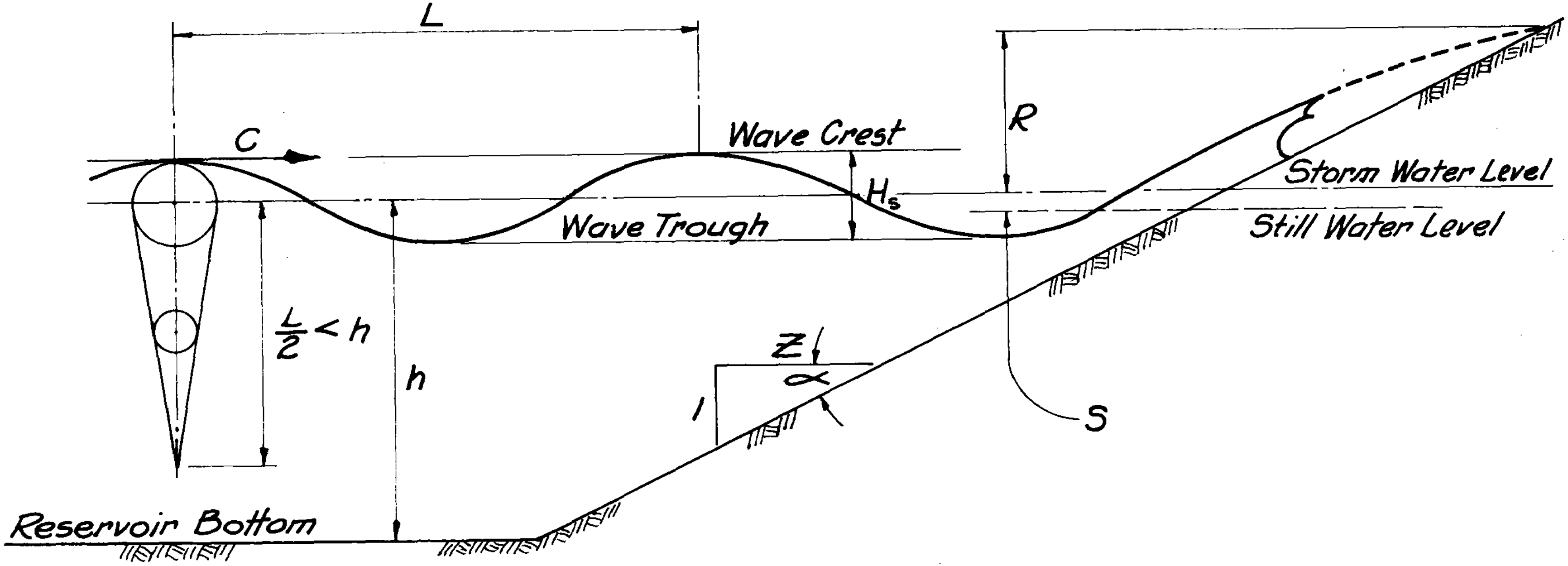

R = Wave Runup
C = Wave Velocity.
h = Depth of Water in Reservoir
H_s = Significant Wave Height.
S = Wind Set-Up.
L = Wave Length.
Deep-Water Condition $\frac{L}{2} < h$ Smooth Embankment Slope.

FIGURE 1

ILLUSTRATION OF DEFINITIONS

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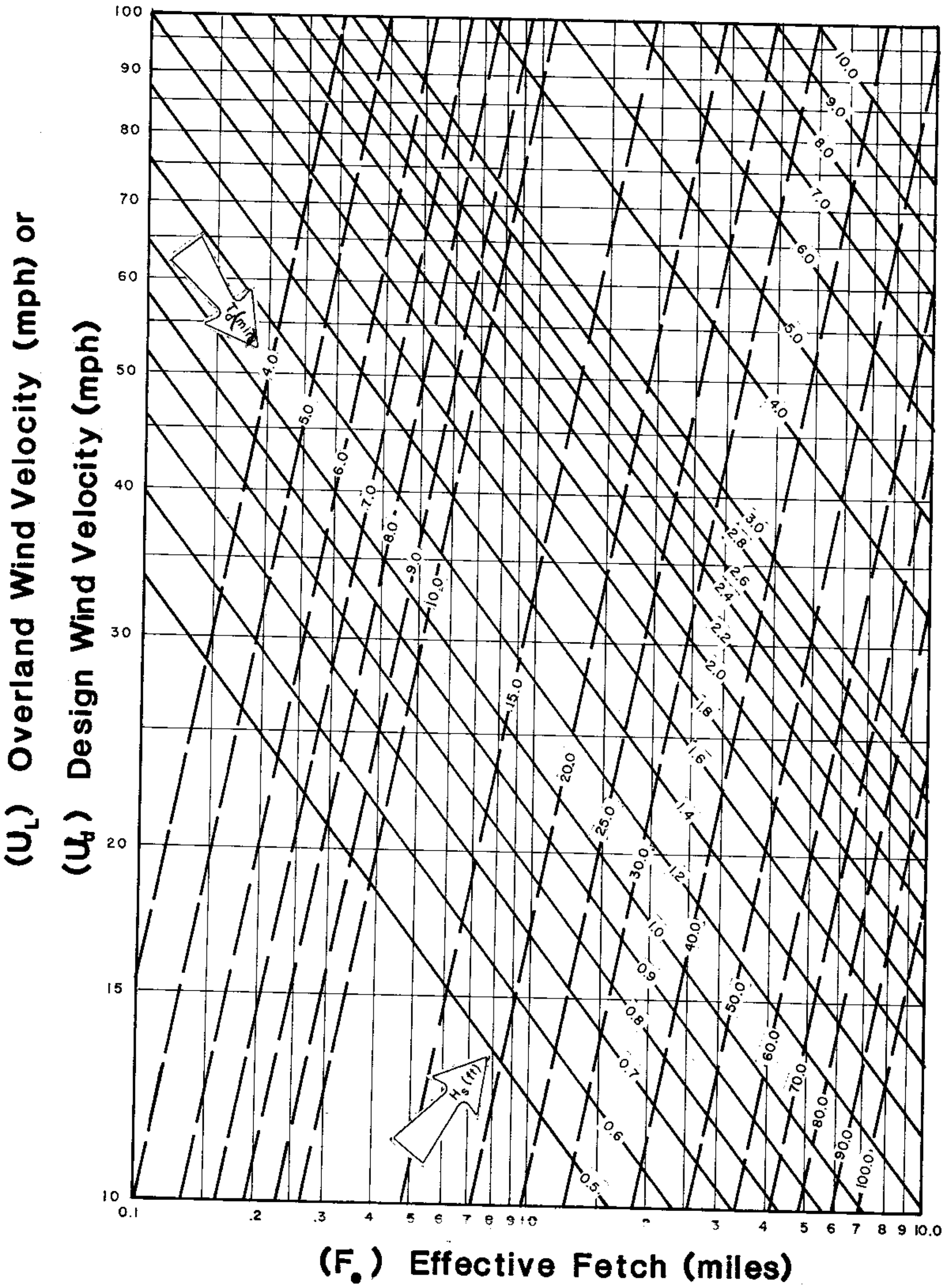

REF. (2)
Equation; (A17) & (A18) From Appendix A

$$g\frac{H_s}{U^2}=0.0026\left(\frac{gF_e}{U^2}\right)^{0.47}$$

$$g\frac{T}{U}=0.46\left(\frac{gF_e}{U^2}\right)^{0.28}$$

FIGURE 2
GENERALIZED CORRELATIONS OF SIGNIFICANT WAVE HEIGHTS WITH RELATED FACTORS

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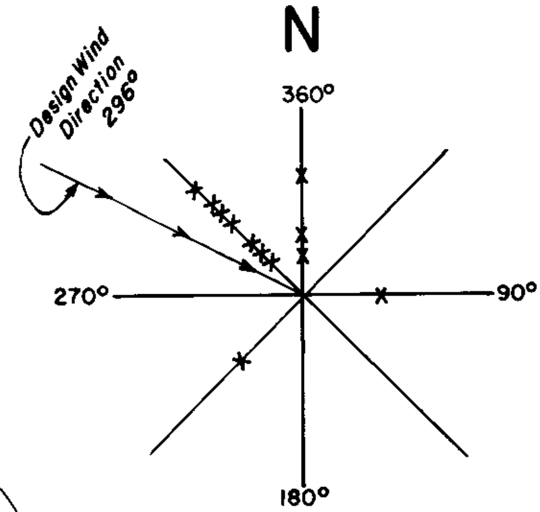
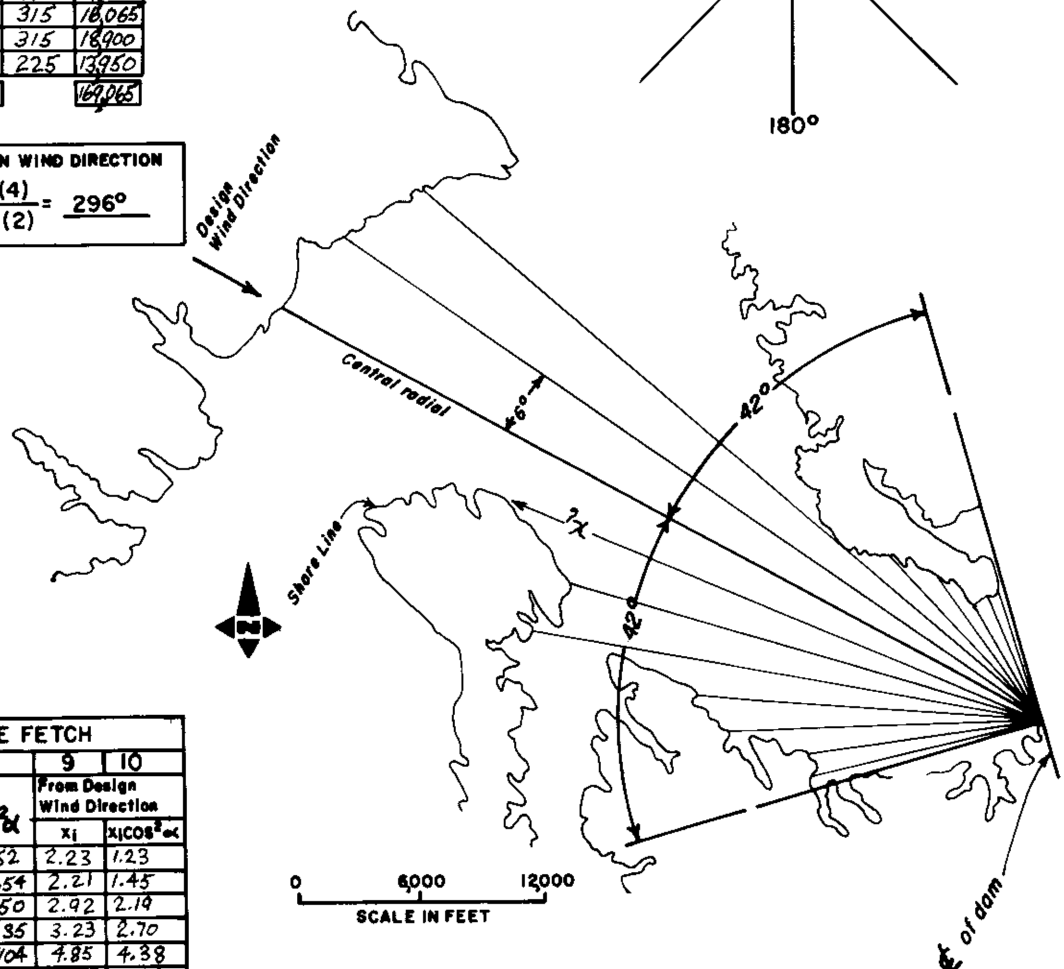
WIND DIRECTION			
1	2	3	4
MON.	Wind Velocity (MPH)	Azimuth θ°	(2x3)
JAN	24	360	8640
FEB	40	360	14400
MAR	25	315	7875
APR	36	315	11340
MAY	59	315	18585
JUN	72	315	22680
JUL	50	90	4500
AUG	63	360	22680
SEP	30	315	9450
OCT	51	315	16,065
NOV	60	315	18900
DEC	62	225	13950
Σ	572		169,065

DESIGN WIND DIRECTION

$$\frac{\Sigma(4)}{\Sigma(2)} = 296^\circ$$





EFFECTIVE FETCH				
6	7	8	9	10
			From Design Wind Direction	
α°	cos α	cos² α	x_i	$x_i \cos^2 \alpha$
42	0.743	0.552	2.23	1.23
36	0.809	0.654	2.21	1.45
30	0.866	0.750	2.92	2.19
24	0.914	0.835	3.23	2.70
18	0.951	0.904	4.85	4.38
12	0.978	0.956	4.58	4.38
6	0.995	0.990	5.45	5.40
0	1.000	1.000	8.02	8.02
6	0.995	0.990	7.86	7.78
12	0.978	0.956	7.54	7.21
18	0.951	0.904	2.12	1.92
24	0.914	0.835	1.71	1.43
30	0.866	0.750	1.24	0.93
36	0.809	0.654	1.24	0.81
42	0.743	0.552	1.22	0.67
Σ	13.512			50.50

EFFECTIVE FETCH

$$F_e = \frac{\Sigma(10)}{13.512} = 3.7 \text{ mi.}$$

Example illustration for determination of wind direction and for effective fetch by Method 1. See page 5.

For x_i, read distance from map and record in column 9 in miles.

FIGURE 3

COMPUTATION OF EFFECTIVE FETCH AND DESIGN WIND DIRECTION

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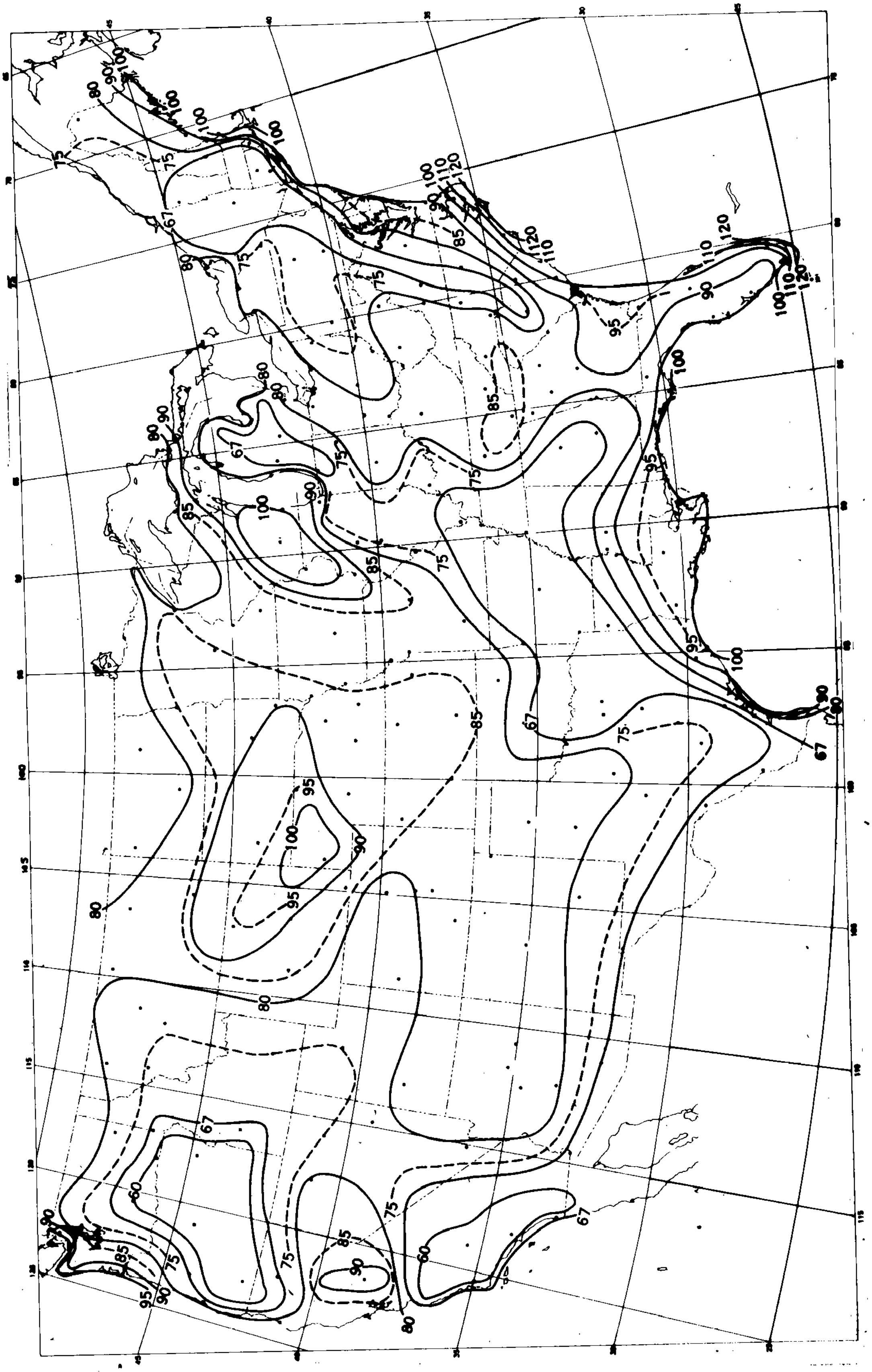

REF. (13)

FIGURE 4
MAXIMUM BASIC
WIND VELOCITY (mph)
(50-year recurrence)

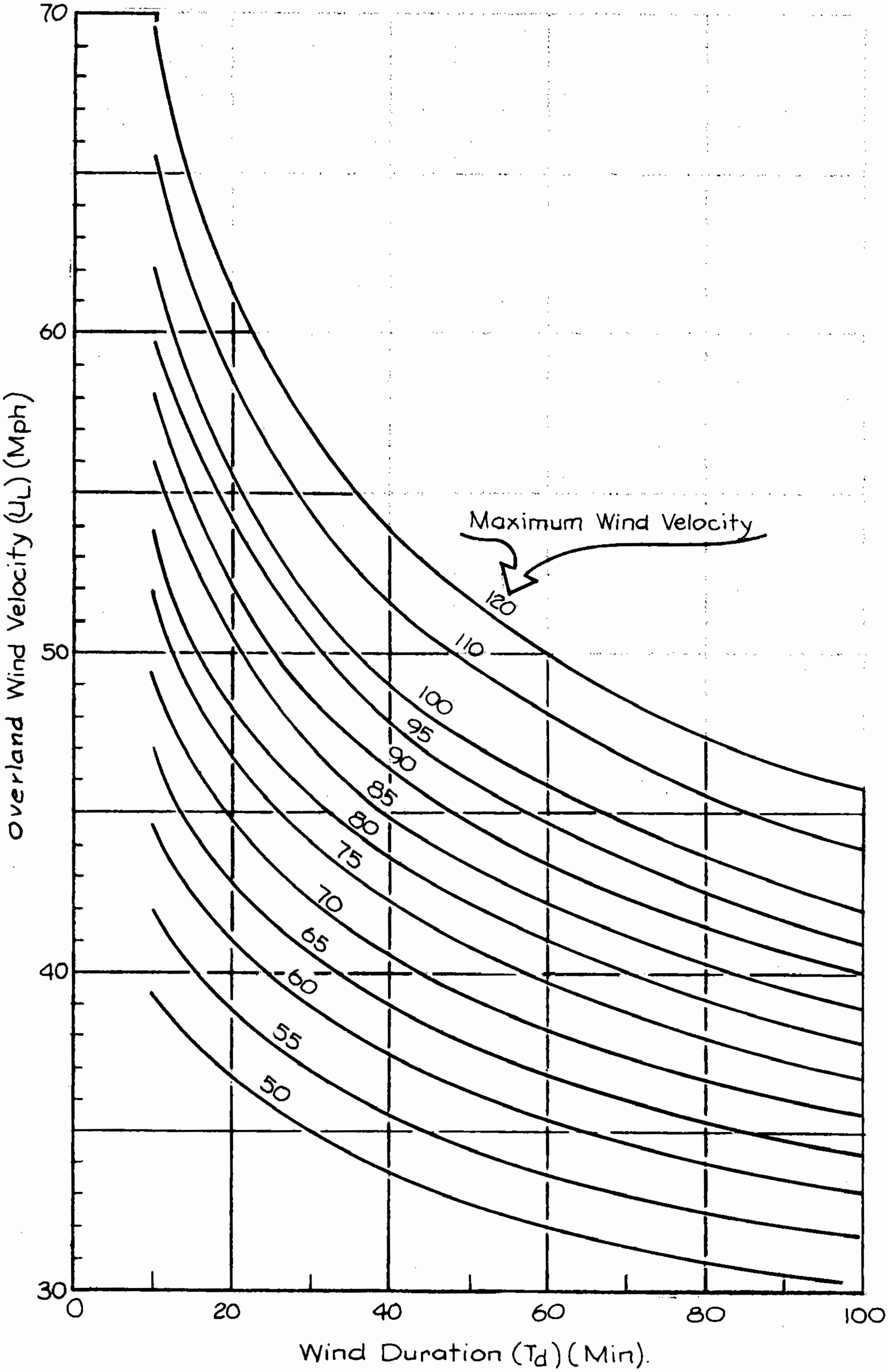

FIGURE 5
MAXIMUM WIND-VELOCITY RELATIONSHIP
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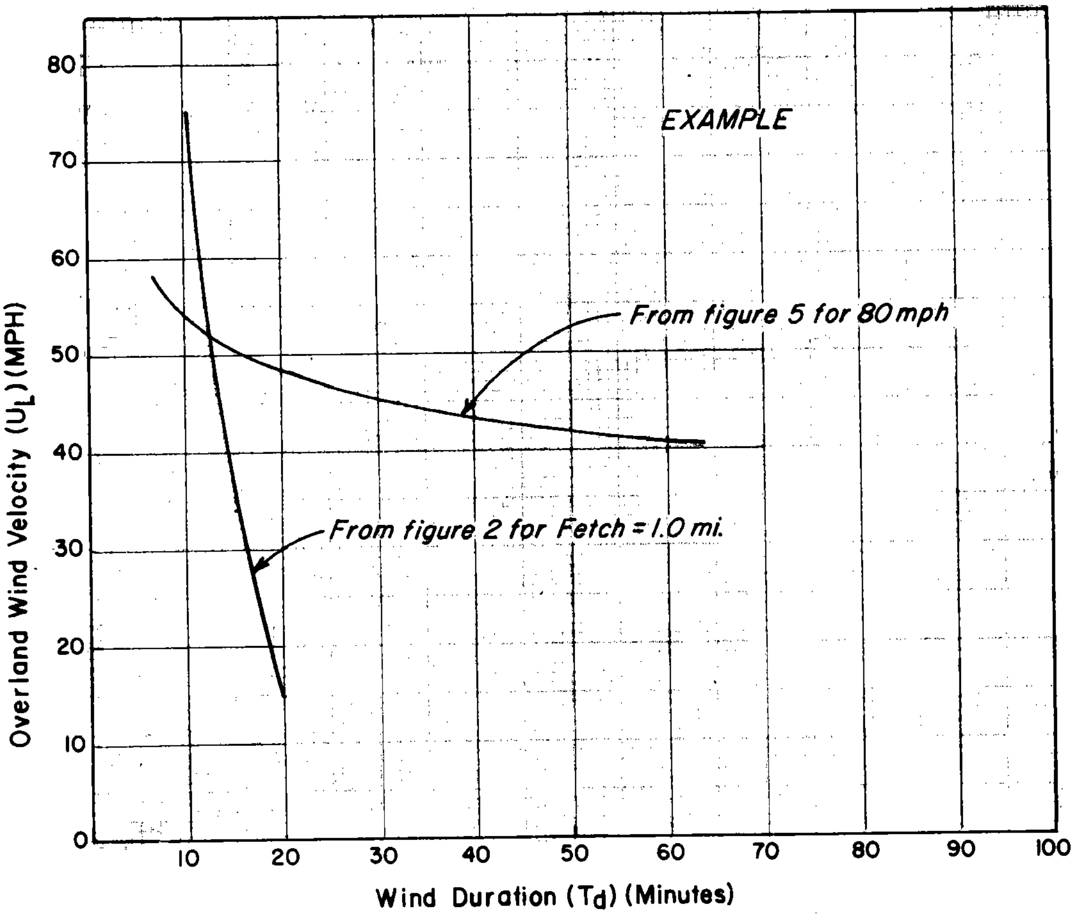


FIGURE 6

DETERMINATION OF OVERLAND WIND VELOCITY

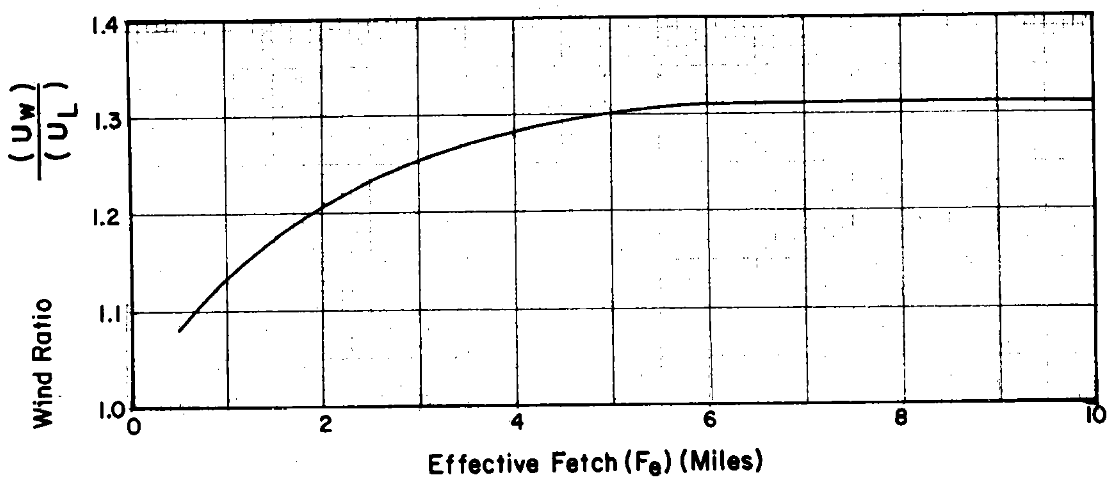
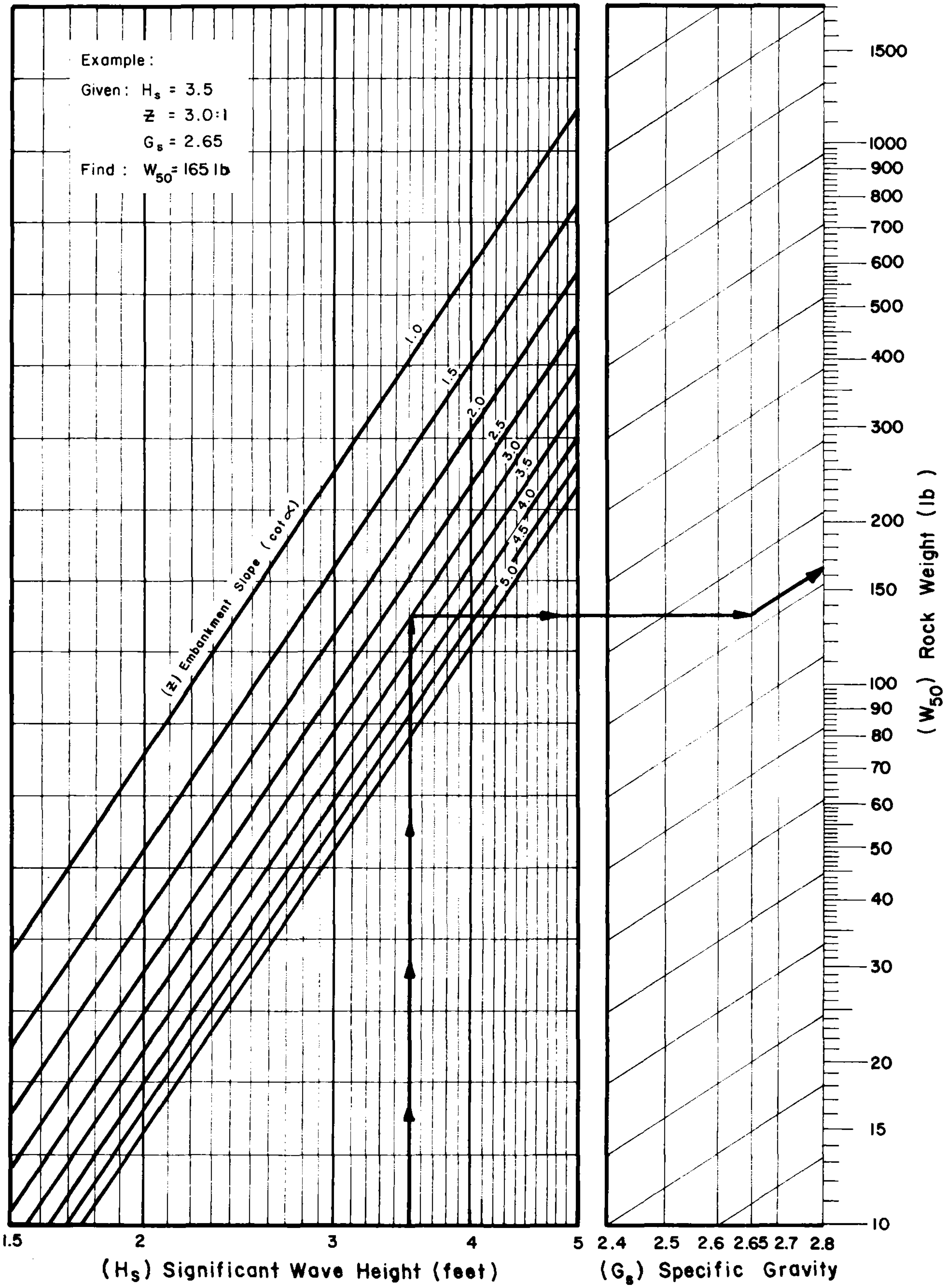


FIGURE 7

WIND RELATIONSHIP OVERWATER TO OVERLAND



Equation (E 14); From Appendix E

$$W_{50} = \frac{19.5\ G_s\ H_s^3}{(G_s - 1)^3\ \cot\alpha}$$

REF (16)

FIGURE 8

ROCK SIZE SELECTION

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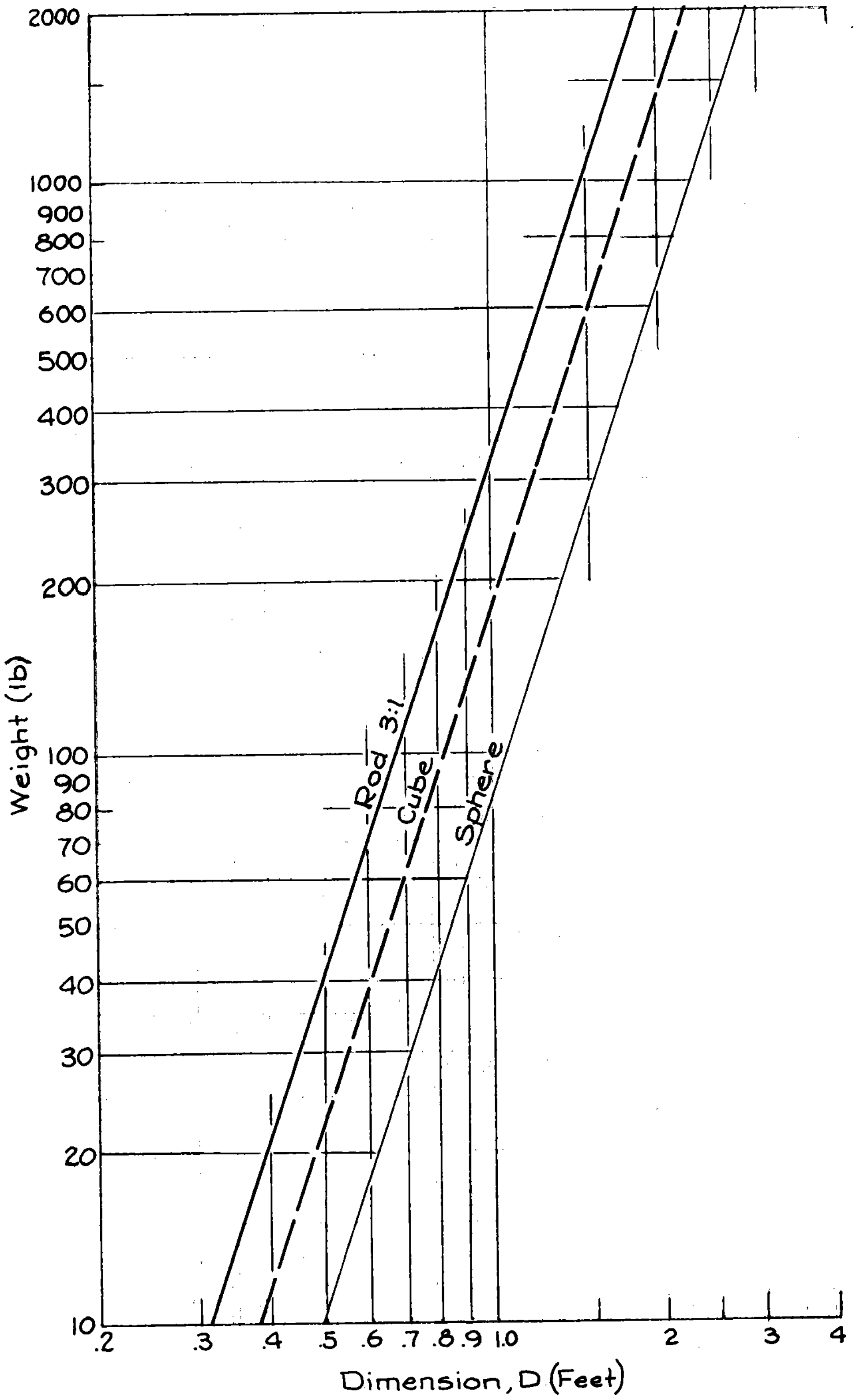

$G_s = 2.6$

$D = 1.0 \sqrt[3]{\frac{w}{62.4\,G_s}}$ cube

$D = 1.24 \sqrt[3]{\frac{w}{62.4\,G_s}}$ sphere

FIGURE 9

ROCK WEIGHT-SIZE RELATIONSHIP

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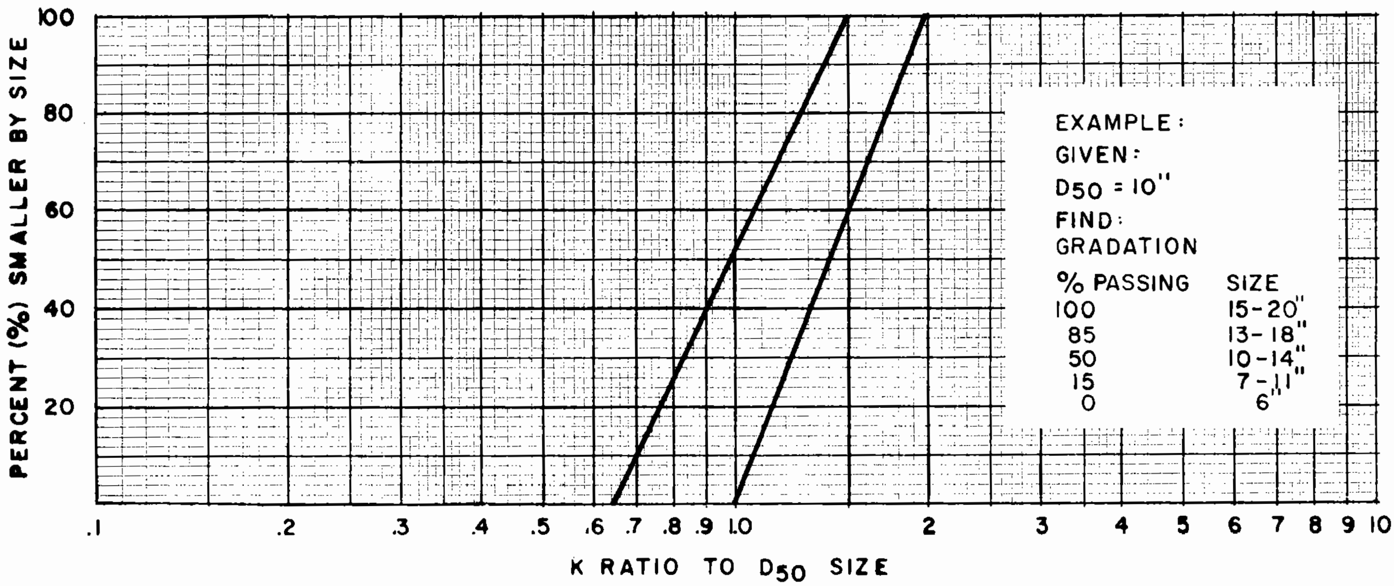
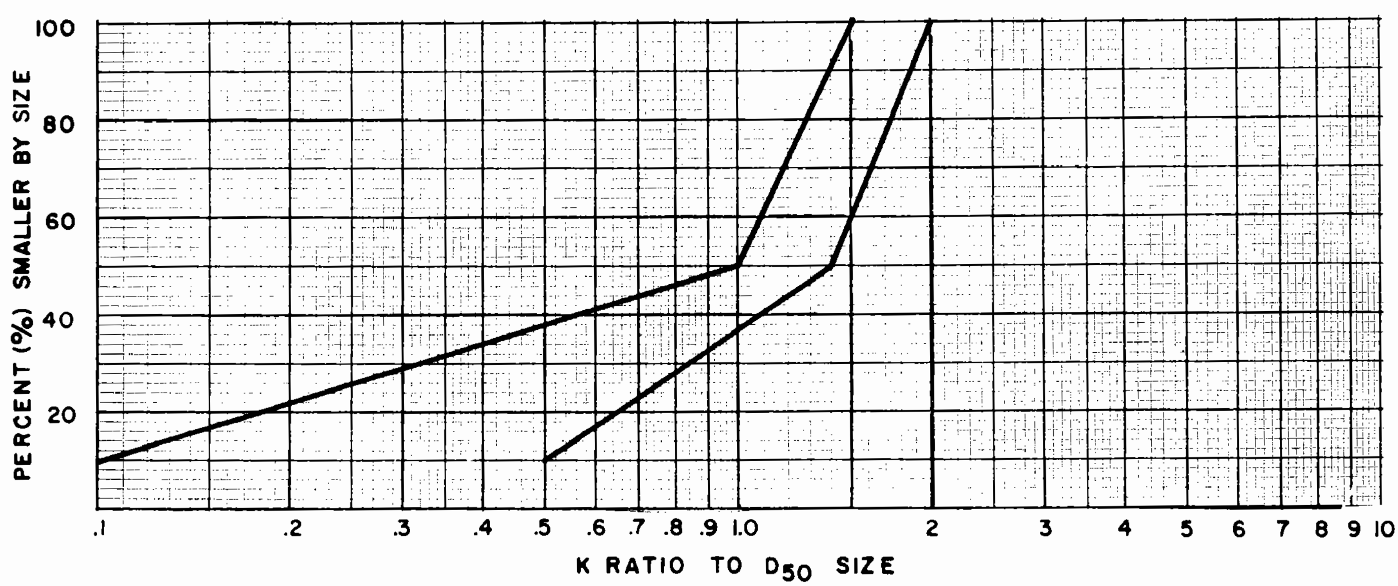


UNIFORM ROCK



GRADED ROCK

FIGURE 10
ROCK
GRADATION LIMITS
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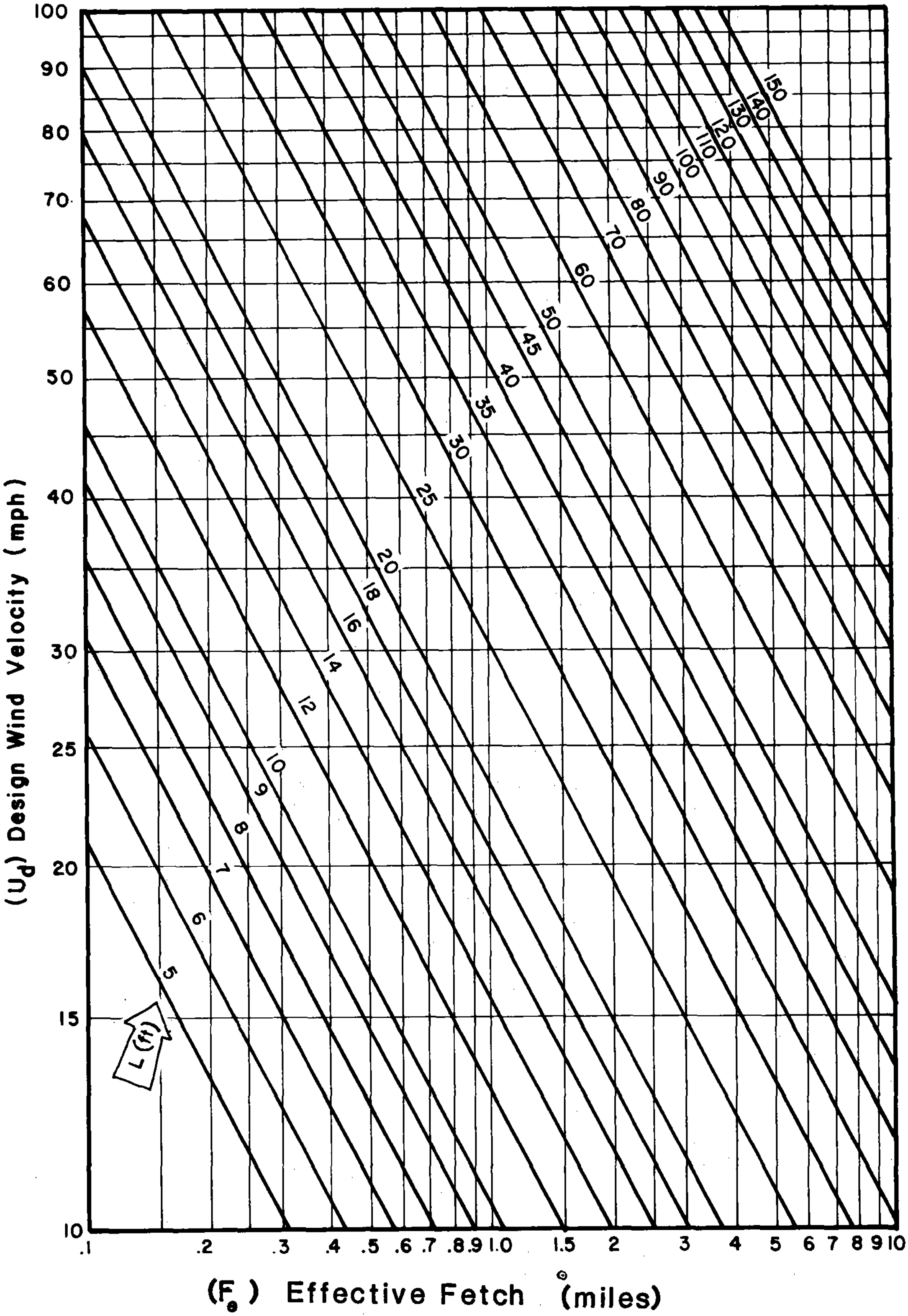

Equation (A21) From Appendix A

$$\frac{g\sqrt{L}}{U} = 1.041\left(\frac{g F_e}{U^2}\right)^{0.28}$$

REF (2) (9)

FIGURE 11
WAVE LENGTH RELATIONSHIP
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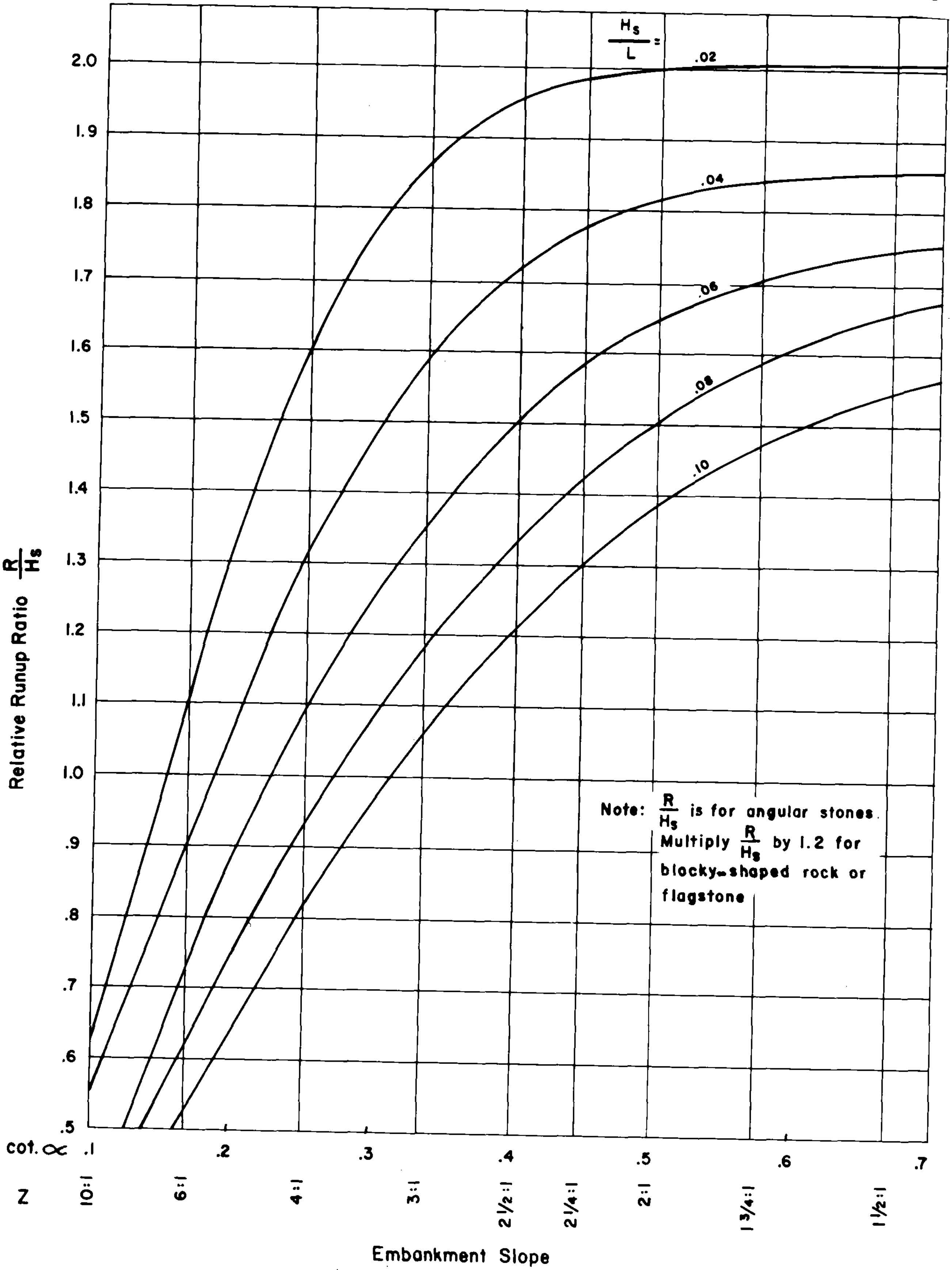

Note: **See Ref. (2) and (20) and footnote 1 on page 9.**

The surface smoothness represented by these curves is simulated by a single layer of rocks of uniform size.

FIGURE 12
WAVE RUNUP RATIO
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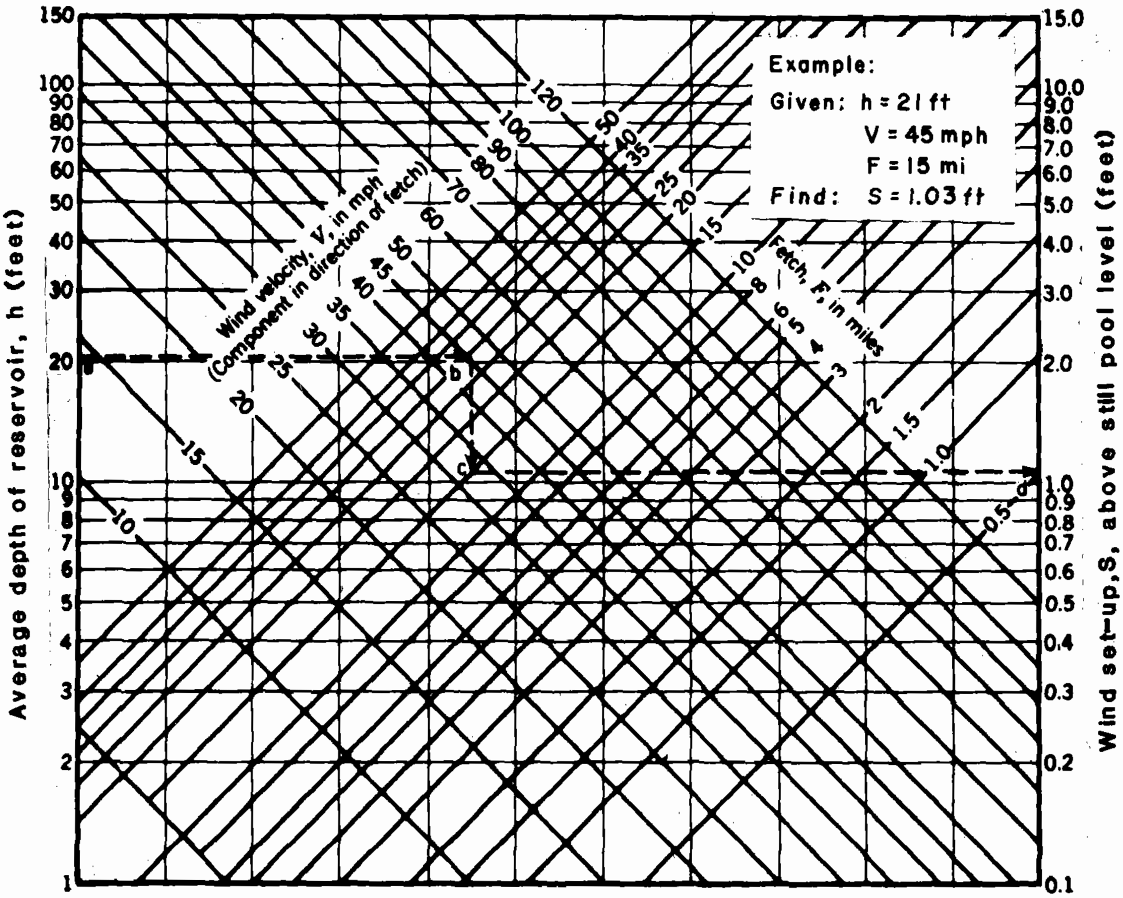

DIAGRAM FOR COMPUTATIONS OF WIND SET-UP IN RESERVOIRS

$$S = \frac{V^2 F}{1400\,h}$$

REF (2)

FIGURE 13

WATER SURFACE CREATED BY WIND SET-UP

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PORTLAND, OREGON

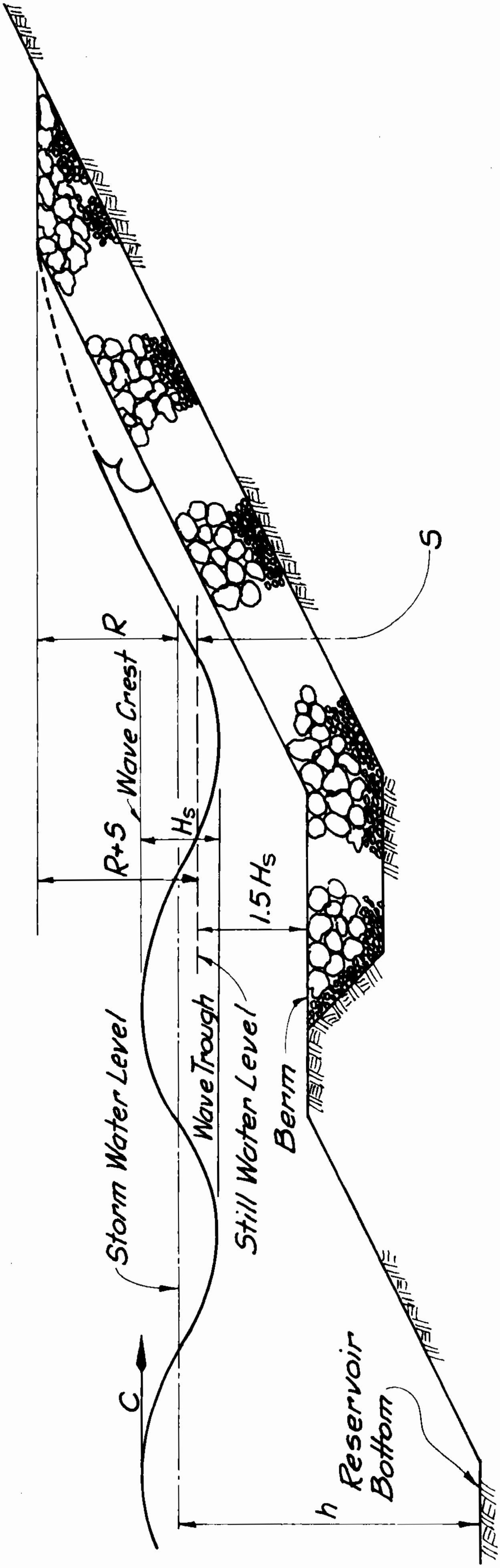

FIGURE 14

RIPRAP LAYOUT VS WAVE ACTION

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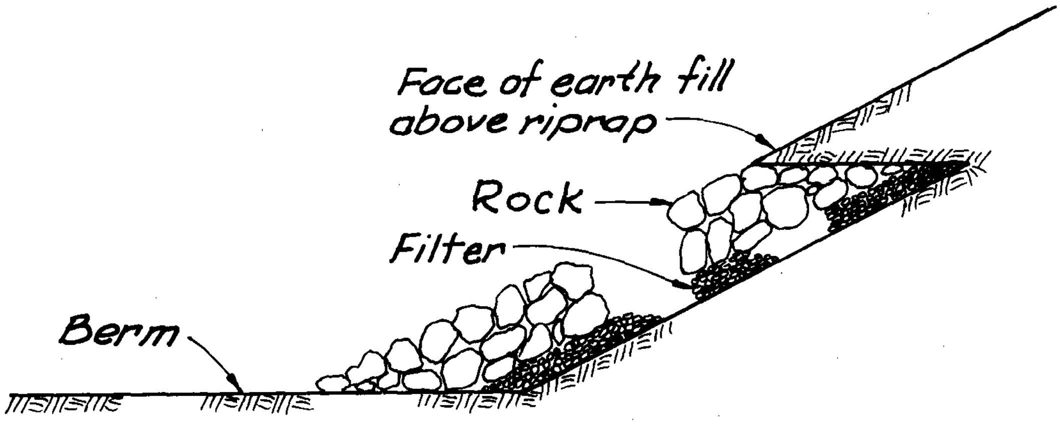
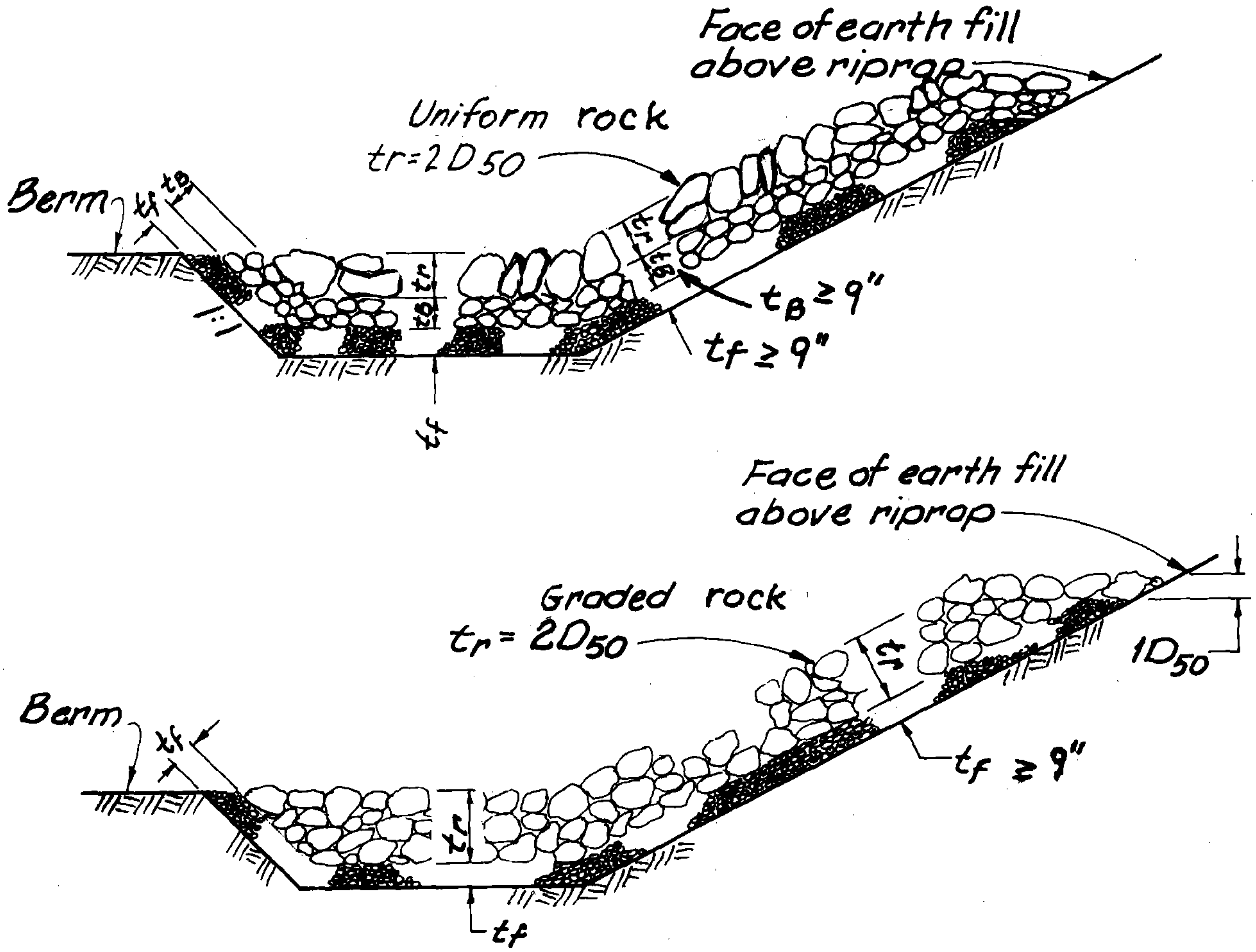


UNACCEPTABLE DETAIL



ACCEPTABLE DETAIL

FIGURE 15

DUMPED ROCK
PLACEMENT DETAIL

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APPENDIX A - DERIVATION OF RELATIONSHIP BETWEEN WAVE VELOCITY, WAVE HEIGHT, EFFECTIVE FETCH, AND WIND DURATION

The following theoretical development is taken in part from reference (9).

The fundamental equations representing wave velocity, wave energy and wave motion, as determined from classical hydrodynamics, are:

Velocity

$$C^2 = \frac{gL}{2\pi} \tanh \frac{2\pi h}{L} \tag{A1}$$

where C is defined as wave velocity.

This paper is concerned only with deep-water waves, which are defined as waves with a wave length (L) equal to or less than two times the depth of water ($L \leq 2h$). For deep-water waves Equation A1 becomes

$$C^2 = \frac{gL}{2\pi} \tag{A2}$$

Energy

$$R_N = 1/2\ s\rho'(U-C)^2k^2a^2C \qquad \text{for } C<U \tag{A3}$$

$$R_T = \gamma^2\pi^2\rho'\delta^2CU^2 \qquad \text{for } U>15 \text{ mph} \tag{A4}$$

$$R_\mu = -2\mu k^3a^2C^2 \tag{A5}$$

$$E = 1/2\ \rho g a^2 \tag{A6}$$

Motion

1. Steady State $C<U$ $\qquad \beta = C/U \therefore \beta<1$

   a. $0 \leq \beta \leq \beta'$

$$\frac{d\beta}{dx} = 2AgU^{-2}\beta^{-3}\ \frac{1 + \alpha\ (1 - \beta)^2}{5 + 2m\beta} \tag{A7}$$

where: $m = \dfrac{d\ \ln\ \delta}{d\beta}$

   b. $\beta \geq \beta'$

$$\frac{d\beta}{dx} = 2Agr\ U^{-2}\ \beta^{-2}\ (2-\beta) \tag{A8}$$

2. Transient State C<U $\qquad \beta = C/U \therefore \beta < 1$

a. $0 \leq \beta \leq \beta'$

$$\frac{d\beta}{dt} = AgU^{-1}\beta^{-2}\left[\frac{1 + \alpha(1 - \beta)^2}{5 + 2m\beta}\right] \qquad \text{(A9)}$$

b. $\beta \geq \beta'$

$$\frac{d\beta}{dt} = AgrU^{-1}\beta^{-1}(2-\beta) \qquad \text{(A10)}$$

Integration of the equations of motion yield the following solutions.

1. Steady State.

a. $0 \leq \beta \leq \beta'$

$$\frac{gX}{U^2} = \frac{m}{A\alpha}\left\{\frac{\beta^3}{3} + \frac{K_1}{2}\beta^2 + K_2\beta + 1/2\ (2K_2 - K_1K_3) \cdot \ln\left[\frac{\beta^2 - 2\beta + K_3}{K_3}\right] + K_4\tan^{-1}\left[\frac{\sqrt{\alpha\beta}}{1 + \alpha(1 - \beta)}\right]\right\} \qquad \text{(A11)}$$

b. $\beta \geq \beta'$

$$\frac{gX}{U^2} = \frac{2}{Ar}\left[\ln\frac{2}{2 - \beta} - \frac{\beta^2}{8} - \frac{\beta}{2}\right] - K_X \qquad \text{(A12)}$$

2. Transient State

a. $0 \leq \beta \leq \beta'$

$$\frac{gt}{U} = \frac{2m}{A\alpha} \left\{ \frac{\beta^2}{2} + K_1\beta + \frac{K2}{2} \ln \left[\frac{\beta^2 - 2\beta + K_3}{K_3} \right] + \left[K_2 - K_1K_3\right] \sqrt{\alpha} \tan^{-1} \left[\frac{\sqrt{\beta}}{1 + \alpha(1 - \beta)} \right] \right\} \quad \text{(A13)}$$

b. $\beta > \beta'$

$$\frac{gt}{U} = \frac{1}{Ar} \left\{ (2 - \beta) - 2\ln (2 - \beta) \right\} - K_t \quad \text{(A14)}$$

where

$K_1 = \frac{5}{2m} + 2 \qquad = 3.536$

$K_2 = \frac{5}{m} + 3 - \frac{1}{a} \qquad = 5.673$

$K_3 = 1 + \frac{1}{a} \qquad = 1.400$

$K_4 = \sqrt{\alpha}\,(2K_2 - K_1K_3 - K_2K_3) = -2.446$

$K_t = 1.705 \times 10^5$
$K_x = 3.539 \times 10^2$ } Constants of integration selected to make solutions continuous at $\beta = \beta'$

If wave height is represented by the dimensionless parameters gH/U^2, then from the definition of wave steepness and Equation A2:

$$H = \delta L = \frac{2\pi\delta C^2}{g} = \frac{2\pi}{g} U^2\delta\beta^2 \quad \text{(A15)}$$

Equation A15 may be written in a nondimensional form as:

$$\frac{gH}{U^2} = 2\pi\delta\beta^2 = f\left(\frac{gX}{U^2}\right) \quad \text{or} \quad f\left(\frac{gt}{U}\right) \quad \text{(A16)}$$

since $\delta = f(\beta)$ and $\beta = f(gX/U^2)$ or $\beta = f(gt/U)$ as indicated by Equations All through A14.

Over the range of interest for inland reservoirs ($10 < g\,F/U^2 < 4000$) Saville, McClendon, and Cochran(2) determined from inland reservoir studies that the dimensionless relationships can be approximated by:

$$\frac{gH_s}{U^2} = 0.0026 \left(\frac{gF_e}{U^2}\right)^{0.47} \qquad \text{(A17)}$$

$$\frac{gT}{U} = 0.460 \left(\frac{gF_e}{U^2}\right)^{0.28} \qquad \text{(A18)}$$

where

F_e = effective fetch (feet)

H_s = significant wave height (feet)

T = wave period (seconds)

Equations A17 and A18 are given in the form of dimensionless graphs in Figure A-1.

Figure 2 was obtained directly from the curves on Figure A-1 and is the graphical diagram developed for forecasting wave heights.

From Equation A2 and the definition of wave velocity

$$C = \frac{L}{T} = \sqrt{\frac{gL}{2\pi}} \qquad \text{(A19)}$$

or

$$T = 0.442\sqrt{L} \qquad \text{(A20)}$$

Substitution of Equation A20 into Equation A18 yields

$$\frac{g\sqrt{L}}{U} = 1.041 \left(\frac{gF_e}{U^2}\right)^{0.28} \qquad \text{(A21)}$$

This equation is presented graphically in Figure 11 and is used to determine wave runup.

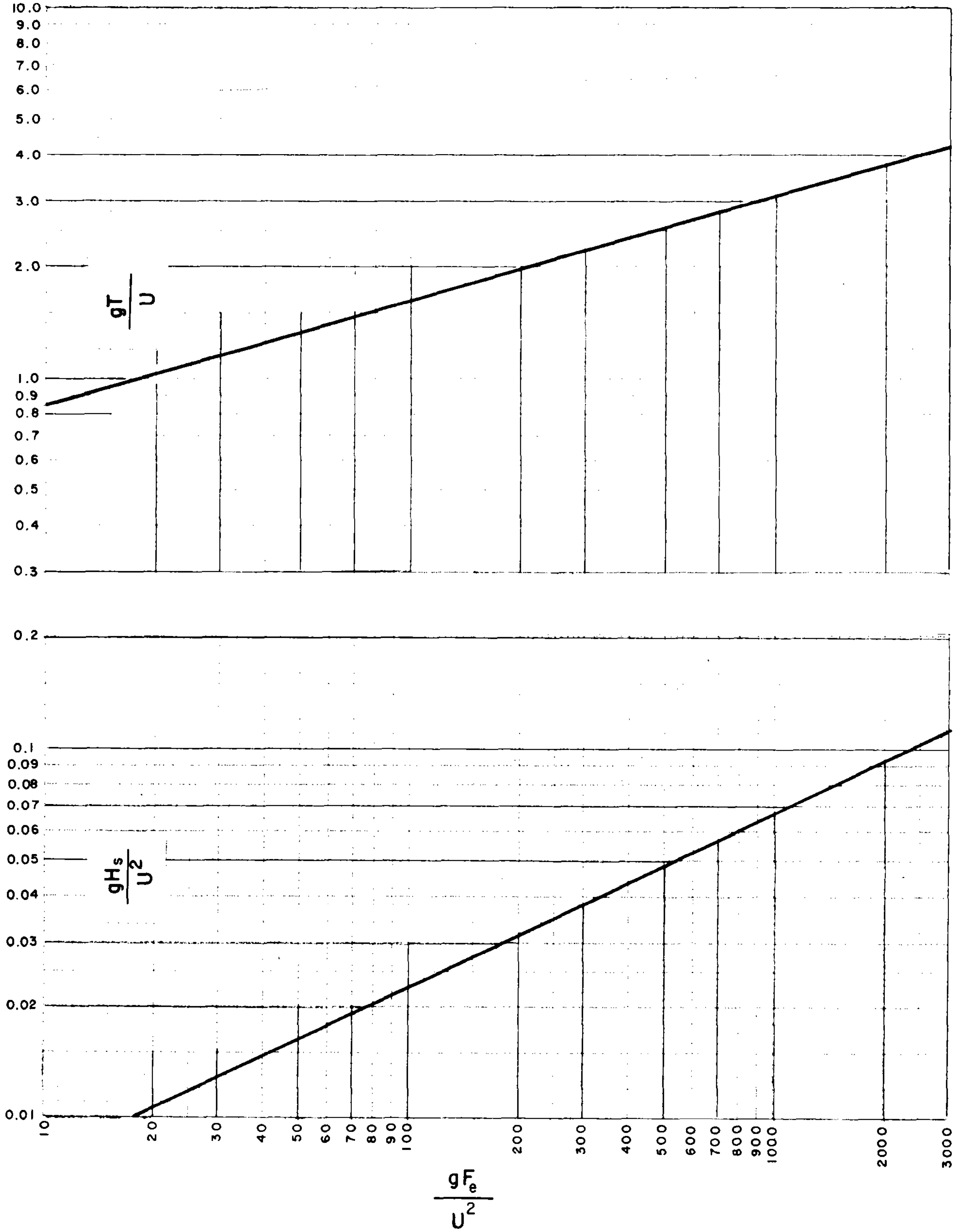

FIGURE A-1

WAVE HEIGHT AS A FUNCTION OF EFFECTIVE FETCH AND WIND SPEE

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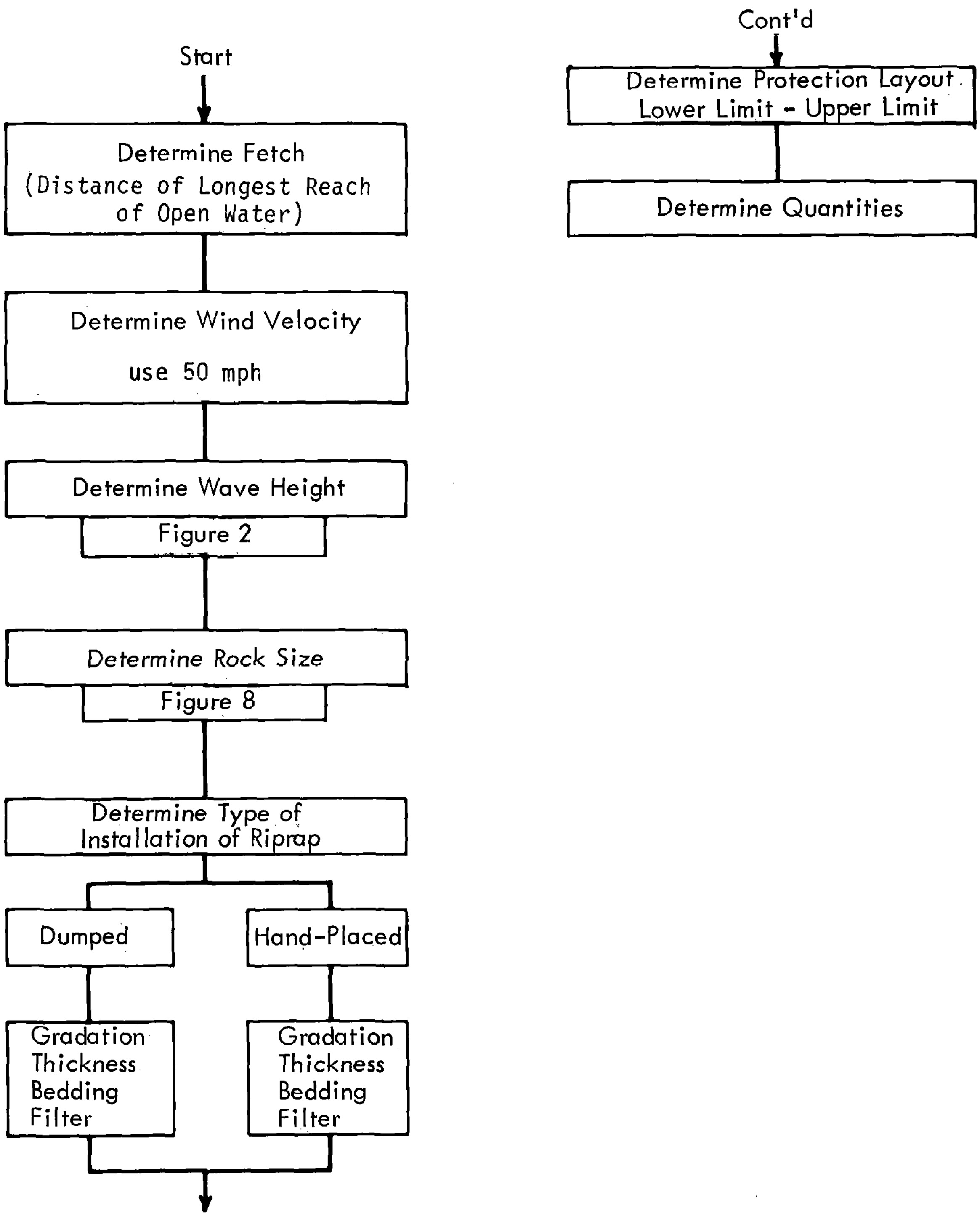
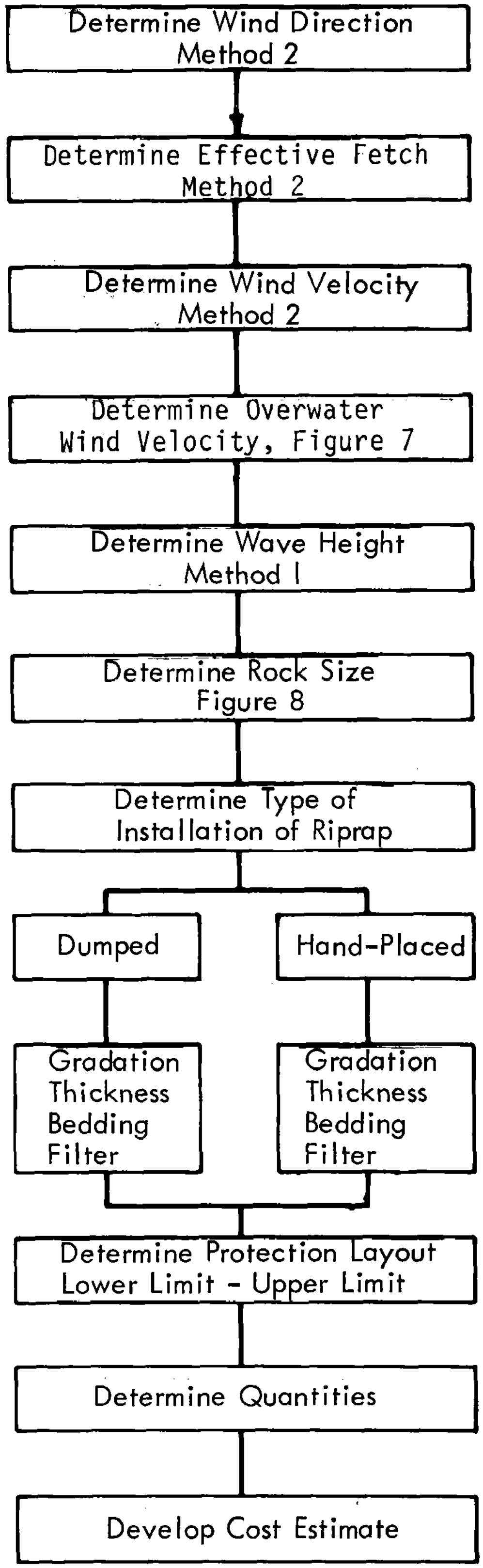
Flow Chart: Procedure for Embankments with Effective Height-Storage Product Less Than 3,000

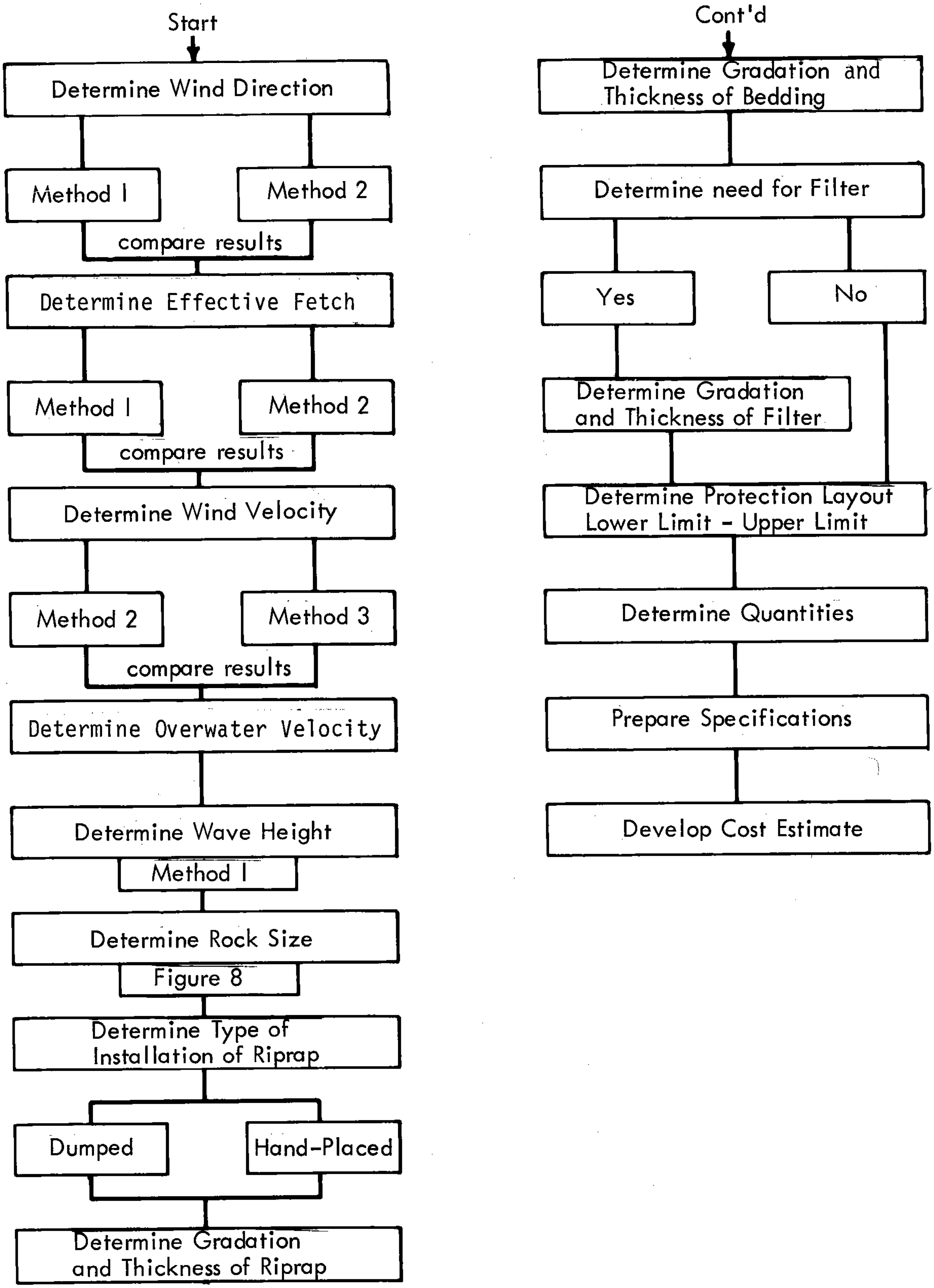


B-2

Flow Chart: Procedure For Planning Purposes



Flow Chart: Procedures For Design



EXAMPLE PROBLEM

Given

1. Multipurpose (recreation + flood-control) reservoir.

2. Portland, Oregon area. Layout and topography are as shown in Exhibit 1D.

3. Normal pool elevation to be 3,200 ft. Average depth of reservoir is 40 ft. The dam has a 3:1 upstream slope, and the specific gravity of available rock is 2.65.

Required: Design of rock riprap for upstream slope protection.

Additional Data as Reference Material: Obtain from National Weather Service a copy of Local Climatological Data for Portland area. Refer to Exhibit 2C.

Solution

Step 1: Determine wind direction. By Method 1, from Exhibit 3C extract the wind speed and direction for the "fastest mile."

Mo.	Speed (mph)	Direction	Azimuth (deg)	Speed x Azimuth
J	54	S	180	9,720
F	61	SW	225	13,725
M	57	S	180	10,260
A	60	S	180	10,800
M	42	SW	225	9,450
J	40	SW	225	9,000
J	31	S	180	5,580
A	29	SW	225	6,525
S	61	S	180	10,980
O	88	S	180	15,840
N	56	SW	225	12,600
D	57	S	180	10,260
	636		2,385	124,740

$$\text{Wind Direction: } \frac{124{,}740}{636} = 196^{\circ}$$

$$\text{Check by } \frac{2385}{12} = 199^{\circ}$$

By observation, this wind direction is away from the dam. Thus, try Method 2.

Azimuth of greatest distance over open water $\cong 331^{\circ}$ NNW (from Exhibit 1C)

Step 2. Determine effective fetch.

Since in step 1 the wind direction had to be determined by Method 2, effective fetch will also be determined by Method 2.

No.	α	cos α	$\cos^2\alpha$	Xi (ft)	$\cos^2\alpha Xi$
1	42	0.743	0.552	1,540	850.08
2	36	.809	.654	1,570	1,026.78
3	30	.866	.750	1,430	1,072.50
4	24	.914	.835	1,460	1,219.10
5	18	.951	.904	1,750	1,582.00
6	12	.978	.956	2,850	2,724.60
7	6	.995	.990	3,500	3,465.00
8	0	1.000	1.000	4,600	4,600.00
9	6	.995	.990	3,350	3,316.50
10	12	.978	.956	2,400	2,294.40
11	18	.951	.904	2,160	1,952.64
12	24	.914	.835	1.710	1,427.85
13	30	.866	.750	1,550	1,162.50
14	36	.809	.654	1,080	706.32
15	42	.743	.552	350	193.20
		Σ 13.512		Σ = 31,300	Σ = 27,593.47

a. Effective Fetch $= \frac{27,593.47}{13.512} = 2,042.1$ ft $= 0.387$ mi (say 0.4 mi)

b. Check $= \frac{31,300}{15} = 2,086.66$ ft $= 0.395$ mi (say 0.4 mi)

Step 3. Determine wind velocity.

a. By Method 1, average fastest mile: Refer to data developed in Step 1.

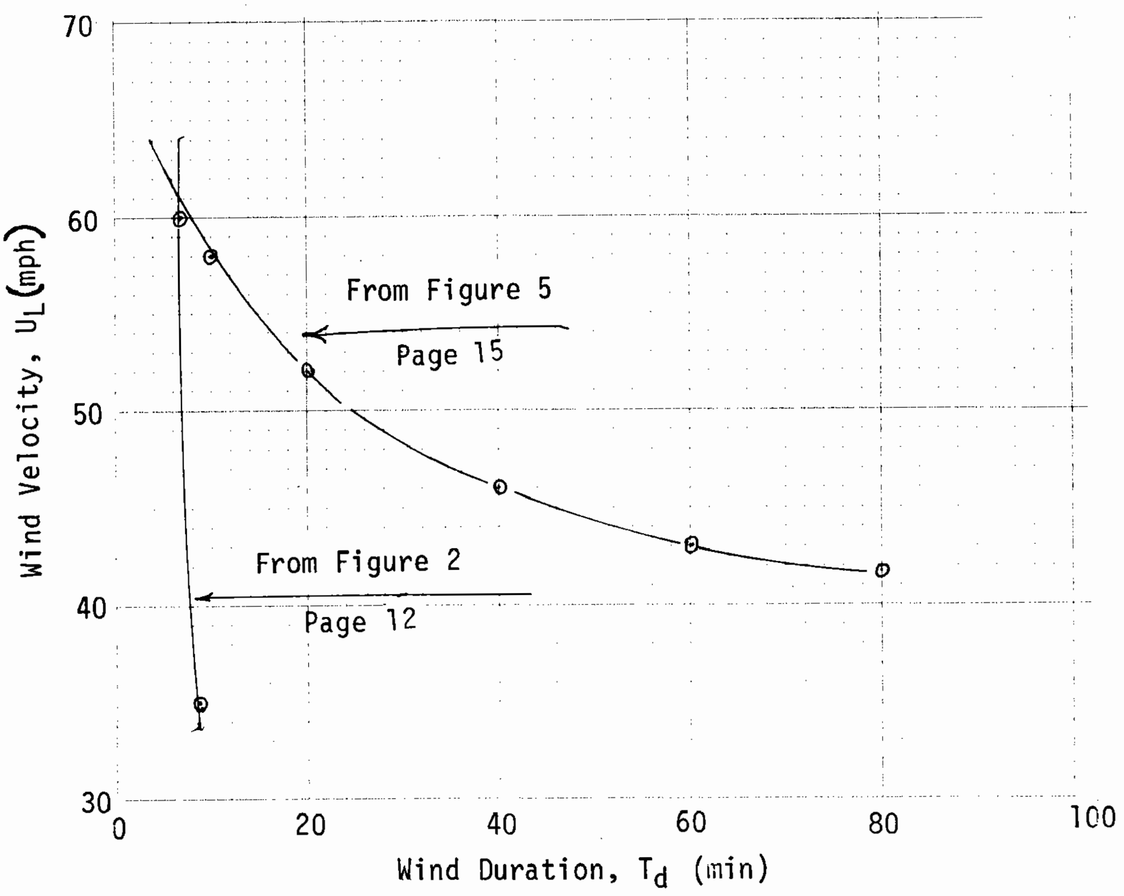
$$\frac{636 \text{ mph}}{12} = 53 \text{ mph}$$

b. By Method 2, Figure 4: The 50-year recurrence isoline for the Portland, Oregon, area is about 75 mph.

c. By Method 3: Maximum fastest mile speed of record from climatological data is 88 mph; however, this must be modified for duration. See Figure 6, page 17.

(1) Plot overland wind velocities and wind durations from Figure 5 corresponding to maximum wind velocity of 88 mph.

(2) Plot overland wind velocities and wind durations from Figure 2, corresponding to an effective fetch of 0.4 mile.



(3) At the point of intersection, read the value of wind velocity (61 mph).

Thus, we have determined overland wind velocities of:

By Method 1 = 53 mph
By Method 2 = 75 mph
By Method 3 = 61 mph
Also Max. Speed of Record = 88 mph

An overland wind velocity of 70 mph (U_L) is selected by the designer.

Step 4. Determine overwater velocity (U_w). From Figure 7, select proper ratio for the effective fetch of 0.4 mi, and read the value of 1.07; thus, 1.07 x 70 = 74.9 mph (say 75 mph).

Step 5. Determine wave height (H_s). By Method 1, using Figure 2, with effective fetch (F_e) - 0.4 mi and design wind velocity (U_d) = 75 mph, read:

$$H_s = 2.2 \text{ ft}$$

Note that for F_e = 0.4 and U_d = 61 mph, H_s = 1.9 ft

By Method 2 - for limited data. With a wind velocity of 50 mph and a fetch of $\frac{(4{,}600 \text{ ft})}{(5{,}280 \text{ ft/mi})} = 0.87$ mi

read H_s = 2.1 ft

Step 6. Determine rock size. With an embankment slope of 3:1, H_s = 2.2 ft, and G_s = 2.65, read W_{50} = 42 lb from Figure 8.

Step 7. Determine gradation and thickness. From Figure 9, read for a 40-lb cube the dimension, D = 0.6 ft.

From Figure 10, the values of gradation for uniform rock size of D_{50} = 0.6 ft (7.2 inches) are as follows:

Percent Passing	Size (inch)
100	11-14
85	9-13
50	7-10
15	5-8
0	4

Required minimum thickness of the rock riprap layer shall be 2 x D_{50} or 14 inches.

Step 8. Determine beddging requirements. Determine bedding gradation by Soil Mechanics Note No. 1, procedure in using the filter as a base. See gradation envelope on Exhibit 5C, Sheet C-10.

Required bedding thickness = 9 inches.

Step 9: Determine limit of riprap

a. Lower limit is:

$1.5H_s = 1.5\ (2.2) = 3.3$ ft vertical distance, or

10.4 ft slope distance

b. Upper limit is:

Obtain value for L from Figure 11; fetch = 0.4 mi, and wind velocity = 75 mph; thus, L = 33 ft.

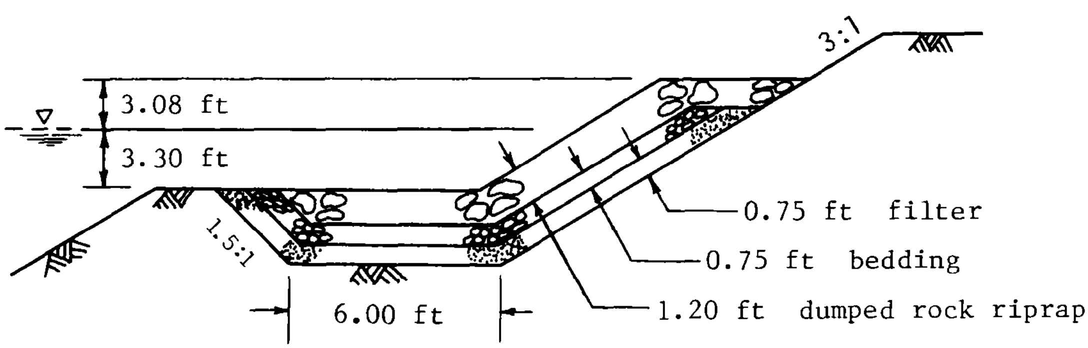
Compute $\frac{H_s}{L} = \frac{2.2}{33} = 0.066$

From Figure 12 determine runup required for the following:
For an embankment slope of 3:1, and $\frac{H_s}{L} = 0.066$, read $\frac{R}{H_s} = 1.30$

$R = 1.30(2.2) = 2.86$ ft

Obtain value for wind set-up (S) from page 8; $S = 0.1(H_s) = 0.1(2.2) - 0.22$ ft, thus, $R+S = 2.86 + 0.22 = 3.08$ ft vertical distance, or 10.31 ft slope distance.

Set-up (S) may also be determined by using Figure 13, page 23, where h = 40 ft, v = 75 mph, F = 0.87 mi (4,600 ft) and S is determined to be 0.10 ft. The maximum value determined should be used.



Note: Uniform rock riprap was used in this example. For graded rock riprap the layer of bedding may not be required. However, with graded riprap, there would be some loss of stability of the smaller rock and the possibility of segregation during placement.

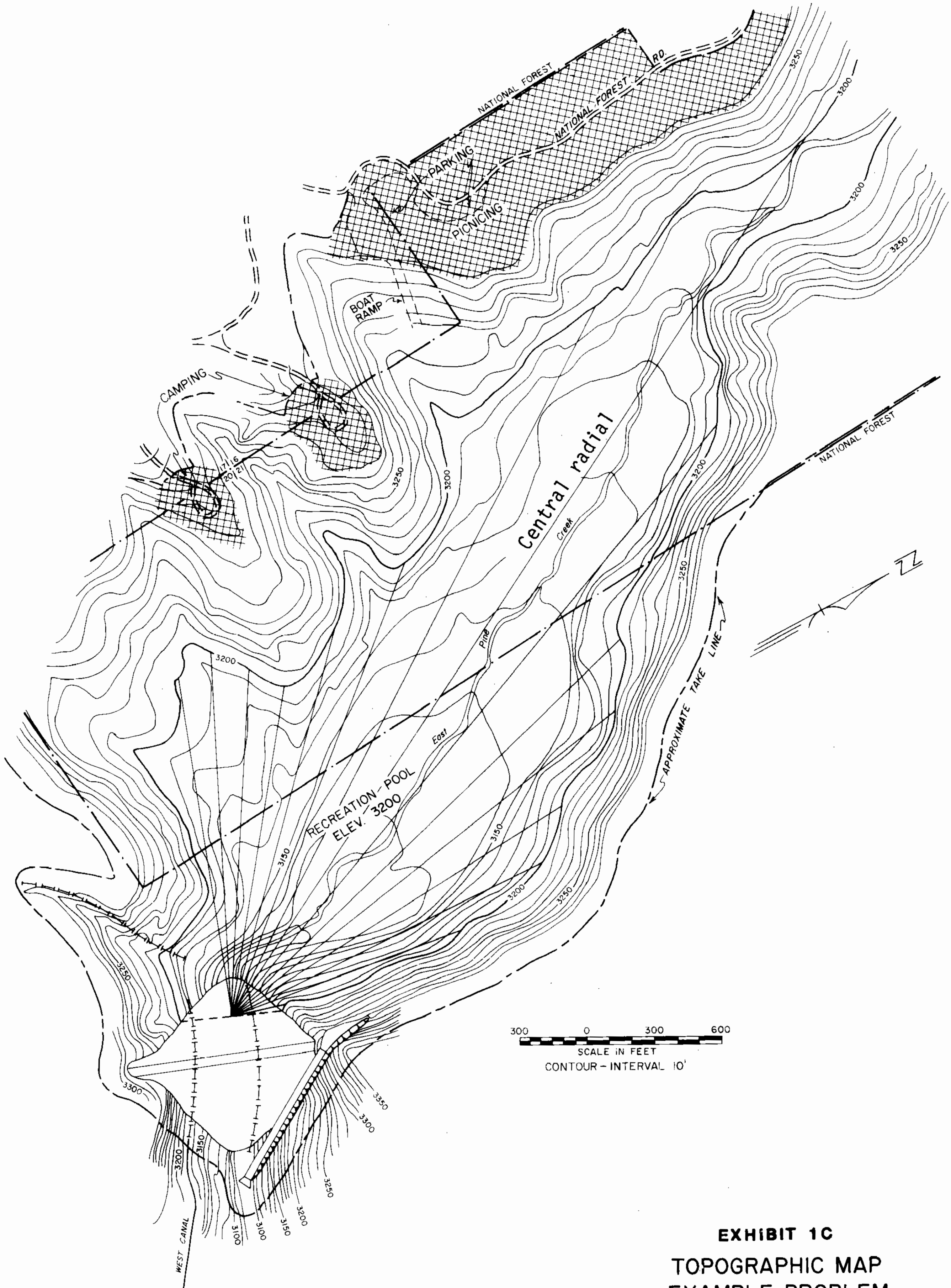


EXHIBIT 1C

TOPOGRAPHIC MAP
EXAMPLE PROBLEM

WNTC ENG. STAFF
PORTLAND, OREGON

Local Climatological Data

Annual Summary With Comparative Data

1976

PORTLAND, OREGON

Exhibit 2C

Narrative Climatological Summary

The Portland Weather Service Office is located six miles north-northeast of downtown Portland. Portland is situated about 65 miles inland from the Pacific Coast and midway between the northerly oriented low coast range on the west and the higher Cascade range on the east, each about 30 miles distant. The airport lies on the south bank of the Columbia River. The coast range provides limited shielding from the Pacific Ocean. The Cascade range provides a steep slope for orographic lift of moisture-laden westerly winds and consequent moderate rainfall and also forms a barrier from continental airmasses originating over the interior Columbia Basin. Airflow is usually northwesterly in Portland in spring and summer and southeasterly in fall and winter, interrupted infrequently by outbreaks of dry continental air moving westward through the Cascade passes.

Portland has a very definite winter rainfall climate. Approximately 88 percent of the annual total occurs in the months of October through May, 9 percent in June and September, while only 3 percent comes in July and August. Precipitation is mostly rain, as on the average there are only 5 days each year with measurable snow. Seldom is snowfall measured for more than a couple of inches, and it generally lasts only a few days. The greatest measured snowfall in period of record is 15 inches.

The winter season is marked by relatively mild temperatures, cloudy skies and rain with southeasterly surface winds predominating. Summer produces pleasantly mild temperatures, northwesterly winds and very little precipitation. Fall and spring are transitional in nature. Fall and early winter are times with most frequent fog. At all times, incursions of marine air are a frequent moderating influence. Outbreaks of continental high pressure from east of the Cascade Mountains produce strong easterly flow through the Columbia Gorge into the Portland area. In winter this brings the coldest weather with the extremes of low temperature registered in the cold airmass. Freezing rain and ice glaze are sometimes transitional effects. In summer hot, dry continental air brings the highest temperatures. Temperatures below zero are very infrequent. The lowest recorded is 3° F. below zero. Temperatures above 100° F. are also infrequent. The highest recorded temperature is 107° F. Temperatures 90° F. or higher are reached every year, but seldom persist for more than 2 or 3 days.

Destructive storms are infrequent in the Portland area. Surface winds seldom exceed gale force and only twice in the period of record have winds reached higher than 75 m.p.h. Thunderstorms occur about once a month through the spring and summer months. Heavy downpours are infrequent but gentle rains occur almost daily during winter months.

Most rural areas around Portland are farmed for berries, green beans, and vegetables for fresh market and processing. The long growing season with mild temperatures and ample moisture favor local nursery and seed industries. Tourist visitation is very heavy in Portland in summer owing to immediate accessibility of choice recreational areas of diversified nature ranging from marine to mountain.

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / ENVIRONMENTAL DATA SERVICE / NATIONAL CLIMATIC CENTER ASHEVILLE, N.C.

Meteorological Data For The Current Year

Station: PORTLAND, OREGON # 24229 INTERNATIONAL AIRPORT Standard time used: PACIFIC Latitude: 45° 36' N Longitude: 122° 36' W Elevation (ground): 21 feet Year: 1976

Month	Temperature °F Averages Daily maximum	Daily minimum	Monthly	Extremes Highest	Date	Lowest	Date	Degree days Base 65 °F Heating	Cooling	Precipitation in inches Water equivalent Total	Greatest in 24 hrs.	Date	Snow, Ice pellets Total	Greatest in 24 hrs.	Date	Relative humidity, pct. Hour 04 (Local time)	Hour 10	Hour 16	Hour 22
JAN	47.9	36.5	42.2	58	15	26	1	698	0	5.14	1.09	6-7	T	T	7	87	85	76	85
FEB	49.2	35.0	42.1	60	22	24	7	658	0	4.92	1.57	26-27	T	T	28	81	75	62	76
MAR	53.0	35.7	44.4	66	16	25	3	632	0	2.93	0.73	13-14	T	T	31	83	73	56	74
APR	60.1	40.4	50.3	82	30	31	2	437	0	2.34	0.53	7-8	T	T	25	81	64	50	71
MAY	67.2	45.9	56.6	84	9	41	25	258	4	2.29	0.63	30-31	T	T	31	79	63	50	66
JUN	70.8	49.9	60.4	89	18	42	13	155	23	0.78	0.37	15-16	0.0	0.0		79	59	46	66
JUL	78.5	55.8	67.2	92	15	46	2	15	89	0.66	0.46	7-8	0.0	0.0		78	61	42	64
AUG	74.3	56.7	65.5	86	29	49	18	41	66	3.29	1.18	6-7	0.0	0.0		82	71	55	74
SEP	74.6	53.8	64.2	87	20	45	8	47	30	0.73	0.46	14	0.0	0.0		88	71	53	75
OCT	64.8	44.5	54.7	82	7	33	21	319	4	1.48	0.50	31	0.0	0.0		88	78	56	80
NOV	56.1	37.8	47.0	68	16	22	28	536	0	0.77	0.35	14-15	0.0	0.0		90	83	66	84
DEC	45.4	33.5	39.5	54	26	23	31	783	0	1.38	0.49	25-26	0.0	0.0		92	91	82	89
YEAR	61.8	43.8	52.8	92	JUL 15	22	NOV 28	4579	216	26.71	1.57	FEB 26-27	T	T	MAY 31	84	73	58	75

Month	Wind Resultant Direction	Speed m.p.h.	Average speed m.p.h.	Fastest mile Speed m.p.h.	Direction	Date	Percent of possible sunshine	Average sky cover, tenths, sunrise to sunset	Number of days Sunrise to sunset Clear	Partly cloudy	Cloudy	Precipitation .01 inch or more	Snow, Ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility ¼ mile or less	Temperature °F Maximum (b) 90° and above	32° and below	Minimum 32° and below	0° and below	Average station pressure mb Elev. 39 feet m.s.l.
JAN	16	4.6	8.4	28	W	11	30	7.7	6	3	22	14	0	0	9	0	0	9	0	1022.4
FEB	18	5.2	10.9	40	SW	24	46	7.5	4	4	21	16	0	0	1	0	0	10	0	1016.3
MAR	22	3.7	9.0	39	SW	24	68	8.4	2	3	26	16	0	0	3	0	0	9	0	1017.6
APR	23	0.6	7.6	26	SE	28	63	7.7	2	7	21	17	0	2	1	0	0	2	0	1015.9
MAY	30	2.4	7.2	28	SW	1	62	6.6	6	10	15	12	0	1	0	0	0	0	0	1017.6
JUN	32	4.1	7.5	23	SW	30	62	7.0	4	8	18	7	0	0	0	0	0	0	0	1016.9
JUL	33	4.8	7.7	20	N	27	72	5.2	12	6	13	6	0	0	0	1	0	0	0	1015.6
AUG	32	2.8	6.8	18	NW	30	53	7.1	6	9	16	10	0	0	0	0	0	0	0	1015.9
SEP	33	2.6	6.6	21	E	9	62	5.2	12	8	10	5	0	0	4	0	0	0	0	1015.2
OCT	13	0.7	6.5	32	SW	31	55	6.3	7	9	15	6	0	0	10	0	0	0	0	1018.6
NOV	12	1.9	7.0	31	E	20	47	7.6	2	9	19	8	0	0	18	0	0	7	0	1021.3
DEC	14	2.5	6.1	25	SW	26	23	8.4	4	2	25	10	0	0	17	0	0	12	0	1021.0
YEAR	25	0.7	7.6	40	SW	FEB 24	56	7.1	67	78	221	127	0	3	63	1	0	49	0	1017.9

Normals, Means, And Extremes

Month	Temperatures °F Normal Daily maximum	Daily minimum	Monthly	Extremes Record highest	Year	Record lowest	Year	Normal Degree days Base 65 °F Heating	Cooling	Precipitation in inches Water equivalent Normal	Maximum monthly	Year	Minimum monthly	Year	Maximum in 24 hrs.	Year	Snow, Ice pellets Maximum monthly	Year	Maximum in 24 hrs.	Year
(a)				36		36					36		36		36		36		36	
J	43.6	32.5	38.1	62	1974	-2	1950	834	0	5.88	12.83	1953	1.02	1949	2.61	1974	41.4	1950	10.6	1950
F	50.1	35.5	42.8	70	1968	-3	1950	622	0	4.06	9.46	1949	0.78	1964	2.00	1968	13.2	1949	3.2	1962
M	54.3	37.0	45.7	80	1947	19	1955	598	0	3.64	7.52	1957	1.10	1965	1.83	1943	12.9	1951	7.7	1951
A	60.3	40.8	50.6	87	1957	29	1955	432	0	2.22	4.72	1955	0.53	1956	1.47	1962	T	1976	T	1976
M	67.0	46.3	56.7	92	1973	29	1954	264	7	2.09	4.57	1945	0.57	1950	1.47	1968	0.6	1953	0.5	1953
J	72.1	51.8	62.0	100	1942	39	1966	128	38	1.59	3.58	1954	0.03	1951	1.82	1958	0.0		0.0	
J	79.0	55.2	67.1	107	1965	43	1955	48	114	0.47	2.01	1974	0.00	1967	0.91	1966	0.0		0.0	
A	78.1	55.0	66.6	104	1972	44	1951	56	106	0.82	4.53	1968	T	1970	1.38	1968	0.0		0.0	
S	73.9	50.5	62.2	101	1944	34	1965	119	35	1.60	3.96	1945	T	1975	2.23	1969	T	1949	T	1949
O	62.9	44.7	53.8	90	1970	26	1971	347	0	3.59	8.04	1947	0.72	1952	2.18	1941	0.2	1950	0.2	1950
N	52.1	38.5	45.3	73	1975	13	1955	591	0	5.61	11.57	1942	0.77	1976	2.62	1973	8.2	1955	4.5	1955
D	46.0	35.3	40.7	64	1950	6	1964	753	0	6.04	11.12	1968	1.38	1976	2.17	1942	15.7	1968	8.0	1964
YR	61.6	43.6	52.6	107	JUL 1965	-3	FEB 1950	4792	300	37.61	12.83	JAN 1953	0.00	JUL 1967	2.62	NOV 1973	41.4	JAN 1950	10.6	JAN 1950

Month	Relative humidity pct. Hour 04 (Local time)	Hour 10	Hour 16	Hour 22	Wind Mean speed m.p.h.	Prevailing direction	Fastest mile Speed m.p.h.	Direction	Year	Pct. of possible sunshine	Mean sky cover, tenths, sunrise to sunset	Mean number of days Sunrise to sunset Clear	Partly cloudy	Cloudy	Precipitation .01 inch or more	Snow, Ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility ¼ mile or less	Temperatures °F Max. (b) 90° and above	32° and below	Min. 32° and below	0° and below	Average station pressure mb. Elev. 39 feet m.s.l.
(a)	36	36	36	36	28	15	28	28		27	28	28	28	28	36	36	36	34	36	36	36	36	4
J	86	82	76	83	10.1	ESE	54	S	1951	24	8.6	2	4	25	19	1	*	4	0	3	13	*	1018.7
F	86	79	67	81	8.9	ESE	61	SW	1958	36	8.3	3	3	22	16	*	*	4	0	*	9	*	1016.4
M	85	72	60	78	8.3	ESE	57	S	1963	43	8.1	3	4	24	17	*	1	2	0	*	6	0	1014.6
A	86	68	54	75	7.2	NW	60	S	1957	49	7.7	4	5	21	14	0	1	1	0	0	1	0	1017.9
M	85	66	53	74	6.9	NW	42	SW	1960	55	7.1	5	7	19	12	*	1	*	*	0	*	0	1017.3
J	84	65	49	71	6.9	NW	40	SW	1958	52	6.8	6	7	17	9	0	1	*	1	0	0	0	1016.4
J	82	61	45	68	7.4	NW	31	S	1956	69	4.5	14	8	9	4	0	1	*	3	0	0	0	1015.7
A	84	65	47	71	7.0	NW	29	SW	1961	63	5.2	11	10	10	5	0	1	*	3	0	0	0	1016.0
S	87	67	49	75	6.4	NW	61	S	1963	60	5.4	11	7	12	7	0	1	3	2	0	0	0	1015.7
O	90	79	64	84	6.4	ESE	88	S	1962	41	7.2	5	7	19	13	0	*	8	*	0	1	0	1017.2
N	88	82	74	85	8.3	ESE	56	SW	1961	28	8.2	3	6	23	17	*	*	6	0	*	5	0	1016.4
D	87	84	79	85	9.5	ESE	57	S	1951	20	8.9	2	2	27	19	1	*	5	0	1	9	0	1019.1
YR	86	72	60	78	7.8	NW	88	S	OCT 1962	48	7.2	69	68	228	152	2	7	33	10	4	44	*	1016.8

Means and extremes above are from existing and comparable exposures. Annual extremes have been exceeded at other sites in the locality as follows: Maximum monthly precipitation 20.14 in December 1882; maximum precipitation in 24 hours 7.66 in December 1882; maximum snowfall in 24 hours 16.0 in January 1937.

(a) Length of record, years, through the current year unless otherwise noted, based on January data.
(b) 70° and above at Alaskan stations.
* Less than one half.
T Trace.

NORMALS - Based on record for the 1941-1970 period.
DATE OF AN EXTREME - The most recent in cases of multiple occurrence.
PREVAILING WIND DIRECTION - Record through 1963.
WIND DIRECTION - Numerals indicate tens of degrees clockwise from true north. 00 indicates calm.
FASTEST MILE WIND - Speed is fastest observed 1-minute value when the direction is in tens of degrees.

Exhibit 3C

SCS-ENG-353 (REV. 3-70)
FILE CODE ENG-22

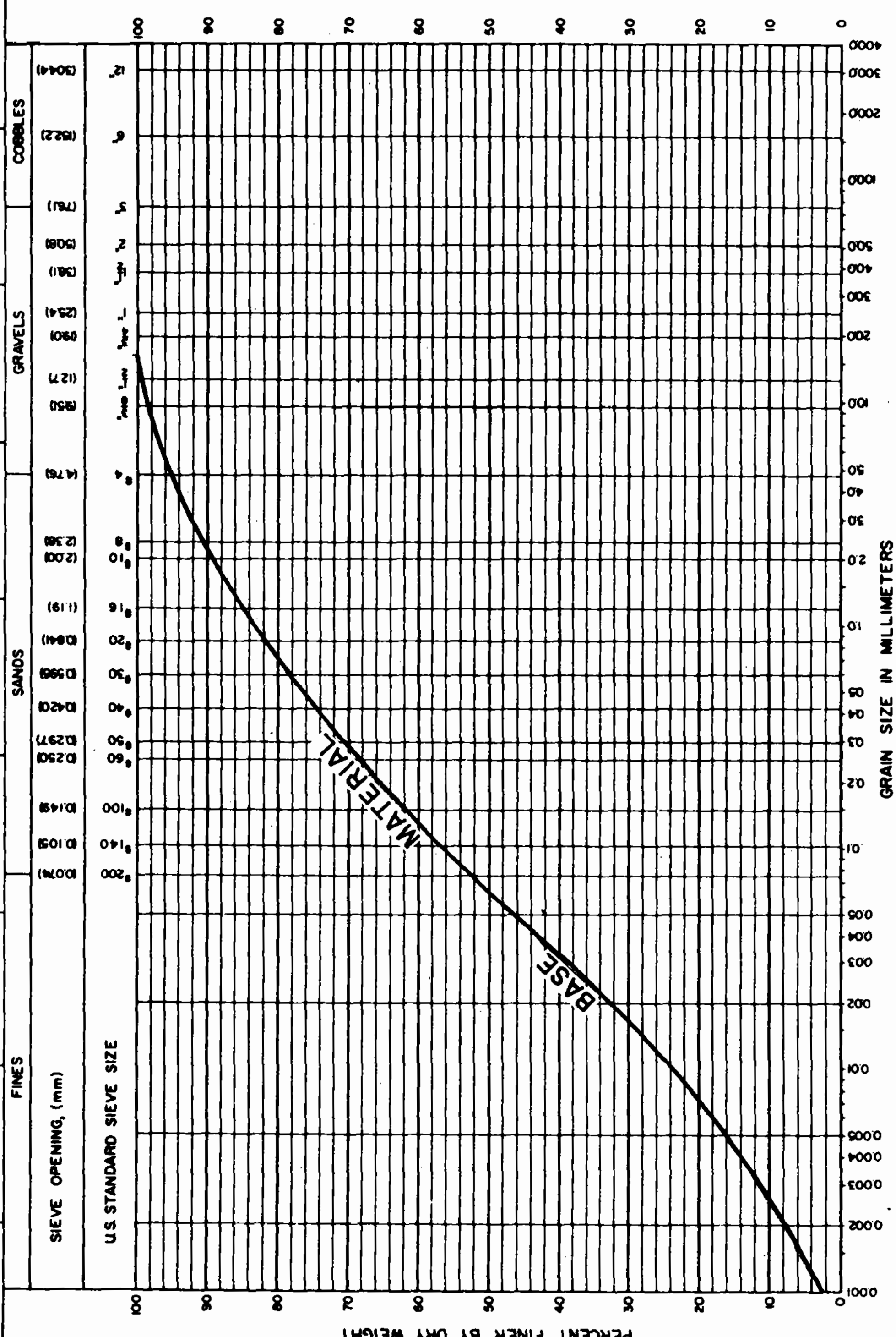
LABORATORY NO.

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	SOIL CLASSIFICATION

PROJECT and STATE: TECHNICAL RELEASE NO. 69		SAMPLE LOCATION	
FIELD SAMPLE NO.	DEPTH	GEOLOGIC ORIGIN	
TYPE OF SAMPLE	TESTED AT	APPROVED BY	DATE
SYMBOL	DESCRIPTION		

GRAIN SIZE DISTRIBUTION

C_c	
C_u	
D_{MAX}	//
D_{85}	
D_{60}	
D_{50}	
D_{30}	
D_{15}	
D_{10}	



UNDISTURBED CONDITION: DRY UNIT WEIGHT g/cc pcf; MOISTURE %

SHRINKAGE LIMIT %

SOLUBLE SALTS %

ATTERBERG LIMITS

NATURAL MOISTURE		AIR DRY		OVEN DRY	
LL	PI	LL	PI	LL	PI

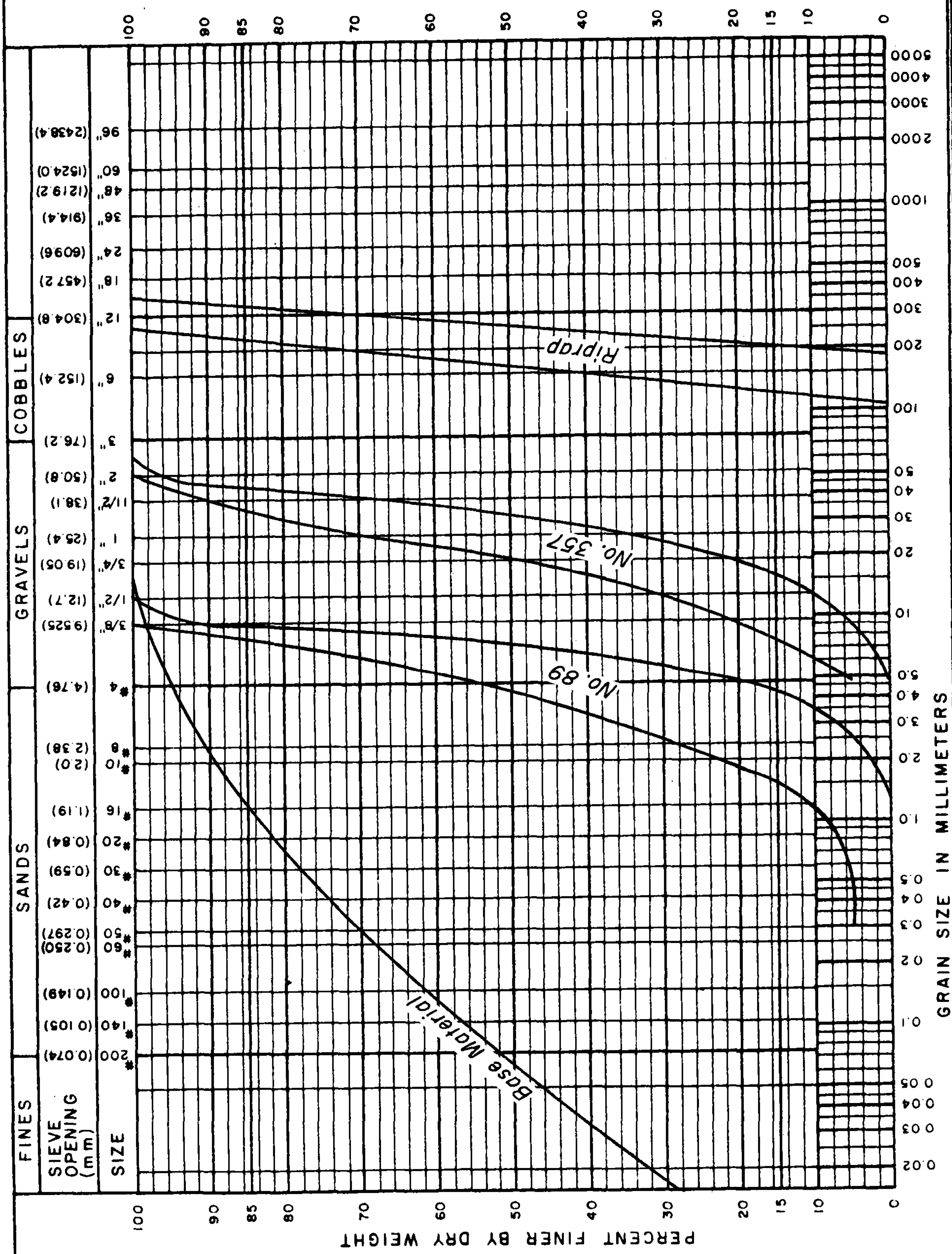
SPECIFIC GRAVITY (G_s): (+) #4; (-) #4

REMARKS:

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

RIPRAP, FILTER OR BEDDING MATERIALS

PROJECT and STATE TECHNICAL RELEASE NO. 69		
DESIGNED AT	BY	DATE



REMARKS

Note: Aggregate gradations are from ASTM C-33

Worksheet for TR-69 Rock Riprap for Slope Protection Against Wave Action

Sht, 1

I. Wind Data ⟶ Significant Wave Ht.

A. Design Wind Direction

Method 1 - Climatological Data from U.S. Weather Service tables of "Normals, Means, and Extremes" or "Climatic Atlas of the United States"

1	2	3	4	5
Month	Speed (mph)	* Direction	* Azimuth	Col. 2 X Col. 4
January				
February				
March				
April				
May				
June				
July				
August				
September				
October				
November				
December				
	Σ(2)=		Σ(4)=	Σ(5)=

$$\text{Wind Direction} = \frac{\Sigma(5)}{\Sigma(2)} = \_\_\_\_\_\_\_\_$$

Check for comparison: $\text{Wind Direction} \quad \frac{\Sigma(4)}{12} = \_\_\_\_\_\_\_\_$

Does wind impinge on dam? ________ < Yes. Go to Part B. / No. Go to Method 2.

* Direction ⟶ Azimuth:

NE =	45°	SW =	225°
E =	90°	W =	270°
SE =	135°	NW =	315°
S =	180°	N =	360°

* Direction from which wind was blowing in terms of degrees clockwise.

Worksheet D-2

Sht. 2

Method 2 - Site Conditions

Azimuth = ___________

B. Effective Fetch

Attach plan view of site w/appropriate radials.

Method ________ used.

EFFECTIVE FETCH					
1	2	3	4	5	6
No.	α	cos α	$\cos^2 \alpha$	Xi scale distance (Ft.)	Col. 4 X Col. 5
1	42	0.743	0.552		
2	36	0.809	0.654		
3	30	0.866	0.750		
4	24	0.914	0.835		
5	18	0.951	0.904		
6	12	0.978	0.956		
7	6	0.995	0.990		
8	0	1.000	1.000		
9	6	0.995	0.990		
10	12	0.978	0.956		
11	18	0.951	0.904		
12	24	0.914	0.835		
13	30	0.866	0.750		
14	36	0.809	0.654		
15	42	0.743	0.552		
		$\Sigma(3) = 13.512$		$\Sigma(5) =$	$\Sigma(6) =$

$$\text{Effective Fetch } (F_e) = \frac{\Sigma(6)}{\Sigma(3)} = \frac{\_\_\_\_\_\_\_\_}{13.512} \text{ ft}$$

______ft. ÷ 5,280 ft/mi = __________mi

< 10 mi? Yes, Continue / No, See references (3, 4, 5, 15)

$$\text{Check: } F_e = \frac{\Sigma(5)}{15(5{,}280)} = \_\_\_\_\_\_\_\_\_\_ \text{ mi}$$

C. Design Wind Velocity (U_d)

1. Overland Wind Velocity (U_L)

Method 1 - Climatological Data. $U_L = \frac{\Sigma \text{ Speed}}{12}$ = __________

Σ Speed = $\Sigma(2)$ from I.A., column 2

Method 2 - Generalized Data. See Fig. 4.

U_L = __________

Method 3 - Maximum Speed of Record

a. Refer to climatological data reference from I.A.

Max. fastest mile velocity = ____________

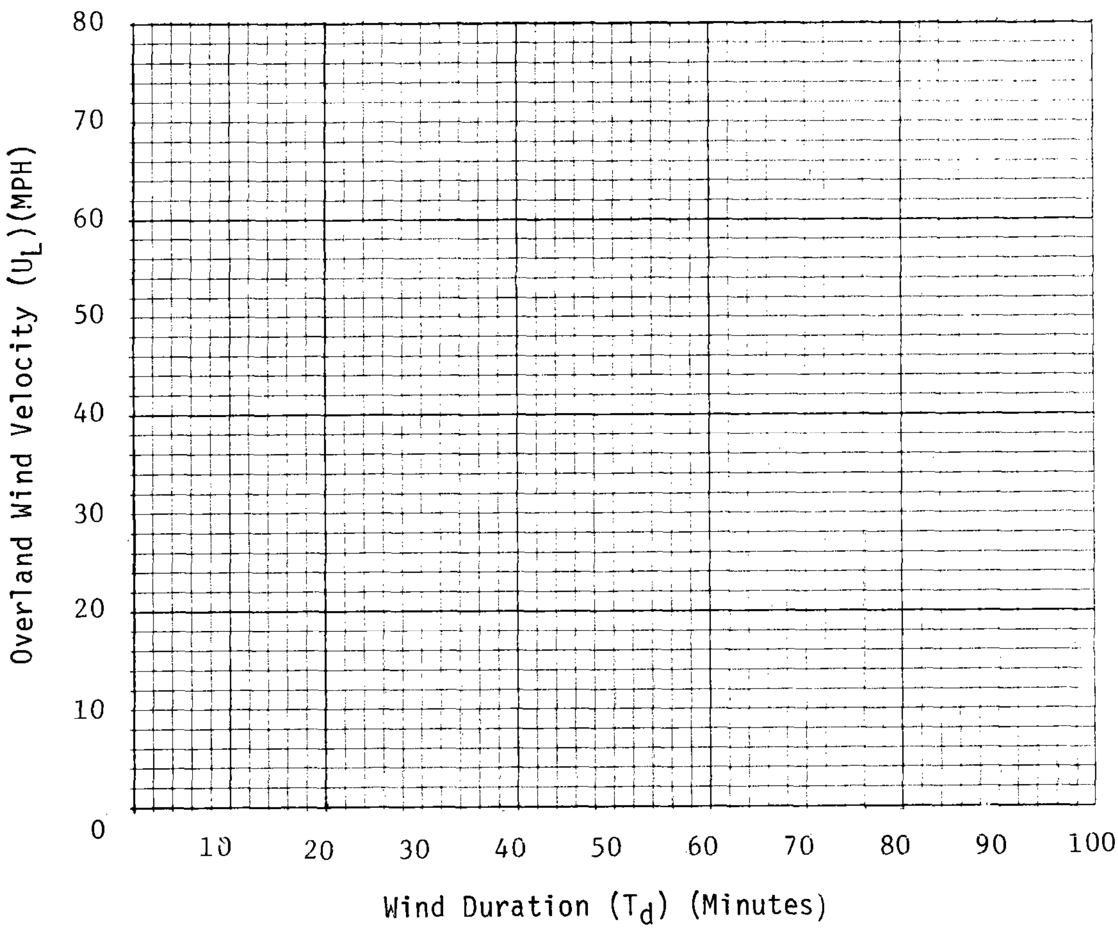
b. Plot below:

(1) U_L vs. T_d for max. fastest mile velocity, see Fig. 5.

(2) U_L vs. T_d for calculated F_e (I.B.), see Fig. 2.

Worksheet D-4

Sht. 4



At intersection of curves U_L = __________

Use U_L = __________

2. Overwater Wind Velocity (U_W): $U_d = U_W$

From Fig. 7 $\frac{U_W}{U_L}$ = __________ for calculated F_e (I.B.)

$U_d = U_W = \frac{U_W}{U_L} (U_L)$ = ________ (______) = ________

D. Significant Wave Ht.

Method 1 - With prescribed data (Fig. 2)

H_s = ______________ < 5'? Yes, Continue
No, See References (3, 4, 5, 15)

Method 2 - Assumed wind velocity is 50 mph. H_s = ___________

II. Design of Rock Protective Layer

A. Determination of Rock Size (Fig. 8)

W_{50} = _______________

B. Gradation and Thickness of Rock Riprap

General shape of local rock? rod
cube
sphere

Method of placement? Type 1 (Equip.) - Go to step 1
Type 2 (Hand) - Go to step 2

1. Type 1 - Gradation desired? Uniform
Graded

Fig. 9, D = D_{50} = ______________

K Factor < min / max: Uniform	K Factor < min / max: Graded	Percent Passing by Wt.	Size (in) = D_{50} (Kmin or Kmax) Min. - Max.
< 1.50 / 2.00		100	-
< 1.30 / 1.80		85	-
< 1.00 / 1.40		50	-
< 0.72 / 1.10		15	-
	< 0.10 / 0.50	10	-
< 0.65		0	-

Minimum $t_r = 2\ D_{50} =$ __________

2. Type 2 - Hand-placed

Fig. 9, D = D min = ____________

D max = 1.5 D min___________

Minimum $t_r =$ D min = _____________

C. Bedding and/or Filter

See Soil Mechanics Note 1: attach computations

D. Slope Protection Layout

1. Lower Limit Elevation ($Elev_{LL}$)

a. Normal water elev. for lowest ungated opening __________

Lowest controlled outlet elev. __________

b. $Elev_{LL} = \begin{matrix}\text{lowest} \\ \text{in "a" above}\end{matrix} - 1.5H_s =$ __________

2. Upper Limit Elevation ($Elev_{UL}$)

Normal Pool $Elev_{NP} =$ __________

a. Wave runup (R)

(1) Fig. 11 L = __________, $\frac{H_s}{L} =$ __________

(2) Fig. 12 $R' = \left(\frac{R}{H_s}\right)H_s =$ __________

$R = \left(\begin{matrix}\text{correction} \\ \text{factor}\end{matrix}\right)R' =$ __________

b. Wind set-up (S)

(1) $S = 0.1\ H_s =$ __________ S max = 0.5'

or

(2) Fig. 13 S = __________

c. $Elev_{UL} = Elev_{NP} + R + S =$ __________

APPENDIX E - DERIVATION OF RELATIONSHIP BETWEEN ROCK SIZE AND SIGNIFICANT WAVE HEIGHT

The following development parallels that given in reference (16).

Waves incident on a rock-riprap embankment slope develop hydrodynamic forces that tend to displace the rock from the embankment slope. These forces consist of a drag force and an inertial force.

The drag force exerted on the rock can be expressed by the general drag equation

$$F_d = 1/2\ C_d \frac{\gamma_w}{g} K_a C^2 \ell^2 \qquad \text{(E1)}$$

in which

C is the velocity of water flowing around or impinging on the rock (feet/second)

C_d is a drag coefficient, dimensionless

ℓ is a characteristic linear dimension of the rock particle (feet)

K_a is the coefficient of effective rock area such that $K_a \ell^2$ equals the projected area of the rock

γ_w is specific weight of water (pound/feet^3)

g is acceleration of gravity (32.2 ft/sec^2)

The inertia force, based on Newton's equation F = Ma, can be expressed as

$$F_m = C_m K_v \ell^3 \frac{\gamma_w}{g} \frac{\partial C}{\partial t} \qquad \text{(E2)}$$

in which

C_m is a virtual mass coefficient, dimensionless

K_v is the coefficient of effective rock volume such that $K_v \ell^3$ equals the volume of a rock, dimensionless

t is time (second)

Because of the difficulties inherent in evaluating the separate sets of coefficients and for simplification of the force equation used, the inertial force effects are combined with the drag force. The resulting equation is:

$$F_q = C_q \ell^2 \frac{\gamma_w}{g} C^2 \tag{E3}$$

in which C_q, the total coefficient, is a function of the terms $\frac{1}{C^2} \frac{\partial C}{\partial t}$, $C_d K_a$ and $C_m K_v$.

For deep water waves

$$C^2 = \frac{gH}{2\pi\delta} \tag{E4}$$

where

H = wave height (feet)

δ = H/L, wave steepness

Substituting this value for velocity into Equation E3 the expression for the force exerted by a wave in terms of wave height is

$$F_q = \frac{C_q \ell^2 \gamma_w H}{2\pi\delta} \tag{E5}$$

For dumped riprap the forces resisting displacement are the buoyant weight of the individual rocks and the friction between the rocks.

Neglecting the contribution due to friction, the principal resisting force is the buoyant weight of the rock which may be written as:

$$W'_r = K_v \ell^3 (\gamma_r - \gamma_w) \tag{E6}$$

Where:
γ_r = specific weight of the rock (pound/feet^3)

For incipient motion, $W'_r = F_q$

$$K_v \ell^3 (\gamma_r - \gamma_w) = \frac{C_q \ell^2 \gamma_w H}{2\pi\delta} \tag{E7}$$

or

$$K_v \ell (G_s - 1) = \frac{C_q H}{2\pi\delta} \tag{E8}$$

The weight of the rock in air $W_r = K_v \ell^3 \gamma_r$ or

$$\ell = \left[\frac{W_r}{K_v \gamma_r}\right]^{1/3} \tag{E9}$$

Substituting this value of ℓ into Equation E8 and rearranging,

$$\frac{\gamma_r^{1/3} H}{(G_s - 1)\, W_r^{1/3}} = \frac{2\pi\delta\, (K_v)^{2/3}}{C_q} \qquad \text{(E10)}$$

in which

$$\frac{2\pi\delta\, (K_v)^{2/3}}{C_q} = f\,\left(\alpha,\, C_d,\, K_a,\, C_m,\, K_v,\, \frac{1}{C^2}\frac{\partial C}{\partial t},\, d/L,\, H/L\right) \qquad \text{(E11)}$$

Laboratory investigation of rubble-mound breakwaters by Hudson indicates, that for embankment slope and shape of rock, the effects of the remaining variables on rock stability are of second-order importance. The empirical equation determined by Hudson is

$$f\,\left(\alpha,\, C_d,\, K_a,\, C_m,\, K_v,\frac{1}{C^2}\frac{\partial C}{\partial t},\, d/L,\, H/L\right) \approx f\,(k_s,\, \alpha)$$
$$= k_s\,(\cot\alpha)^{1/3} \qquad \text{(E12)}$$

in which k_s is a stability coefficient.

If $K_\Delta = k_s^{\,3}$, then Equations B10 and B12 may be combined and rewritten as

$$W_r = \frac{\gamma_r H_s^{\,3}}{K_\Delta (G_s - 1)^3 \cot\alpha} \qquad \text{(E13)}$$

For dumped rock riprap a value of 3.2 is recommended for K_Δ.

Substituting this value for K_Δ and assuming $W_r = W_{50}$, Equation E13 becomes

$$W_{50} = \frac{\gamma_r H_s^3}{3.2\,(G_s - 1)^3 \cot\alpha} = \frac{19.5\, G_s H_s^3}{(G_s - 1)^3 \cot\alpha} \qquad \text{(E14)}$$

The solution of Equation E14 is shown graphically in Figure 8 and is the basis for sizing rock riprap.

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