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Hydraulic Design of Riprap Gradient Control Structures

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HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

TECHNICAL RELEASE NO. 59
Design Unit
January 23, 1976

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PREFACE

Mr. M. M. Culp, former Chief of the Design Branch, suggested the Design Unit make a study of a steepened riprap channel to obtain gradient control. The resulting investigation led Mr. Paul D. Doubt, former Head of the Design Unit, to conceive and develop the riprap gradient control structure presented in this technical release. The first version of a computer program to determine the dimensions and parameters associated with the design of this riprap structure and portions of a preliminary draft of this technical release were written by Mr. Doubt.

A draft of this technical release dated July 14, 1975, was circulated through the Engineering Division and sent to the Engineering and Watershed Planning Unit Design Engineers for review and comment.

A publication is being prepared which will contain the necessary charts for the graphical solution of parameters used in the design of a limited class of riprap structures.

This technical release was prepared by Mr. H. J. Goon with the assistance of Mr. John A. Brevard, both of the Design Unit, Design Branch, Engineering Division, Hyattsville, Maryland.

TECHNICAL RELEASE NUMBER 59

HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

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NOMENCLATURE

This technical release uses, insofar as possible, nomenclature which commonly appears in hydraulic literature. However, when nomenclature involves lower case letters, subscripts, and Greek letters, difficulties are encountered in presenting, describing, and interpreting computer input and output. Therefore, sometimes two symbols have the same meaning; one is used in the text and the other is used in describing computer input and output data. The symbols used for input and output data are also defined in the "Computer Program" section of this technical release.

a ≡ Flow area, ft^2

a_a ≡ Average flow area, ft^2

a_c ≡ Flow area corresponding to critical depth, d_c, ft^2

a_n ≡ Flow area corresponding to normal depth, d_n, ft^2

b ≡ Bottom width of trapezoidal section, ft

b_a ≡ Average width of channel, ft

b_j ≡ Bottom width of the transition at any section j, ft

BS ≡ Bottom width at the ends of the riprap structure, ft

BU ≡ Bottom width of the prismatic channel of riprap structure, ft

C_{50} = C50 ≡ Coefficient relating critical tractive stress to riprap D_{50} size, $\tau_{bc} = C_{50} D_{50}$

C_n = CN ≡ Coefficient relating Manning's n to riprap D_{50} size, $n = C_n \left[D_{50} \right]^{EXPN}$

CONV ≡ Rate of convergence of the bottom width of the upstream transition, ft/ft

CS $= \frac{s_n}{s_c}$ ≡ Maximum allowable ratio of bottom slope to critical slope

CSU $= \frac{SN}{SC}$ ≡ Ratio of bottom slope to critical slope used in the design of a particular riprap structure

CTAUB ≡ A coefficient used to determine the maximum tractive stress along the boundary of the riprap lining on the bottom of the prismatic channel

CTAUS ≡ A coefficient used to determine the maximum tractive stress along the boundary of the riprap lining on the side slope of the prismatic channel

$C_{\tau b}$ $= \frac{\tau_{bm}}{\tau_{av}}$ ≡ Ratio of maximum tractive stress on bottom of channel to average tractive stress

$C_{\tau s}$ $= \frac{\tau_{sm}}{\tau_{av}}$ ≡ Ratio of maximum tractive stress on side slope of channel to average tractive stress

d ≡ Depth of flow, ft

D_{50} = D50 ≡ Size of rock in riprap of which 50 percent by weight is finer, ft

D50U ≡ The D_{50} size of riprap used in the design of a particular riprap structure, ft

d_c ≡ Critical depth corresponding to design discharge, Q, ft

DC ≡ Critical depth corresponding to design discharge, Q, in the prismatic channel of riprap structure, ft

DIV ≡ Rate of divergence of the bottom width of the downstream transition, ft/ft

d_n ≡ Normal depth corresponding to design discharge, Q, ft

DN ≡ Normal depth corresponding to the design discharge, Q, in the prismatic channel of riprap structure, ft

$d_{n,d}$ ≡ Normal depth in the downstream channel, ft

$d_{n,u}$ ≡ Normal depth in the upstream channel, ft

DS ≡ Depth of flow corresponding to the design discharge, Q, at the ends of the riprap structure, ft

EXPN ≡ Value of the exponent in the equation for computing Manning's roughness coefficient, $n = C_n [D_{50}]^{EXPN}$

F ≡ Resultant of horizontal forces acting on the body of moving water, lb

F_1 ≡ Resultant of hydrostatic pressures acting at Section 1, lb

F_2 ≡ Resultant of hydrostatic pressures acting at Section 2, lb

F_f ≡ Total frictional force, lb

FS ≡ Factor of safety

FSU ≡ Factor of safety used in the design of a particular riprap structure

g ≡ Acceleration of gravity, ft/sec^2

H ≡ Specific energy head corresponding to the design discharge, Q, ft

HC ≡ Critical specific energy head corresponding to the design discharge, Q, ft

h_f ≡ Friction head loss, $\frac{\text{ft-lb}}{\text{lb}}$

HN ≡ Normal specific energy head corresponding to the design discharge, Q, in the prismatic channel of the riprap structure, ft

$$J \equiv \frac{\left[\begin{array}{c}\text{Distance in the transition from any} \\ \text{section j to section of width BU}\end{array}\right]}{\text{total length of the transition}}$$

$$K = \frac{\tau_{sc}}{\tau_{bc}} = \sqrt{1 - \frac{\sin^2(\cot^{-1} z)}{\sin^2 \theta}}$$ ≡ Ratio of critical tractive stress on side slope to critical tractive stress on bottom of the trapezoidal channel

$$KPS = \frac{p_n}{s_n}$$ ≡ Ratio of wetted perimeter to bottom slope of the prismatic channel

ℓ ≡ Horizontal length of a portion of a channel, ft

LDT ≡ Length of downstream transition, ft

LPC ≡ Length of prismatic channel, ft

LT ≡ Length of the transition, ft

LUT ≡ Length of upstream transition, ft

M $= \frac{\gamma\, Qdt}{g}$ ≡ mass of body of water between Sections 1 and 2

n = N ≡ Manning's coefficient of roughness

p ≡ Wetted perimeter, ft

p_c ≡ Wetted perimeter corresponding to the critical depth, d_c, ft

p_n ≡ Wetted perimeter corresponding to the normal depth, d_n, ft

Q ≡ Design discharge through the riprap structure, cfs

$Q_{n,d}$ ≡ Normal discharge corresponding to depth, d, cfs

r = RN ≡ Hydraulic radius at normal depth, ft

s ≡ Energy gradient, ft/ft

s_c = SC ≡ Critical slope corresponding to the design discharge, Q, in the prismatic channel of the riprap structure, ft/ft

s_n = SN ≡ Bottom slope of the prismatic channel of the riprap structure and also normal slope corresponding to the design discharge, Q, ft/ft

s_o ≡ Slope of channel bottom, ft/ft

t ≡ Time, sec

TAUBA $= \frac{C50 \times D50U}{FSU}$ ≡ The allowable tractive stress for the riprap lining on the bottom of the prismatic channel, lb/ft^2

TAUBM = (CTAUB)(γ)(RN)(SN) ≡ The maximum tractive stress along the riprap lining on the bottom of the prismatic channel, lb/ft^2

TAUSA $= K \frac{C50 \times D50U}{FSU}$ ≡ The allowable tractive stress for the riprap lining on the side slope of the prismatic channel, lb/ft^2

TAUSM = (CTAUS)(γ)(RN)(SN) ≡ The maximum tractive stress along the riprap lining on the side slope of the prismatic channel, lb/ft^2

T_c ≡ Top width of flow corresponding to critical depth, d_c, ft

THETA = θ ≡ Angle of repose of the riprap, degrees

v ≡ Velocity corresponding to the design discharge, Q, ft/sec

v_a ≡ Average velocity, ft/sec

VN ≡ Velocity at normal depth corresponding to the design discharge, Q, in the prismatic channel of riprap structure, ft/sec

VS ≡ Velocity corresponding to the design discharge, Q, at the ends of the riprap structure, ft/sec

W ≡ Total weight of water between sections, lb

x_c $= \frac{d_c}{b} \equiv$ Ratio of critical depth to bottom width

x_n $= \frac{d_n}{b} \equiv$ Ratio of normal depth to bottom width

z $\equiv$ Side slope of trapezoidal section expressed as a ratio of horizontal to vertical, ft/ft

ZL $\equiv$ Side slope of the left bank at the ends of riprap structure, see SECTION A-A of Figure 1, ft/ft

ZR $\equiv$ Side slope of the right bank (looking downstream) at the ends of riprap structure, ft/ft

ZS $\equiv$ Side slope of trapezoidal section at the ends of riprap structure, ft/ft

ZU $\equiv$ Side slope of the prismatic channel of the riprap structure, ft/ft

γ $\equiv$ Unit weight of water, lb/ft^3

θ $=$ THETA $\equiv$ Angle of repose of the riprap, degrees

τ $\equiv$ Tractive stress, lb/ft^2

τ_{av} $= \gamma rs$ $\equiv$ The average tractive stress, lb/ft^2

τ_{ba} $= \frac{\tau_{bc}}{FS}$ $\equiv$ The allowable tractive stress for the riprap lining on the bottom of the trapezoidal channel, lb/ft^2

τ_{bc} $= C_{50}\ D_{50}$ $\equiv$ The critical tractive stress for the riprap lining on the bottom of the trapezoidal channel, lb/ft^2

τ_{bm} $\equiv$ The maximum tractive stress along the riprap lining on the bottom of the trapezoidal channel, lb/ft^2

τ_{sa} $= K\ \tau_{ba}$ $\equiv$ The allowable tractive stress for the riprap lining on the side slope of the trapezoidal channel, lb/ft^2

τ_{sc} $= K\ \tau_{bc}$ $\equiv$ The critical tractive stress for the riprap lining on the side slope of the trapezoidal channel, lb/ft^2

τ_{sm} $\equiv$ The maximum tractive stress along the riprap lining on the side slope of the trapezoidal channel, lb/ft^2

TECHNICAL RELEASE
NUMBER 59

HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

Introduction

In some cases a riprap gradient control structure can be used economically to dissipate excess energy and establish a stable gradient in a channel where the gradient without some such control would be too steep and would cause erosive velocities.

The riprap gradient control structure discussed herein consists of a riprap prismatic channel with a riprap transition at each end (see Figure 1). Its essential feature is that the specific energy of the flow at design discharge is constant throughout the structure and is equal to the specific energy of the flow in the channel immediately upstream and downstream of the structure. Thus, for the design discharge, the dissipation of hydraulic energy in the structure is at the same rate as the energy gain due to the gradient. The structure, which is made steeper and narrower than the adjoining channel upstream and downstream, maximizes energy dissipation.

For brevity, riprap gradient control structures will be referred to in this technical release as riprap structures or simply as structures. All channels and structures considered in this technical release have trapezoidal cross sections and subcritical slopes.

Report 108

The National Cooperative Highway Research Program Report 108[1] entitled "Tentative Design Procedure for Riprap-Lined Channels" presents the analyses of experimental results, development of criteria, and design procedures for the stability of riprap linings. Hereafter, this publication is referred to as Report 108. It contains information useful in the design of trapezoidal channels constructed in noncohesive sand and gravel materials and of riprap linings which form the boundary of channels and gradient control structures. Report 108 also presents criteria and recommendations for riprap layer thicknesses and for required filters. Report 108 states that laboratory experimental studies on linings designed in accordance with its procedures showed the linings did not fail until discharges reached values in excess of the design discharges.

St. Anthony Falls Hydraulic Laboratory Project Report No. 146 entitled "Tentative Design Procedures for Riprap-Lined Channels - Field Evaluation" by Alvin G. Anderson, June, 1973, for National Cooperative Highway Research Program, presents the results of field evaluation studies of four constructed riprap-lined channels designed in accordance with the procedures contained in Report 108. The studies showed that all four channels were performing satisfactorily, and two of the channels were without signs of erosion after having been subjected to discharges that approach the design discharges.

[1] Publication of the Transportation Research Board, National Research Council, National Academy of Sciences - National Academy of Engineering, 1970

Purpose of Technical Release

The purpose of this technical release is to present procedures for the design and proportioning of riprap gradient control structures. These procedures can also be used to obtain a riprap channel design. This technical release also documents the criteria and procedures used in the associated computer program.

Computer Program

A computer program, written in FORTRAN for IBM equipment, determines dimensions and parameters associated with the design of a riprap gradient control structure. The program operates in any of four modes. Mode 1 obtains only the design of a riprap prismatic channel. Modes 2, 3, and 4 obtain the design of a riprap structure including the prismatic channel and both transitions of the structure. Modes 3 and 4 permit greater flexibility of design.

Input and output data information is discussed under the "Computer Program" section. Computer design runs may be obtained by request to

Head, Design Unit
Engineering Division
Soil Conservation Service
Federal Center Building
Hyattsville, Maryland 20782.

Riprap Gradient Control Structure

A riprap gradient control structure is a riprap structure consisting of a prismatic channel with a converging inlet transition at the upstream end and a diverging outlet transition at the downstream end of the prismatic channel. The riprap structure as designed should have essentially a straight alignment as shown in Figure 1.

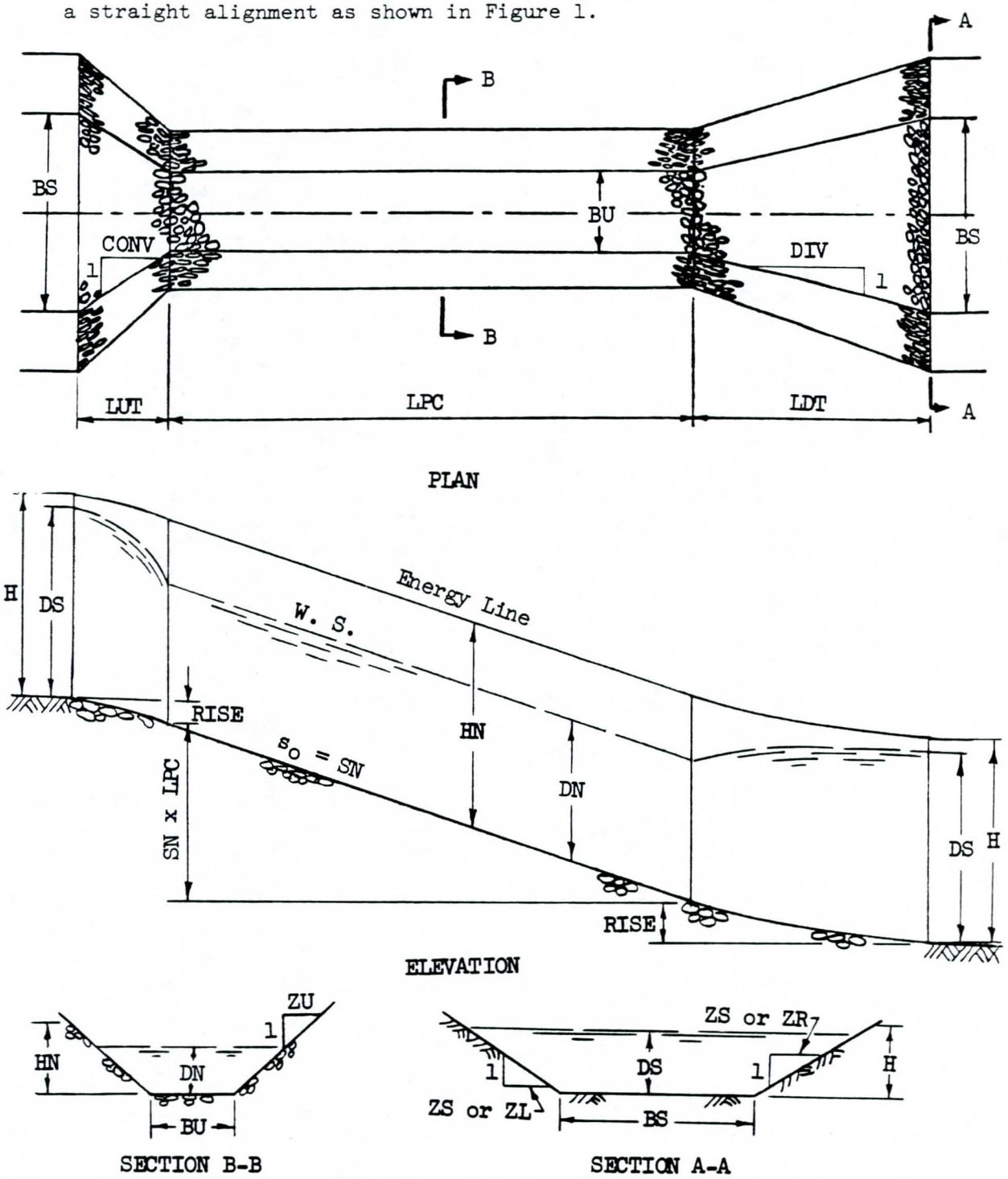


Figure 1. Riprap gradient control structure

Riprap Structure Concept

The following discussion on energy dissipation will assist in the understanding of the principles used in the development of the riprap structure concept and the reason for designing it to maintain a constant specific energy head.

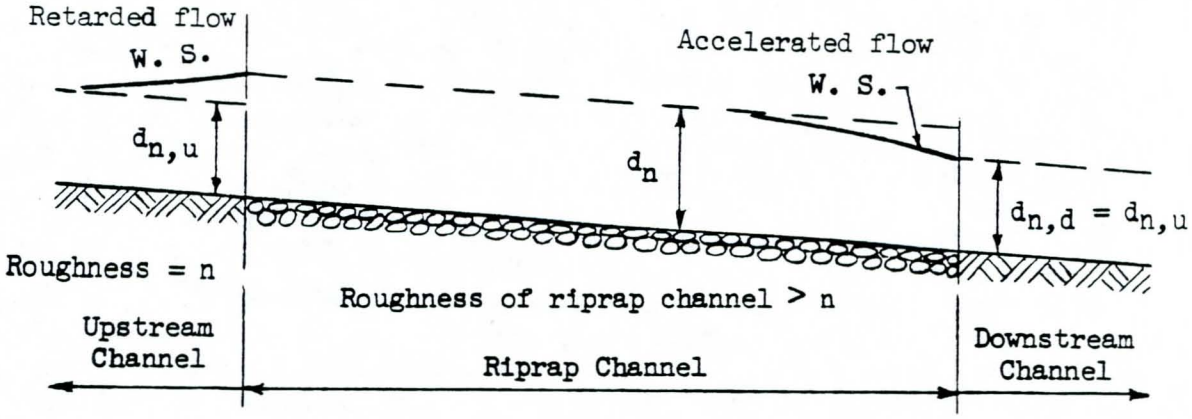
In a system of channels having mild slopes, i.e., flows are subcritical, the depth of flow for a given discharge is physically fixed by the downstream characteristics of the channel system and upstream characteristics have no effect on this depth. Since flows are subcritical, water surface profile computations are usually required for the channel downstream of the riprap prismatic channel or structure. These water surface profile computations evaluate the starting depth at the downstream end of the structure. For the purpose of stability analyses, the lowest probable starting depth corresponding to the discharge should always be used.

Consider a riprap channel and its adjoining upstream and downstream earth channels, all having the same dimensions and bottom slopes, but the riprap channel having a larger coefficient of roughness. Since the normal depth corresponding to a discharge, Q, in a prismatic channel is a function of the side slope, z, bottom slope, s_o, bottom width, b, and Manning's coefficient of roughness, n, the normal depth of the riprap channel will be greater than the normal depth of its adjoining channels. (See Figure 2a.) If the bottom slope of the riprap channel is increased sufficiently, the normal depth of the riprap channel, d_n, will be less than that of its adjoining channels. If the depth at the junction of the riprap channel and its adjoining channel downstream is equal to the normal depth of the downstream channel, $d_{n,d}$, then flow just upstream in the riprap channel is retarded flow. (See Figure 2b.) Thus the rate of friction loss is less than the bottom slope, and the velocity is increasing and the specific energy head is decreasing in the upstream direction. The maximum tractive stresses occur at the junction of the riprap channel and its adjoining upstream channel. The velocity may become so great that the upstream channel is unstable. In this situation the riprap roughness has not been used efficiently to dissipate energy.

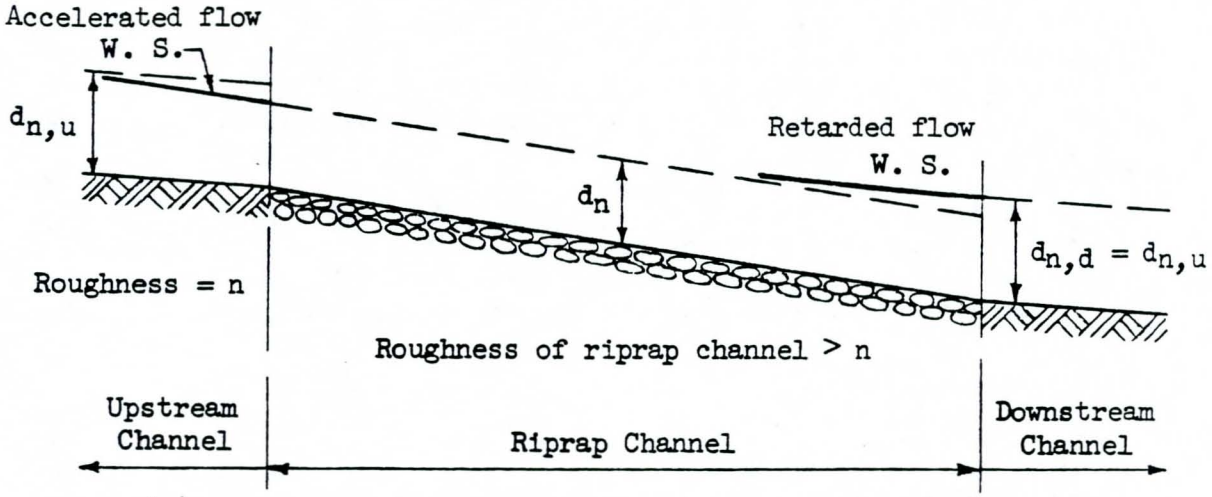
If the bottom slope of the riprap channel is adjusted such that the normal depth of the riprap channel equals the normal depth of the adjoining channels, the flow is uniform. Therefore, the rate of friction loss in the riprap channel is equal to its bottom slope and energy is dissipated uniformly. In this situation the riprap roughness is used more efficiently to dissipate energy. Furthermore, the specific energy head at the upstream end of the structure is equal to that at the downstream end. This is more compatible with a stable design of the upstream channel.

However, often the bottom slope of the riprap channel can be increased and the bottom width narrowed from a width, BS, to a width, BU, such that the specific energy head at normal depth in the riprap channel equals the specific energy head at the junction of the riprap channel and the downstream channel. Then the rate of friction loss in the riprap channel equals its bottom slope, s_n. Since the bottom slope is increased and the rate of friction loss equals the bottom slope, more energy dissipation is obtained in the same length of riprap channel. Thus, the riprap roughness is used more efficiently than in any of the previously considered riprap channels.

Also, since the bottom slope is increased and the bottom width is decreased, less riprap is required. Of course, when the riprap channel has been narrowed to the width BU < BS, transitions of sufficient length are required to convert potential energy to kinetic energy, and vice versa, with acceptable distribution of velocities. This reasoning leads directly to the riprap structure shown in Figure 1.



(a). Riprap channel and its adjoining channels have same bottom slope and bottom width



(b). Riprap channel has the same bottom width but steeper bottom slope than its adjoining channels

Figure 2. Development of riprap structure concept

Hydraulic Design of Structure

The design procedures for stability in this technical release have been confined to clear water flows. The conveyance of bed loads presents a much more complex set of considerations. In the general stability problem involving bed loads, the channel is designed for both clear water and bed load flows; each design fulfilling the capacity and stability requirements. Thus, such a design requires that the capacity of the channel be sufficient in the fully aggraded state. In addition, the design requires that the banks will not slough, erode, or silt laterally and the bed will not aggrade or degrade beyond the design limits. Design for only clear water flows implies that the greatest degraded condition has occurred and that a certain amount of sediment may be carried in suspension, but there will be no future deposition of sediment to cause aggradation on the bed or banks.

Design Discharge

For purposes of this technical release, design discharge means the largest discharge for which stability of the channel or structure is required. The design discharge is assumed to be wholly within the banks of the structure. The design discharge of the riprap structure is the same as the design discharge used in evaluating the stability of the channel at both ends of the structure.

Usually, structures that are stable for the design discharge will also be stable for all discharges less than the design discharge. However, if the structure tailwater decreases very rapidly with small decreases in discharge, theoretically discharges less than the design discharge may cause higher tractive stresses than the design discharge. In this case the lesser discharge would actually control the design. Thus where tailwater changes very rapidly with respect to discharge, designs should be obtained for the design discharge and several lesser discharges.

If a discharge occurs which is greater than the design discharge, the structure may not function properly. Therefore, it is important that the design discharge, Q, be selected sufficiently large to minimize the possibility of extensive damage during the design life of the channel and structure.

Specific Energy Head

When the bottom slope is subcritical, the normal depth is greater than critical depth. If the depth of flow is normal, then the rate of friction loss is equal to the bottom slope. This implies that all energy gained by virtue of the drop through the riprap structure is dissipated by friction losses. Normal or uniform flow may be characterized as flow at a constant specific energy head. Specific energy head is given by

$$H = d + \frac{v^2}{2g} = d + \frac{Q^2}{2ga^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Observe that a channel not flowing at critical depth has two depths corresponding to the same specific energy head; one depth is subcritical and the other is supercritical. All intervening depths have a smaller specific

energy head. Therefore, if flow in the channel downstream of the structure is subcritical, supercritical flow cannot occur anywhere in the riprap structure if the structure maintains constant specific energy head and slopes are subcritical.

Manning's Roughness Coefficient

The predetermination that a riprap channel will flow at a constant specific energy head for a given discharge requires a careful evaluation of Manning's coefficient of roughness, n, for the channel and also the careful establishment of the tailwater elevation at the downstream end of the structure. The coefficient of roughness, n, for riprap has been experimentally evaluated as

$$n = C_n(D_{50})^{EXPN} \quad \ldots \quad (2)$$

where (from Report 108) $C_n = 0.0395$
$EXPN = 1/6$

Maximum Slope of Prismatic Channel

When the bottom slope of a channel is near the critical slope corresponding to a particular discharge, flow in the channel at this discharge is considered unstable, i.e., the depth of flow at a section is unpredictable because the depth fluctuates rapidly with any change in boundary condition. For this reason the prismatic channel bottom slope, s_n, is set equal to or less than 0.7 of the critical slope, s_c. The bottom slope, s_n, will be expressed as a fraction of the critical slope, i.e.,

$$s_n = CS(s_c) \quad \ldots \quad (3)$$

where $0 < CS \leq 0.7$

Prismatic Channel

The depth of flow in the prismatic channel of the riprap structure is set equal to the normal depth corresponding to the design discharge, Q. Therefore, the dissipation of hydraulic energy is at the same rate as the energy gain due to the gradient. The specific energy head, H, at every section of the riprap structure is set equal to the specific energy head of the downstream channel at the junction of the downstream transition and the downstream channel, Section A-A of Figure 1.

The following development shows that there is a unique prismatic channel bottom width which will meet the above requirement for a given set of values of Q, H, z, and CS. However, this theoretical procedure is not used directly in the computer program due to its obvious complexity. Instead, a procedure involving a series of iterations is used as outlined in the "Computer Program" section.

The discharge, Q, flowing at normal depth, d_n, in a channel of bottom width, b, and bottom slope, s_n, where $s_n = CS(s_c)$, is from Manning's formula

$$Q^2 = \left[\frac{1.486}{n}\right]^2 \frac{a_n^{10/3}}{p_n^{4/3}} CS(s_c) \quad \ldots \quad (4)$$

The discharge, Q, flowing at normal depth $d_n = d_c$, in a channel of bottom width, b, and bottom slope, s_c, is

$$Q^2 = \left[\frac{1.486}{n}\right]^2 \frac{a_c^{10/3}}{p_c^{4/3}} s_c \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Equating equations (4) and (5)

$$\frac{a_c^{10/3}}{p_c^{4/3}} = \frac{a_n^{10/3}}{p_n^{4/3}} \text{ CS} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Let $x_c = \frac{d_c}{b}$, $x_n = \frac{d_n}{b}$, and z = the side slope of a trapezoidal section, and expand equation (6)

$$\frac{b^{20/3}\left[(1 + z\, x_c)x_c\right]^{10/3}}{b^{4/3}\left[1 + 2x_c\sqrt{z^2 + 1}\right]^{4/3}} = \frac{b^{20/3}\left[(1 + z\, x_n)x_n\right]^{10/3}}{b^{4/3}\left[1 + 2x_n\sqrt{z^2 + 1}\right]^{4/3}} \text{ CS}$$

or

$$\frac{\left[(1 + z\, x_c)x_c\right]^{10}}{(1 + 2x_c\sqrt{z^2 + 1})^4} = \frac{\left[(1 + z\, x_n)x_n\right]^{10}}{(1 + 2x_n\sqrt{z^2 + 1})^4} (\text{CS})^3 \quad \ldots\ldots \quad (7)$$

Equation (7) gives the relation of the critical depth, d_c, and normal depth, d_n, of a channel having a bottom slope, $s_o = s_n = \text{CS}(s_c)$. Observe that the relation is independent of Manning's n value. The functional relationship of equation (7) is:

$$x_n = f(x_c, z, \text{CS}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7a)$$

The discharge, Q, corresponding to the critical depth, d_c, is

$$Q^2 = g\,\frac{a_c^3}{T_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

again let $x_c = \frac{d_c}{b}$ and expand equation (8)

$$\frac{Q^2}{b^5} = \frac{g\left[(1 + z\, x_c)x_c\right]^3}{(1 + 2z\, x_c)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

or

$$x_c = f_1\left[\frac{Q}{b^{5/2}}, z\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9a)$$

From equations (7a) and (9a) and for a given value of CS

$$x_n = f_2\left[\frac{Q}{b^{5/2}}, z\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

The specific energy head, H, in the riprap structure is

$$H = d_n + \frac{Q^2}{2g}\frac{1}{a_n^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

dividing by b, expanding, and letting $x_n = \frac{d_n}{b}$

$$\frac{H}{b} = \frac{d_n}{b} + \frac{Q^2}{2g\ a_n^{\ 2}\ b} = x_n + \frac{Q^2}{b^5}\left[\frac{1}{2g\left[(1 + z\ x_n)\ x_n\right]^2}\right] \quad . . . \quad (12)$$

or

$$\frac{H}{b} = f_3\left[\frac{Q}{b^{5/2}},\ z,\ x_n\right] \quad . . . . . \quad (12a)$$

From equations (10) and (12a) and for a given value of CS

$$\frac{H}{b} = f_4\left[\frac{Q}{b^{5/2}},\ z\right] \quad . . . . . \quad (13)$$

Rearranging equation (12)

$$\frac{Q^2}{b^5} = \left[2g(\frac{H}{b} - x_n)\right]\left[(1 + z\ x_n)x_n\right]^2$$

Taking the square root and multiplying by $\left[\frac{b}{H}\right]^{5/2}$

$$\frac{b^{5/2}}{H^{5/2}}\ \frac{Q}{b^{5/2}} = \frac{Q}{H^{5/2}} = \left[2g\ (\frac{H}{b} - x_n)\right]^{1/2}\left[(1 + z\ x_n)x_n\right]\left[\frac{b}{H}\right]^{5/2}$$

$$\frac{H}{b} = f_5\left[\frac{Q}{H^{5/2}},\ z,\ x_n\right] \quad . . . . . \quad (14)$$

Repeating equations (10) and (13)

$$x_n = f_2\left[\frac{Q}{b^{5/2}},\ z\right]$$

$$\frac{H}{b} = f_4\left[\frac{Q}{b^{5/2}},\ z\right]$$

Thus, for a given value of CS

$$x_n = f_6(\frac{H}{b},\ z) \quad . . . . . \quad (15)$$

Combining equations (14) and (15)

$$\therefore\ \frac{H}{b} = f_7\left[\frac{Q}{H^{5/2}},\ z\right] \quad . . . . . \quad (16)$$

Thus, for a given design discharge, Q, flowing at normal depth, d_n, and for given values of H, z, and CS, there exists one unique bottom width, b. However, it should be noted that a solution is not always possible.

The relation given in equation (16) is independent of the value of the parameter D_{50}. However, the critical slope, s_c, depends on the value of n, and n is a function of D_{50} since from equation (2), $n = C_n(D_{50})^{1/6}$. Therefore, the slope of the prismatic channel, s_n, depends on the D_{50} size of the riprap.

Thus, from equation (5)

$$s_c = \frac{n^2 Q^2}{1.486^2} \frac{p_c^{4/3}}{a_c^{10/3}} = \frac{C_n^2 D_{50}^{1/3} Q^2}{1.486^2} \frac{p_c^{4/3}}{a_c^{10/3}} \quad . . . . . \quad (17)$$

or

$$\frac{s_c}{D_{50}^{1/3}} = \left[\frac{C_n Q}{1.486}\right]^2 \frac{p_c^{4/3}}{a_c^{10/3}} = \left[\frac{C_n Q}{1.486}\right]^2 \frac{\left[b(1 + 2x_c \sqrt{z^2 + 1})\right]^{4/3}}{\left[b^2 x_c(1 + z x_c)\right]^{10/3}}$$

or

$$\frac{s_c}{D_{50}^{1/3}} = \left[\frac{C_n}{1.486}\right]^2 \frac{Q^2}{b^5} \left[\frac{(1 + 2x_c\sqrt{z^2 + 1})^{4/3}}{b^{1/3}\left[x_c(1 + z x_c)\right]^{10/3}}\right] . . . \quad (18)$$

and from equation (3), $s_n = CS(s_c)$

Transitions

The function of a transition is to convert potential energy to kinetic energy, or vice versa, in such a manner that an acceptable velocity distribution is provided. Generally, transitions are designed to avoid excessive energy losses in the flows they convey. This function is contrary to the goal of the designer of transitions for these gradient control structures. However, the design for either function leads to the same basic proportioning of the transition.

Converging inlet transitions located at the upstream end of the riprap structures are designed with a rate of convergence of the bottom width, CONV. The length of the upstream transition, LUT, is equal to $\text{CONV}\left[\frac{BS - BU}{2}\right]$. The inlet transition conveying the design discharge, Q, at subcritical flow, converts potential energy to kinetic energy. The velocity increases and the depth decreases in the direction of flow. See Figure 1.

Diverging outlet transitions located at the downstream end of the riprap structures are designed with a rate of divergence of the bottom width, DIV. The length of the downstream transition, LDT, is equal to $\text{DIV}\left[\frac{BS - BU}{2}\right]$. Flows in diverging transitions are expanding. If the rate of divergence is too rapid, the expanding flows tend to separate from the boundary and an uneven velocity distribution may occur. Therefore, a long transition is required to ensure an acceptable velocity distribution. The outlet transition converts kinetic energy to potential energy, and the velocity decreases and depth increases in the direction of flow.

The transitions associated with the riprap structure are designed to convey the design discharge, Q, throughout the transitions at a constant specific energy head, H. To maintain a constant H when the bottom width is changing requires that the bottom slope of the transition be variable, changing from the slope of the riprap prismatic channel to flatter slopes at the upstream and downstream ends of the structure. The instantaneous bottom slope at any section of the transition is equal to the rate of friction head loss at that section when the design discharge, Q, is flowing at normal depth, d_n, and at the design specific energy head, H.

The bottom width of the transition, b_j, varies linearly from BS to BU through the length of transition, LT. The side slope, z, also varies linearly from ZS to ZU through the length, LT. Thus, at a particular section, j, of the transition

$$b_j = BU + J(BS - BU) \quad \text{and}$$

$$z = ZU + J(ZS - ZU)$$

where

$$J = \frac{\text{Distance in the transition from section j to section of width BU}}{LT}$$

Thus at a section j the constant specific energy head, H, is

$$H = d + \frac{Q^2}{2g\left[(b_j + zd)d\right]^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

The rate of energy loss, s, at section j of the transition having a bottom slope, s_o, and conveying the design discharge, Q, at normal depth, d_n, is

$$s = s_o\left[\frac{Q}{Q_{n,d}}\right]^2 = \frac{Q^2\, n^2\, p_n^{4/3}}{(1.486)^2\, a_n^{10/3}} \quad \ldots\ldots\ldots\ldots\ldots \quad (20)$$

where

$$p_n = b_j + 2d_n\sqrt{z^2 + 1}$$

$$a_n = (b_j + zd_n)d_n$$

The bottom slope of the transition at section j is equal to the energy slope, s.

Conversion losses in the transitions are not considered in the design of the riprap structure since a more conservative design of the structure is obtained by ignoring these losses. If the conversion losses were considered, the depth of flow in the structure would be increased slightly, the velocity decreased, and the tractive stress decreased. However, the conversion losses may be significant in the determination of an upper limit for the water surface profile upstream of the riprap structure, particularly where structures are used in series and some accumulation of conversion losses may occur.

The approximate conversion losses are given in the computer output following the riprap structure design. The equations used to determine the conversion losses are taken from Henderson[2]

$$\text{Conversion head loss in diverging transition} = \frac{0.3(VN-VS)^2}{2g}$$

$$\text{Conversion head loss in converging transition} = \frac{C(VN)^2}{2g}$$

$$\text{When } \frac{DN}{BU} \leq 1.0 \;; \quad C = 0.04$$

$$\frac{DN}{BU} \geq 1.3 \;; \quad C = 0.11$$

In the computer program when $1.0 < \frac{DN}{BU} < 1.3$, the coefficient, C, varies linearly from 0.04 to 0.11.

[2]F. M. Henderson. "Open Channel Flow" (The MacMillan Company, New York; Collier-MacMillan, Canada, LTD., Toronto, Ontario, 1966), p. 237-238.

Design of Riprap

Riprap as used in this technical release consists of loose rocks or granulars of rock having a unit weight of approximately 165 lbs/ft^3. The individual rocks or granulars have no cohesive property nor are they cemented. The experimental results in Report 108 show the D_{50} size of the riprap varying approximately within the interval:

$$3.3 \times 10^{-4} \text{ ft} (\approx 0.1 \text{ mm}) \leq D_{50} \leq 1.0 \text{ ft } (\approx 305 \text{ mm})$$

where

$D_{50} \equiv$ Size of rock in riprap of which 50 percent by weight is finer, ft.

Thus, channels constructed in granular noncohesive materials of sufficient size, such as loose sands and gravels, may be designed using the same procedures used for riprap channels.

The riprap is designed to prevent significant movement of the rock when the structure is conveying the design discharge, Q. The stability design is accomplished by providing

1. riprap of sufficient size that no significant movement of the individual rocks or particles occurs due to the tractive stresses caused by the flow and

2. riprap lining of sufficient thickness or the combination of riprap lining and filter layer to prevent leaching.

The following discussion defines the critical and allowable tractive stresses as related to riprap D_{50} size and describes how to obtain the values of the actual maximum tractive stress on the sides and bottom of a prismatic channel. Then, the criteria for determining the minimum acceptable riprap size is given along with other riprap requirements.

Critical Tractive Stress

The critical tractive stress is that tractive stress which initiates movement of the riprap. For a given riprap size, the tractive stress required to initiate movement is less for riprap placed on the side slopes of a trapezoidal channel than for riprap placed on the bottom of the channel. The critical tractive stress for riprap on the bottom of the channel, τ_{bc}, as obtained from experimentation is approximately a linear function of the riprap size, D_{50}.

$$\tau_{bc} = C_{50} D_{50} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

where $C_{50} = 4.0$ (from Report 108)

Riprap placed on the side slopes of a trapezoidal channel is subjected to the gravitational force, which tends to pull the riprap down the side slope, in addition to the tractive stress caused by the flow. The critical tractive stress for riprap placed on the side slope of the trapezoidal channel, τ_{sc}, being somewhat less than τ_{bc}, is set equal to K times τ_{bc}. The coefficient, K, depends chiefly on the angle of repose, θ, of the riprap and the side slope, z, on which the riprap is placed. The angle of repose depends on the size, angularity, and shape of the riprap. Approximate values of the angle of repose are given by Figure 16 in Report 108. The relation of K, θ, and z is often taken as

$$K = \frac{\tau_{sc}}{\tau_{bc}} = \sqrt{1 - \frac{\sin^2 (\cot^{-1} z)}{\sin^2 \theta}} \quad \ldots\ldots\ldots\ldots\ldots (22)$$

The critical tractive stress for riprap placed on a side slope becomes

$$\tau_{sc} = K\, \tau_{bc} = K\, C_{50}\, D_{50} \quad \ldots\ldots\ldots\ldots\ldots (23)$$

Allowable Tractive Stress

As with many engineering calculations, a factor of safety, FS, is applied to determine the allowable tractive stress. The allowable tractive stress is obtained by dividing the critical tractive stress by the factor of safety. Thus, the allowable tractive stress for the channel bottom, τ_{ba}, and for the side slopes, τ_{sa}, becomes

$$\tau_{ba} = \frac{C_{50}\, D_{50}}{FS} \quad \ldots\ldots\ldots\ldots\ldots (24)$$

$$\tau_{sa} = \frac{K\, C_{50}\, D_{50}}{FS} \quad \ldots\ldots\ldots\ldots\ldots (25)$$

Average Tractive Stress

The average tractive stress, τ_{av}, may be analytically ascertained by the assumption that all frictional losses are caused by frictional forces on the boundary of the riprap lining. This frictional force, F_f, acting on a moving body of water in a direction opposite to that of the flow is shown in Figure 3.

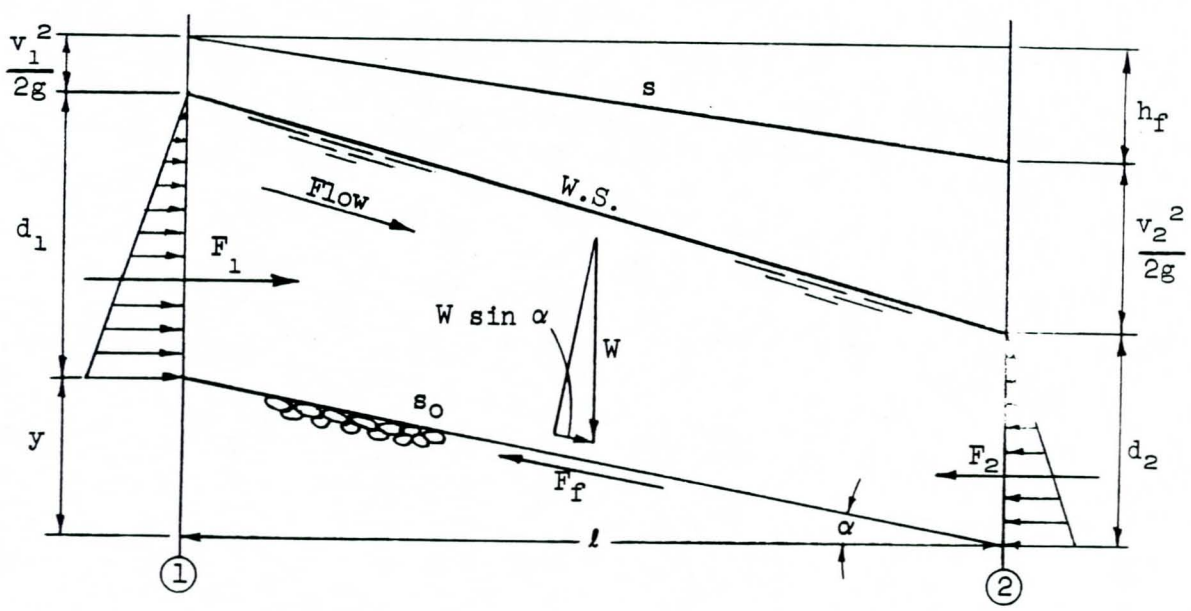


Figure 3. Forces acting on a moving body of water

Assumptions; $\sin\alpha = \tan\alpha = s_o$ and $\cos\alpha = 1$

$$F_1 = \frac{\gamma\, b_a\, d_1^{\,2}}{2}$$

$$F_2 = \frac{\gamma\, b_a\, d_2^{\,2}}{2}$$

$$\text{average velocity, } v_a = \frac{v_1 + v_2}{2}$$

$$\text{average flow area, } a_a = b_a\left(\frac{d_1 + d_2}{2}\right)$$

where

v_1 and v_2 ≡ average velocity at Sections 1 and 2 respectively
b_a ≡ average width of the channel

From Newton's second law of motion

$$F = M\frac{dv}{dt}$$

Where from Figure 3;

$M = \frac{\gamma\, Qdt}{g}$ ≡ mass of body of water between Sections 1 and 2

dt ≡ time interval for flow to move from Section 1 to Section 2

dv ≡ the change in velocity of flow between Section 1 and Section 2

$F = F_1 - F_2 + \cos\alpha(W\sin\alpha - F_f)$ ≡ Summation of all horizontal forces acting on the body of moving water

$$F = F_1 - F_2 + W\, s_o - F_f = \frac{\gamma\, Qdt}{g}\left(\frac{v_2 - v_1}{dt}\right)$$

$$F_f = F_1 - F_2 + W\, s_o + \frac{\gamma Q(v_1 - v_2)}{g} \quad \ldots\ldots\ldots\ldots \quad (26)$$

The energy loss in ft-lb per pound of water between sections 1 and 2 is equal to $F_f\ell$ divided by the weight of water, W,

or

$$\frac{F_f\ell}{W} = \frac{F_f\, v_a\, dt}{\gamma\, Q\, dt} = \frac{F_f}{\gamma\, a_a}$$

Substitute the values of F_1, F_2, and $W\, s_o$ into Equation (26) and divide by $\gamma\, a_a$

$$\frac{F_f}{\gamma\, a_a} = \frac{\gamma\, b_a}{2\gamma\, a_a}(d_1^{\,2} - d_2^{\,2}) + \frac{\gamma\, Q\, dt}{\gamma\, a_a}\frac{y}{\ell} + \frac{\gamma\, Q}{\gamma\, a_a\, g}(v_1 - v_2)$$

$$\frac{F_f}{\gamma\, a_a} = b_a\frac{(d_1 + d_2)}{2}\frac{(d_1 - d_2)}{a_a} + v_a\, dt\,\frac{y}{\ell} + v_a\left(\frac{v_1 - v_2}{g}\right)$$

$$\frac{F_f}{\gamma\, a_a} = a_a\frac{(d_1 - d_2)}{a_a} + \frac{\ell y}{\ell} + \frac{(v_1 + v_2)}{2}\frac{(v_1 - v_2)}{g}$$

$$\frac{F_f}{\gamma\, a_a} = d_1 - d_2 + y + \frac{v_1^{\,2} - v_2^{\,2}}{2g} \quad \ldots\ldots\ldots\ldots \quad (27)$$

From Bernoulli's equation of conservation of energy, the total energy at Section 1 is equal to the total energy at Section 2 plus the energy loss between Sections 1 and 2; refer to Figure 3.

$$y + d_1 + \frac{v_1^2}{2g} = d_2 + \frac{v_2^2}{2g} + h_f$$

$$h_f = d_1 - d_2 + y + \frac{v_1^2 - v_2^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots \quad (28)$$

$\therefore \; h_f = \dfrac{F_f}{\gamma\, a_a} \equiv$ total energy loss between Sections 1 and 2 in ft-lb per pound of water

or

$$F_f = \gamma\, a_a\, h_f$$

The average tractive stress, τ_{av}, in pounds per unit area, on the boundary of the riprap lining is equal to F_f divided by $p\ell$

$$\tau_{av} = \frac{F_f}{p\ell} = \gamma\, \frac{a}{p}\, \frac{h_f}{\ell} = \gamma\, rs \quad \ldots\ldots\ldots\ldots\ldots \quad (29)$$

where $\gamma \equiv$ Unit weight of water = 62.4 lb/ft^3

$r = \dfrac{a}{p} \equiv$ Hydraulic radius, ft

$a \equiv$ Flow area, ft^2

$p \equiv$ Wetted perimeter of riprap lining, ft

$s = s_o\left(\dfrac{Q}{Q_{n,d}}\right)^2 \equiv$ Rate of friction loss, ft/ft

Distribution of Tractive Stress

Tractive stresses are not uniformly distributed along the boundary of the riprap lining, see Figure 4. The maximum tractive stress depends on

1. the ratio of the bottom width, b, to the depth of flow, d, and
2. the side slope of the channel, z.

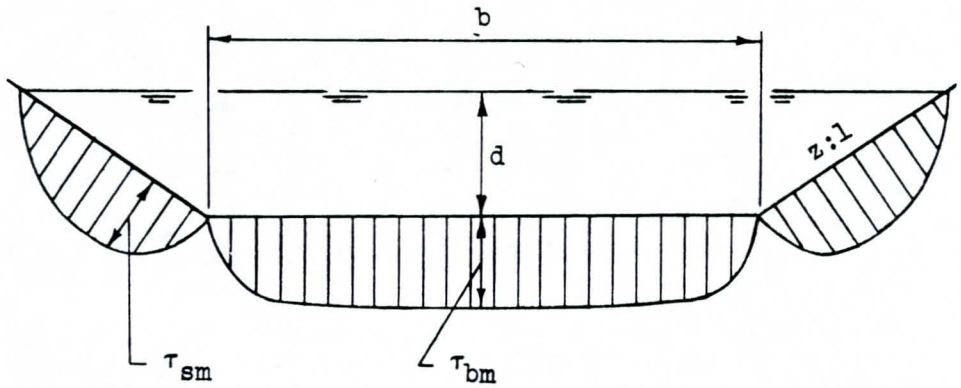


Figure 4. Distribution of tractive stress along the wetted perimeter of a riprap lining

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Usually the maximum tractive stress is on the bottom of the riprap section. For small values of $\frac{b}{d}$, the maximum tractive stress is on the side slopes of the riprap section, see Figures 5 and 6. These figures, obtained from Report 108, give the values of $C_{\tau s} = \frac{\tau_{sm}}{\tau_{av}}$ and $C_{\tau b} = \frac{\tau_{bm}}{\tau_{av}}$, respectively. τ_{sm} is the maximum tractive stress along the riprap lining on the side slopes of the channel and τ_{bm} is the maximum tractive stress along the riprap lining on the bottom of the trapezoidal section.

Minimum Acceptable Riprap Size

The minimum acceptable riprap size is determined from one of the following two criteria, whichever controls:

1. the maximum tractive stress along the bottom, τ_{bm}, must be equal to or less than the allowable tractive stress for the riprap on the bottom

$$\tau_{bm} \leq \tau_{ba}$$

where

$$\tau_{bm} = C_{\tau b}\ \gamma\ r\ s$$

$$\tau_{ba} = \frac{C_{50}\ D_{50}}{FS}$$

2. the maximum tractive stress along the sides, τ_{sm}, must be equal to or less than the allowable tractive stress for the riprap on the sides.

$$\tau_{sm} \leq \tau_{sa}$$

where

$$\tau_{sm} = C_{\tau s}\ \gamma\ r\ s$$

$$\tau_{sa} = \frac{K\ C_{50}\ D_{50}}{FS}$$

Thus, to prevent movement of the individual rocks or particles by the tractive stress caused by the flow, the above two conditions must be satisfied at every section in the riprap structure.

Riprap Gradation

The riprap gradation should yield a smooth size distribution curve and the riprap should not be skip graded. The recommended Gradation Index evaluated from the distribution curves for the materials used in the channel stability experiments of Report 108 is

$$\text{Gradation Index} = \left[\frac{D_{85}}{D_{50}} + \frac{D_{50}}{D_{15}}\right] \leq 5.5$$

The riprap gradation affects the required thickness of riprap lining. For well graded riprap, the interstices between larger rocks are filled with smaller rocks; thus the leaching potential is reduced and the required riprap lining thickness is smaller than that for a more uniformly graded riprap. Therefore, as the gradation index increases, the riprap lining thickness may be decreased.

Filter

Leaching is the process by which the finer base materials beneath the riprap are picked up and carried away by the turbulence that penetrates the interstices of the riprap. Leaching is reduced to a negligible rate by using a properly designed filter under the riprap or by making the riprap layer thick enough and with fine enough interstices to keep erosive currents away from underlying soil.

Report 108 recommends the use of a filter layer if the following criteria are not met:

$$\frac{D_{15}\ \text{Riprap}}{D_{85}\ \text{Base}} < 5 < \frac{D_{15}\ \text{Riprap}}{D_{15}\ \text{Base}} < 40$$

$$\frac{D_{50}\ \text{Riprap}}{D_{50}\ \text{Base}} < 40$$

where D_{15}, D_{50}, and D_{85} are the sizes of riprap and base material of which 15, 50, and 85 percent are finer by weight.

Thickness of Riprap Lining

The required thickness of the riprap lining is based largely on experience. Construction techniques, discharge, size of channel, sizes and gradation of riprap, etc., should be taken into consideration when determining the thickness of riprap lining. The following three criteria for thickness of riprap lining have been suggested:

1. a thickness of three times the D_{50} size if a filter layer is not used
2. a thickness of one and a half to two times the D_{50} size if a filter layer is used
3. a thickness at least one and a half times the maximum particle size if a filter layer is used.

Riprap Quantity in Prismatic Channel

The wetted perimeter, p_n, and bottom slope, s_n, associated with the design of a riprap structure affect the quantity of riprap. For a given design and amount of gradient control required in the prismatic channel, the least amount of riprap is obtained when the value of $\frac{p_n}{s_n}$ is minimum. A side slope, ZU, in the range of 2, 2.5, or 3 usually yields a minimum value of $\frac{p_n}{s_n}$.

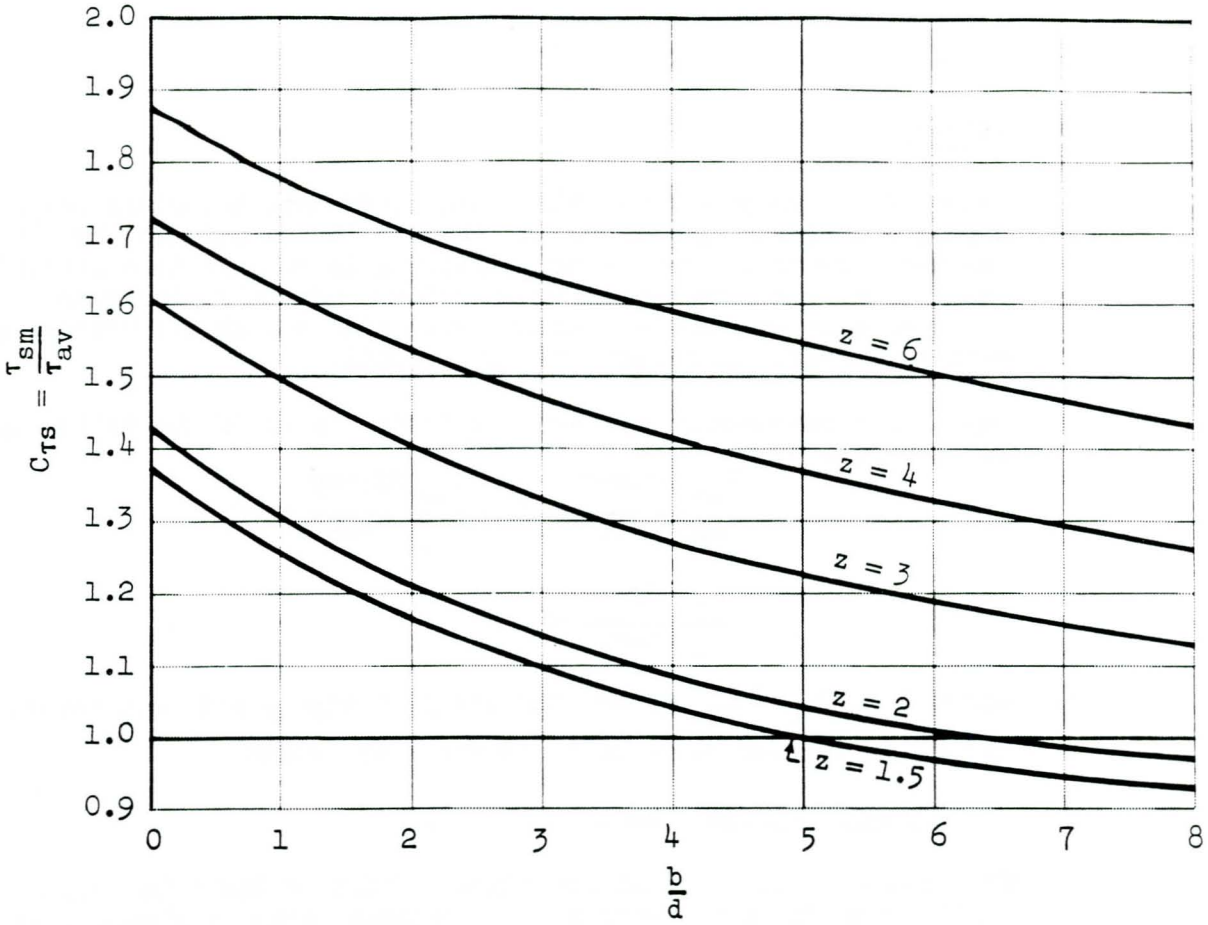

Figure 5. Maximum tractive stress on sides of trapezoidal channels

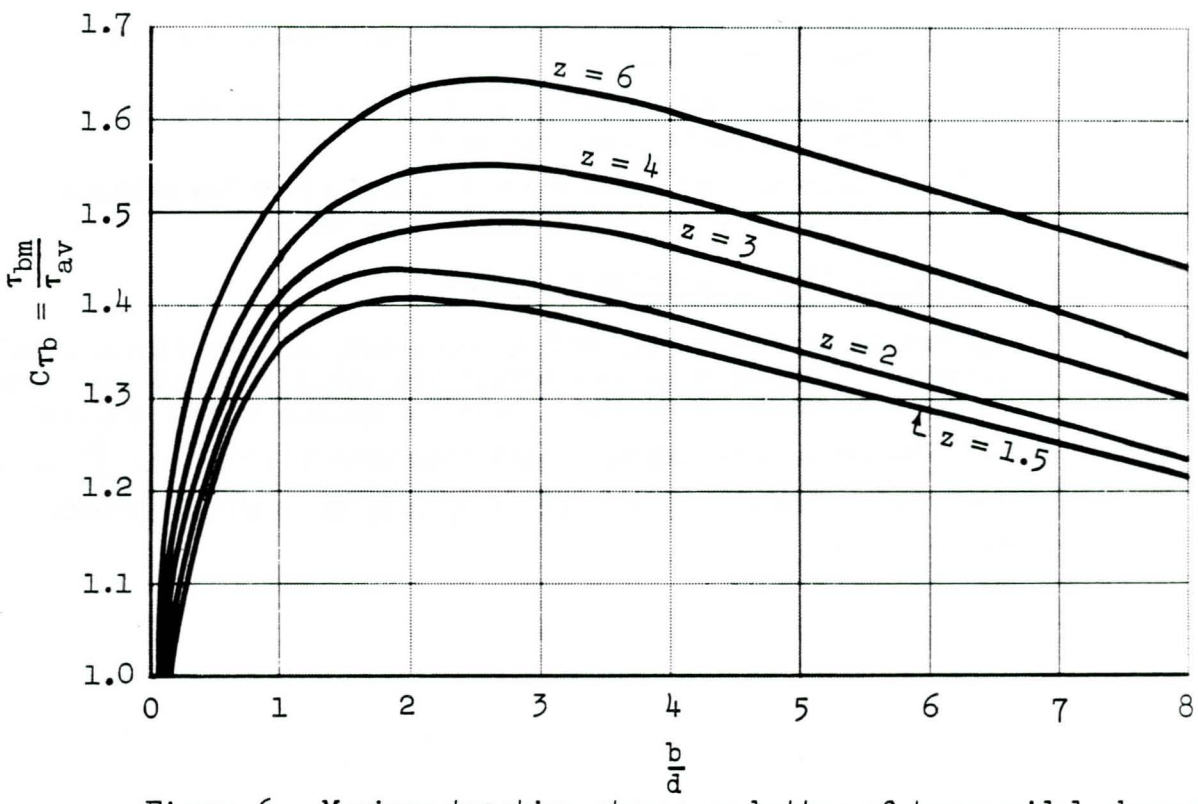

Figure 6. Maximum tractive stress on bottom of trapezoidal channels

Summary of Design Criteria

The following basic criteria govern the design of the riprap structure:

1. The specific energy head, H, at every section of the riprap structure is set equal to the specific energy head at the junction of the downstream transition and the downstream channel, Section A-A of Figure 1. Specific energy head is given by

$$H = d + \frac{v^2}{2g} = d + \frac{Q^2}{2ga^2}$$

2. The prismatic channel bottom slope, s_n, is set equal to or less than 0.7 of the critical slope, s_c. The bottom slope, s_n, is expressed as a fraction of the critical slope, i.e.,

$$s_n = CS(s_c)$$

$$\text{where} \quad 0 < CS \leq 0.7$$

3. Manning's coefficient of roughness, n, is a function of the D_{50} size of the riprap and has been evaluated to be

$$n = 0.0395\ (D_{50})^{1/6}$$

4. The critical tractive stress is a linear function of the D_{50} size of the riprap, i.e.,

$$\tau_{bc} = 4.0\ D_{50}$$

$$\tau_{sc} = K(4.0\ D_{50})$$

5. The riprap size and structure dimensions are selected so that for the design discharge the maximum tractive stress on the riprap does not exceed the allowable tractive stress. Either side or bottom tractive stress may control.

For a given design discharge, Q, specific energy head, H, and side slope, z, the variables that must be adjusted to meet these conditions are bottom width, b; bottom slope, s_o; and riprap size, D_{50}.

The length of the prismatic channel, LPC, is equal to the vertical drop of the prismatic channel divided by the bottom slope, s_n. The vertical drop of the prismatic channel depends on the amount of gradient control required.

Recommended Value for DIV

The outlet transition of a riprap gradient control structure has a rate of divergence of the bottom width of DIV. If this rate of divergence is too rapid, the flow in the transition tends to separate from the boundary and concentrate in the center of the transition and hence on into the exit channel. This flow condition causes eddies to form on the sides of the transition and causes an uneven velocity distribution throughout the transition and into the downstream channel. If the flow velocity is sufficiently high, scour will develop at the end of the structure.

The Corps of Engineers at the Waterways Experiment Station in Vicksburg, Mississippi conducted a series of prototype tests of the downstream transition to determine the minimum rate of divergence, DIV, that would produce a uniform distribution of flow in the downstream transition, thus minimizing scour downstream of the riprap structure. From the tests, the Corps concluded and recommended that a rate of divergence of DIV = 16 should be used in design.

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Computer Program

A computer program is available which determines dimensions and parameters associated with the design of a riprap gradient control structure. The structure is designed to flow at a constant specific energy head when conveying the design discharge, Q. The design is made for either the maximum D50 riprap size or for the maximum CS value, whichever controls.

The parameters Q, ZU, and H (or the equivalent of H, in terms of two of the parameters BS, DS and VS) are always input to the program. The solution for each design is highly implicit. Two basically different design approaches are used in the program. The applicable approach depends on whether or not D50 is specified by the user. These two approaches in simplified form are shown in the flow chart of Figure 7.

Default values are used for certain parameters if their values are not specified by the user. These parameters are called default parameters.

Modes

The computer program operates in one of four modes numbered 1 through 4. A mode must be specified for each design run. A computer job may contain one or more design runs consisting of the same or different modes.

Mode 1 obtains only the design of a riprap prismatic channel. Modes 2, 3, and 4 obtain the design of the prismatic channel and both transitions of the riprap structure.

Mode 1 permits the specification of the default parameter, D50.

Mode 2 permits the specification of any or all of the three default parameters D50, CONV, and DIV. Mode 2 requires that two and only two of the four parameters H, BS, DS, and VS be specified; otherwise, the computer prints an error code and the computations for this design run cease.

Mode 3 is the same as mode 2 except for an additional line of input which permits the user to specify values for any or all of the default parameters CS, C50, FS, THETA, CN, and EXPN.

Mode 4 is the same as mode 3 except for the parameter, ZS; instead of ZS mode 4 requires the specification of ZL and ZR for different side slopes at the ends of the riprap structure. Also, in mode 4 the parameters BS and DS must be specified.

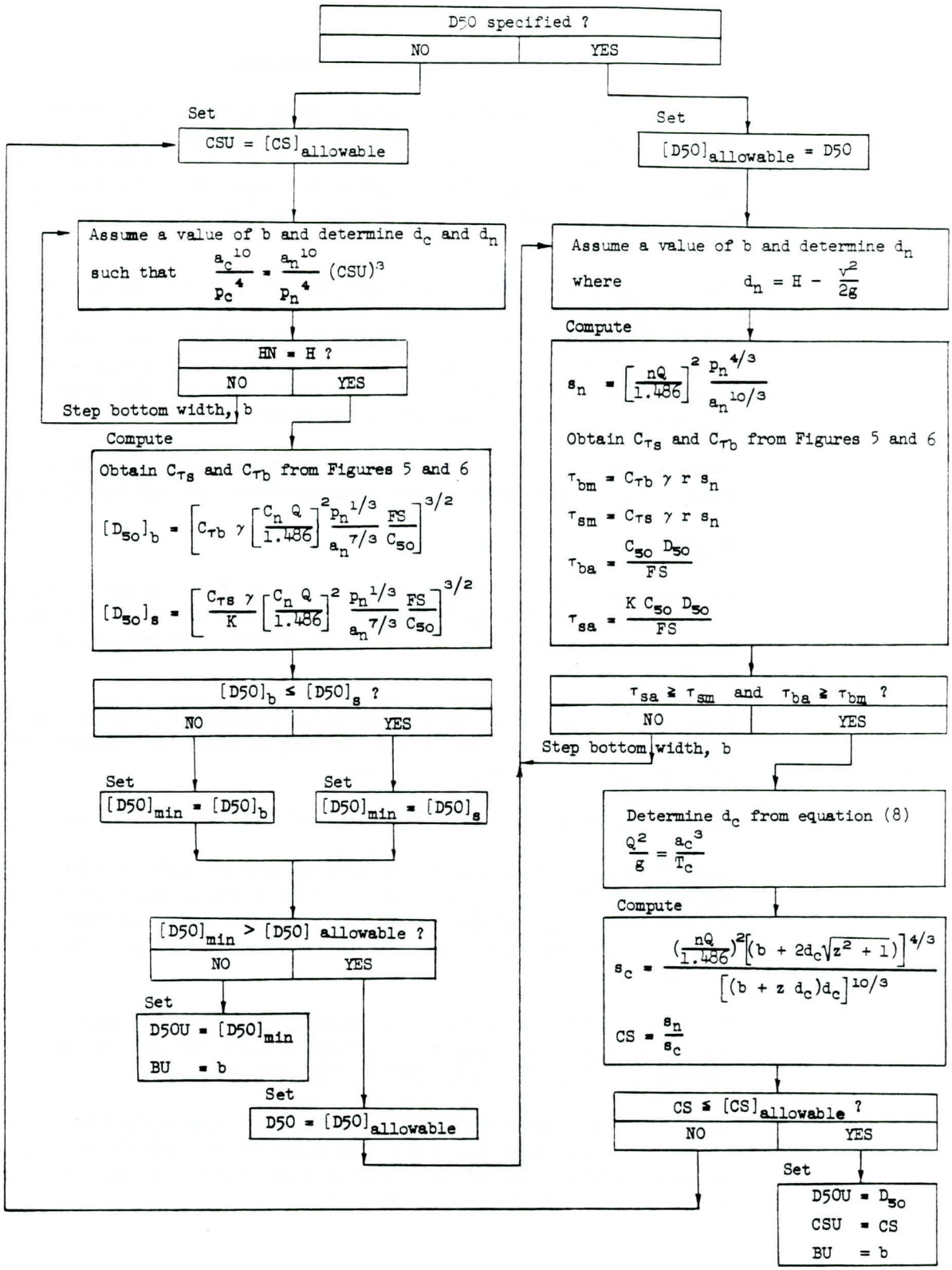

Figure 7. Flow chart of procedure used in computer program to determine the bottom width

Summary of Input Data

XX ≡ Required parameters

XX ≡ Default parameters, default values used unless values are specified by the user

XX ≡ Two and only two of the four parameters, H, BS, DS, and VS are required

Mode	Required Lines	Order of Parameters							
1	1st line	–	1.0	Q	ZU	D50	H	–	–
2	1st line	–	2.0	Q	ZU	D50	H	–	–
	2nd line	–	ZS	–	BS	DS	VS	CONV	DIV
3	1st line	–	3.0	Q	ZU	D50	H	–	–
	2nd line	–	ZS	–	BS	DS	VS	CONV	DIV
	3rd line	–	CS	C50	FS	THETA	CN	–	EXPN
4	1st line	–	4.0	Q	ZU	D50	–	–	–
	2nd line	–	ZL	ZR	BS	DS	–	CONV	DIV
	3rd line	–	CS	C50	FS	THETA	CN	–	EXPN

Input Data

The line arrangement of input data and their locations for the four modes is given in the "Summary of Input Data" on the preceding page.

Required data common to all modes. Each computer job requires two lines of information. Each line consists of 80 or less alphanumeric characters. This information must be placed ahead of the other input data and is generally for identifying and documenting the designs. Other required data common to all modes are:

1. Mode number (1.0, 2.0, 3.0, or 4.0)
2. Q, design discharge to be conveyed within the prismatic channel of the riprap structure
3. ZU, side slopes of the prismatic channel of the riprap structure.

Other required data.

1. Mode 1 requires the specific energy head, H, corresponding to the design discharge.
2. Modes 2 and 3
   a. Two, and only two, of the parameters H, BS, DS and VS are required. The other two parameters are ascertained by the computer.

      BS ≡ Bottom width at the ends of riprap structure, ft

      DS ≡ Depth of flow at design discharge at the ends of riprap structure, ft

      VS ≡ Velocity at design discharge at the ends of riprap structure, ft/sec

   b. ZS, the side slope at the ends of riprap structure is required
3. Mode 4 requires ZL, ZR, BS, and DS. The specific energy head, H, and the velocity, VS, are defined by the specified BS and DS.

   ZL ≡ Side slope of the left bank at the ends of riprap structure, see SECTION A-A, Figure 1, ft/ft

   ZR ≡ Side slope of the right bank (looking downstream) at the ends of riprap structure, ft/ft

Default Parameters

All other parameter values required for the design are obtained by default unless they are specified. The specified value of each parameter must be greater than zero. Default parameters D50, CONV, and DIV may be specified in modes 2, 3, and 4. The remaining default parameters may be specified only in modes 3 and 4. A value of 0.0 or a blank for a default parameter is interpreted to mean the default value is to be used.

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The default parameters D50 and CS have default values equal to their recommended maximum allowable values. These are:

D50 = 1.0 ft] Default values and recommended maximum
CS = 0.7] allowable values

where

D50 ≡ Size of rock in riprap of which 50 percent by weight is finer, ft (D50 > 1.0 ft may be specified)

CS ≡ Ratio of normal slope, SN, to critical slope, SC

The default parameters CONV and DIV have default values equal to their recommended minimum allowable values. These are:

CONV = 2.0] Default values and recommended minimum
DIV = 4.0] allowable values

where

CONV ≡ Rate of convergence of the bottom width of the upstream transition, see Figure 1, ft/ft

DIV ≡ Rate of divergence of the bottom width of the downstream transition, ft/ft

The values of any of the following default parameters may be specified. The default values of these default parameters are:

FS = 1.25

C50 = 4.0

THETA = 35°

CN = 0.0395

EXPN = 0.1667

where

FS ≡ Factor of safety

C50 ≡ Coefficient used in the equation, $\tau_{bc} = C_{50} D_{50}$

THETA ≡ Angle of repose of the riprap, degrees

CN ≡ Coefficient used in the equation for computing Manning's roughness coefficient, $n = C_n \left[D_{50}\right]^{EXPN}$

EXPN ≡ Value of the exponent in the equation for computing Manning's roughness coefficient, n.

Limitations

When the input data are not consistent or have exceeded the limitations set in the program, a message will be printed out indicating the reason computations cannot be continued and what the next course of action will be. For example:

"FOR CS = 0.7000 THE COMPUTED VALUE OF D50 = 1.182 FT IS GREATER THAN THE SPECIFIED OR ALLOWABLE D50. SOLUTION FOR CS WILL BE MADE USING SPECIFIED OR ALLOWABLE D50 OF 1.000 FT."

For details of maximum and minimum allowable values and limitations, refer to the discussions under "Default Parameters" and the error codes under "Messages."

Output Data

The alphanumeric information in the first two lines of input are printed by each design run. The printed alphanumeric information is followed by the data used for the design run.

The output data for the dimensions and parameters of the structure are given in the following order:

1. Transition at the downstream end
2. Prismatic channel
3. Transition at the upstream end

The output for values of KPS and FRIC SLOPE are given in an E format code containing an exponent. The exponent is the power of 10 by which the output value is multiplied to obtain its true value. For example:

$$3.72E\text{-}03 = 3.72 \times 10^{-3} = 0.00372$$

The headings used for the output for the transitions are:

LENGTH FT	≡ Length from the downstream end of the transition to any section j of the transition, ft
RISE FT	≡ The vertical distance from the bottom of the channel, at the downstream end of the transition, to the bottom of the channel at any section j in the transition, ft
WIDTH FT	≡ The bottom width at any section j in the transition, ft
Z	≡ Modes 2 and 3 only; the side slope at any section j in the transition, ft/ft
ZLT	≡ Mode 4 only; the left side slope at any section j in the transition, ft/ft
ZRT	≡ Mode 4 only; the right side slope at any section j in the transition, ft/ft
DEPTH FT	≡ The depth at any section j in the transition, ft
TOP WD FT	≡ Mode 4 only; the top width at any section j in the transition corresponding to DEPTH, ft
TAU LB/SQ. FT.	≡ Modes 2 and 3 only; the maximum tractive stress at any section j in the transition, lb/ft^2
TAUO LB/SQ. FT.	≡ Mode 4 only; the average tractive stress at any section j in the transition. The maximum tractive stress cannot be obtained, because the value of $C_{\tau b}$ or $C_{\tau s}$ is unknown for trapezoidal cross sections having unequal side slopes, lb/ft^2
VELOCITY FT/SEC	≡ The velocity at any section j of the transition, ft/sec
FRIC SLOPE FT/FT	≡ The instantaneous slope of the energy grade line at any section j, ft/ft

The symbols used for output for the prismatic channel are:

D50U ≡ The D_{50} size of riprap used in the design of riprap structure, ft

CSU $\equiv \frac{SN}{SC}$ ≡ Ratio of bottom slope to critical slope used in the design of riprap structure

FSU ≡ Factor of safety used in the design of riprap structure

BU ≡ Bottom width of the prismatic channel, ft

ZU ≡ Side slope of the prismatic channel, ft/ft

SN ≡ Bottom slope of the prismatic channel, ft/ft

HN ≡ Normal specific energy head corresponding to the design discharge, Q, in the prismatic channel, ft

DN ≡ Depth of flow corresponding to the design discharge, Q, in the prismatic channel, ft

VN ≡ Velocity at normal depth corresponding to the design discharge, Q, in the prismatic channel, ft/sec

RN ≡ Hydraulic radius at normal depth in the prismatic channel, ft

SC ≡ Critical slope corresponding to the design discharge, Q, in the prismatic channel, ft/ft

HC ≡ Critical specific energy head corresponding to the design discharge, Q, in the prismatic channel, ft

DC ≡ Critical depth corresponding to the design discharge, Q, in the prismatic channel, ft

N $= CN(D50U)^{EXPN}$ ≡ Manning's coefficient of roughness

K ≡ Ratio of critical tractive stress on side slope to critical tractive stress on bottom of the trapezoidal channel

KPS $= \frac{p_n}{s_n}$ ≡ Ratio of wetted perimeter to bottom slope of the prismatic channel

CTAUB ≡ A coefficient used to determine the maximum tractive stress along the boundary of the riprap lining on the bottom of the prismatic channel

TAUBM $= (CTAUB)(\gamma)(RN)(SN)$ ≡ The maximum tractive stress along the riprap lining on the bottom of the prismatic channel, lb/ft^2

TAUBA $= \frac{C50 \times D50U}{FSU}$ ≡ The allowable tractive stress for the riprap lining on the bottom of the prismatic channel, lb/ft^2

CTAUS ≡ A coefficient used to determine the maximum tractive stress along the boundary of the riprap lining on the side slope of the prismatic channel

TAUSM $= (CTAUS)(\gamma)(RN)(SN)$ ≡ The maximum tractive stress along the riprap lining on the side slope of the prismatic channel, lb/ft^2

TAUSA $= K \frac{C50 \times D50U}{FSU}$ ≡ The allowable tractive stress for the riprap lining on the side slope of the prismatic channel, lb/ft^2

Messages

When the computer detects an input error, it prints out a message containing an error code. No computations are attempted for this design. The error codes are as follows:

Code 1 ≡ Value of 7th field of line 1 is not zero or blank

Code 2 ≡ C50 < 0

Code 3 ≡ FS < 0 or 0 < FS < 1.0

Code 4 ≡ CS < 0

Code 5 ≡ THETA < 20°

Code 6 ≡ CN < 0

Code 8 ≡ EXPN < 0

Code 9 ≡ H < 0

Code 10 ≡ BS < 0

Code 11 ≡ DS < 0

Code 12 ≡ VS < 0

Code 13 ≡ BS, DS, H are all zero or blank

Code 14 ≡ DS, VS, H are all zero or blank

Code 15 ≡ BS, DS, VS are all zero or blank

Code 16 ≡ BS, VS, H are all zero or blank

Code 17 ≡ BS, DS, H are all specified

Code 18 ≡ DS, VS, H are all specified

Code 19 ≡ BS, VS, H are all specified

Code 20 ≡ BS, DS, VS are all specified

Code 21 ≡ H = 0.0 or blank when design mode = 1.0

Code 22 ≡ Q ≤ 0

Code 23 ≡ ZU ≤ 1.0

Code 24 ≡ ZS ≤ 0

Code 25 ≡ CONV < 0

Code 26 ≡ DIV < 0

Code 27 ≡ Value of 7th field of line 1 is not zero or blank

Code 28 ≡ Design mode is not 1.0, 2.0, 3.0, or 4.0

Code 29 ≡ D50 < 0

Code 30 ≡ DS ≥ H

Code 31 ≡ CS > 0.7

Code 32 ≡ CONV < 1.0

Code 33 ≡ DIV < 4.0

Code 34 ≡ $(VS)^2/2g \geq H$, ∴ DS ≤ 0

Code 35 ≡ ZL ≤ 0

Code 36 ≡ ZR ≤ 0

Code 44 ≡ The value of $\frac{\sin^2(\cot^{-1} z)}{\sin^2 \theta} \geq 1.0$, see equation (22)

Example No. 1

Given:

Design discharge, Q = 2500 cfs
Side slopes, ZU = 3.0
Specific energy head, H = 6.5 ft
Riprap size, D50 = 1.25 ft

Required:

Design a riprap trapezoidal channel having the steepest stable bottom slope consistent with the above conditions.

Solution:

The design obtained from the computer using mode 1 is as follows:

```
==============================================================================
  DESIGN OF RIPRAP PRISMATIC CHANNEL FOR A CONSTANT SPECIFIC ENERGY HEAD

      SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
                                FOR
                          EXAMPLE DESIGN NO. 1
                           JANUARY 23, 1976

CAUTION--THE SPECIFIED D50= 1.250 FT EXCEEDS THE EXPERIMENTAL DATA SHOWN IN
REPORT 108.  HOWEVER, THE SPECIFIED D50 WILL BE USED AS THE ALLOWABLE D50.

            DIMENSIONS AND PARAMETERS OF THE RIPRAP CHANNEL

     Q= 2500.00 CFS        H=  6.500 FT        ZU=  3.00 FT/FT

     ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

    D50=  1.250 FT        CS= 0.7000        THETA= 35.0 DEGREES
    C50=  4.00 LB/CU.FT.  CN= 0.0395
     FS=  1.250         EXPN=  0.1667

FOR D50= 1.250 FT THE COMPUTED VALUE OF CS=0.7371 IS GREATER THAN THE ALLOWABLE
CS.  SOLUTION FOR D50 WILL BE MADE USING THE ALLOWABLE VALUE CS=0.7000

       DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL

  D50U=   1.176 FT   SN= 0.011279    SC= 0.016113   CTAUB =  1.335
   CSU=   0.7000     HN= 6.500 FT    HC= 6.429 FT    TAUBM=  3.602 LB/SQ.FT.
   FSU=   1.25       DN= 5.090 FT    DC= 4.619 FT    TAUBA=  3.764 LB/SQ.FT.
    BU=  36.30  FT   VN= 9.52 FPS     N= 0.0406     CTAUS =  1.164
    ZU=   3.00       RN= 3.83 FT      K= 0.8343      TAUSM=  3.141 LB/SQ.FT.
                                    KPS= 6.07E+03    TAUSA=  3.141 LB/SQ.FT.

==============================================================================
```

Observe that the last output message indicates why the D50 = 1.25 ft riprap cannot be used in the design. Also observe that, although the maximum tractive stress occurs on the bottom of the channel, the controlling tractive stress occurs on the side slopes of the channel.

Example No. 2

Given:

Design discharge, Q = 2750 cfs
Side slopes, ZU = 2.5 and ZS = 3.0
Riprap size, D50 = 1.0 ft
Bottom width, BS = 100.0 ft
Starting depth, DS = 7.0 ft
Factor of safety, FS = 1.25

Required:

Design a riprap structure and determine the length of the structure if the total vertical drop desired for gradient control is 6.0 ft.

Solution:

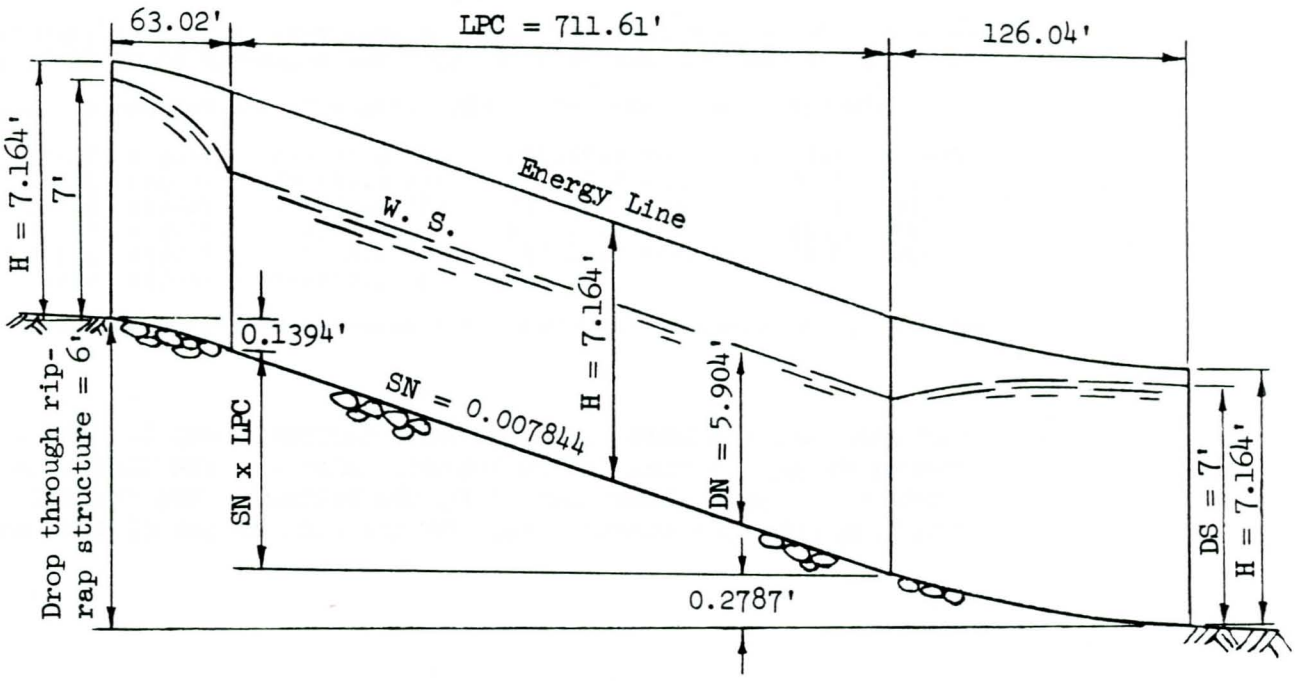
The design obtained from the computer using mode 2 is given on the next page.

The vertical drop in the prismatic channel is equal to the drop through the riprap structure minus the vertical drop contained in both transitions. The length of the prismatic channel, LPC, is equal to the vertical drop in the prismatic channel divided by the bottom slope of the prismatic channel, or

$$LPC = \frac{6.0 - 0.2787 - 0.1394}{0.007844} = 711.61 \text{ ft}$$

The total length of the structure is equal to the length of the prismatic channel plus the lengths of both transitions or

the total length = 711.61 + 126.04 + 63.02 = 900.67 ft



ELEVATION

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 2
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS H= 7.164 FT ZS= 3.00 FT/FT
BS= 100.000 FT DS= 7.000 FT VS= 3.247 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT CS= 0.7000 THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT. CN= 0.0395 CONV= 2.000
FS= 1.250 EXPN= 0.1667 DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	3.00	7.000	0.278	3.247	7.03E-04
12.60	0.0095	93.70	2.95	6.979	0.322	3.448	8.03E-04
25.21	0.0204	87.40	2.90	6.954	0.377	3.677	9.27E-04
37.81	0.0331	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.0480	74.79	2.80	6.883	0.533	4.247	1.28E-03
63.02	0.0658	68.49	2.75	6.833	0.646	4.611	1.55E-03
75.62	0.0876	62.19	2.70	6.767	0.799	5.051	1.91E-03
88.23	0.1150	55.89	2.65	6.677	1.011	5.598	2.43E-03
100.83	0.1507	49.58	2.60	6.545	1.325	6.309	3.23E-03
113.44	0.2002	43.28	2.55	6.334	1.838	7.305	4.62E-03
126.04	0.2787	36.98	2.50	5.904	2.910	9.003	7.84E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 1.000 FT SN= 0.007844 SC= 0.014965 CTAUB = 1.339
CSU= 0.5242 HN= 7.164 FT HC= 6.920 FT TAUBM= 2.910 LB/SQ.FT.
FSU= 1.25 DN= 5.904 FT DC= 4.943 FT TAUBA= 3.200 LB/SQ.FT.
BU= 36.98 FT VN= 9.00 FPS N= 0.0395 CTAUS = 1.122
ZU= 2.50 RN= 4.44 FT K= 0.7621 TAUSM= 2.439 LB/SQ.FT.
KPS= 8.77E+03 TAUSA= 2.439 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	36.98	2.50	5.904	2.910	9.003	7.84E-03
6.30	0.0393	43.28	2.55	6.334	1.838	7.305	4.62E-03
12.60	0.0640	49.58	2.60	6.545	1.325	6.309	3.23E-03
18.91	0.0819	55.89	2.65	6.677	1.011	5.598	2.43E-03
25.21	0.0955	62.19	2.70	6.767	0.799	5.051	1.91E-03
31.51	0.1064	68.49	2.75	6.833	0.646	4.611	1.55E-03
37.81	0.1154	74.79	2.80	6.883	0.533	4.247	1.28E-03
44.11	0.1228	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.1292	87.40	2.90	6.954	0.377	3.677	9.27E-04
56.72	0.1346	93.70	2.95	6.979	0.322	3.448	8.03E-04
63.02	0.1394	100.00	3.00	7.000	0.278	3.247	7.03E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.15 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.05 FT

Example No. 3

Given:

Design discharge, Q = 2750 cfs
Side slopes, ZU = 2.5, ZS = 3.0
Riprap size, D50 = 1.0 ft
Bottom width, BS = 100.0 ft
Starting depth, DS = 7.0 ft
Factor of safety, FS = 2.0
Value of CS = 0.6

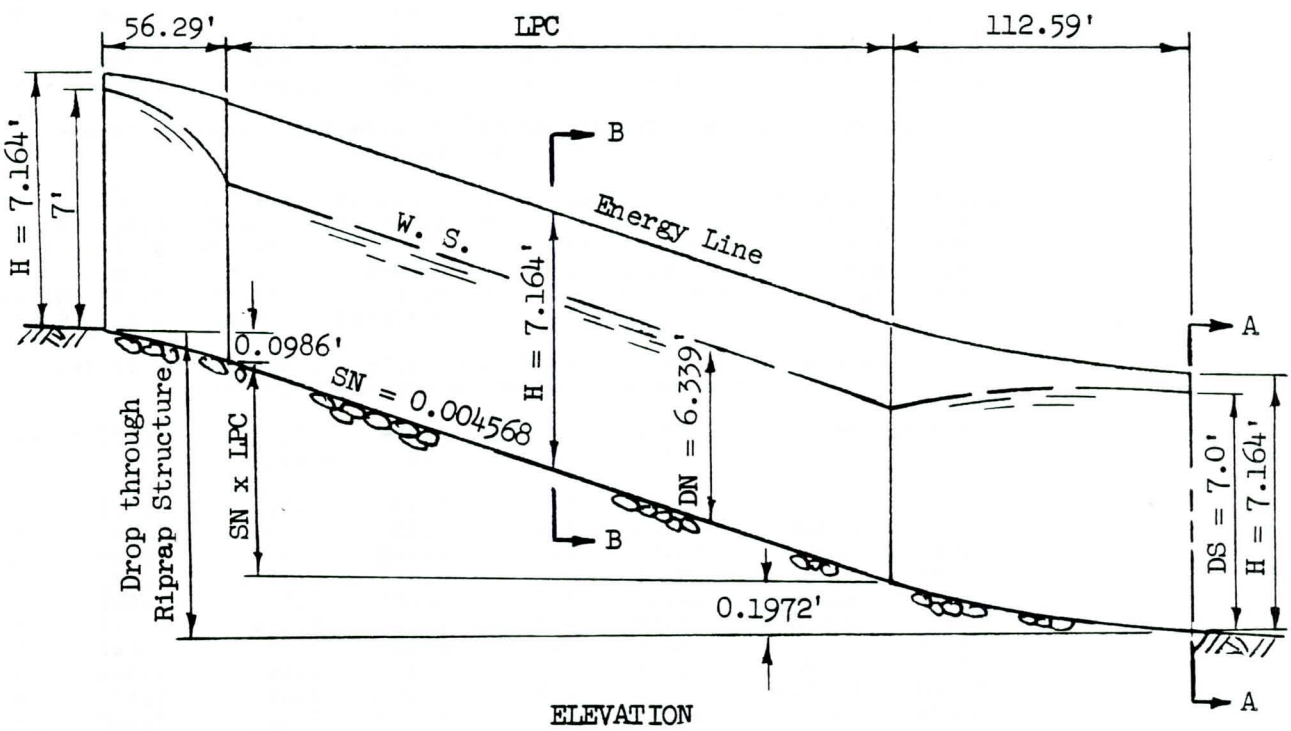
Note that the given parameters for this example are the same as Example No. 2 except for FS and CS values.

Required:

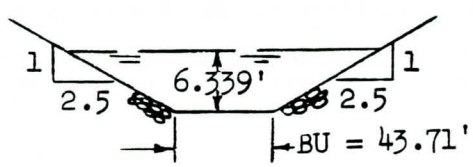
Design the riprap structure.

Solution:

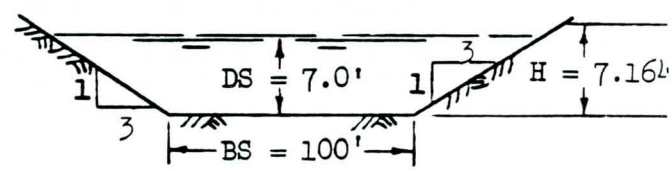
The design obtained from the computer using mode 3 is given on the next page. Observe, although the value of CS was specified, it was not used in the design since CSU < CS.



ELEVATION



SECTION B-B



SECTION A-A

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 3
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS H= 7.164 FT ZS= 3.00 FT/FT
BS= 100.000 FT DS= 7.000 FT VS= 3.247 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT CS= 0.6000 THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT. CN= 0.0395 CONV= 2.000
FS= 2.000 EXPN= 0.1667 DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	3.00	7.000	0.278	3.247	7.03E-04
11.26	0.0084	94.37	2.95	6.981	0.317	3.426	7.92E-04
22.52	0.0179	88.74	2.90	6.959	0.365	3.628	8.99E-04
33.78	0.0288	83.11	2.85	6.933	0.423	3.856	1.03E-03
45.03	0.0413	77.48	2.80	6.900	0.494	4.117	1.19E-03
56.29	0.0559	71.85	2.75	6.860	0.584	4.419	1.40E-03
67.55	0.0732	66.22	2.70	6.810	0.699	4.773	1.67E-03
78.81	0.0941	60.59	2.65	6.744	0.850	5.197	2.04E-03
90.07	0.1199	54.97	2.60	6.656	1.057	5.717	2.55E-03
101.33	0.1529	49.34	2.55	6.531	1.354	6.381	3.31E-03
112.59	0.1972	43.71	2.50	6.339	1.819	7.285	4.57E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL OF THE RIPRAP STRUCTURE

D50U= 1.000 FT SN= 0.004568 SC= 0.015123 CTAUB = 1.316
CSU= 0.3020 HN= 7.164 FT HC= 6.422 FT TAUBM= 1.819 LB/SQ.FT.
FSU= 2.00 DN= 6.339 FT DC= 4.540 FT TAUBA= 2.000 LB/SQ.FT.
BU= 43.71 FT VN= 7.28 FPS N= 0.0395 CTAUS = 1.103
ZU= 2.50 RN= 4.85 FT K= 0.7621 TAUSM= 1.524 LB/SQ.FT.
KPS= 1.70E+04 TAUSA= 1.524 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	43.71	2.50	6.339	1.819	7.285	4.57E-03
5.63	0.0222	49.34	2.55	6.531	1.354	6.381	3.31E-03
11.26	0.0387	54.97	2.60	6.656	1.057	5.717	2.55E-03
16.89	0.0515	60.59	2.65	6.744	0.850	5.197	2.04E-03
22.52	0.0620	66.22	2.70	6.810	0.699	4.773	1.67E-03
28.15	0.0706	71.85	2.75	6.860	0.584	4.419	1.40E-03
33.78	0.0779	77.48	2.80	6.900	0.494	4.117	1.19E-03
39.41	0.0842	83.11	2.85	6.933	0.423	3.856	1.03E-03
45.03	0.0896	88.74	2.90	6.959	0.365	3.628	8.99E-04
50.66	0.0944	94.37	2.95	6.981	0.317	3.426	7.92E-04
56.29	0.0986	100.00	3.00	7.000	0.278	3.247	7.03E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.08 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.03 FT

LIBRARY

Example No. 4

Given:

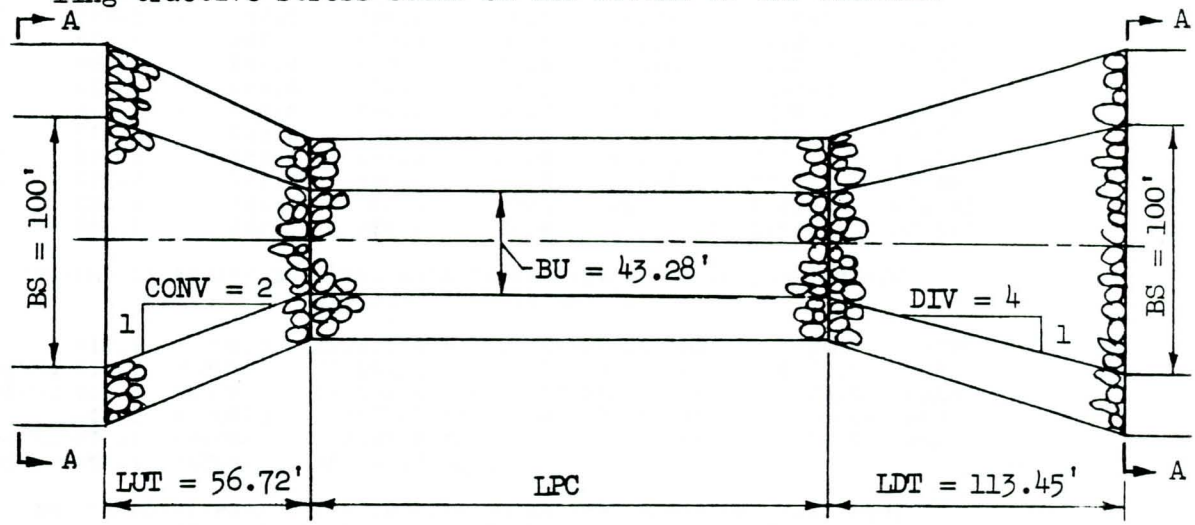
Design discharge, Q = 2750 cfs
Side slopes, ZU = 3.0, ZL = 4.0, and ZR = 3.0
Riprap size, D50 = 0.75 ft
Bottom width, BS = 100.0 ft
Starting depth, DS = 7.0 ft
Rate of convergence, CONV = 2.0
Factor of safety, FS = 2.0
Angle of repose, THETA = 42°

Required:

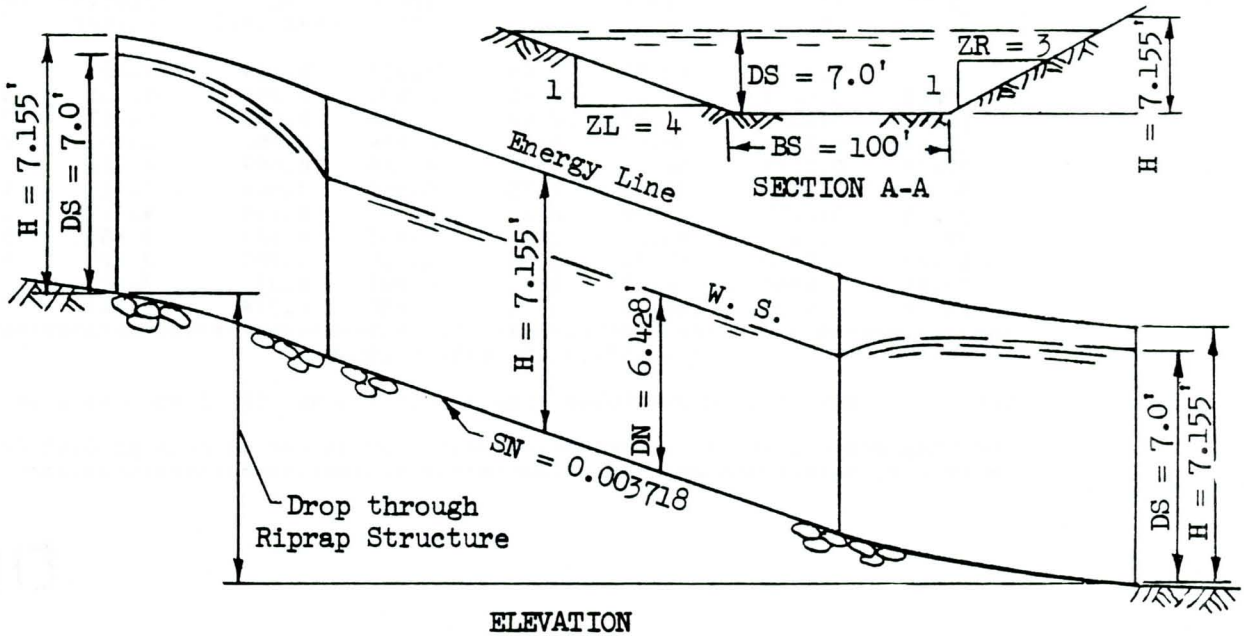
Design a riprap structure where the adjoining channels have side slopes ZL = 4.0 and ZR = 3.0 (See SECTION A-A).

Solution:

The design obtained from the computer using mode 4 is given on the next page and the dimensions and parameters are outlined in the sketch below. Observe that both the maximum tractive stress and the controlling tractive stress occur on the bottom of the channel.



PLAN



ELEVATION

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DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 4
JANUARY 23. 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS

ZL= 4.000 DS= 7.000 FT H= 7.155 FT
ZR= 3.000 BS=100.000 FT VS= 3.155 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 0.750 FT CS= 0.7000 THETA= 42.0 DEGREES
C50= 4.00 LB/CU.FT. CN= 0.0395 CONV= 2.000
FS= 2.000 EXPN= 0.1667 DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZLT	ZRT	DEPTH FT	TOP WD FT	TAUO LB/SQ.FT.	VEL. FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	4.00	3.00	7.000	149.00	0.222	3.155	6.17E-04
11.34	0.01	94.33	3.90	3.00	6.983	142.51	0.248	3.326	6.94E-04
22.69	0.02	88.66	3.80	3.00	6.963	136.00	0.278	3.516	7.86E-04
34.03	0.03	82.98	3.70	3.00	6.938	129.47	0.314	3.731	8.98E-04
45.38	0.04	77.31	3.60	3.00	6.909	122.91	0.358	3.976	1.04E-03
56.72	0.05	71.64	3.50	3.00	6.873	116.31	0.413	4.258	1.21E-03
68.07	0.06	65.97	3.40	3.00	6.828	109.66	0.481	4.587	1.44E-03
79.41	0.08	60.29	3.30	3.00	6.770	102.94	0.571	4.977	1.74E-03
90.76	0.10	54.62	3.20	3.00	6.693	96.12	0.690	5.452	2.15E-03
102.10	0.13	48.95	3.10	3.00	6.586	89.12	0.858	6.048	2.76E-03
113.45	0.17	43.28	3.00	3.00	6.428	81.84	1.111	6.839	3.72E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 0.750 FT SN= 0.003718 SC= 0.013810 CTAUB = 1.350
CSU= 0.2692 HN= 7.155 FT HC= 6.301 FT TAUBM= 1.500 LB/SQ.FT.
FSU= 2.00 DN= 6.428 FT DC= 4.488 FT TAUBA= 1.500 LB/SQ.FT.
BU= 43.28 FT VN= 6.84 FPS N= 0.0377 CTAUS = 1.177
ZU= 3.00 RN= 4.79 FT K= 0.8813 TAUSM= 1.308 LB/SQ.FT.
KPS= 2.26E+04 TAUSA= 1.322 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZLT	ZRT	DEPTH FT	TOP WD FT	TAUO LB/SQ.FT.	VEL. FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	43.28	3.00	3.00	6.428	81.84	1.111	6.839	3.72E-03
5.67	0.02	48.95	3.10	3.00	6.586	89.12	0.858	6.048	2.76E-03
11.34	0.03	54.62	3.20	3.00	6.693	96.12	0.690	5.452	2.15E-03
17.02	0.04	60.29	3.30	3.00	6.770	102.94	0.571	4.977	1.74E-03
22.69	0.05	65.97	3.40	3.00	6.828	109.66	0.481	4.587	1.44E-03
28.36	0.06	71.64	3.50	3.00	6.873	116.31	0.413	4.258	1.21E-03
34.03	0.07	77.31	3.60	3.00	6.909	122.91	0.358	3.976	1.04E-03
39.71	0.07	82.98	3.70	3.00	6.938	129.47	0.314	3.731	8.98E-04
45.38	0.08	88.66	3.80	3.00	6.963	136.00	0.278	3.516	7.86E-04
51.05	0.08	94.33	3.90	3.00	6.983	142.51	0.248	3.326	6.94E-04
56.72	0.08	100.00	4.00	3.00	7.000	149.00	0.222	3.155	6.17E-04

==========

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.06 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.03 FT

==========

Example No. 5

Given:

Design discharge, Q = 2750 cfs
Side slopes, ZU = 2.5, ZS = 3.0
Riprap size, D50 = 1.0 ft
Downstream bottom width, BS = 100.0 ft
Upstream bottom width, BS = 150.0 ft
Starting depth, DS = 7.0 ft
Factor of safety, FS = 1.25

Note that the given parameters of this example are the same as Example No. 2 except that the bottom width, BS, at the downstream end of the structure is not the same as the BS at the upstream end of the structure.

Required:

Design the riprap structure where the adjoining channels have different bottom widths.

Solution:

Since the bottom widths at the upstream end and downstream end of the structure are not equal, two design runs are required. The first design run is for BS = 100 ft. The second design run is for BS = 150 ft and it uses the same specific energy head, H, as was used in the first design run. The final design is composed of the following:

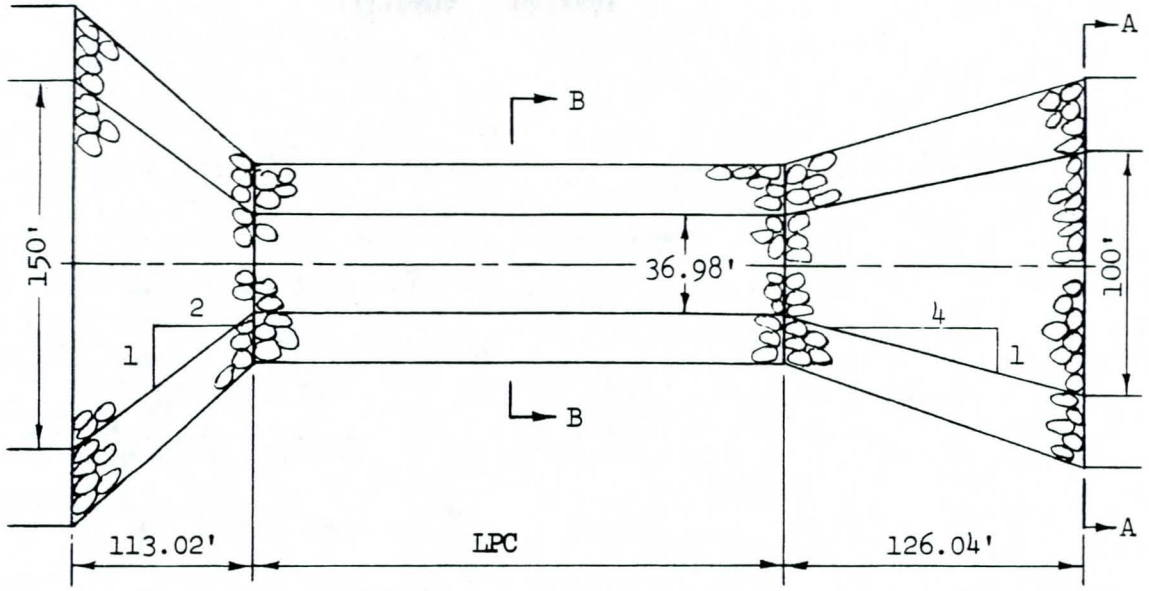
1. the design of the downstream transition from the first design run, i.e., for BS = 100 ft (The design of the upstream transition for this run is disregarded.)
2. the design of the prismatic channel from either design run (They are the same.)
3. the design of the upstream transition from the second design run, i.e., for BS = 150 ft (The design of the downstream transition for this run is disregarded.)

The composite design is given on the next three pages.

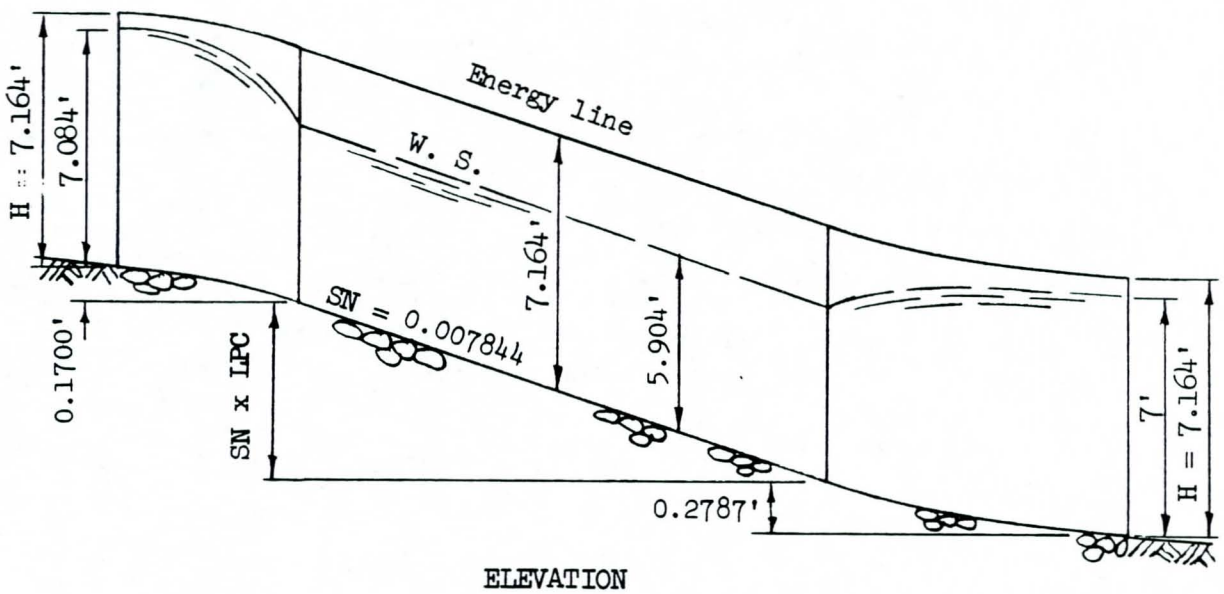
Observe that the depths at the ends of the structure are not equal. The larger depth occurs at the upstream end of the riprap structure because

1. the bottom width at the upstream end is larger than the bottom width at the downstream end and
2. the structure maintains a constant specific energy head at subcritical flow throughout the structure.

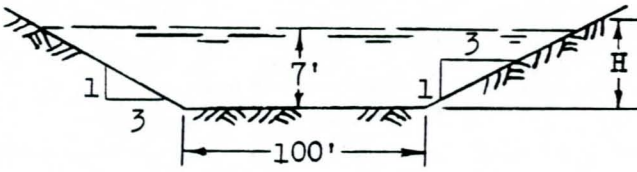
Since the depth at the upstream end is larger than the depth at the downstream end, the velocity at the upstream end is smaller than the velocity at the downstream end at constant specific energy head.



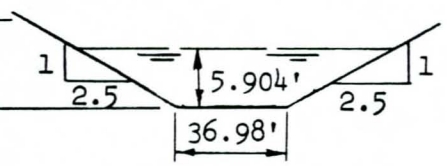
PLAN



ELEVATION



SECTION A-A



SECTION B-B

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 5
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS H= 7.164 FT ZS= 3.00 FT/FT
BS= 100.000 FT DS= 7.000 FT VS= 3.247 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT CS= 0.7000 THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT. CN= 0.0395 CONV= 2.000
FS= 1.250 EXPN= 0.1667 DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	3.00	7.000	0.278	3.247	7.03E-04
12.60	0.0095	93.70	2.95	6.979	0.322	3.448	8.03E-04
25.21	0.0204	87.40	2.90	6.954	0.377	3.677	9.27E-04
37.81	0.0331	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.0480	74.79	2.80	6.883	0.533	4.247	1.28E-03
63.02	0.0658	68.49	2.75	6.833	0.646	4.611	1.55E-03
75.62	0.0876	62.19	2.70	6.767	0.799	5.051	1.91E-03
88.23	0.1150	55.89	2.65	6.677	1.011	5.598	2.43E-03
100.83	0.1507	49.58	2.60	6.545	1.325	6.309	3.23E-03
113.44	0.2002	43.28	2.55	6.334	1.838	7.305	4.62E-03
126.04	0.2787	36.98	2.50	5.904	2.910	9.003	7.84E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 1.000 FT SN= 0.007844 SC= 0.014965 CTAUB = 1.339
CSU= 0.5242 HN= 7.164 FT HC= 6.920 FT TAUBM= 2.910 LB/SQ.FT.
FSU= 1.25 DN= 5.904 FT DC= 4.943 FT TAUBA= 3.200 LB/SQ.FT.
BU= 36.98 FT VN= 9.00 FPS N= 0.0395 CTAUS = 1.122
ZU= 2.50 RN= 4.44 FT K= 0.7621 TAUSM= 2.439 LB/SQ.FT.
KPS= 8.77E+03 TAUSA= 2.439 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	36.98	2.50	5.904	2.910	9.003	7.84E-03
6.30	0.0393	43.28	2.55	6.334	1.838	7.305	4.62E-03
12.60	0.0640	49.58	2.60	6.545	1.325	6.309	3.23E-03
18.91	0.0819	55.89	2.65	6.677	1.011	5.598	2.43E-03
25.21	0.0955	62.19	2.70	6.767	0.799	5.051	1.91E-03
31.51	0.1064	68.49	2.75	6.833	0.646	4.611	1.55E-03
37.81	0.1154	74.79	2.80	6.883	0.533	4.247	1.28E-03
44.11	0.1228	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.1292	87.40	2.90	6.954	0.377	3.677	9.27E-04
56.72	0.1346	93.70	2.95	6.979	0.322	3.448	8.03E-04
63.02	0.1394	100.00	3.00	7.000	0.278	3.247	7.03E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.15 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.05 FT

LIBRARY

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 5
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS	H= 7.164 FT	ZS= 3.00 FT/FT
BS= 150.000 FT	DS= 7.084 FT	VS= 2.267 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT	CS= 0.7000	THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT.	CN= 0.0395	CONV= 2.000
FS= 1.250	EXPN= 0.1667	DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	150.00	3.00	7.084	0.123	2.267	3.17E-04
22.60	0.0078	138.70	2.95	7.072	0.143	2.437	3.71E-04
45.21	0.0169	127.40	2.90	7.056	0.168	2.636	4.39E-04
67.81	0.0279	116.09	2.85	7.036	0.200	2.871	5.29E-04
90.42	0.0412	104.79	2.80	7.009	0.252	3.153	6.51E-04
113.02	0.0579	93.49	2.75	6.974	0.328	3.500	8.21E-04
135.63	0.0792	82.19	2.70	6.923	0.439	3.938	1.07E-03
158.23	0.1078	70.89	2.65	6.848	0.608	4.511	1.46E-03
180.83	0.1484	59.58	2.60	6.727	0.888	5.305	2.13E-03
203.44	0.2119	48.28	2.55	6.503	1.422	6.519	3.49E-03
226.04	0.3399	36.98	2.50	5.904	2.910	9.003	7.84E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U=	1.000 FT	SN= 0.007844	SC= 0.014966	CTAUB =	1.339
CSU=	0.5242	HN= 7.164 FT	HC= 6.920 FT	TAUBM=	2.910 LB/SQ.FT.
FSU=	1.25	DN= 5.904 FT	DC= 4.943 FT	TAUBA=	3.200 LB/SQ.FT.
BU=	36.98 FT	VN= 9.00 FPS	N= 0.0395	CTAUS =	1.122
ZU=	2.50	RN= 4.44 FT	K= 0.7621	TAUSM=	2.439 LB/SQ.FT.
			KPS= 8.77E+03	TAUSA=	2.439 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	36.98	2.50	5.904	2.910	9.003	7.84E-03
11.30	0.0640	48.28	2.55	6.503	1.422	6.519	3.49E-03
22.60	0.0958	59.58	2.60	6.727	0.888	5.305	2.13E-03
33.91	0.1161	70.88	2.65	6.848	0.608	4.511	1.46E-03
45.21	0.1304	82.19	2.70	6.923	0.439	3.938	1.07E-03
56.51	0.1410	93.49	2.75	6.974	0.328	3.500	8.21E-04
67.81	0.1494	104.79	2.80	7.009	0.252	3.153	6.51E-04
79.11	0.1560	116.09	2.85	7.036	0.200	2.871	5.29E-04
90.42	0.1615	127.40	2.90	7.056	0.168	2.636	4.39E-04
101.72	0.1661	138.70	2.95	7.072	0.143	2.437	3.71E-04
113.02	0.1700	150.00	3.00	7.084	0.123	2.267	3.17E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.21 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.05 FT

PREFACE

Mr. Paul D. Doubt, former Head of the Design Unit, Design Branch, Engineering Division, did the theoretical work and much of the computer programming necessary for preparing the charts used in the graphical solution of riprap gradient control structures. Technical Release No. 59, "Hydraulic Design of Riprap Gradient Control Structures," contains a detailed discussion of the riprap gradient control structure and is referenced frequently in this supplement.

A draft of this supplement dated April 7, 1976, was circulated through the Engineering Division and sent to the Engineering and Watershed Planning Unit Design Engineers for review and comment.

Mr. John A. Brevard of the Engineering Division Design Unit, Hyattsville, Maryland prepared this supplement. Mrs. Joan Robison and Mr. Stanley E. Smith assisted in the preparation of the charts.

TECHNICAL RELEASE NO. 59, SUPPLEMENT 1

GRAPHICAL SOLUTION FOR THE HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

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Engineering Standard Drawings

Drawing No.	Title or Description
ES-208	RIPRAP GRADIENT CONTROL STRUCTURES: Determination of K and Determination of Whether Sides or Bottom Controls the Design
ES-209	RIPRAP GRADIENT CONTROL STRUCTURES: Prismatic Channels (ZU = 2)
ES-210	RIPRAP GRADIENT CONTROL STRUCTURES: Prismatic Channels (ZU = 3)
ES-211	RIPRAP GRADIENT CONTROL STRUCTURES: Transitions
ES- 55	HYDRAULICS: Uniform Depths and Discharges in Trapezoidal and Rectangular Channels

NOMENCLATURE

This supplement uses almost exclusively the nomenclature of TR-59. Only four symbols are used which are not included in the nomenclature for TR-59. These are m, RISE, $RISE]_j$, and s_j.

a ≡ Flow area, ft^2

b ≡ Bottom width of trapezoidal section, ft

BS ≡ Bottom width at the ends of the riprap structure, ft

BU ≡ Bottom width of the prismatic channel of riprap structure, ft

C50 ≡ Coefficient relating critical tractive stress to riprap D_{50} size, $\tau_{bc} = C50\ D_{50}$

CN ≡ Coefficient relating Manning's n to riprap D_{50} size,

$n = CN[D_{50}]^{EXPN}$

CONV ≡ Rate of convergence of the bottom width of the upstream transition, ft/ft

CS $= \frac{s_n}{s_c}$ ≡ Maximum allowable ratio of bottom slope to critical slope

$C_{\tau b} = \frac{\tau_{bm}}{\tau_{av}}$ ≡ Ratio of maximum tractive stress on bottom of channel to average tractive stress

$C_{\tau s} = \frac{\tau_{sm}}{\tau_{av}}$ ≡ Ratio of maximum tractive stress on side slope of channel to average tractive stress

d ≡ Depth of flow, ft

D_{50} ≡ Size of rock in riprap of which 50 percent by weight is finer, ft

DIV ≡ Rate of divergence of the bottom width of the downstream transition, ft/ft

d_n ≡ Normal depth corresponding to design discharge, Q, ft

DN ≡ Normal depth corresponding to the design discharge, Q, in the prismatic channel of riprap structure, ft

DS ≡ Depth of flow corresponding to the design discharge, Q, at the ends of the riprap structure, ft

EXPN ≡ Value of the exponent in the equation for computing Manning's roughness coefficient, $n = CN[D_{50}]^{EXPN}$

FS ≡ Factor of safety

g ≡ Acceleration of gravity, ft/sec^2

H ≡ Specific energy head corresponding to the design discharge, Q, ft

K $= \frac{\tau_{sc}}{\tau_{bc}} = \sqrt{1 - \frac{\sin^2(\cot^{-1} z)}{\sin^2 \theta}}$ ≡ Ratio of critical tractive stress on side slope to critical tractive stress on bottom of the trapezoidal channel

LDT ≡ Length of downstream transition, ft

LPC ≡ Length of prismatic channel, ft

LUT ≡ Length of upstream transition, ft

m ≡ Number of equal parts that the transition length is divided into for computational purposes

n ≡ Manning's coefficient of roughness

Q ≡ Design discharge through the riprap structure, cfs

RISE ≡ The vertical distance from the bottom of the channel at the downstream end of the transition to the bottom of the channel at the upstream end of the transition, ft

$\text{RISE}]_j$ ≡ The vertical distance from the bottom of the channel at the downstream end of the transition to the bottom of the channel at any section j in the transition, ft

s ≡ Energy gradient, ft/ft

s_c ≡ Critical slope corresponding to the design discharge, Q, in the prismatic channel of the riprap structure, ft/ft

s_j ≡ Energy gradient at any section j in the transition, ft/ft

s_n ≡ Bottom slope of the prismatic channel of the riprap structure and also normal slope corresponding to the design discharge, Q, ft/ft

s_o ≡ Slope of channel bottom, ft/ft

v ≡ Velocity corresponding to the design discharge, Q, ft/sec

z ≡ Side slope of trapezoidal section expressed as a ratio of horizontal to vertical, ft/ft

ZS ≡ Side slope of trapezoidal section at the ends of riprap structure, ft/ft

ZU ≡ Side slope of the prismatic channel of the riprap structure, ft/ft

θ ≡ Angle of repose of the riprap, degrees

τ_{av} ≡ The average tractive stress, lb/ft^2

$\tau_{bc} = C50\ D_{50}$ ≡ The critical tractive stress for the riprap lining on the bottom of the trapezoidal channel, lb/ft^2

τ_{bm} ≡ The maximum tractive stress along the riprap lining on the bottom of the trapezoidal channel, lb/ft^2

$\tau_{sc} = K\ \tau_{bc}$ ≡ The critical tractive stress for the riprap lining on the side slope of the trapezoidal channel, lb/ft^2

τ_{sm} ≡ The maximum tractive stress along the riprap lining on the side slope of the trapezoidal channel, lb/ft^2

TECHNICAL RELEASE NO. 59, SUPPLEMENT 1

GRAPHICAL SOLUTION FOR THE HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

Introduction

In some cases a riprap gradient control structure can be used economically to dissipate excess energy and establish a stable gradient in a channel where the gradient without such control would be too steep and would cause erosive velocities.

The riprap gradient control structure discussed in this supplement consists of a riprap prismatic channel with a riprap transition at each end (see Figure 1). The structure's essential feature is that the specific energy of the flow at design discharge is constant throughout the structure and is equal to the specific energy of the flow in the channel immediately upstream and downstream of the structure. Thus, for the design discharge, the dissipation of hydraulic energy in the structure is at the same rate as the energy gain due to the gradient. The structure, which is steeper and narrower than the adjoining upstream and downstream channels, maximizes energy dissipation.

For brevity, this supplement refers to the riprap gradient control structure as riprap structure or simply as structure. All channels and structures considered in this supplement have trapezoidal cross sections and subcritical slopes.

Technical Release No. 59

Technical Release No. 59, "Hydraulic Design of Riprap Gradient Control Structures," presents a detailed discussion of the concept of the riprap gradient control structure, the hydraulic design of the structure, and the design of the riprap. TR-59 also contains the information needed to use the available computer program for the riprap structure design.

Purpose of Supplement

The purpose of this supplement is to present the graphical procedures for the design of riprap gradient control structures. The procedures may also be used to obtain a riprap prismatic channel design. This supplement presumes the user is familiar with TR-59.

The graphical solution as contained in this supplement is limited since the prismatic channel design charts are only for side slopes of 2:1 and 3:1. Structures with other prismatic channel side slopes may be designed using the computer program described in TR-59.

Riprap Gradient Control Structure

A riprap gradient control structure is a riprap structure consisting of a prismatic channel with a converging inlet transition at the upstream end and a diverging outlet transition at the downstream end of the prismatic channel. The riprap structure should have an essentially straight alignment as shown in Figure 1.

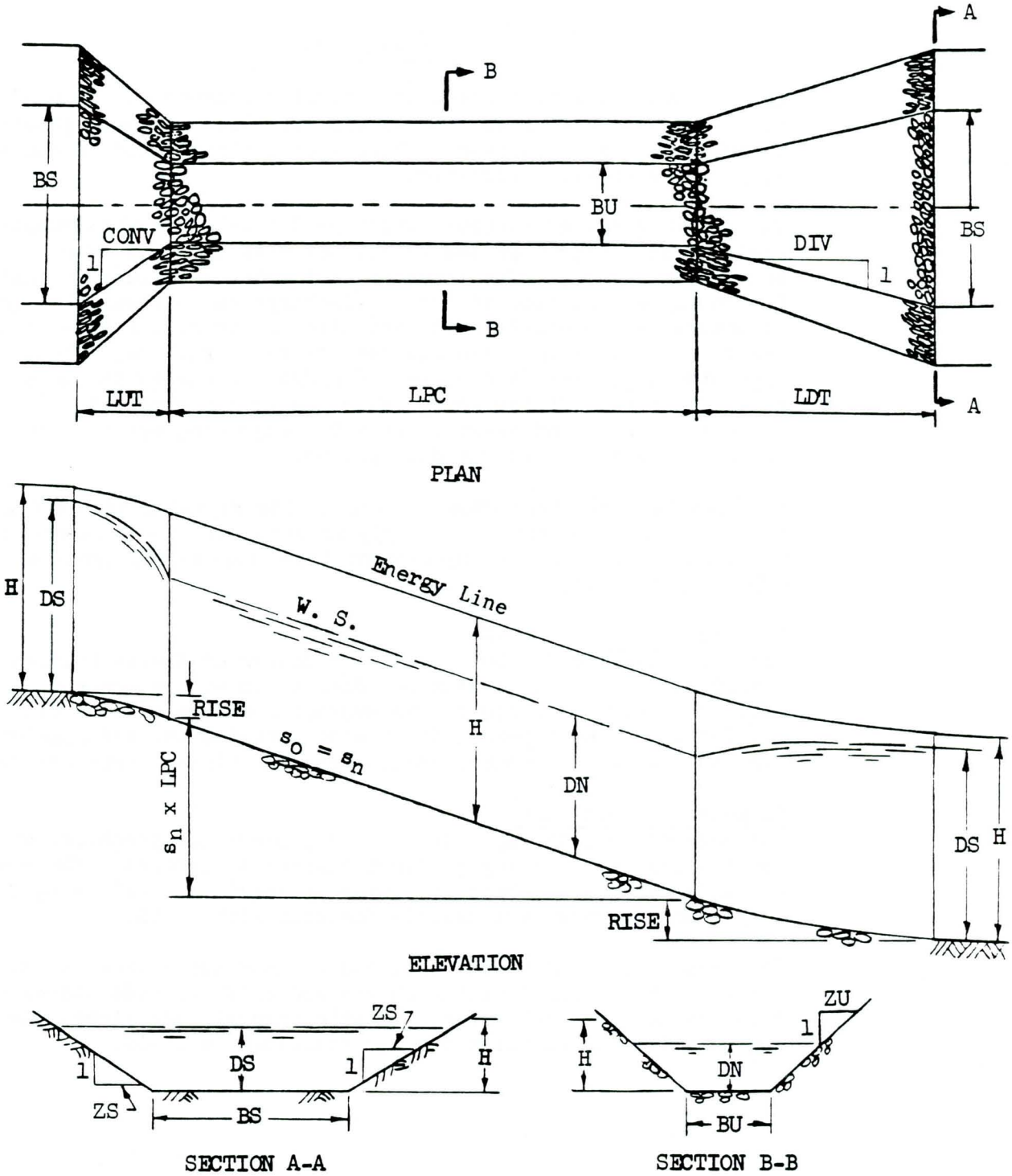

Figure 1. Riprap gradient control structure

Prismatic Channel Design

The depth of flow in the prismatic channel of the riprap structure is set equal to the normal depth corresponding to the design discharge, Q. Therefore, the dissipation of hydraulic energy is at the same rate as the energy gain due to the gradient. The specific energy head, H, at every section of the riprap structure is set equal to the specific energy head at the junction of the downstream transition and the downstream channel, Section A-A of Figure 1.

As shown in TR-59, a unique prismatic channel bottom width meets the above requirement for a given set of Q, H, ZU, and CS values. However, a solution is not possible if the above parameters are not compatible.

The graphical solution for the prismatic channel design uses the same design criteria used in the computer program described in TR-59.

Charts

For a side slope, ZU, a set of three basic charts is used for the prismatic channel design. A set of charts for ZU = 2 is contained in ES-209 and a set of charts for ZU = 3 is in ES-210. Each of the three basic charts is plotted with $\frac{Q}{H^{2.5}}$ vs. $\frac{H}{BU}$ and contains either a family of $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$, $s_n\left(\frac{K}{FS}\right)^{0.5}$, or CS curves.

Where ZU = 2, the maximum tractive stress on the sides, τ_{sm}, always controls the design; therefore, only a set of charts where sides control is required for the graphical solution. However, where ZU = 3, the maximum tractive stress on the sides, τ_{sm}, or the maximum tractive stress on the bottom, τ_{bm}, may control. Thus, a set of charts for each condition is provided.

When ZU = 3, ES-208 may be used to determine if side or bottom controls for values of the angle of repose, θ, and $\frac{BU}{DN}$. (Approximate values for the angle of repose may be obtained from Figure 2.) From ES-208, where θ is less than 38.8 degrees, the sides control for all values of $\frac{BU}{DN}$. The tractive stress on the sides often controls the design; therefore, it is suggested that the charts for side control be used for the initial design attempt.

The charts are for particular values of the coefficients C50, CN, and EXPN. In the computations for the charts, these coefficients have the following values:

C50 = 4.0

CN = 0.0395

EXPN = 1/6.

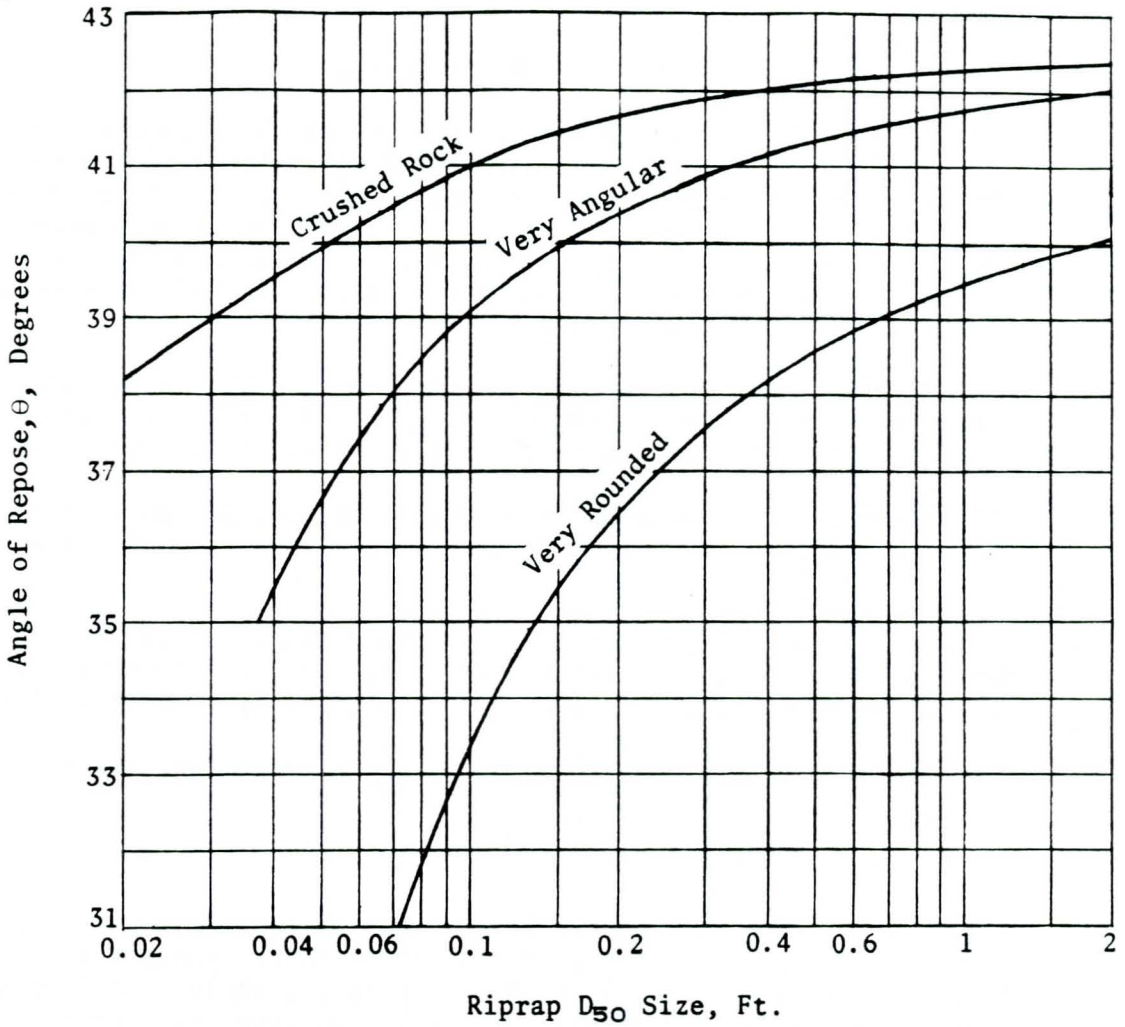

Figure 2. Riprap angle of repose for riprap shape and D_{50} size (taken from Figure 24 of NCHRP Report 108[1])

For the same input information, the graphical solution will not always produce precisely the same answers as given by the computer program solution. The differences occur because the research data is approximated by slightly different techniques in the computations for the charts and in the computer program.

Where the intersection of the $\frac{Q}{H^{2.5}}$ and $\frac{H}{BU}$ values is above the top curve plotted, the corresponding CS value exceeds the maximum allowable CS value of 0.7.

Procedure Flow Charts

The procedure for determining the prismatic channel design is given in the flow charts of Figure 3 and Figure 4. Figure 3 contains the flow chart for the basic graphical solution of the riprap prismatic channel. Figure 4 is the same as Figure 3 except that the flow chart includes the procedure for rounding the values of BU and/or D_{50}.

[1]Publication of the Transportation Research Board, National Research Council, National Academy of Sciences - National Academy of Engineering, 1970

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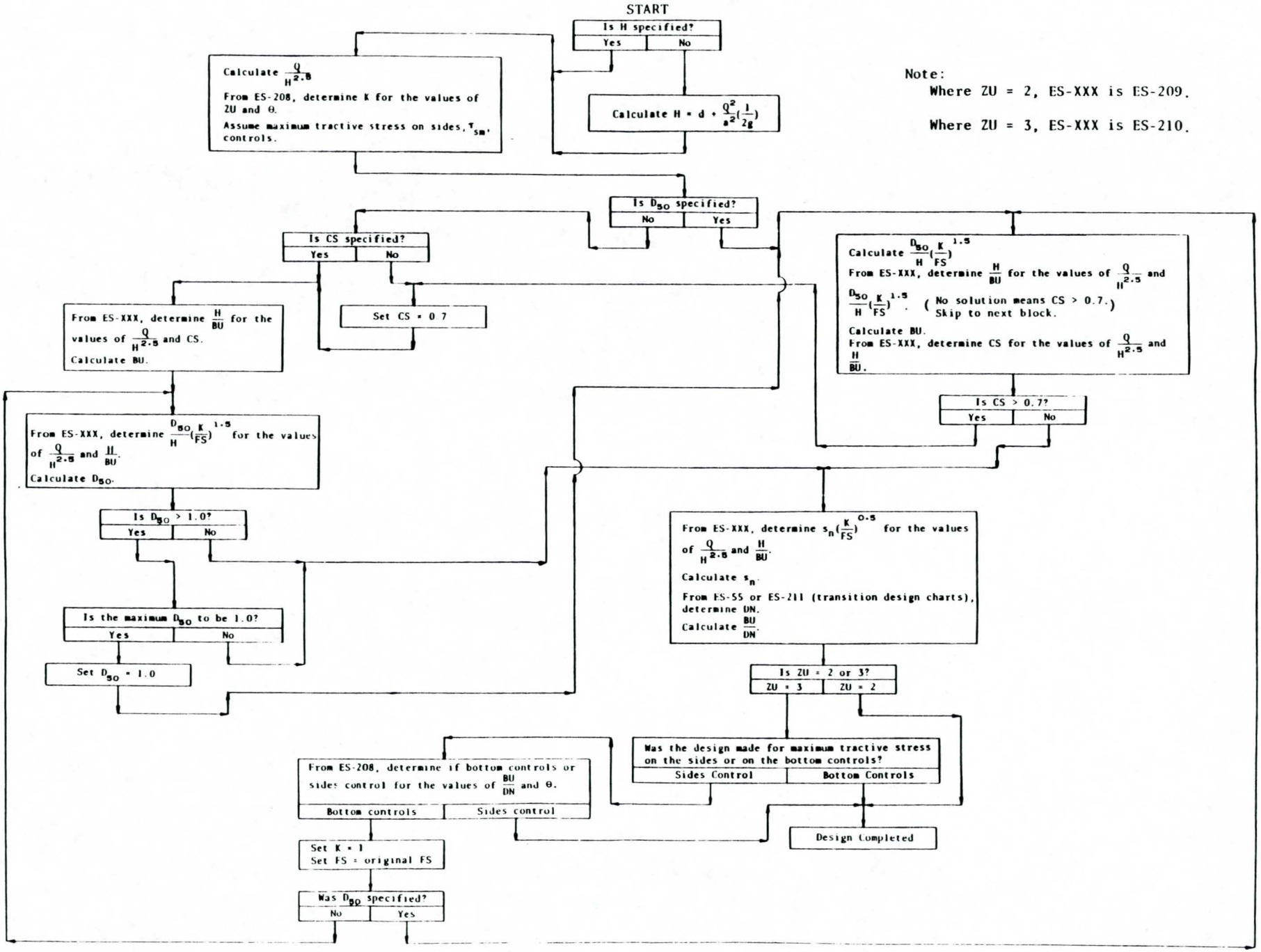

Figure 3. Flow chart for graphical solution of prismatic channel

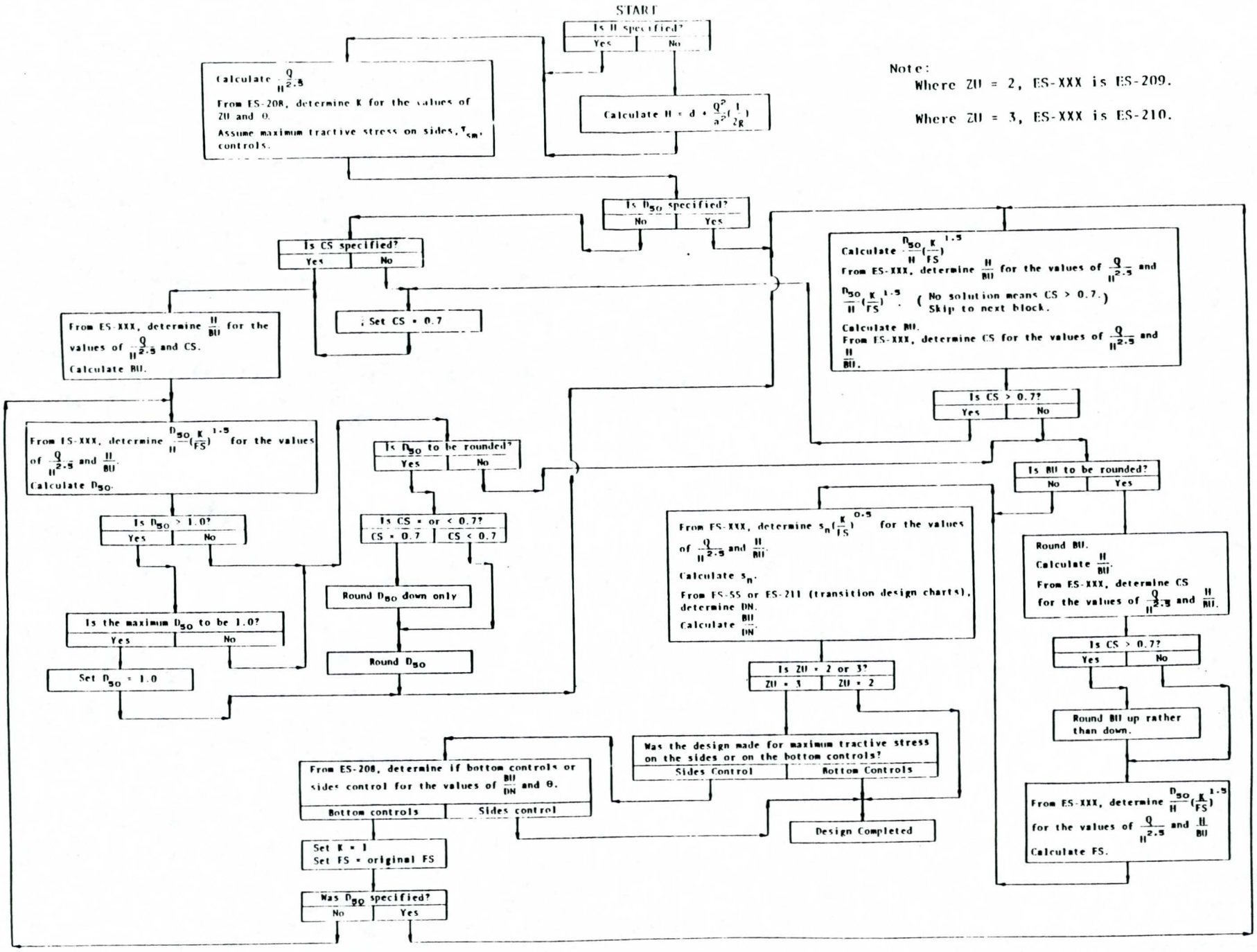

Figure 4. Flow chart for graphical solution of prismatic channel with rounding of BU and/or D_{50}

Transition Design

The transitions associated with the riprap structure are designed to convey the design discharge, Q, through the transitions at a constant specific energy head, H. To maintain a constant H when the bottom width is changing requires that the bottom slope of the transition be variable, changing from the slope of the riprap prismatic channel to flatter slopes at the upstream and downstream ends of the structure. The instantaneous bottom slope of the transition equals the rate of friction head loss at that section when the design discharge, Q, flows at normal depth, d_n, and at the design specific energy head, H.

The bottom width of the transition, b, varies linearly from the bottom width of the channel, BS, immediately upstream or downstream of the structure to the bottom width of the prismatic channel, BU. The side slope of the transition, z, also varies linearly from the side slope of the channel, ZS, immediately upstream or downstream of the structure to the side slope of the prismatic channel, ZU.

The recommended minimum allowable value of the rate of convergence, CONV, of the bottom width of the upstream transition is two. The length of the upstream transition, LUT, is equal to $\mathrm{CONV}(\frac{BS-BU}{2})$. The recommended minimum allowable value for the rate of divergence, DIV, of the bottom width of the downstream transition is four. The length of the downstream transition, LDT, is equal to $\mathrm{DIV}(\frac{BS-BU}{2})$.

Charts

The charts used for the transition design are contained in ES-211. ES-211 is plotted with $\frac{zd}{b}$ vs. $\frac{b^5}{z^3Q^2}$ for a family of $\frac{zH}{b}$ curves and with $\frac{zd}{b}$ vs. $s(\frac{b^5}{z^3Q^2})(\frac{b}{D_{50}})^{1/3}$ for a family of z curves.

The conversion losses in the transition are not considered in the design of the riprap structure since a more conservative design of the structure is obtained by ignoring these losses. However, the conversion losses may be significant in determining an upper limit for the water surface profile upstream of the riprap structure. TR-59 gives two equations that may be used to determine conversion losses in transitions.

Procedure Flow Chart

The procedure for determining the transition design is given in the flow chart of Figure 5.

The transition bottom width, b, varies linearly from BS to BU. The transition side slope, z, varies linearly from ZS to ZU.

Calculate $LUT = CONV\left(\frac{BS - BU}{2}\right)$

Calculate $LDT = DIV\left(\frac{BS - BU}{2}\right)$

For computational purposes, divide the length of the transition into m equal parts; thus, there are m + 1 sections in the transition.

↓

Determine b and z at each section.

↓

Calculate $\frac{b^5}{z^3Q^2}$ and $\frac{zH}{b}$ at each section.

↓

From ES-211, determine $\frac{zd}{b}$ for the values of $\frac{b^5}{z^3Q^2}$ and $\frac{zH}{b}$ at each section.

Calculate d at each section.

↓

From ES-211, determine $s\left(\frac{b^5}{z^3Q^2}\right)\left(\frac{b}{D_{50}}\right)^{1/3}$ for the values of $\frac{zd}{b}$ and z at each section.

Calculate s at each section.

↓

Calculate the total rise at each section. At any section j, the total rise is $RISE]_j = \frac{1}{2}(s_j + s_{j-1})\left(\frac{LUT}{m} \text{ or } \frac{LDT}{m}\right) + RISE]_{j-1}$

Figure 5. Flow chart for graphical solution of transitions

Summary of Design Criteria

The following basic criteria govern the design of the riprap structure:

1. The specific energy head, H, at every section of the riprap structure is set equal to the specific energy head at the junction of the downstream transition and the downstream channel, Section A-A of Figure 1. Specific energy head is given by

$$H = d + \frac{v^2}{2g} = d + \frac{Q^2}{2ga^2}$$

2. The prismatic channel bottom slope, s_n, is set equal to or less than 0.7 of the critical slope, s_c. The bottom slope s_n, is expressed as a fraction of the critical slope, i.e.,

$$s_n = CS(s_c)$$

$$\text{where} \quad 0 < CS \leq 0.7$$

3. Manning's coefficient of roughness, n, is a function of the D_{50} size of the riprap and has been evaluated to be

$$n = 0.0395\ (D_{50})^{1/6}$$

4. The critical tractive stress is a linear function of the D_{50} size of the riprap, i.e.,

$$\tau_{bc} = 4.0\ D_{50}$$

$$\tau_{sc} = K(4.0\ D_{50})$$

5. The riprap size and structure dimensions are selected so that for the design discharge the maximum tractive stress on the riprap does not exceed the allowable tractive stress. Either side or bottom tractive stress may control.

For a given design discharge, Q, specific energy head, H, and side slope, ZU, the variables that must be adjusted to meet these conditions are bottom width, BU; bottom slope, s_o; and riprap size, D_{50}.

The length of the prismatic channel, LPC, is equal to the vertical drop of the prismatic channel divided by the bottom slope, s_n. The vertical drop of the prismatic channel depends on the amount of gradient control required.

Example No. 1

Given:

$Q = 1000$ cfs	$CS = 0.7$
$H = 4.8$ ft	$\theta = 39^{o}$
$ZU = 2$	$FS = 1.5$

Required:

Design a riprap trapezoidal channel with D_{50} not exceeding 1.0 ft.

Solution:

I. Determine the values of $\frac{Q}{H^{2.5}}$ and K.

$$\frac{Q}{H^{2.5}} = \frac{1000}{(4.8)^{2.5}} = 19.8$$

Use ES-208, plot for K vs. θ.

For ZU = 2 and $\theta = 39^{o}$, read K = 0.704.

II. Determine the bottom width of the prismatic channel, BU.

Use ES-209, sheet 5.

For $\frac{Q}{H^{2.5}} = 19.8$ and CS = 0.7, read $\frac{H}{BU} = 0.194$.

Then

$$BU = \frac{4.8}{0.194} = 24.7 \text{ ft}$$

III. Determine the riprap D_{50} size.

Use ES-209, sheet 1.

For $\frac{Q}{H^{2.5}} = 19.8$ and $\frac{H}{BU} = 0.194$, read $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.085$.

Then

$$D_{50} = (0.085)H\left(\frac{FS}{K}\right)^{1.5} = (0.085)(4.8)\left(\frac{1.5}{0.704}\right)^{1.5} = 1.27 \text{ ft}$$

Set D_{50} to 1.0 ft.

Then

$$\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = \frac{1.0}{4.8}\left(\frac{0.704}{1.5}\right)^{1.5} = 0.067$$

IV. Determine the bottom width of the prismatic channel, BU.

Use ES-209, sheet 1.

For $\frac{Q}{H^{2.5}} = 19.8$ and $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.067$, read $\frac{H}{BU} = 0.188$.

Then

$$BU = \frac{4.8}{0.188} = 25.5 \text{ ft}$$

V. Determine CS.

Use ES-209, sheet 5.

For $\frac{Q}{H^{2.5}} = 19.8$ and $\frac{H}{BU} = 0.188$, read CS = 0.60

VI. Determine the bottom slope of the prismatic channel, s_n.

Use ES-209, sheet 3.

For $\frac{Q}{H^{2.5}} = 19.8$ and $\frac{H}{BU} = 0.188$, read $s_n\left(\frac{K}{FS}\right)^{0.5} = 0.0069$.

Then

$$s_n = (0.0069)\left(\frac{FS}{K}\right)^{0.5} = (0.0069)\left(\frac{1.5}{0.704}\right)^{0.5} = 0.010$$

VII. Determine the depth of flow in the prismatic channel, DN.

Use ES-55.

$$\frac{n\,Q}{BU^{8/3}\,s_n^{1/2}} = \frac{0.0395(1.0)^{1/6}(1000)}{(25.5)^{8/3}(0.010)^{1/2}} = 0.070$$

Use ES-55, sheet 2.

For $\frac{n\,Q}{BU^{8/3}\,s_n^{1/2}} = 0.070$ and ZU = 2, read $\frac{DN}{BU} = 0.151$.

$$DN = (0.151)(25.5) = 3.85 \text{ ft}$$

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Example No. 2

Given:

$Q = 2500$ cfs
$ZU = 3$
$H = 6.5$ ft

$D_{50} = 1.25$ ft (trial value)
$\theta = 35^{o}$
$FS = 1.25$

Required:

Design a riprap trapezoidal channel having the steepest stable bottom slope consistent with the above conditions. (Notice that this example is the same as Example No. 1 in TR-59.)

Solution:

I. Determine the values of $\frac{Q}{H^{2.5}}$ and $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$.

$$\frac{Q}{H^{2.5}} = \frac{2500}{(6.5)^{2.5}} = 23.2$$

Use ES-208, plot of K vs. θ.
For $ZU = 3$ and $\theta = 35^{o}$, read $K = 0.834$.
Then

$$\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = \frac{1.25}{6.5}\left(\frac{0.834}{1.25}\right)^{1.5} = 0.105$$

II. Determine the bottom width of the prismatic channel.

Use ES-208, plot of $\frac{BU}{DN}$ vs. θ

For $\theta = 35^{o}$ and any value of $\frac{BU}{DN}$, tractive stress on the sides controls. Thus, use ES-210 and charts where tractive stress on the sides, τ_{sm}, controls.

Use ES-210, sheet 1.

For $\frac{Q}{H^{2.5}} = 23.2$ and $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.105$, the intersection is above the plotted values indicating that CS is greater than the maximum allowable CS of 0.7.
Therefore, CS is set equal to 0.7.

Use ES-210, sheet 9.

For $\frac{Q}{H^{2.5}} = 23.2$ and $CS = 0.7$, read $\frac{H}{BU} = 0.179$.

Then

$$BU = \frac{6.5}{0.179} = 36.3 \text{ ft}$$

III. Determine the riprap D_{50} size corresponding to CS = 0.7.

Use ES-210, sheet 1.

For $\frac{Q}{H^{2.5}} = 23.2$ and $\frac{H}{BU} = 0.179$, read $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.095$.

Then

$$D_{50} = (0.095)\ H\ \left(\frac{FS}{K}\right)^{1.5} = (0.095)(6.5)\left(\frac{1.25}{0.834}\right)^{1.5} = 1.1 \text{ ft}$$

The recommended maximum allowable D_{50} is 1.0 ft (this is the upper limit of the experimental data), but the calculated D_{50} will be used.

IV. Determine the bottom slope of the prismatic channel, s_n.

Use ES-210, sheet 3.

For $\frac{Q}{H^{2.5}} = 23.2$ and $\frac{H}{BU} = 0.179$, read $s_n\left(\frac{K}{FS}\right)^{0.5} = 0.0090$.

Then

$$s_n = (0.0090)\left(\frac{FS}{K}\right)^{0.5} = (0.0090)\left(\frac{1.25}{0.834}\right)^{0.5} = 0.011$$

V. Determine the depth of flow in the prismatic channel, DN.

Use ES-55.

$$\frac{nQ}{BU^{8/3}\ s_n^{1/2}} = \frac{0.0395(1.1)^{1/6}(2500)}{(36.3)^{8/3}(0.011)^{1/2}} = 0.066$$

Use ES-55, sheet 2.

For $\frac{n\ Q}{BU^{8/3}\ s_n^{1/2}} = 0.066$ and ZU = 3, read $\frac{DN}{BU} = 0.14$.

Then

$$DN = (0.14)(36.3) = 5.1 \text{ ft}$$

Note: If the D_{50} = 1.25 ft is used, the factor of safety, FS, will be increased. The FS associated with D_{50} = 1.25 ft and CS = 0.7 may be obtained from step III, where $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.095$. Solving for FS, obtain FS = 1.33. Of course, the associated values of s_n and DN must be computed.

Example No. 3

Given:

$Q = 2750$ cfs
$DS = 7.0$ ft
$BS = 100$ ft
$ZS = 3$

$ZU = 3$
$D_{50} = 0.75$ ft
$\theta = 42^{o}$
$FS = 2.0$

Required:

Design a riprap trapezoidal channel having the steepest stable bottom slope consistent with the above conditions.

Solution:

I. Determine the specific energy head, H, and the values of

$$\frac{Q}{H^{2.5}} \text{ and } \frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}.$$

$$H = DS + \frac{v^2}{2g} = DS + \frac{Q^2}{a^2}\left(\frac{1}{2g}\right).$$

$$a = (BS + ZS(DS))DS = (100 + 3(7))7 = 847 \text{ ft}^2$$

Then

$$H = 7.0 + \left(\frac{2750}{847}\right)^2\left(\frac{1}{64.32}\right) = 7.0 + 0.16 = 7.16 \text{ ft}$$

$$\frac{Q}{H^{2.5}} = \frac{2750}{(7.16)^{2.5}} = 20.0$$

Use ES-208, plot of K vs. θ.

For $ZU = 3$ and $\theta = 42^{o}$, read $K = 0.881$.

Then

$$\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = \left(\frac{0.75}{7.16}\right)\left(\frac{0.881}{2.0}\right)^{1.5} = 0.031$$

II. Determine the bottom width of the prismatic channel, BU.

Use ES-210, sheet 1, assuming that the maximum tractive stress on the sides, τ_{sm}, controls.

For $\frac{Q}{H^{2.5}} = 20.0$ and $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.031$, read $\frac{H}{BU} = 0.168$.

Then

$$BU = \frac{7.16}{0.168} = 42.6 \text{ ft}$$

III. Determine CS

Use ES-210, sheet 9.

For $\frac{Q}{H^{2.5}} = 20.0$ and $\frac{H}{BU} = 0.168$, read CS = 0.275

IV. Determine the bottom slope of the prismatic channel, s_n.

Use ES-210, sheet 3.

For $\frac{Q}{H^{2.5}} = 20.0$ and $\frac{H}{BU} = 0.168$, read $s_n\left(\frac{K}{FS}\right)^{0.5} = 0.0025$.

Then

$$s_n = (0.0025)\left(\frac{FS}{K}\right)^{0.5} = (0.0025)\left(\frac{2.0}{0.881}\right)^{0.5} = 0.0038$$

V. Determine the depth of flow in the prismatic channel, DN.

Use ES-55.

$$\frac{n\,Q}{BU^{8/3}\,s_n^{1/2}} = \frac{0.0395(0.75)^{1/6}(2750)}{(42.6)^{8/3}\,(0.0038)^{1/2}} = 0.076$$

Use ES-55, sheet 2.

For $\frac{n\,Q}{BU^{8/3}\,s_n^{1/2}} = 0.076$ and ZU = 3, read $\frac{DN}{BU} = 0.151$.

DN = (0.151)(42.6) = 6.43 ft

VI. Determine whether maximum tractive stress on sides or on bottom controls.

Use ES-208, plot of $\frac{BU}{DN}$ vs θ.

For $\frac{BU}{DN} = \frac{1}{0.151} = 6.6$ and $\theta = 42^{\circ}$, maximum tractive stress on the bottom controls. Therefore, the charts for maximum tractive stress on the bottom, τ_{bm}, controls must be used to de-

termine the values of BU, CS, and s_n. Set K = 1.

VII. Determine bottom width, BU.

$$\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = \left(\frac{0.75}{7.16}\right)\left(\frac{1}{2.0}\right)^{1.5} = 0.037$$

Use ES-210, sheet 5.

For $\frac{Q}{H^{2.5}} = 20.0$ and $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.037$, read $\frac{H}{BU} = 0.165$.

Then

$$BU = \frac{7.16}{0.165} = 43.4 \text{ ft}$$

VIII. Determine CS.

Use ES-210, sheet 9.

For $\frac{Q}{H^{2.5}} = 20.0$ and $\frac{H}{BU} = 0.165$, read CS = 0.265.

IX. Determine the bottom slope, s_n.

Use ES-210, sheet 7.

For $\frac{Q}{H^{2.5}} = 20.0$ and $\frac{H}{BU} = 0.165$, read $s_n\left(\frac{K}{FS}\right)^{0.5} = 0.0026$.

Then

$$s_n = (0.0026)\left(\frac{FS}{K}\right)^{0.5} = (0.0026)\left(\frac{2.0}{1}\right)^{0.5} = 0.0037$$

X. Determine the depth of flow, DN.

Use ES-55.

$$\frac{n\,Q}{BU^{8/3}s_n^{1/2}} = \frac{0.0395(0.75)^{1/6}(2750)}{(43.4)^{8/3}(0.0037)^{1/2}} = 0.073$$

Use ES-55, sheet 2.

For $\frac{n\,Q}{BU^{8/3}\,s_n^{1/2}} = 0.073$ and ZU = 3, read $\frac{DN}{BU} = 0.148$.

Then

$$DN = (0.148)(43.4) = 6.42 \text{ ft}$$

Example No. 4

Given:

Q	= 1200 cfs	θ	= 35°
DS	= 6.0 ft	FS	= 1.2
BS	= 30 ft	CONV	= 2
ZS	= 3	DIV	= 4
ZU	= 3	Total drop in grade through structure = 3.0 ft	
D_{50}	= 0.75 ft		

Required:

The riprap structure required if the determined bottom width is rounded to the next higher even foot.

Solution:

I. Determine the specific energy head, H, and the values of $\frac{Q}{H^{2.5}}$ and $\frac{D_{50}}{H}(\frac{K}{FS})^{1.5}$

$$H = DS + \frac{v^2}{2g} = DS + \frac{Q^2}{a^2}(\frac{1}{2g})$$

$$a = (BS + ZS(DS))DS = (30 + 3(6))6 = 288 \text{ ft}^2$$

Then

$$H = 6.0 + (\frac{1200}{288})^2(\frac{1}{64.32}) = 6.0 + 0.27 = 6.27 \text{ ft}$$

$$\frac{Q}{H^{2.5}} = \frac{1200}{(6.27)^{2.5}} = 12.2$$

Use ES-208, plot of K vs. θ.
For ZU = 3 and $\theta = 35^{o}$, read K = 0.834.

Then

$$\frac{D_{50}}{H}(\frac{K}{FS})^{1.5} = \frac{0.75}{6.27}(\frac{0.834}{1.2})^{1.5} = 0.069$$

II. Determine the bottom width of the prismatic channel of the riprap structure.

Use ES-208, plot of $\frac{BU}{DN}$ vs. θ.

For $\theta = 35^{o}$ and any value of $\frac{BU}{DN}$, tractive stress on the sides controls. Thus, use ES-210 and charts where tractive stress on the sides, τ_{sm}, controls.

Use ES-210, sheet 1.

For $\frac{Q}{H^{2.5}} = 12.2$ and $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.069$, read $\frac{H}{BU} = 0.47$.

Then

$$BU = \frac{H}{0.47} = \frac{6.27}{0.47} = 13.3 \text{ ft}$$

III. Determine CS.
Use ES-210, sheet 9.

For $\frac{Q}{H^{2.5}} = 12.2$ and $\frac{H}{BU} = 0.47$, read CS = 0.48.

CS is less than maximum allowable CS of 0.7.
Round BU to 14 ft.
Then

$$\frac{H}{BU} = \frac{6.27}{14} = 0.448.$$

Then, for $\frac{Q}{H^{2.5}} = 12.2$ and $\frac{H}{BU} = 0.448$, read CS = 0.43.

IV. Determine revised factor of safety, FS.
Use ES-210, sheet 1.

For $\frac{Q}{H^{2.5}} = 12.2$ and $\frac{H}{BU} = 0.448$, read $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5} = 0.06$

Then

$$FS = K\left(\frac{D_{50}}{H(0.06)}\right)^{\frac{1}{1.5}} = (0.834)\left(\frac{0.75}{6.27(0.06)}\right)^{\frac{1}{1.5}}$$

FS = 1.32

V. Determine the bottom slope of the prismatic channel of the riprap structure, s_n.
Use ES-210, sheet 3.

For $\frac{Q}{H^{2.5}} = 12.2$ and $\frac{H}{BU} = 0.448$, read

$$s_n\left(\frac{K}{FS}\right)^{0.5} = 0.0053.$$

$$s_n = 0.0053\left(\frac{FS}{K}\right)^{0.5} = 0.0053\left(\frac{1.32}{0.834}\right)^{0.5} = 0.0067$$

VI. Determine the depth of flow in the prismatic channel of the riprap structure, DN.
Use ES-55.

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$$\frac{nQ}{BU^{8/3}\ s_n^{1/2}} \quad \frac{0.0395(0.75)^{1/6}\ (1200)}{(14)^{8/3}(0.0067)^{1/2}} = 0.485$$

Use ES-55, sheet 3.

For $\frac{n\ Q}{BU^{8/3}\ s_n^{1/2}} = 0.485$ and ZU = 3, read $\frac{DN}{BU} = 0.387$

DN = 0.387(14) = 5.42 ft

VII. Determine the parameters for the design of the transitions. At the junction of the upstream transition and the prismatic channel of the riprap structure, the bottom width of the transition is 14 ft.
Thus

$$\frac{b^5}{z^3\ Q^2} = \frac{(14)^5}{(3)^3(1200)^2} = 0.0138 = 1.38 \times 10^{-2}$$

$$\frac{zH}{b} = \frac{3(6.27)}{14} = 1.34$$

Use ES-211, sheet 2.

For $\frac{b^5}{z^3\ Q^2} = 1.38 \times 10^{-2}$ and $\frac{zH}{b} = 1.34$, read $\frac{zd}{b} = 1.16$.

$$d = \frac{1.16(14)}{3} = 5.41 \text{ ft}$$

Use ES-211, sheet 4.

For $\frac{zd}{b} = 1.16$ and z = 3, read $Y = s\left(\frac{b^5}{z^3\ Q^2}\right)\left(\frac{b}{D_{50}}\right)^{1/3} = 2.5 \times 10^{-4}$.

Then

$$s = \frac{2.5 \times 10^{-4}}{\left(\frac{14}{0.75}\right)^{1/3}(0.0138)} = 0.0068$$

Knowing that the bottom width in the transition varies linearly from BS = 30 ft to BU = 14 ft and using the computational steps above, the parameters for the design of the transitions can be determined.

In the tables shown below, the transitions are divided into four equal parts for computations; however, any number of divisions may be used. The rise for each section of the transition is calculated from the average friction slope for the section times the length between sections. The accumulation of the rise values or the total rise to a section appears in the "RISE" column.

Upstream Transition

Length (ft)	Width, b (ft)	$\frac{b^5}{z^3 Q^2}$	$\frac{zH}{b}$	$\frac{zd}{b}$	Depth, d (ft)	$s(\frac{b^5}{z^3Q^2})(\frac{b}{D_{50}})^{1/3}$	$(\frac{b}{D_{50}})^{1/3}$	Friction Slope, s (ft/ft)	RISE (ft)
0	14	0.0138	1.34	1.16	5.41	2.5×10^{-4}	2.65	0.0068	0
4	18	0.0486	1.045	0.947	5.68	5.7×10^{-4}	2.88	0.0041	0.022
8	22	0.1326	0.855	0.795	5.83	1.1×10^{-3}	3.08	0.0027	0.036
12	26	0.3056	0.723	0.682	5.91	2.1×10^{-3}	3.26	0.0021	0.046
16	30	0.6250	0.627	0.598	5.98	3.5×10^{-3}	3.42	0.0016	0.053

Downstream Transition

Length (ft)	Width, b (ft)	$\frac{b^5}{z^3 Q^2}$	$\frac{zH}{b}$	$\frac{zd}{b}$	Depth, d (ft)	$s(\frac{b^5}{z^3Q^2})(\frac{b}{D_{50}})^{1/3}$	$(\frac{b}{D_{50}})^{1/3}$	Friction Slope, s (ft/ft)	RISE (ft)
0	14	Same as above	Same as above	Same as above	Same as above	Same as above	Same as above	Same as above	0
8	18								0.044
16	22								0.071
24	26								0.090
32	30								0.105

VIII. Determine the total length of the riprap structure.
The total drop in grade through the structure is 3.0 ft.
Drop through prismatic channel of the riprap structure
= 3.0 - (rise in upstream transition) - (rise in downstream transition)

= 3.0 - 0.05 - 0.11

= 2.84 ft

Length of prismatic channel, LPC $= \frac{2.84}{s_n}$

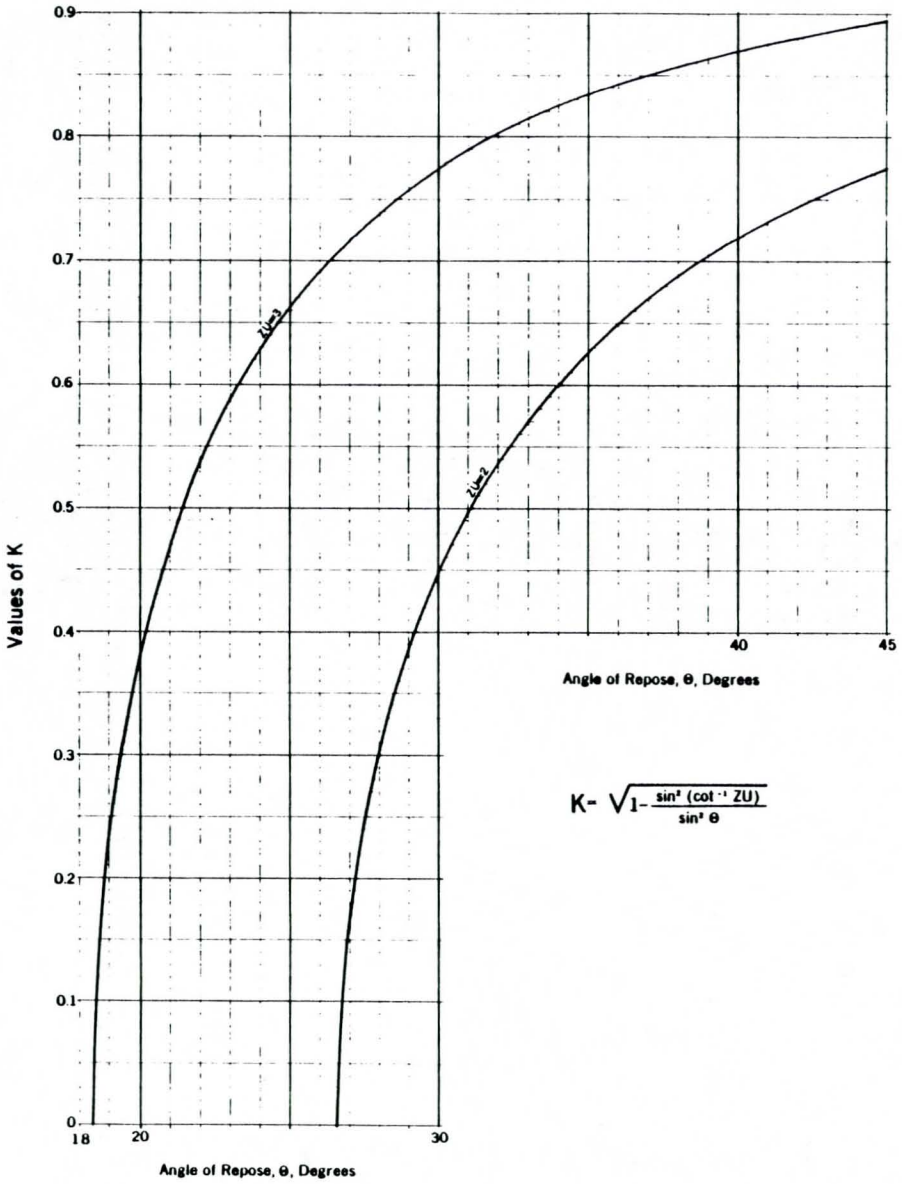
$= \frac{2.84}{0.0067}$

= 424 ft

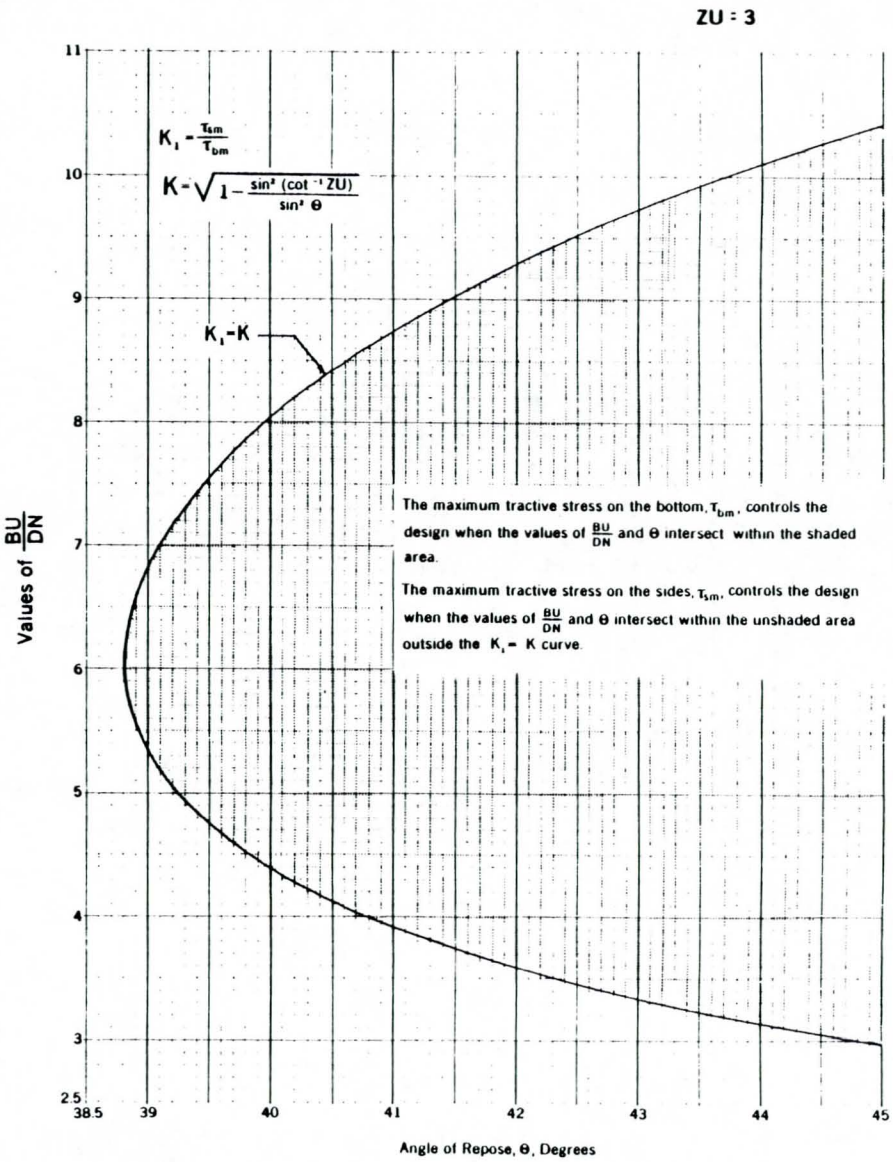
Total length of riprap structure = Length of upstream transition + Length of downstream transition + LPC

Total length = 16 + 32 + 424 = 472 ft

RIPRAP GRADIENT CONTROL STRUCTURES: Determination of K and Determination of Whether Sides or Bottom Controls the Design



$$K = \sqrt{1 - \frac{\sin^2(\cot^{-1} ZU)}{\sin^2 \theta}}$$



The maximum tractive stress on the bottom, τ_{bm}, controls the design when the values of $\frac{BU}{DN}$ and θ intersect within the shaded area.

The maximum tractive stress on the sides, τ_{sm}, controls the design when the values of $\frac{BU}{DN}$ and θ intersect within the unshaded area outside the $K_1 = K$ curve.

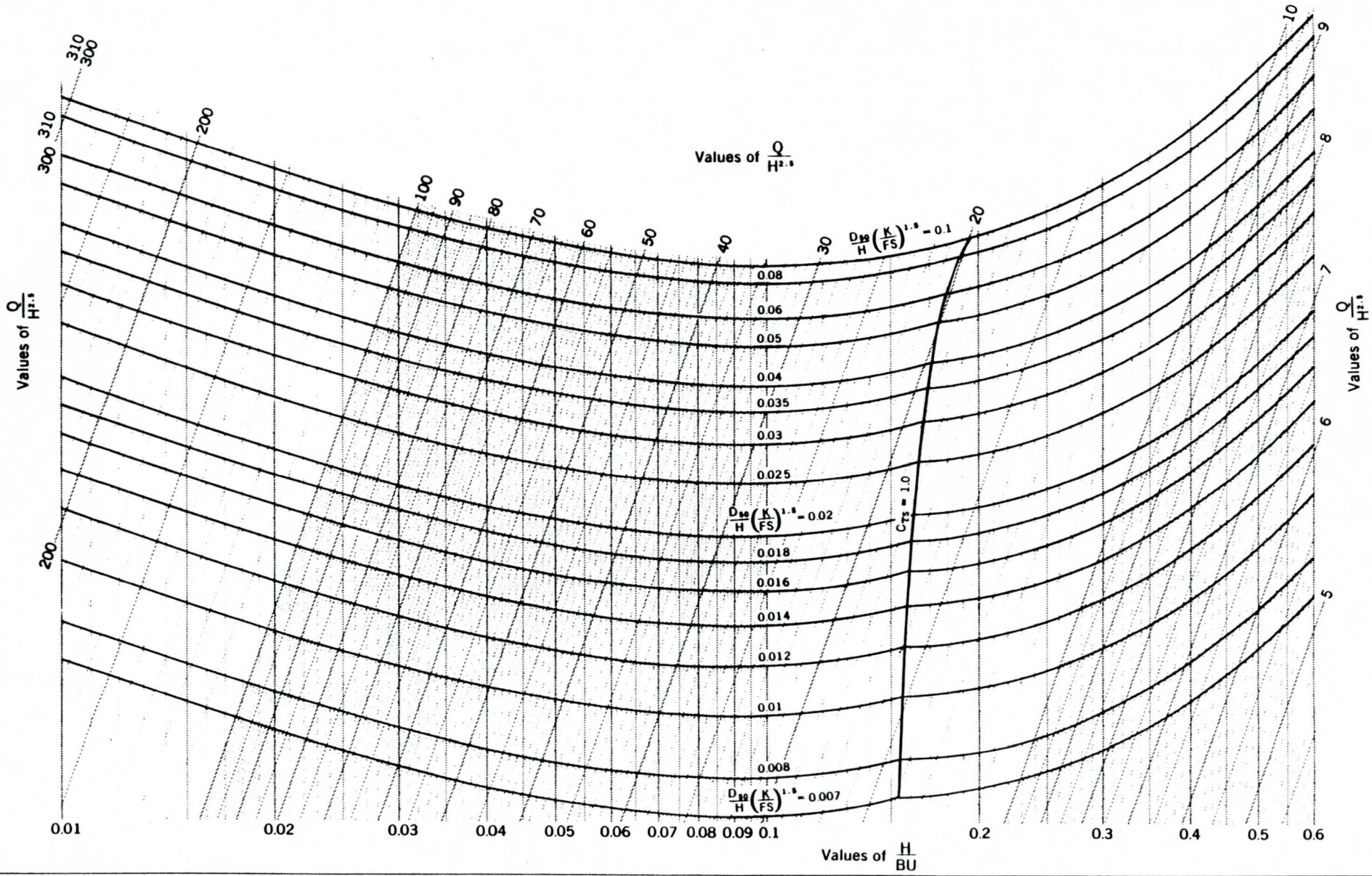
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION DESIGN UNIT

STANDARD DWG. NO.
ES 208
SHEET 1 OF 1
DATE 1/76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$ curves

ZU = 2



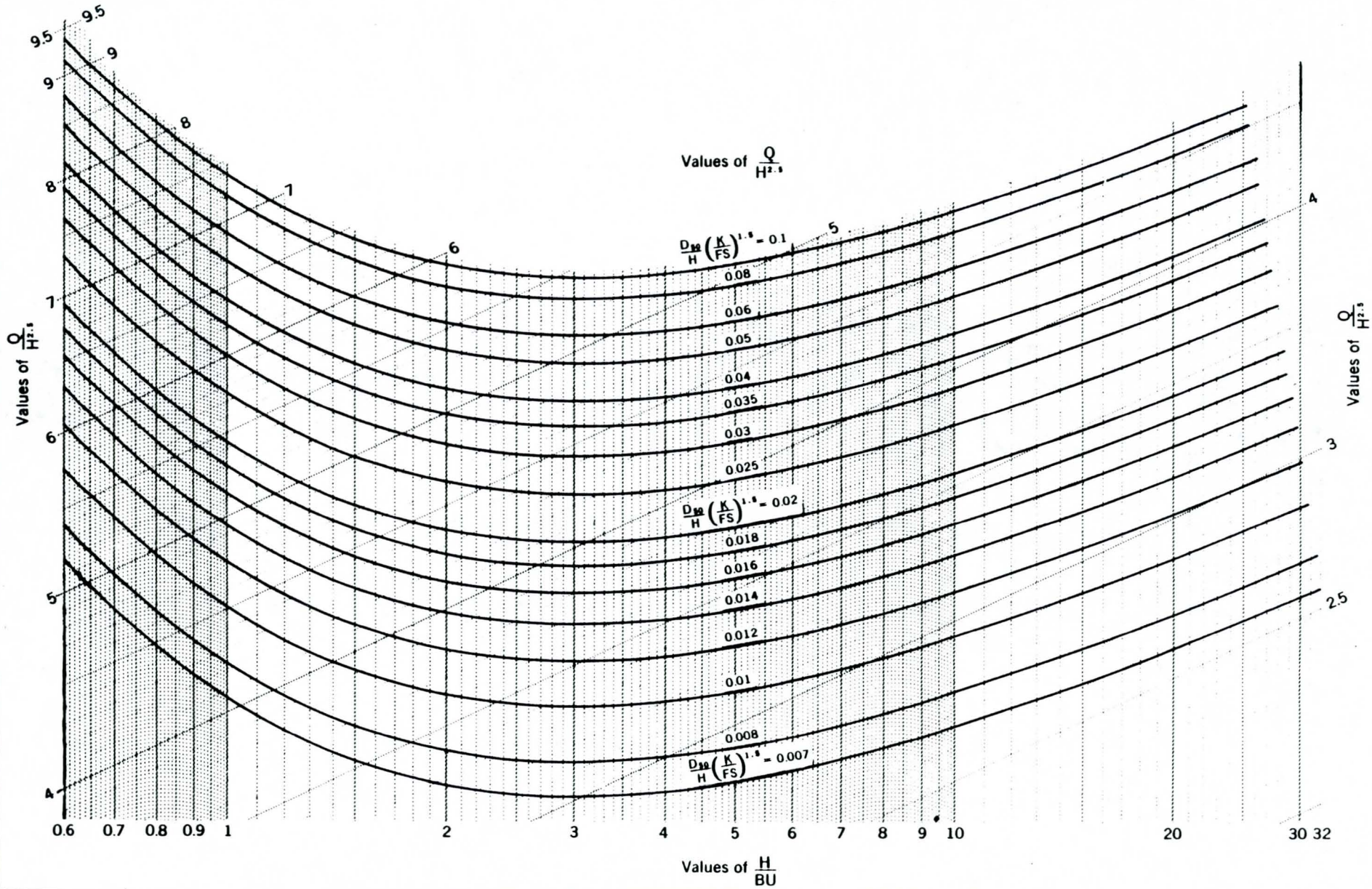
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-209
SHEET 1 OF 6
DATE 1 76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$ curves

ZU = 2



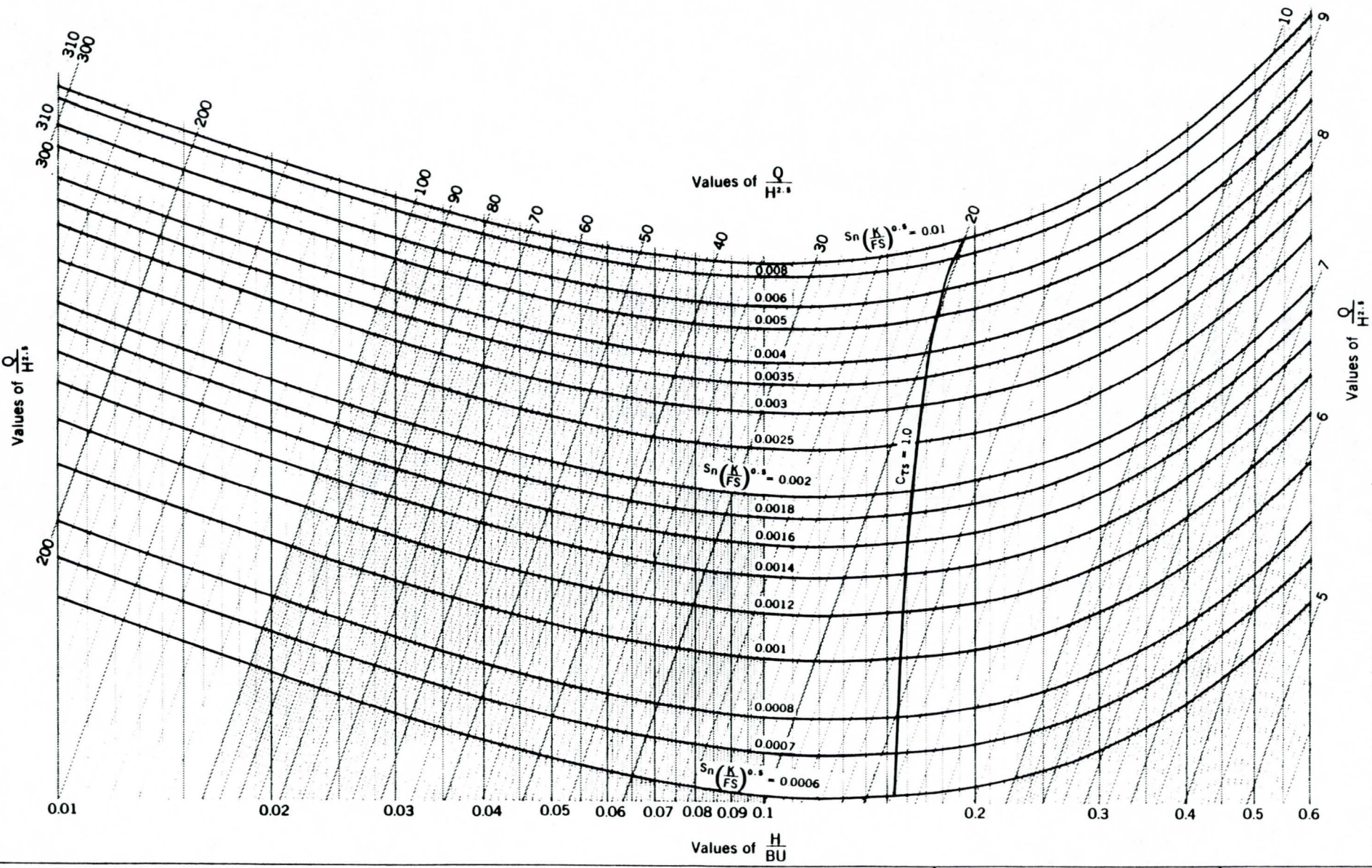
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO. ES-209
SHEET 2 OF 6
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $S_n\left(\frac{K}{FS}\right)^{0.5}$ curves

ZU = 2



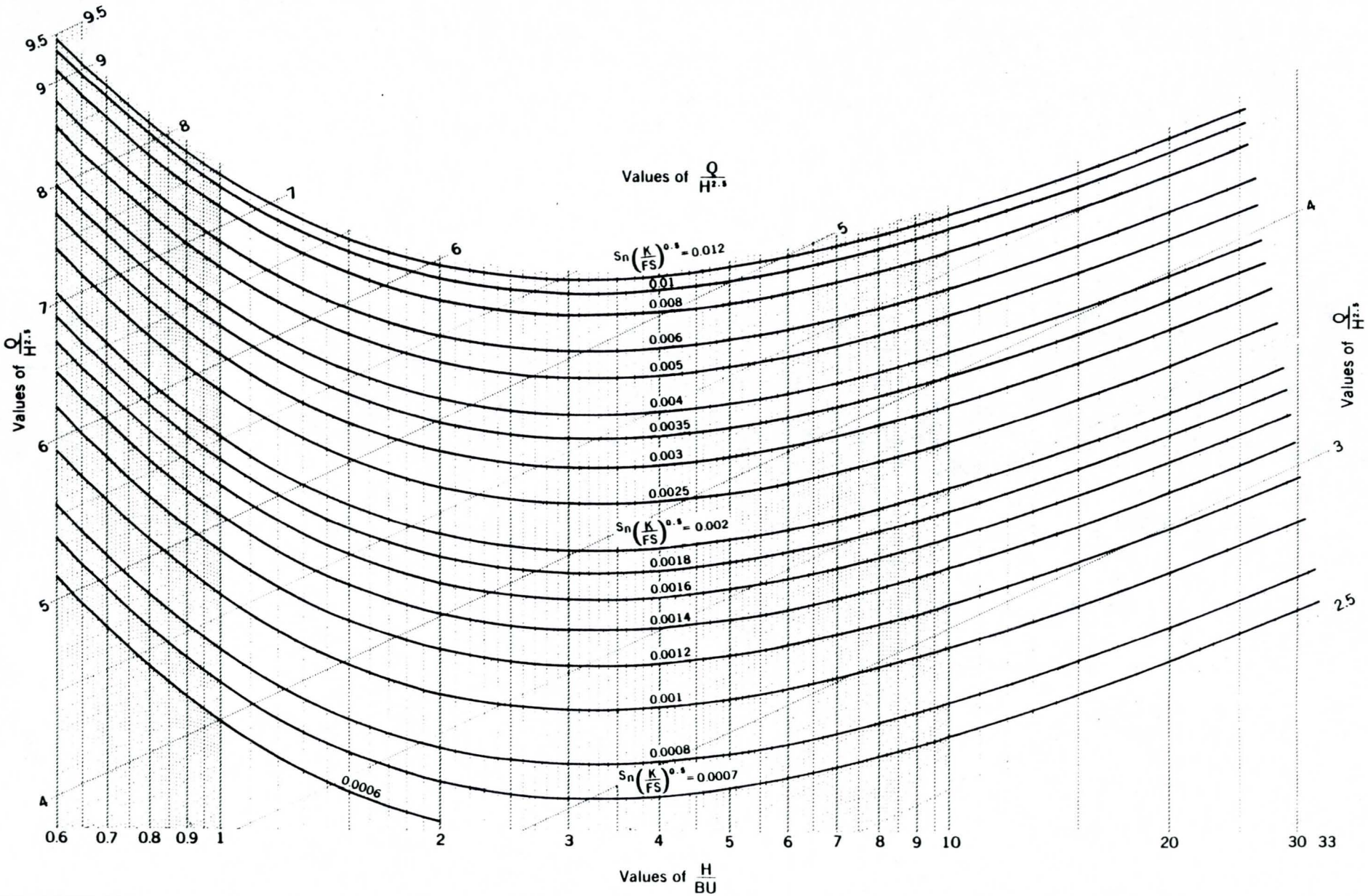
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-209
SHEET 3 OF 6
DATE 1 76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $Sn\left(\frac{K}{FS}\right)^{0.5}$ curves

ZU = 2



REFERENCE

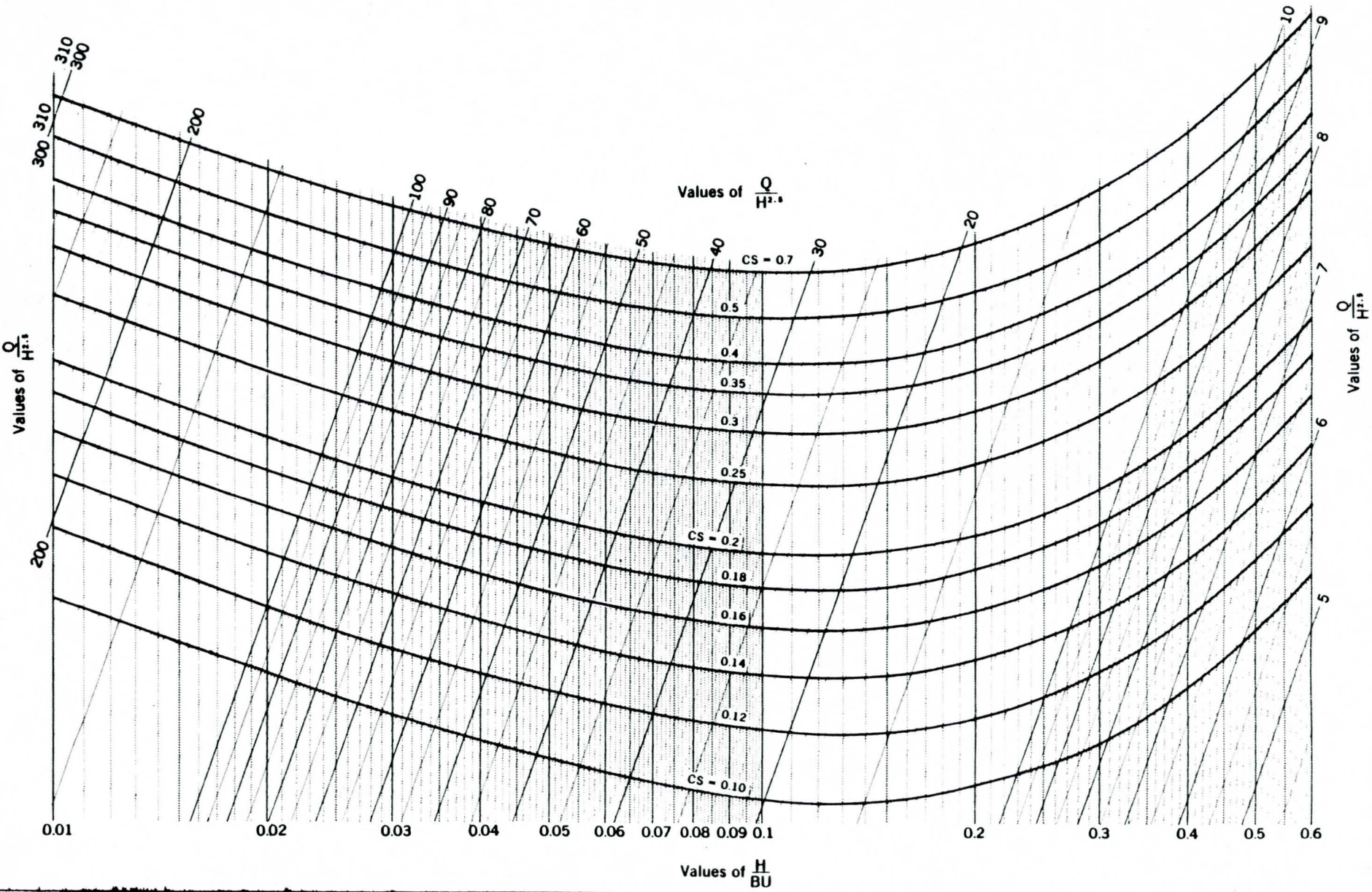
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-209
SHEET 4 OF 6
DATE 1 76

LIBRARY

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with CS curves

ZU = 2



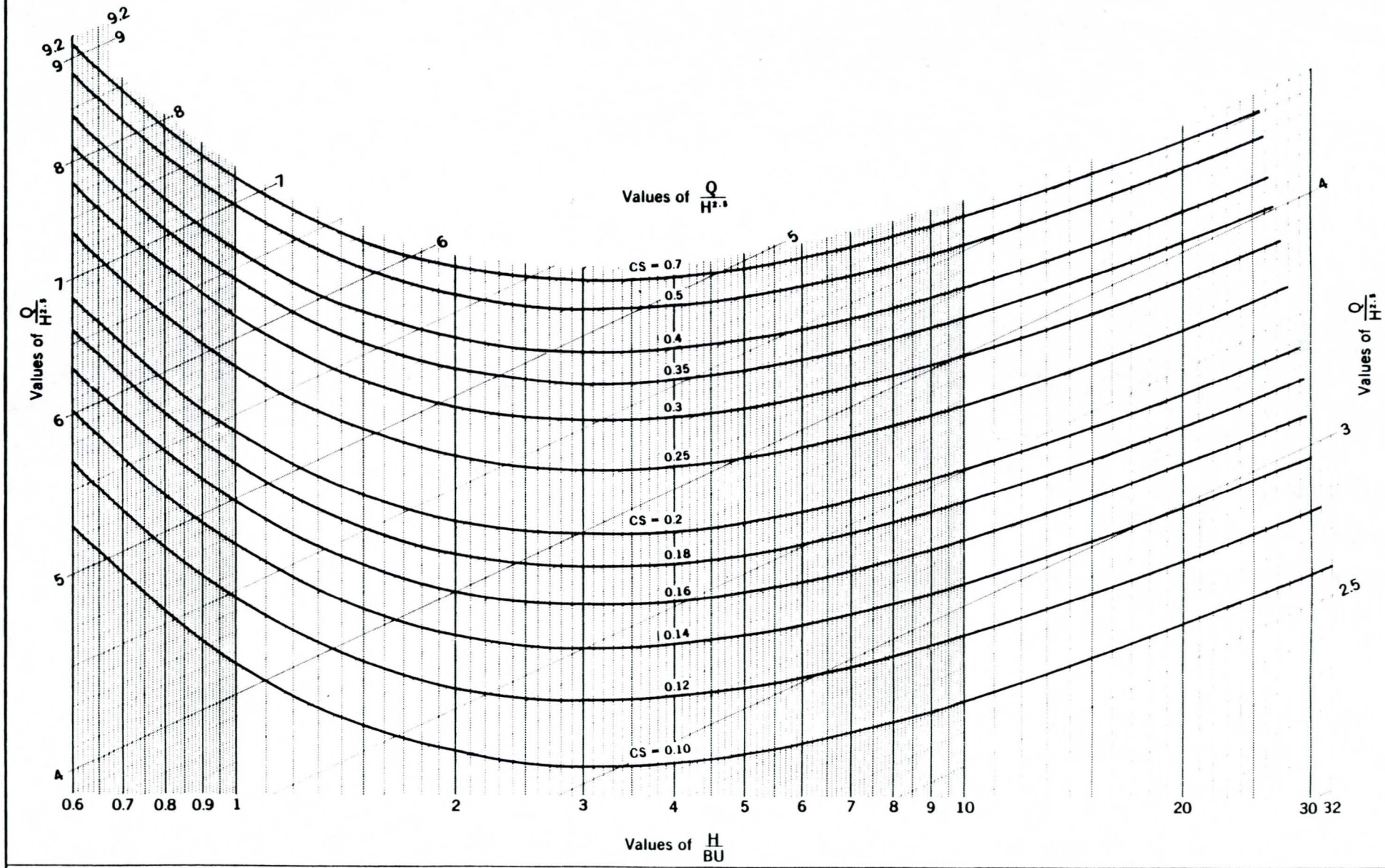
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION · DESIGN UNIT

STANDARD DWG. NO.
ES-209
SHEET 5 OF 6
DATE 1 76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with CS curves

ZU = 2



REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION · DESIGN UNIT

STANDARD DWG. NO.
ES-209
SHEET 6 OF 6
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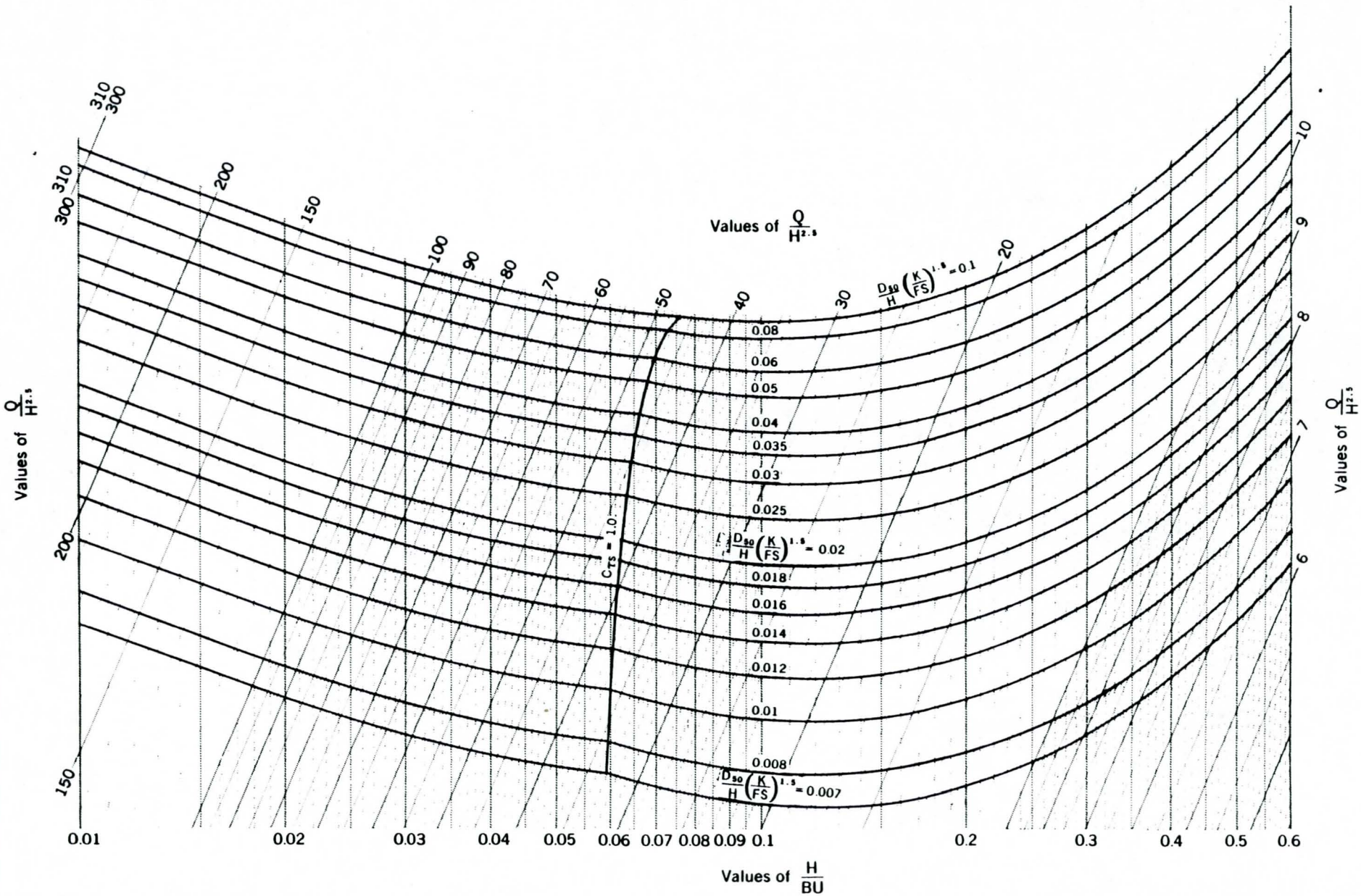
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$ curves

ZU = 3
τ_{sm} controls



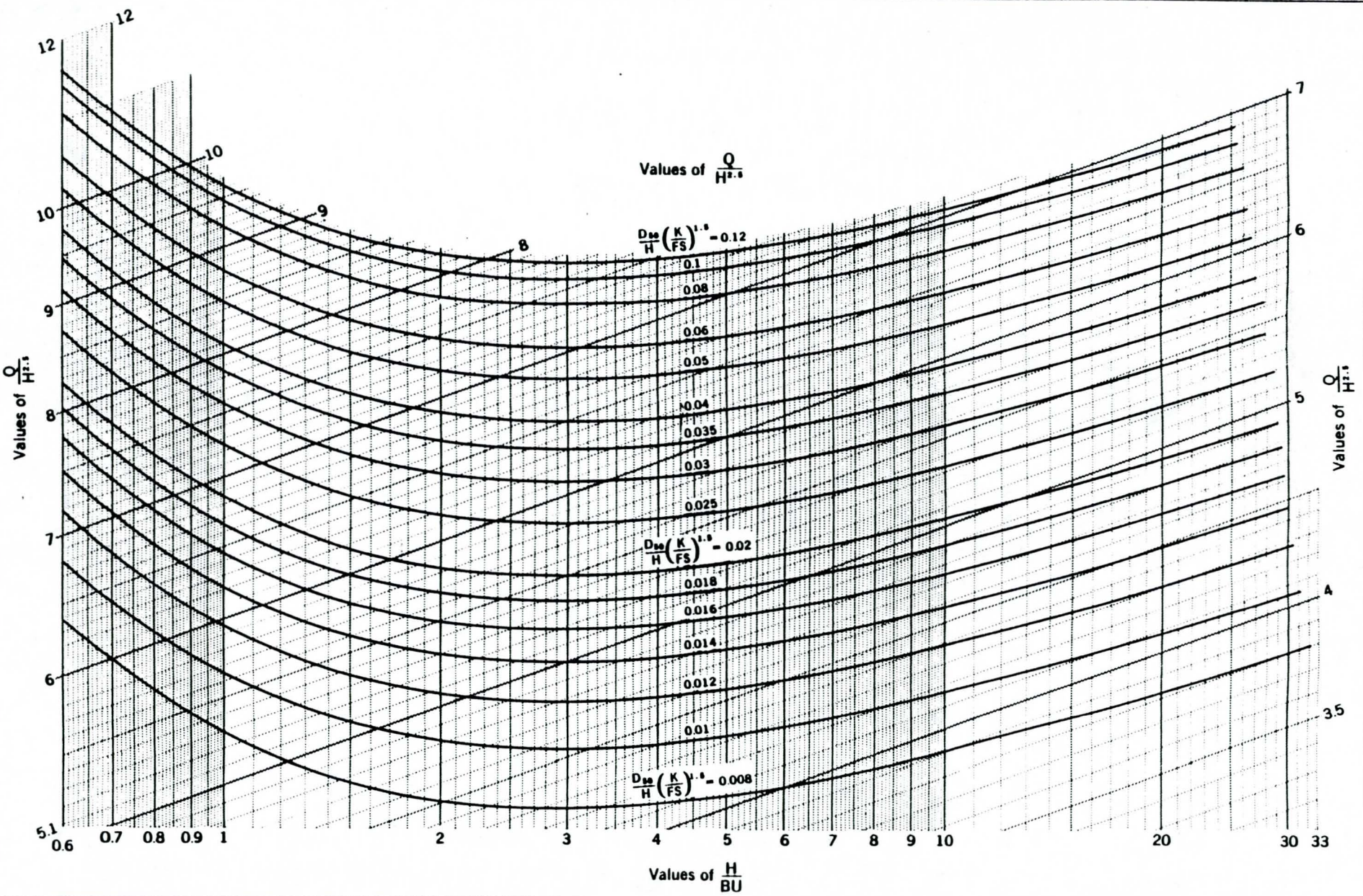
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-210
SHEET 1 OF 10
DATE 1 76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$ curves

ZU = 3
τ_{sm} controls



REFERENCE

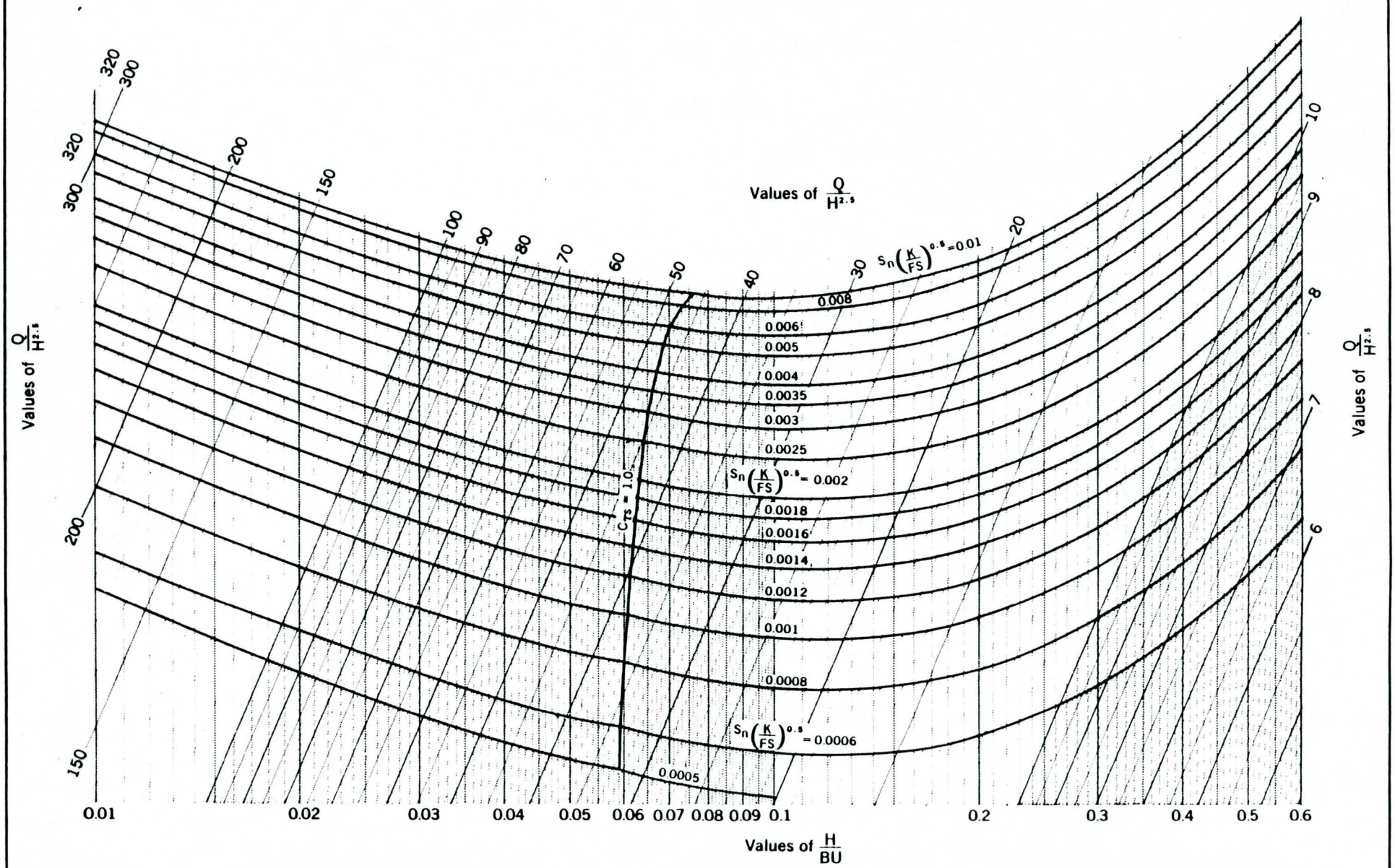
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-210
SHEET 2 OF 10

LIBRARY

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $S_n\left(\frac{K}{FS}\right)^{0.5}$ curves

ZU = 3
τ_{sm} controls



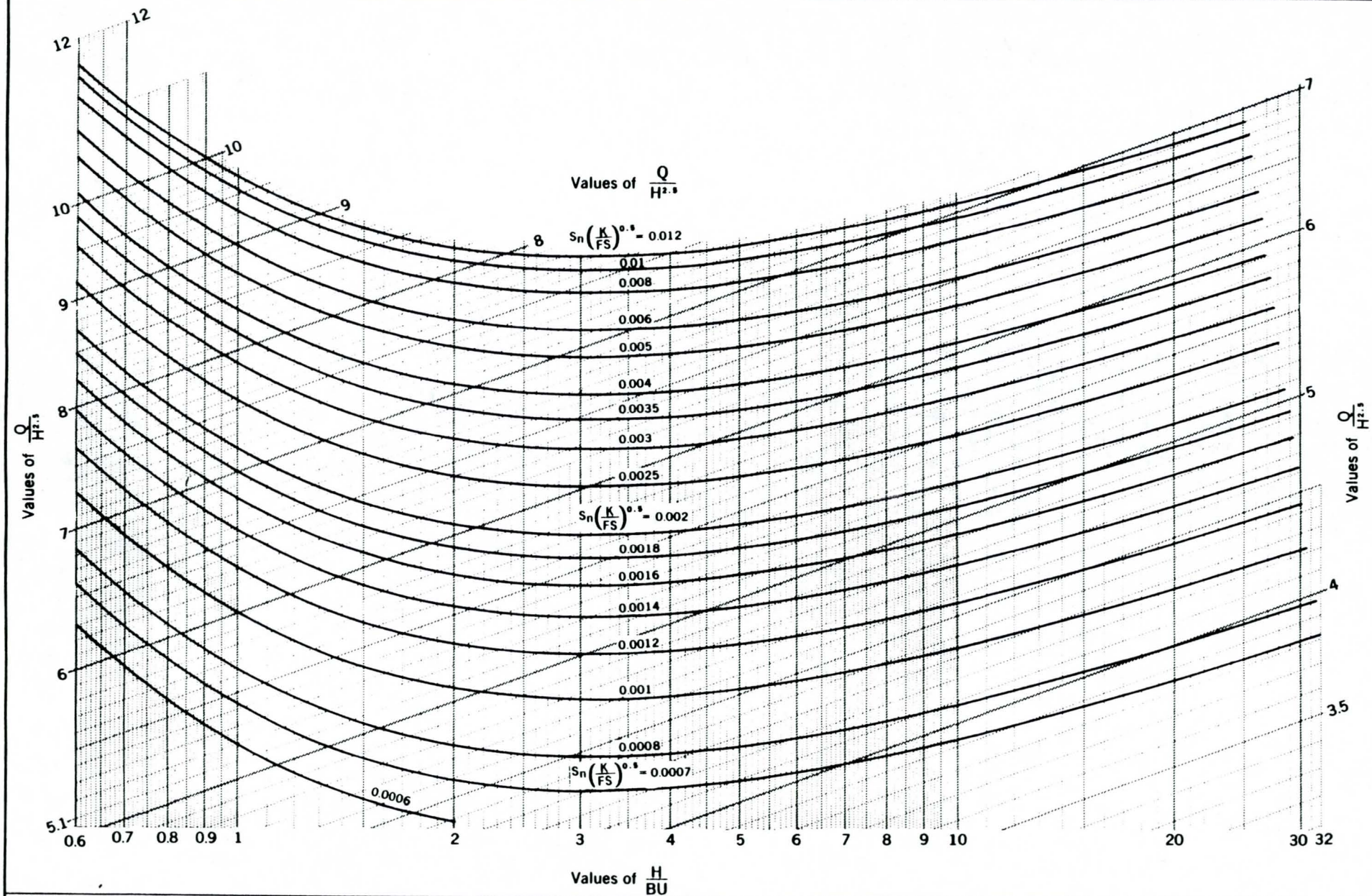
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-210
SHEET 3 OF 10
DATE 1 76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $S_n\left(\frac{K}{FS}\right)^{0.5}$ curves

ZU = 3
τ_{sm} controls



REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION · DESIGN UNIT

STANDARD DWG. NO.
ES-210
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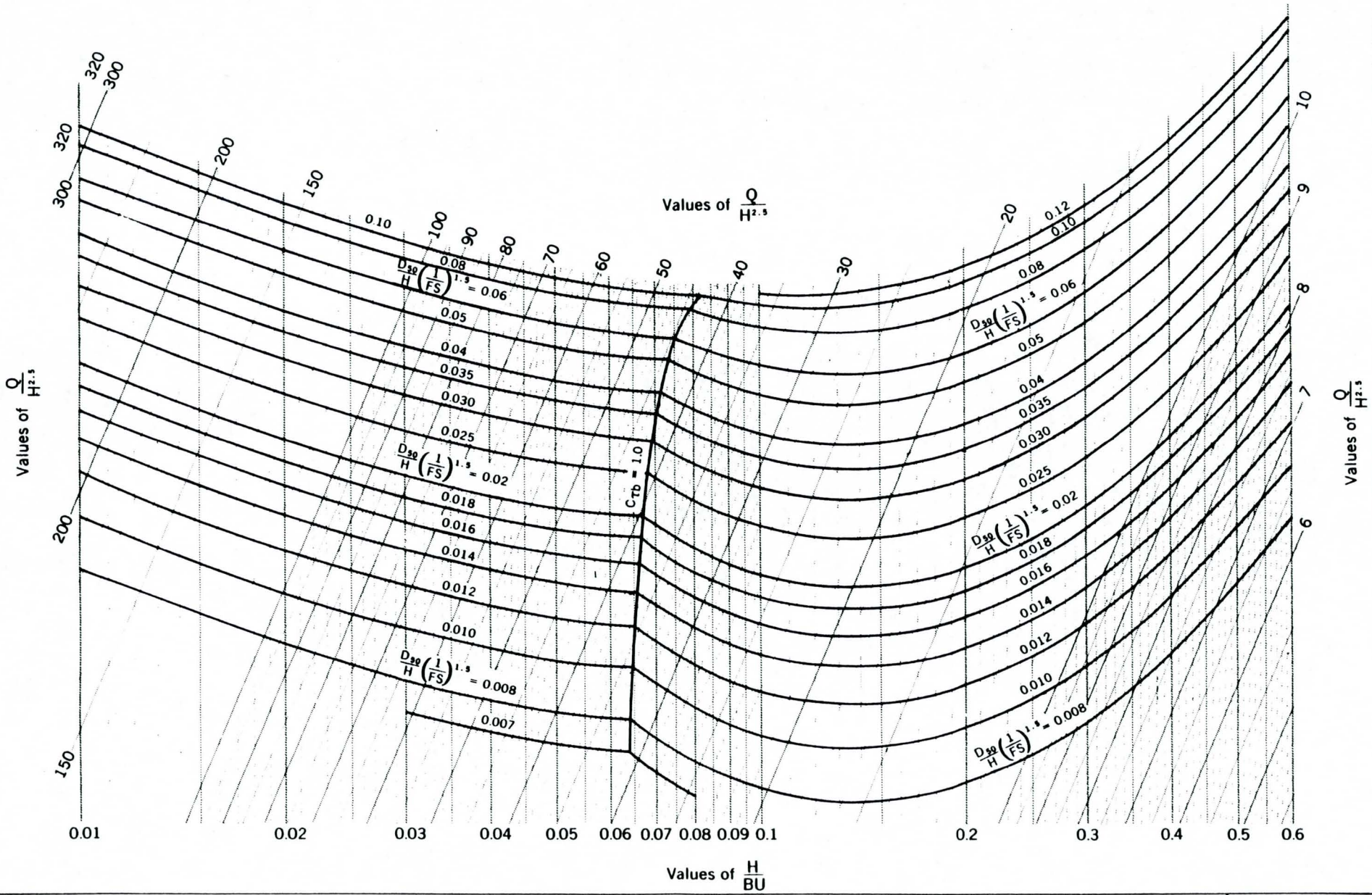
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{1}{FS}\right)^{1.5}$ curves

ZU = 3
τ_{bm} controls



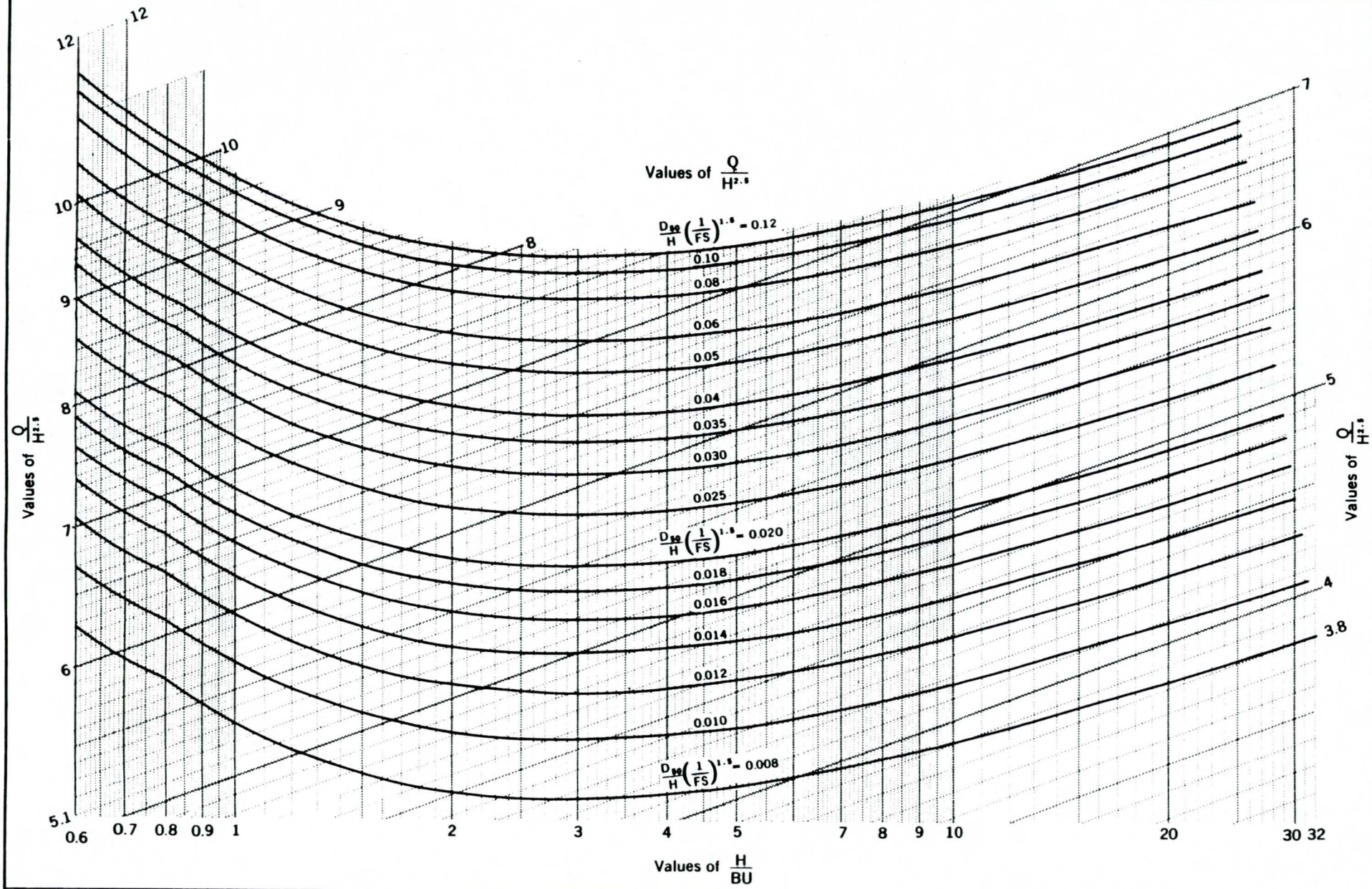
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-210
SHEET 5 OF 10
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{1}{FS}\right)^{1.5}$ curves

ZU = 3
τ_{bm} controls



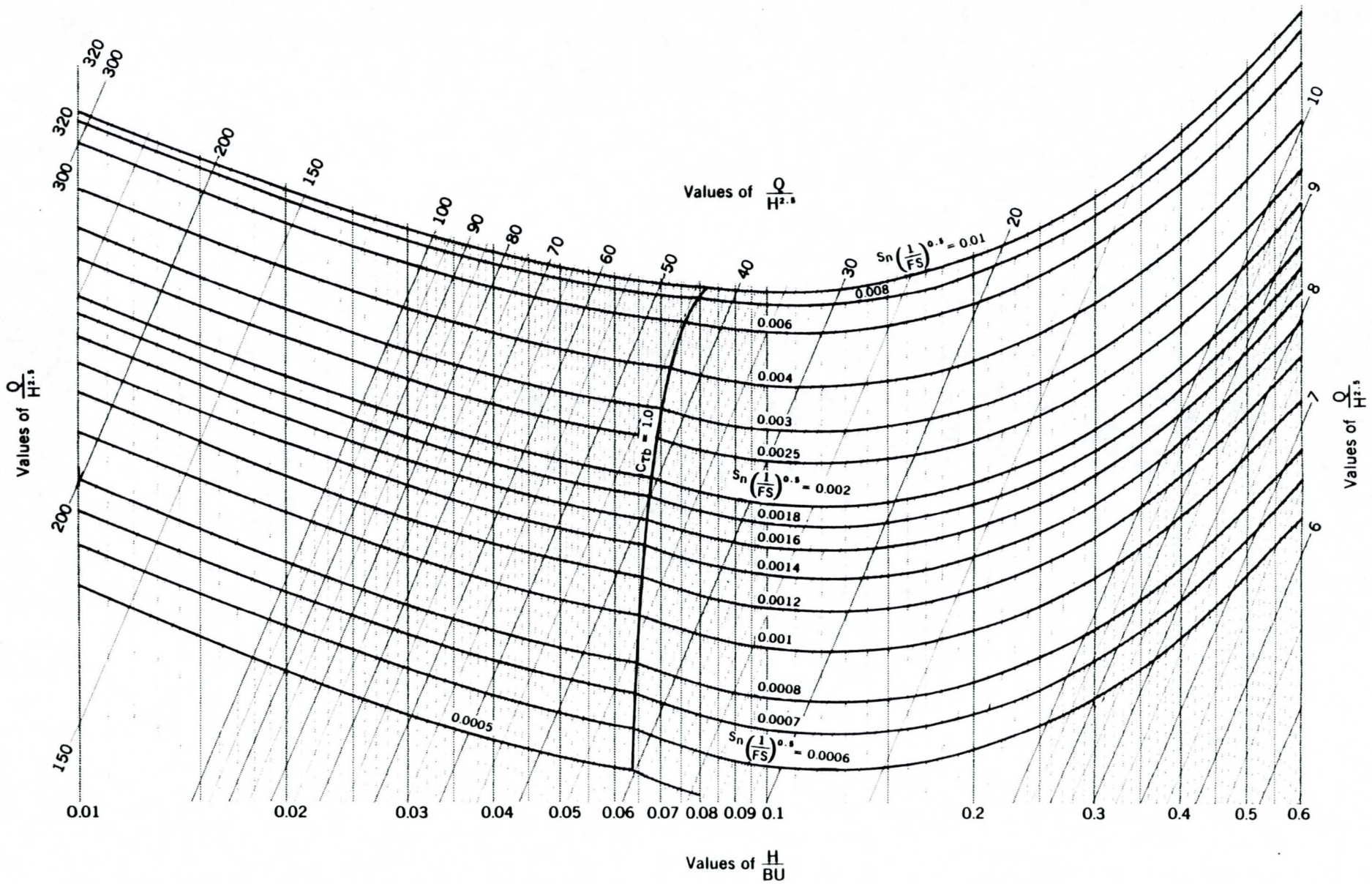
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-210
SHEET 6 OF 10
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $S_n\left(\frac{1}{FS}\right)^{0.5}$ curves

ZU = 3
τ_{bm} controls



REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION · DESIGN UNIT

STANDARD DWG. NO.
ES-210
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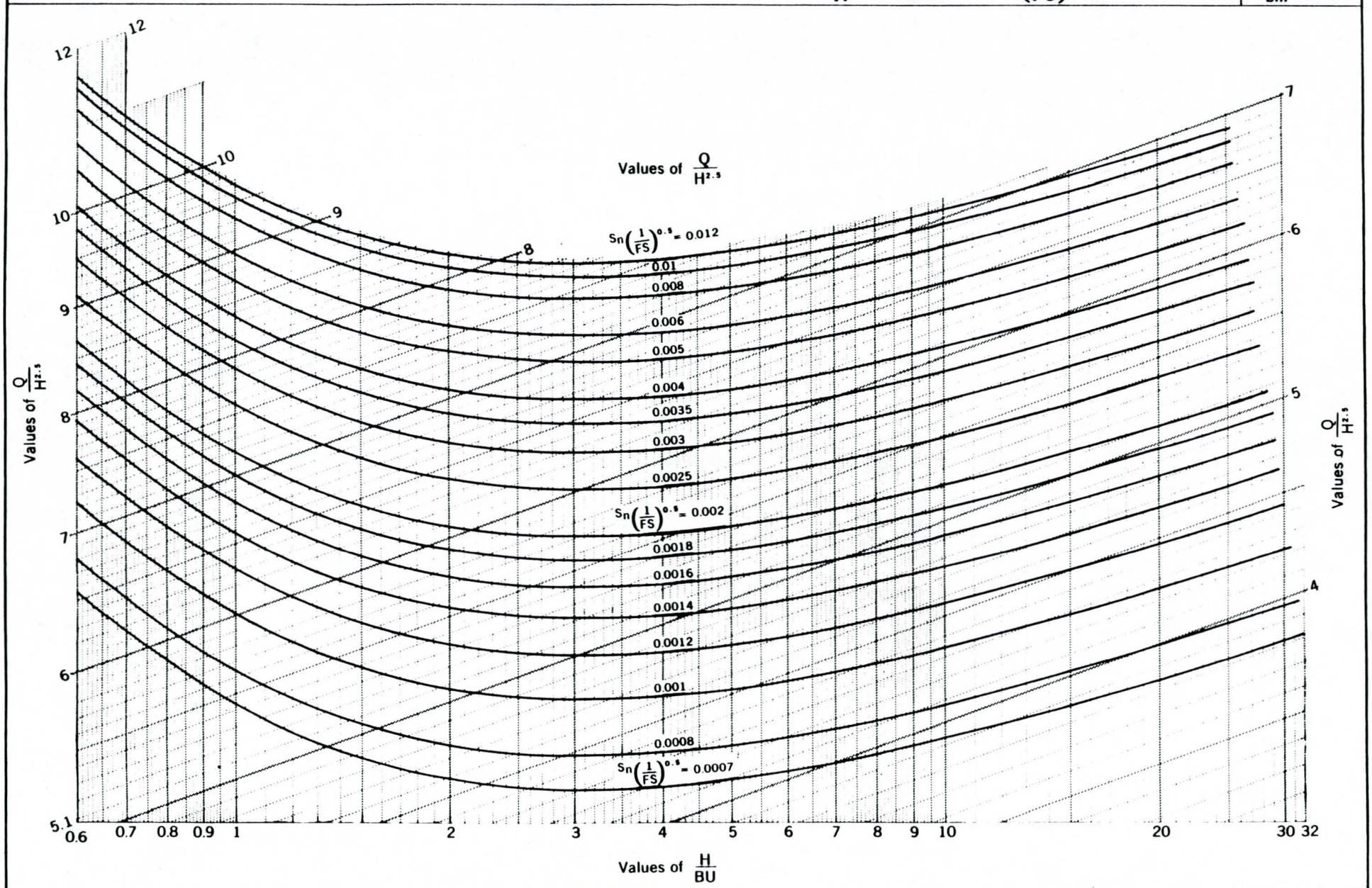
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $S_n\left(\frac{1}{FS}\right)^{0.5}$ curves

ZU = 3
τ_{bm} controls



REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-210
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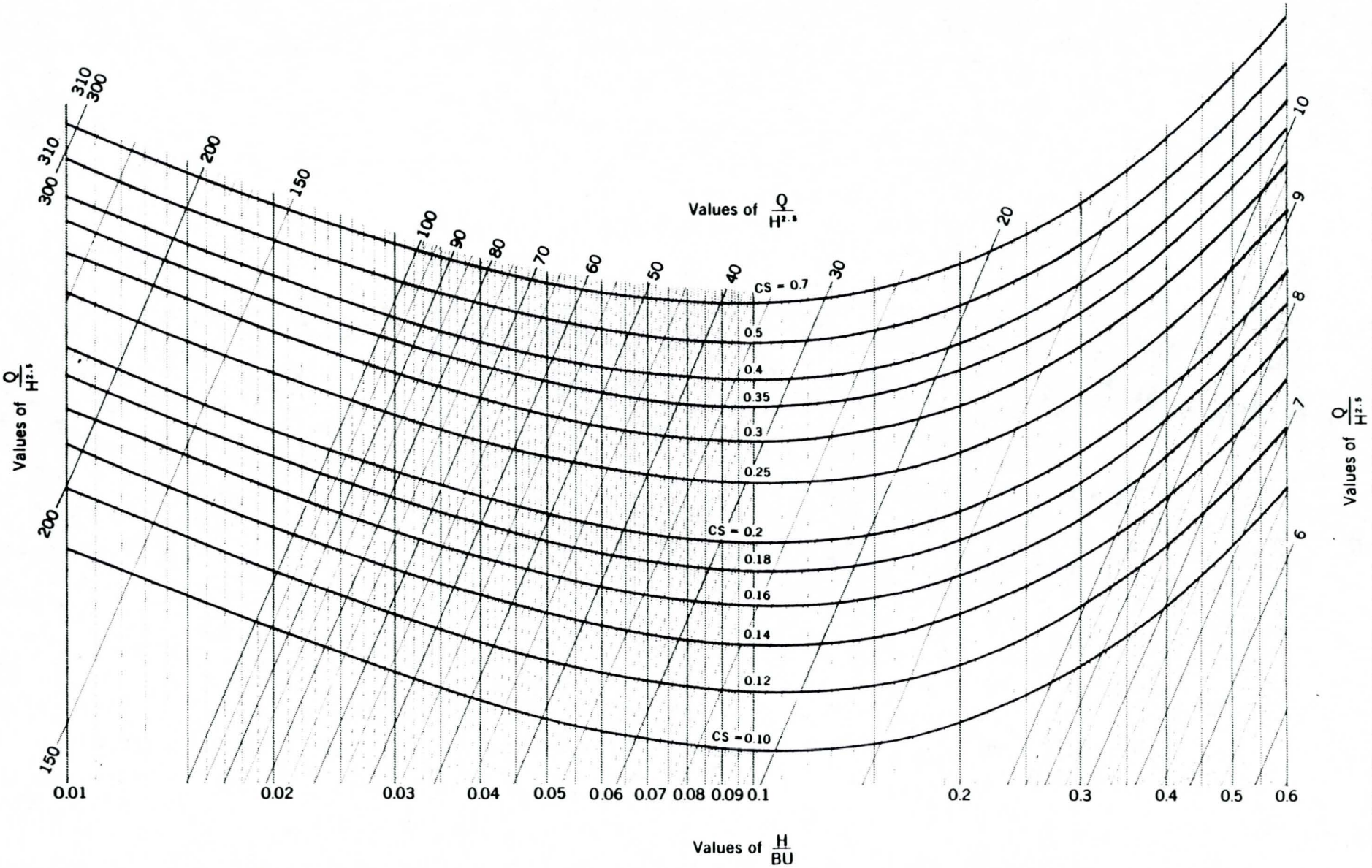
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with CS curves

ZU = 3



REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-210
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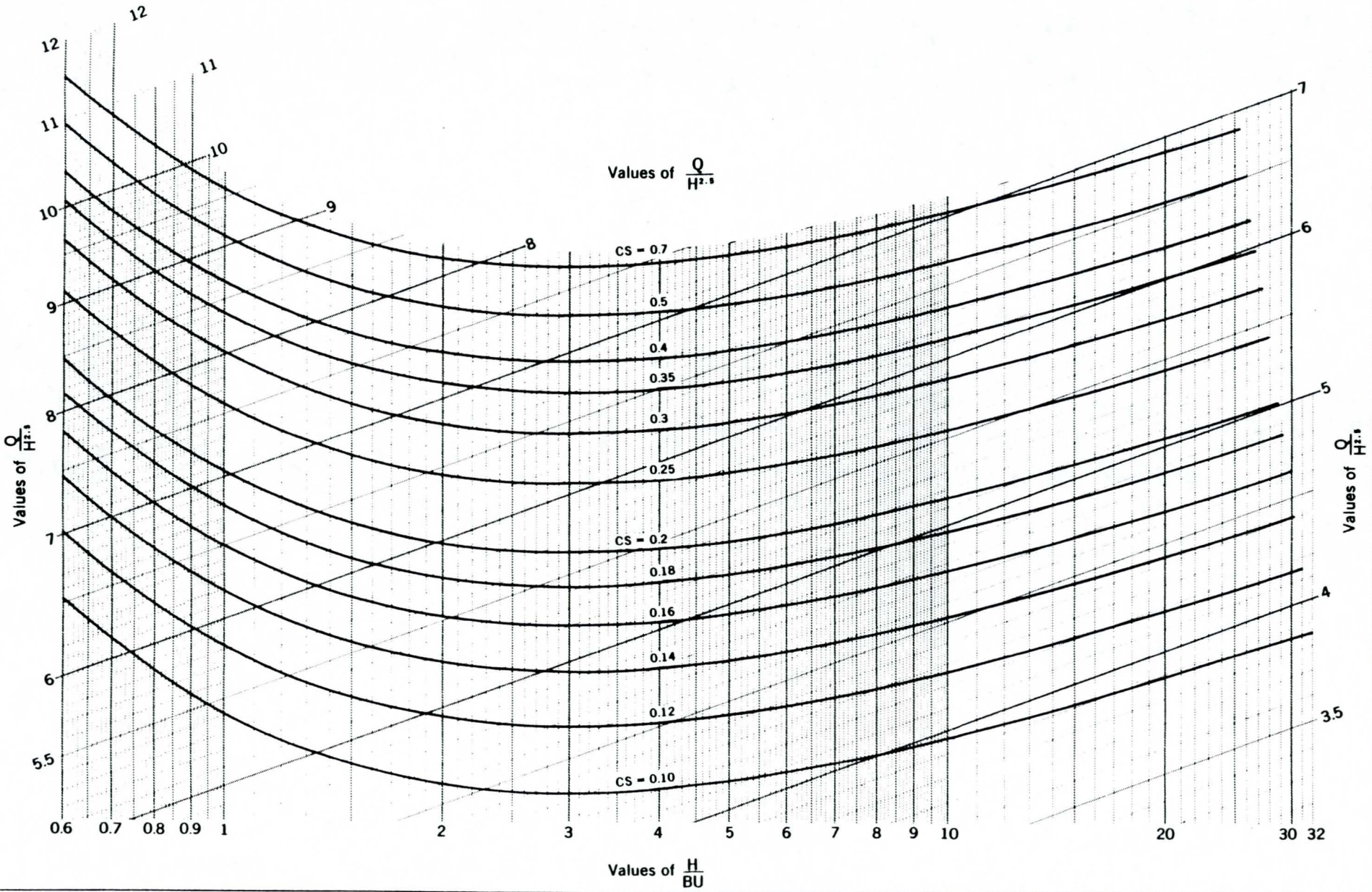
DATE 1/76

RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with CS curves

ZU = 3



REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-210
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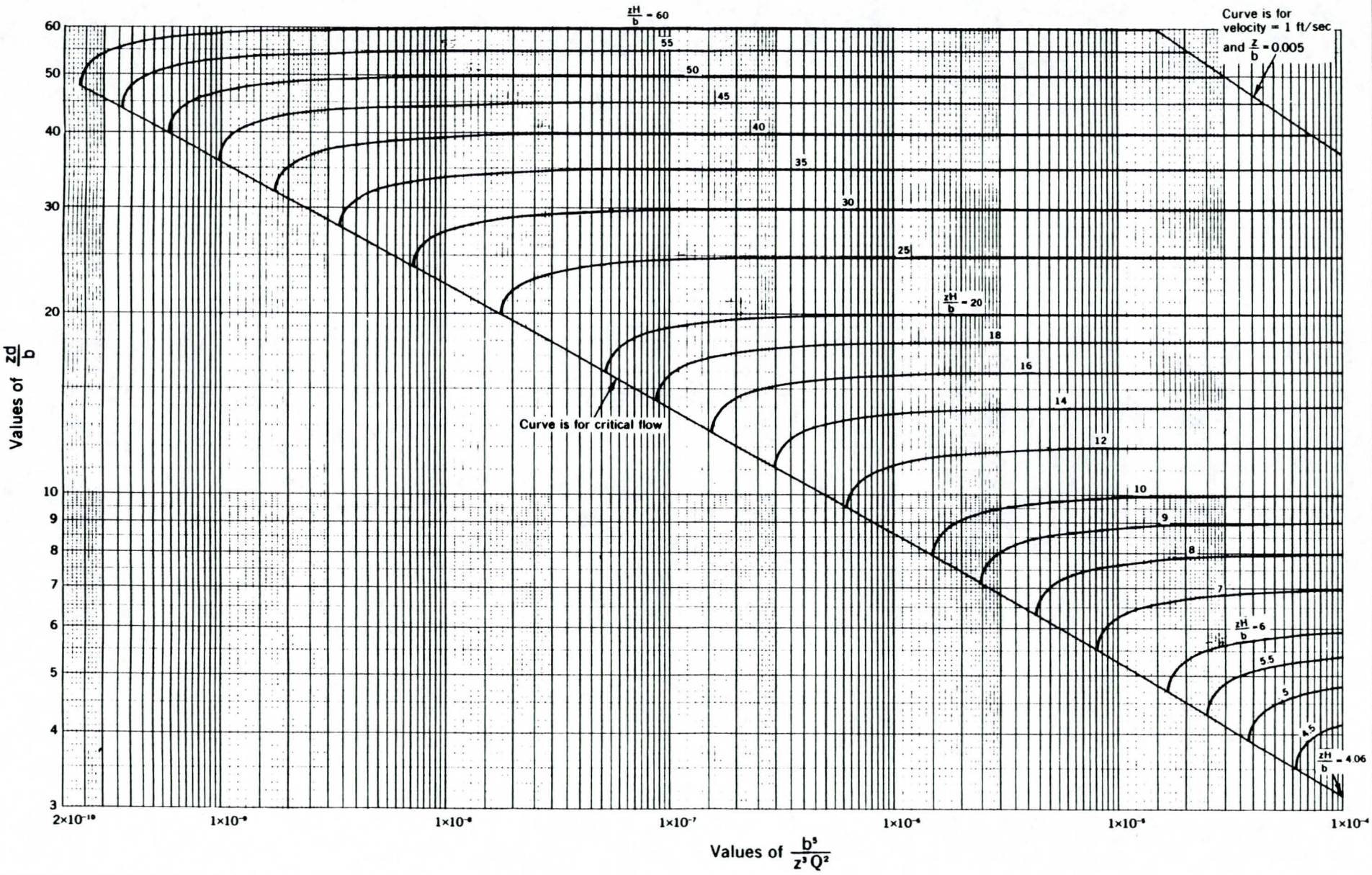
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs $\frac{b^5}{z^3Q^2}$ with $\frac{zH}{b}$ curves



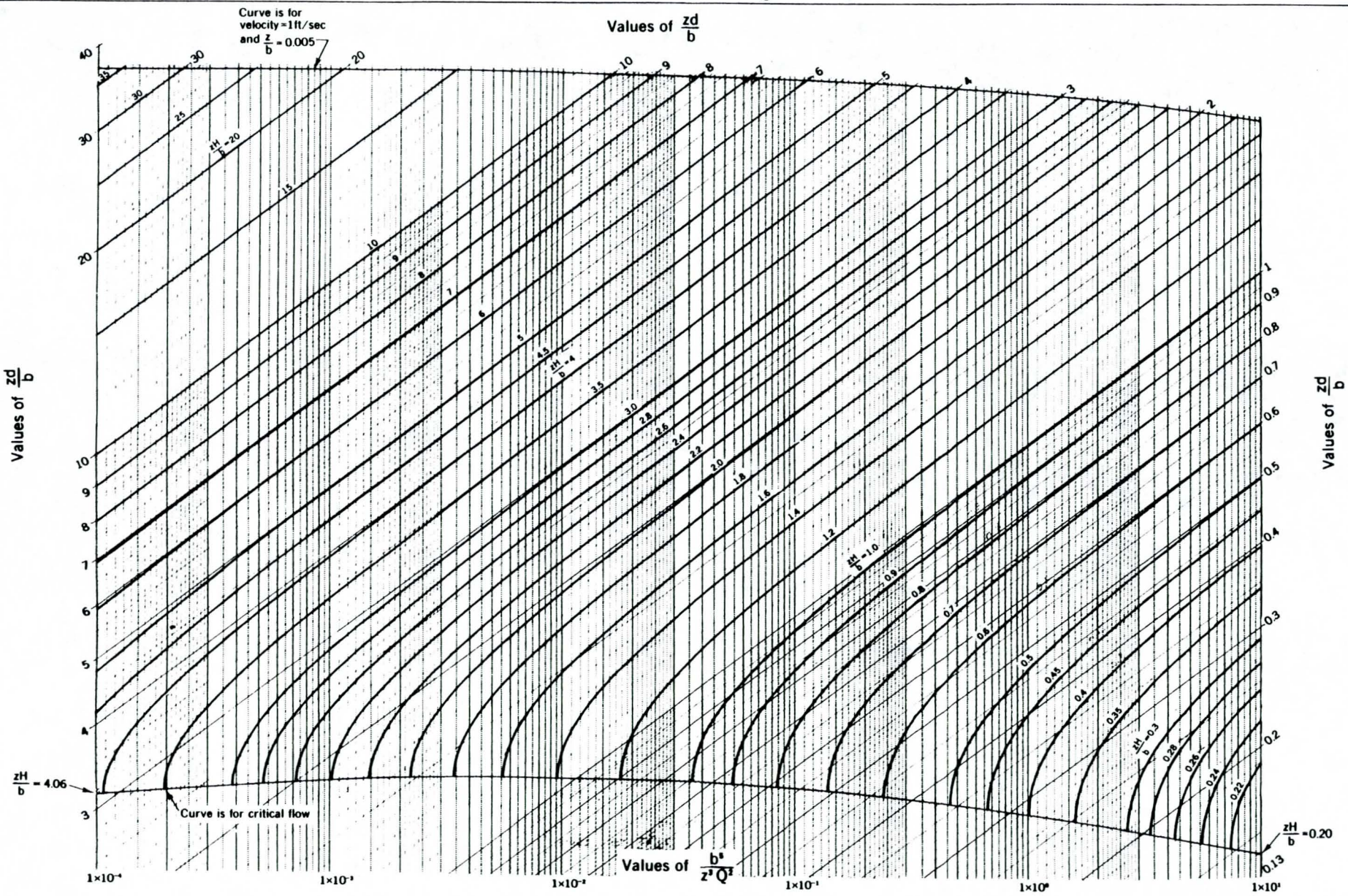
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-211
SHEET 1 OF 5
DATE 1-76

LIBRARY

RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs $\frac{b^5}{z^3Q^2}$ with $\frac{zH}{b}$ curves

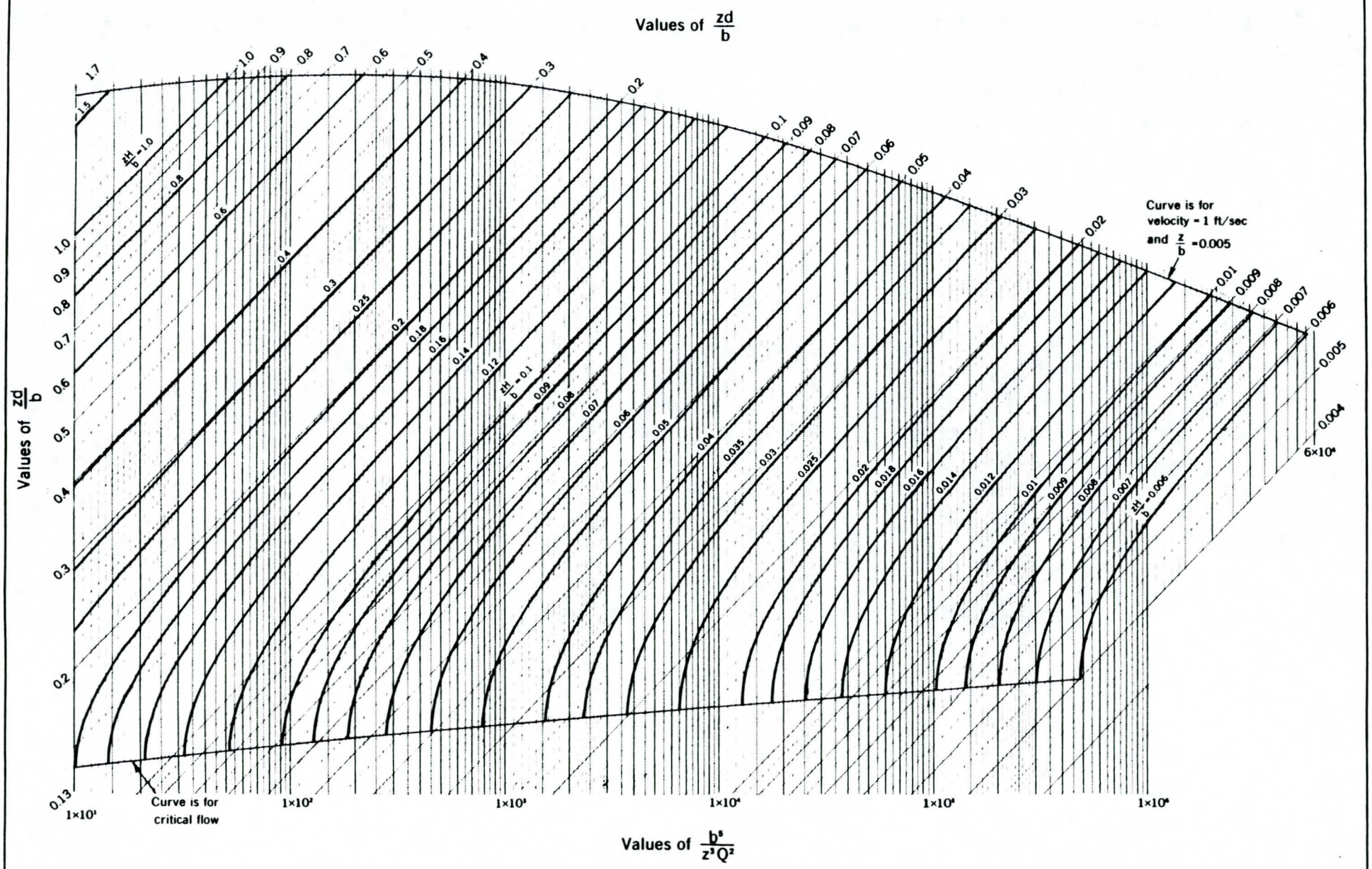


REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-211
SHEET 2 OF 5
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs $\frac{b^5}{z^3Q^2}$ with $\frac{zH}{b}$ curves

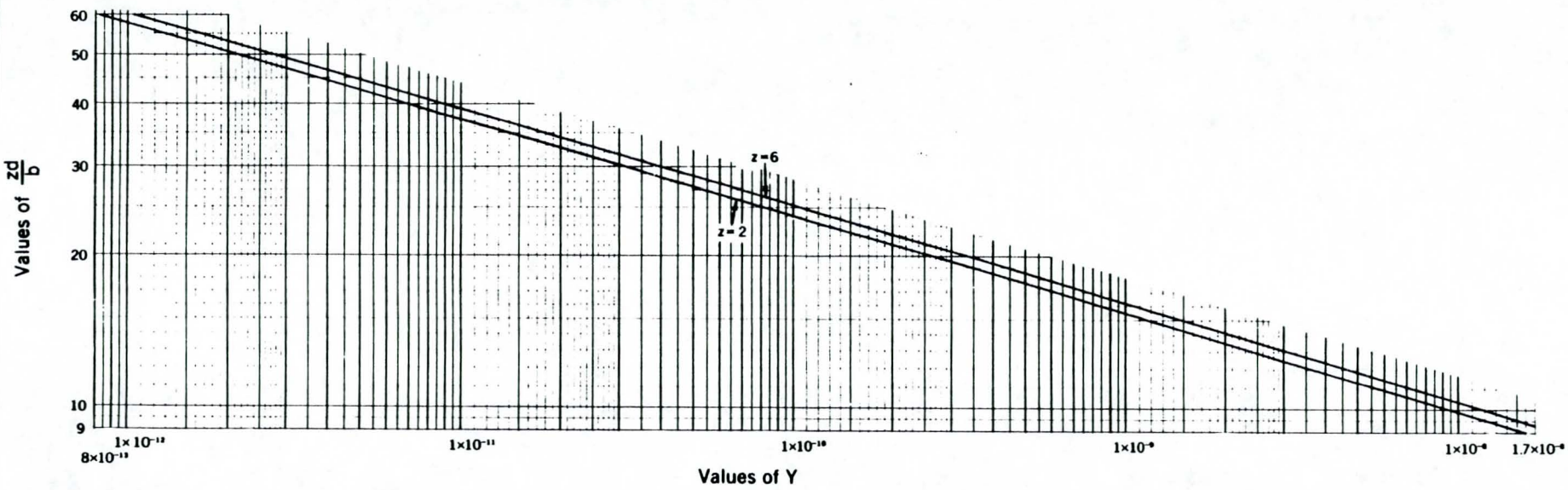


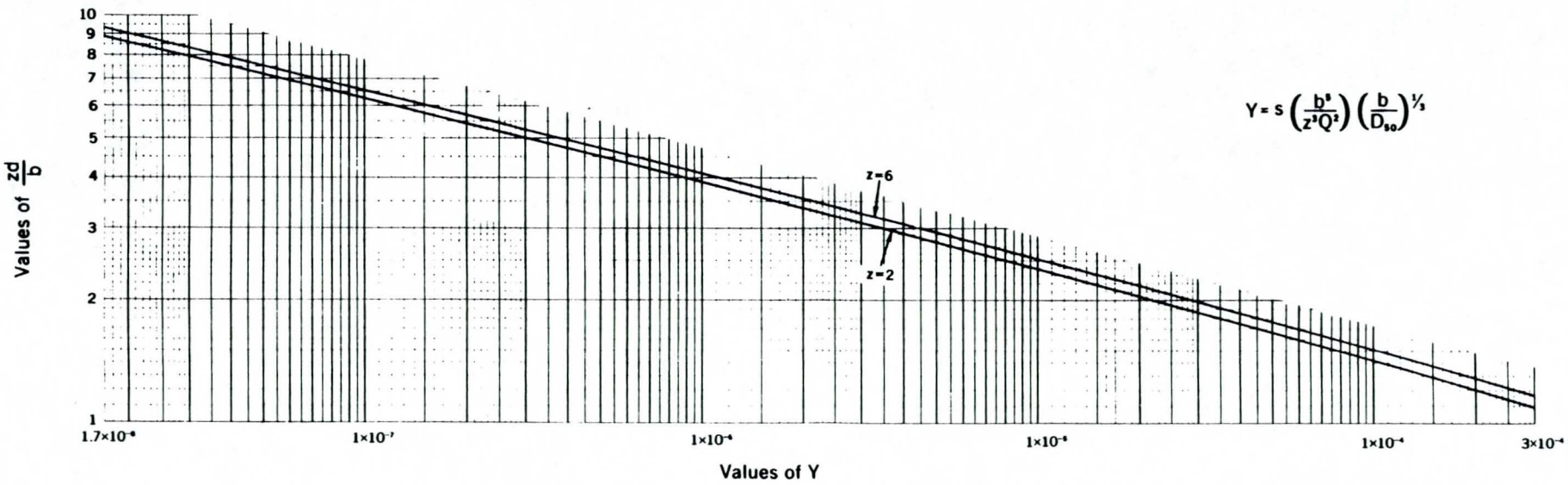
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-211
SHEET 3 OF 5
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs Y with z curves





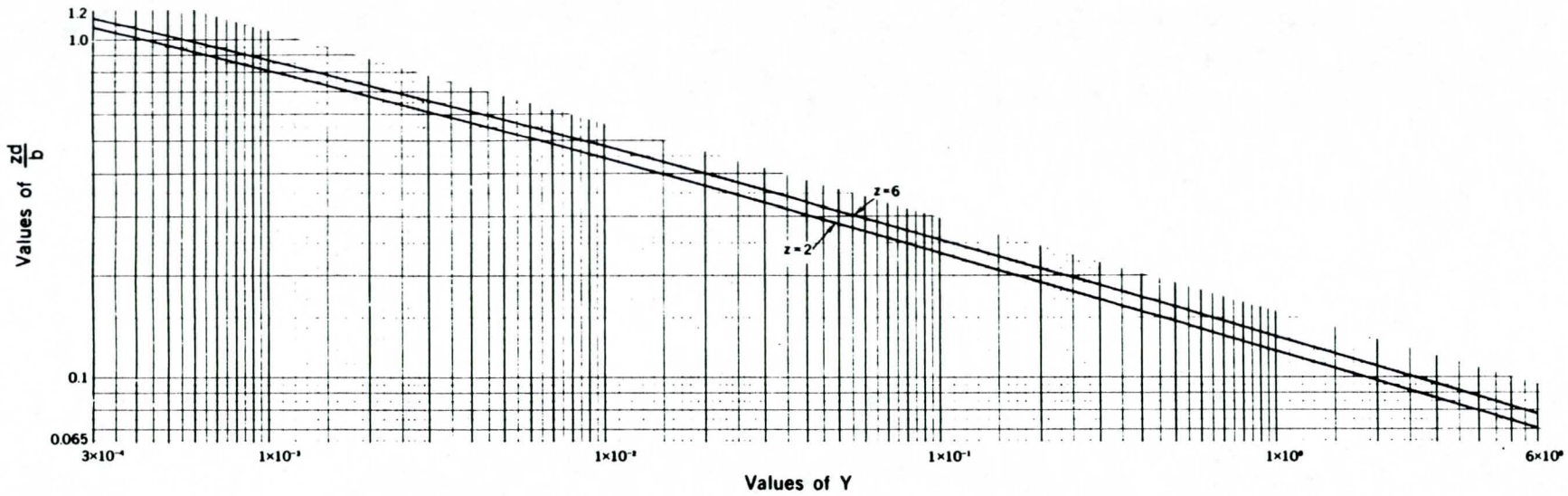
$$Y = s\left(\frac{b^8}{z^3Q^2}\right)\left(\frac{b}{D_{50}}\right)^{1/3}$$

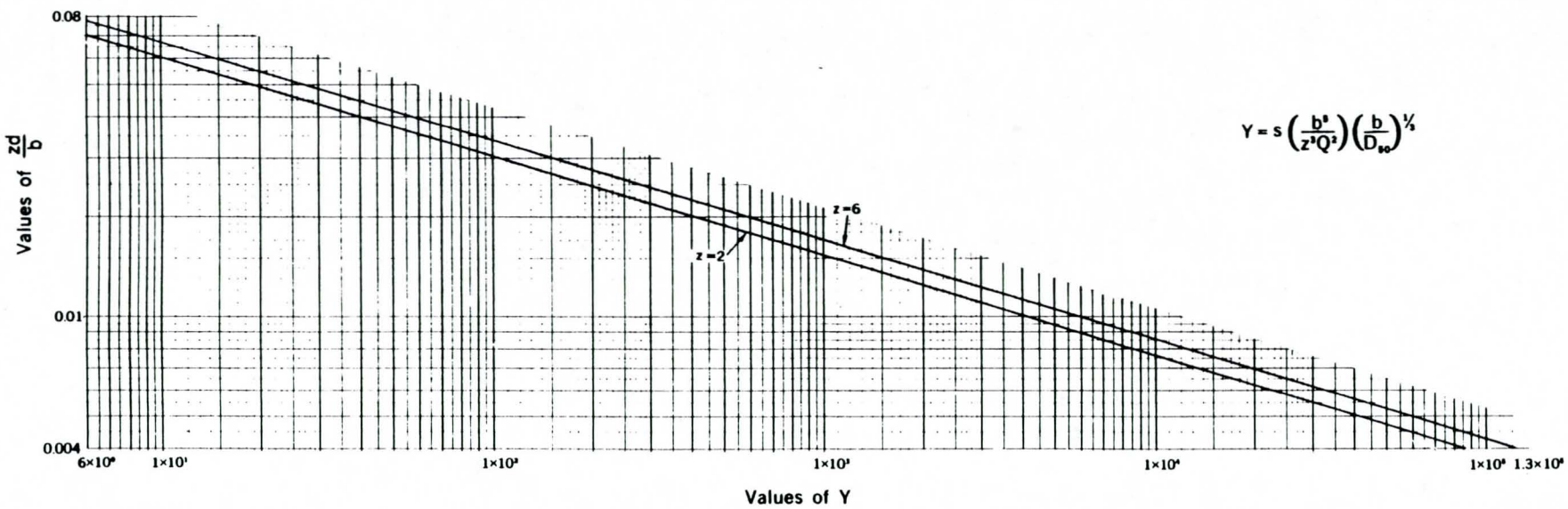
REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-211
SHEET 4 OF 5
DATE 1-76

RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs Y with z curves





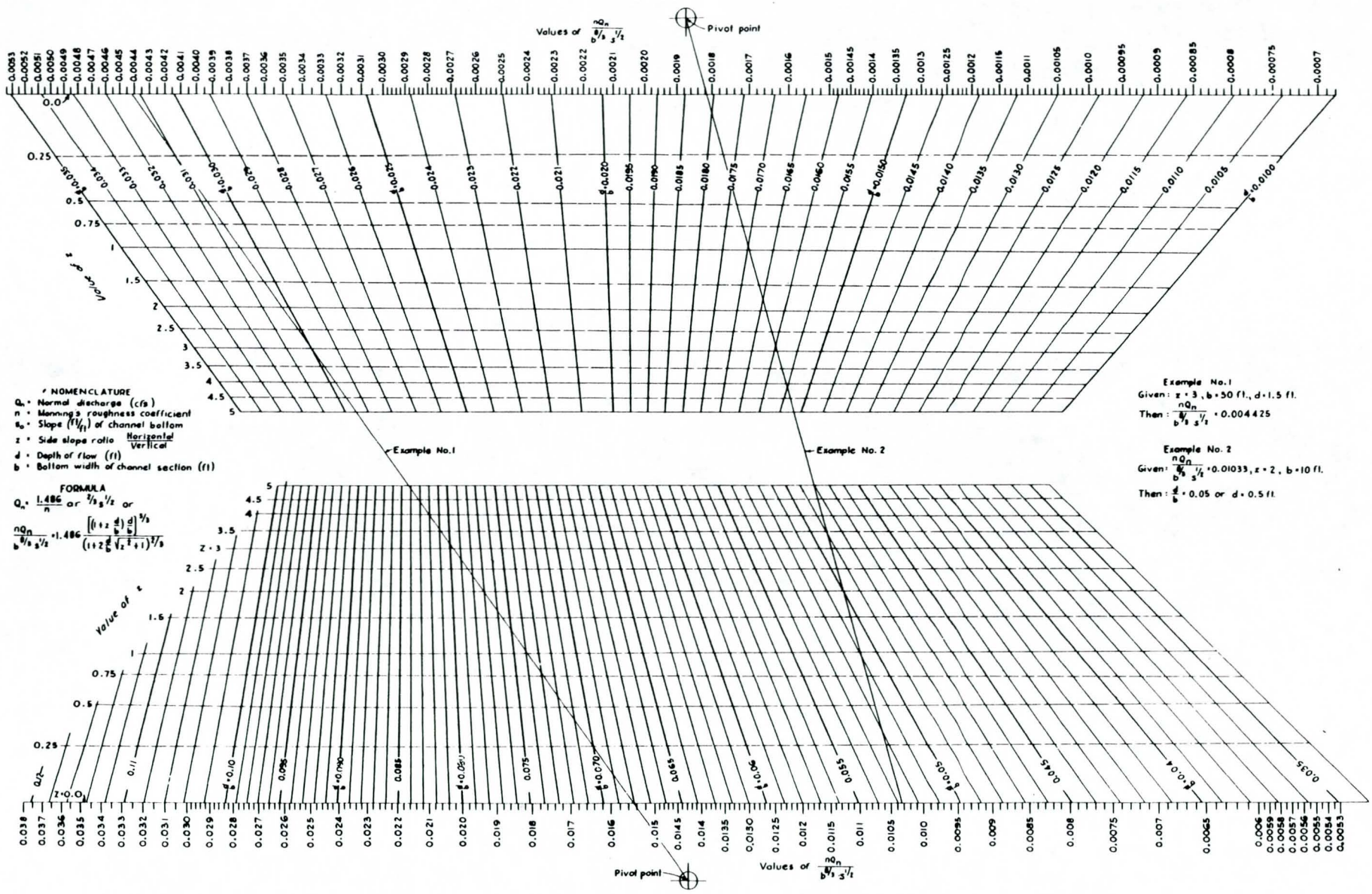
$$Y = s\left(\frac{b^8}{z^3Q^2}\right)\left(\frac{b}{D_{90}}\right)^{1/3}$$

REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES-211
SHEET 5 OF 5
DATE 1-76

HYDRAULICS: UNIFORM DEPTHS AND DISCHARGES IN TRAPEZOIDAL AND RECTANGULAR CHANNELS



NOMENCLATURE

Q_n = Normal discharge (cfs)
n = Manning's roughness coefficient
s_o = Slope (ft/ft) of channel bottom
z = Side slope ratio $\frac{\text{Horizontal}}{\text{Vertical}}$
d = Depth of flow (ft)
b = Bottom width of channel section (ft)

FORMULA

$$Q_n = \frac{1.486}{n} \text{ or } {}^2/_3 s^{1/2} \text{ or}$$

$$\frac{nQ_n}{b^{8/3} s^{1/2}} = 1.486 \frac{\left[\left(1 + z\frac{d}{b}\right)\frac{d}{b}\right]^{5/3}}{\left(1 + 2\frac{d}{b}\sqrt{z^2 + 1}\right)^{2/3}}$$

Example No. 1

Given: $z = 3$, $b = 50$ ft., $d = 1.5$ ft.

Then: $\frac{nQ_n}{b^{8/3} s^{1/2}} = 0.004425$

Example No. 2

Given: $\frac{nQ_n}{b^{8/3} s^{1/2}} = 0.01033$, $z = 2$, $b = 10$ ft.

Then: $\frac{d}{b} = 0.05$ or $d = 0.5$ ft.

REFERENCE

This nomogram was developed by Paul D. Doubt of the Design Section.

Revised 8-17-53

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

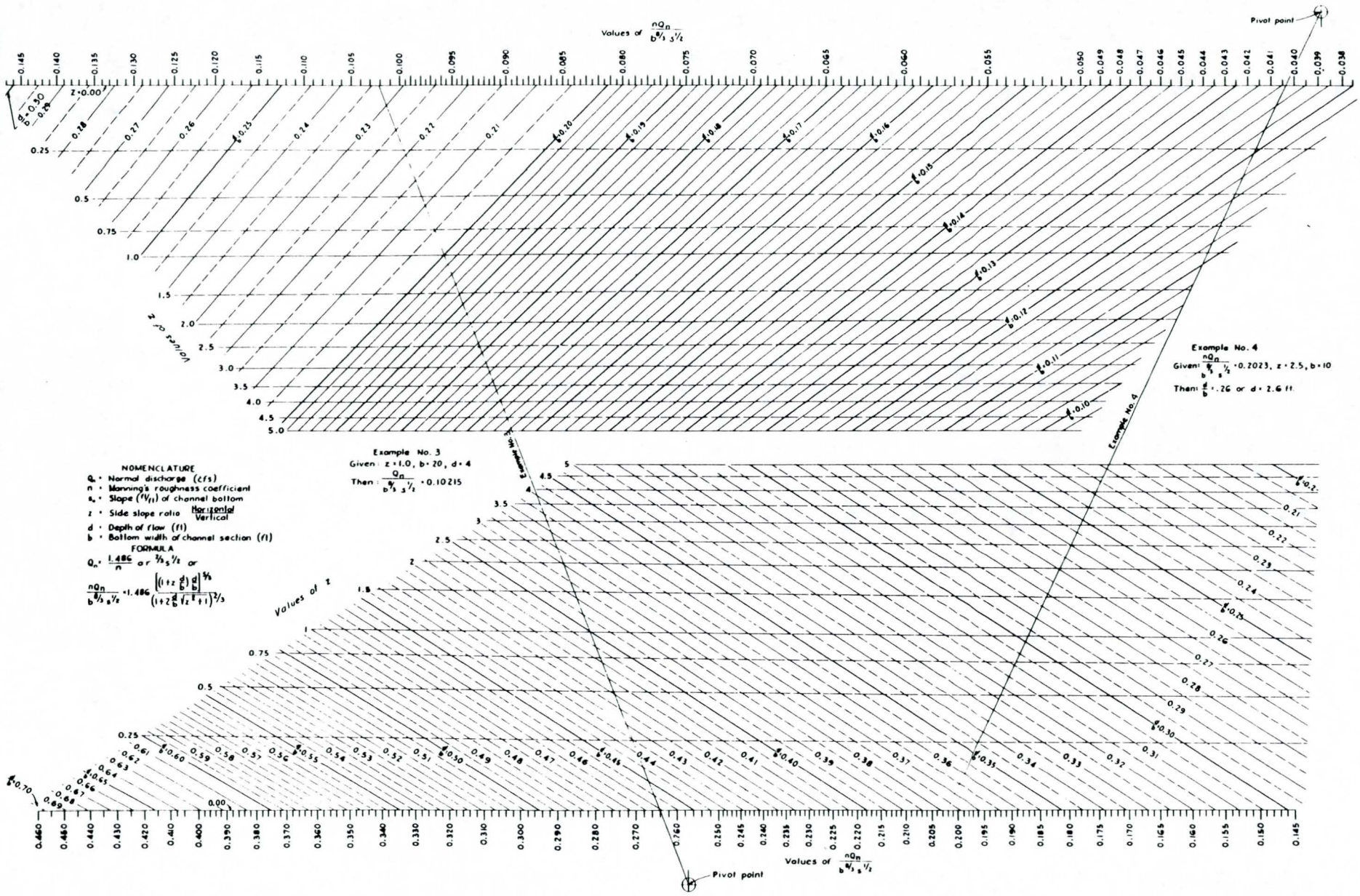
ENGINEERING STANDARDS UNIT

STANDARD DWG. NO. ES-55

SHEET 1 OF 4

DATE 4-30-51

HYDRAULICS: UNIFORM DEPTHS AND DISCHARGES IN TRAPEZOIDAL AND RECTANGULAR CHANNELS



NOMENCLATURE

Q_n = Normal discharge (cfs)
n = Manning's roughness coefficient
s_o = Slope (ft/ft) of channel bottom
z = Side slope ratio $\frac{\text{Horizontal}}{\text{Vertical}}$
d = Depth of flow (ft)
b = Bottom width of channel section (ft)

FORMULA

$$Q_n = \frac{1.486}{n} a r^{2/3} s^{1/2} \text{ or}$$

$$\frac{nQ_n}{b^{8/3} s^{1/2}} = 1.486 \frac{\left[\left(1+z\frac{d}{b}\right)\frac{d}{b}\right]^{5/3}}{\left(1+2\frac{d}{b}\sqrt{z^2+1}\right)^{2/3}}$$

REFERENCE

This nomogram was developed by Paul D. Doubt of the Design Section.

Revised 8-17-53

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

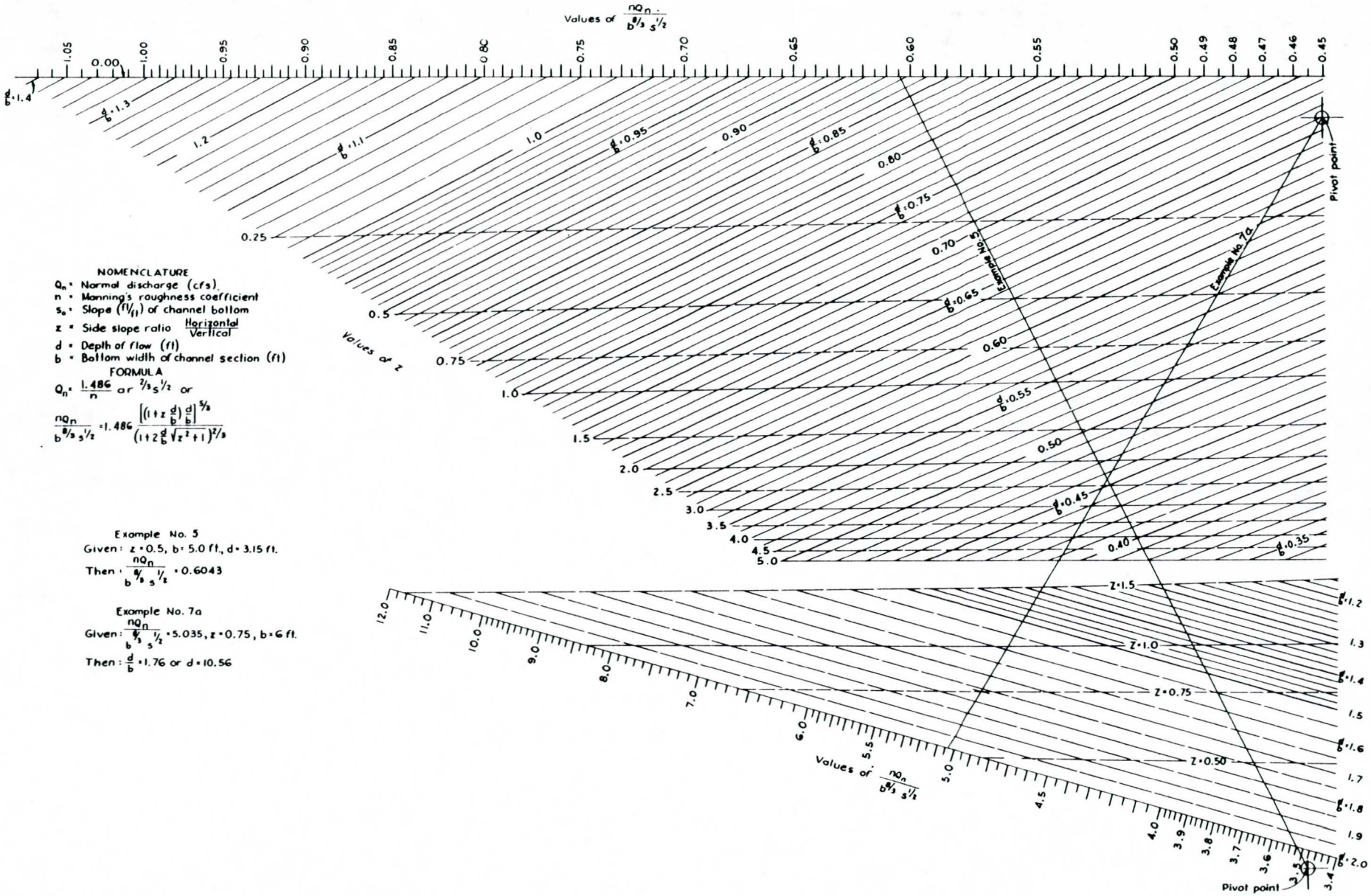
ENGINEERING STANDARDS UNIT

STANDARD DWG. NO. ES-55

SHEET 2 OF 4

DATE 4-30-51

HYDRAULICS: UNIFORM DEPTHS AND DISCHARGES IN TRAPEZOIDAL AND RECTANGULAR CHANNELS



NOMENCLATURE

Q_n = Normal discharge (cfs)
n = Manning's roughness coefficient
s_o = Slope (ft/ft) of channel bottom
z = Side slope ratio $\frac{\text{Horizontal}}{\text{Vertical}}$
d = Depth of flow (ft)
b = Bottom width of channel section (ft)

FORMULA

$$Q_n = \frac{1.486}{n} a r^{2/3} s^{1/2} \text{ or}$$

$$\frac{nQ_n}{b^{8/3} s^{1/2}} = 1.486 \frac{\left[\left(1 + z\frac{d}{b}\right)\frac{d}{b}\right]^{5/3}}{\left(1 + 2\frac{d}{b}\sqrt{z^2+1}\right)^{2/3}}$$

Example No. 5

Given: z = 0.5, b = 5.0 ft., d = 3.15 ft.

Then: $\frac{nQ_n}{b^{8/3} s^{1/2}} = 0.6043$

Example No. 7a

Given: $\frac{nQ_n}{b^{8/3} s^{1/2}} = 5.035$, z = 0.75, b = 6 ft.

Then: $\frac{d}{b} = 1.76$ or d = 10.56

REFERENCE

This nomogram was developed by Paul D. Doubt of the Design Section.

Revised 8-17-53

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

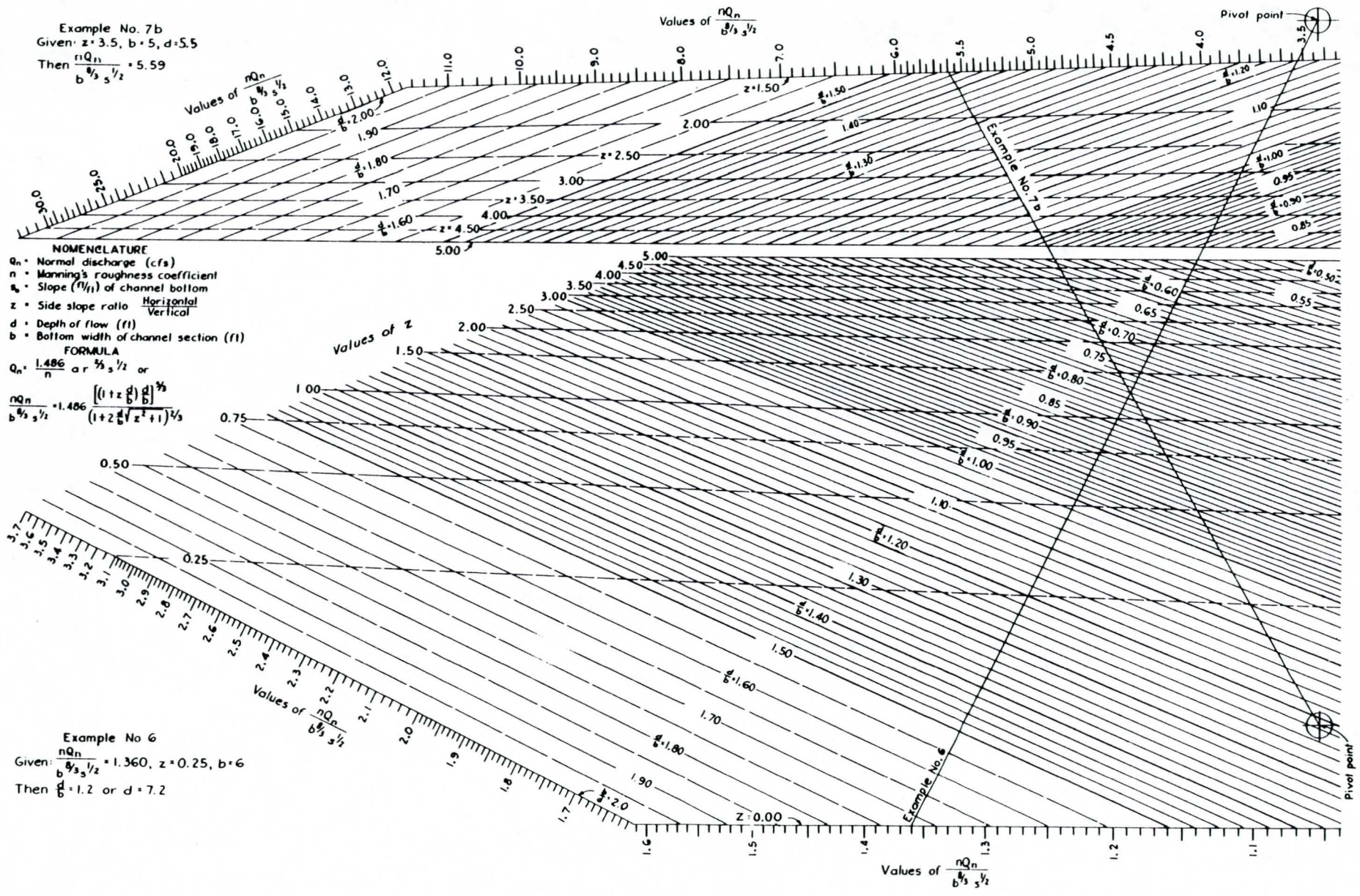
ENGINEERING STANDARDS UNIT

STANDARD DWG. NO. ES-55

SHEET 3 OF 4

DATE 4-30-51

HYDRAULICS: UNIFORM DEPTHS AND DISCHARGES IN TRAPEZOIDAL AND RECTANGULAR CHANNELS



NOMENCLATURE

Q_n = Normal discharge (cfs)
n = Manning's roughness coefficient
s = Slope (ft/ft) of channel bottom
z = Side slope ratio $\frac{\text{Horizontal}}{\text{Vertical}}$
d = Depth of flow (ft)
b = Bottom width of channel section (ft)

FORMULA

$Q_n = \frac{1.486}{n} a r^{2/3} s^{1/2}$ or

$$\frac{nQ_n}{b^{8/3} s^{1/2}} = 1.486 \frac{\left[\left(1 + z\frac{d}{b}\right)\frac{d}{b}\right]^{5/3}}{\left(1 + 2\frac{d}{b}\sqrt{z^2+1}\right)^{2/3}}$$

REFERENCE

This nomogram was developed by Paul D. Doubt of the Design Section.

Revised 8-17-53

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SOIL CONSERVATION SERVICE

ENGINEERING STANDARDS UNIT

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PREFACE

TR-59 procedure may be used as a design tool to design a riprap gradient control structure for a design discharge and a tailwater condition. The structure will satisfy both capacity and stability requirements. However, an analytical procedure is needed to investigate the effects, if any, of other discharge-tailwater conditions or other parameters on the structure. This supplement contains such a procedure.

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TECHNICAL RELEASE NO. 59, SUPPLEMENT 2

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

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NOMENCLATURE

This supplement uses the same nomenclature as contained in Technical Release No. 59. Usually, each new term used in the supplement is defined where it first appears in the text. Not all nomenclature is listed. For any nomenclature or symbols not listed, the meaning may be ascertained from this supplement or Technical Release No. 59. The symbols used for input and output data are defined in the "Computer Program" section of this supplement.

a ≡ Flow area, ft^2

C_n = CN ≡ Coefficient relating Manning's n to riprap D_{50} size,

$n = C_n[D_{50}]^{EXPN}$

d ≡ Depth of flow, ft

D_{50} = D50 ≡ Size of rock in riprap of which 50 percent by weight is finer, ft

DS ≡ Depth of flow corresponding to the discharge, Q, at the ends of the riprap structure, ft

EXPN ≡ Value of the exponent in the equation for computing Manning's roughness coefficient, $n = C_n[D_{50}]^{EXPN}$

FS ≡ Factor of safety

g ≡ Acceleration of gravity, ft/sec^2

h_f ≡ Friction head loss, $\frac{ft\text{-}lb}{lb}$

ℓ ≡ Horizontal length of a portion of a channel or length of a computational reach, ft

n = N ≡ Manning's coefficient of roughness

P ≡ Wetted perimeter, ft

Q ≡ Discharge through the riprap structure, cfs

s ≡ Energy gradient, ft/ft

v ≡ Velocity corresponding to the discharge, Q, ft/sec

TECHNICAL RELEASE NO. 59, SUPPLEMENT 2

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

Introduction

A riprap gradient control structure can be used to dissipate excess energy and establish a stable gradient in a channel where the gradient without some such control would be too steep and would cause erosive velocities. The procedures for the hydraulic design and proportioning of such structures are given in TR-59.

Technical Release No. 59

Technical Release No. 59, "Hydraulic Design of Riprap Gradient Control Structures," presents a detailed discussion of the concept of the riprap gradient control structure, procedures for the hydraulic design and proportioning of the structures, and procedures used in the associated computer program to obtain the design of the structure.

Purpose of Supplement

Technical Release No. 59 procedure provides the design of a riprap structure for a given design discharge and tailwater condition. However, by use of this technical release, the capacity and stability of the riprap structure are not investigated for discharges other than the design discharge nor for other tailwater conditions. A water surface profile program is needed which will evaluate the depth of flow and tractive stress at various locations throughout the structure for any combination of discharge and downstream starting depth. Therefore, the purpose of this supplement is to: (1) present procedures for the computation of water surface profiles for various parameters, and (2) investigate the effect of various parameters on the capacity and stability of the riprap structure.

Computer Program

A computer program, written in FORTRAN for IBM equipment, determines the water surface profile, maximum tractive stresses, and various other hydraulic parameters associated with the riprap structure under investigation.

Input and output data information is discussed under the "Computer Program" section. Computer runs may be obtained by request to

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Riprap Gradient Control Structure

The purpose of a riprap gradient control structure is channel gradient control. The concept and the hydraulic design of the riprap gradient control structure are contained in TR-59. For brevity, riprap gradient control structures will be referred to in this supplement as riprap structures or simply as structures.

Discharges and Starting Depths

The design of a riprap structure obtained from TR-59 procedure is for a design discharge and tailwater condition; in the design, both capacity and stability of the structure are satisfied. The design discharge is equal to the discharge used in evaluating the stability of both the upstream and downstream channels adjacent to the structure.

Generally, riprap structures that are stable for the design discharge will also be stable for all discharges less than the design discharge. However, if a rating curve is such that the tailwater decreases very rapidly with small decreases in discharge, such a discharge-tailwater combination may cause tractive stress greater than those associated with the design discharge. Further, if the actual tailwater depth corresponding to the design discharge is subsequently determined to be less than the starting depth, DS, used in the riprap structure design, the water depth in the structure, especially in the downstream transition, will be lower than normal depth. Thus, velocity and tractive stress in the structure will be increased.

The procedure in this supplement may be used to compute water surface profiles and tractive stresses at various locations throughout the riprap structure for any combination of discharge-tailwater conditions. If the tractive stress at any location in the structure is greater than the allowable tractive stress, the riprap structure should be redesigned using TR-59 procedures for the controlling discharge-tailwater condition. Locations most likely to experience tractive stresses that are larger than the allowable value are usually the most downstream end of the prismatic channel and the upstream half of the downstream transition.

If a discharge greater than the design discharge occurs, the structure may not function properly; the structure may be overtopped and tractive stress greater than allowable may occur. Therefore, as stated in TR-59, the design discharge should be selected sufficiently large and the lowest tailwater depth corresponding to the design discharge should always be used.

Size of Riprap, D_{50}

Since the value of the roughness coefficient, n, and the critical tractive stress, τ_{bc} or τ_{sc} are functions of the size of riprap, D_{50}, any variation of D_{50} size will have some effect on the performance of the riprap structure. The procedures in this supplement may be used to check the capacity and stability of the structure if the actual D_{50} size used in the construction differs somewhat from the design value of D_{50}.

Manning's Roughness Coefficient

The coefficient of roughness, n, for the riprap has been experimentally evaluated as

$$n = C_n (D_{50})^{EXPN}$$

where (from Report 108 and used as default values in TR-59)

$$C_n = 0.0395$$

$$EXPN = 1/6$$

A constant n value based on the above equation was used in the design procedure of TR-59. However, the procedure in this supplement may be used to investigate what effects the various roughness coefficients may have on the capacity and stability of the riprap structure. Water depths and tractive stresses at various preselected sections of the riprap structure will be computed corresponding to the desired n value.

Prismatic Channel

Generally, the most critical section for stability is that section where the velocity and tractive stress are the greatest. For flow conditions other than the discharge-tailwater condition used in the riprap structure design, the most critical section is usually at the most downstream end of the prismatic channel. However, if supercritical flow exists in the downstream transition, the most critical section may be in the transition.

For a discharge less than the design discharge and/or a starting depth less than the DS used in the design, the depth at the most downstream end of the prismatic channel could be as low as critical depth; and the water surface profile in the structure upstream from this section will approach normal depth. For a discharge greatly exceeding the design discharge, it is theoretically possible to have supercritical flow in the prismatic channel.

Water Surface Profile

The water surface profile (WSP) in a riprap structure depends on the discharge and the starting depth. Thus, for every discharge-starting depth combination, there is a corresponding water surface profile which can be used to obtain the capacity and maximum tractive stress values in the riprap structure. The starting depth at the most downstream section of the riprap structure must be predetermined before profile computations can be started. The water surface profile is merely the determination of the depth of flow at preselected sections throughout the structure. These preselected sections are the ten equally spaced sections within each element of the structure. These elements are the downstream transition, upstream transition, and the prismatic channel. The preselected sections in the transitions may be obtained from the computer output of TR-59.

Hydraulic Theory

The theory and assumptions used in the determination of water surface profiles are taken from NEH-5, Hydraulics. It is assumed that the law of conservation of energy (Bernoulli's Theorem) is valid for varied flow and that Manning's formula defines the slope of the energy line.

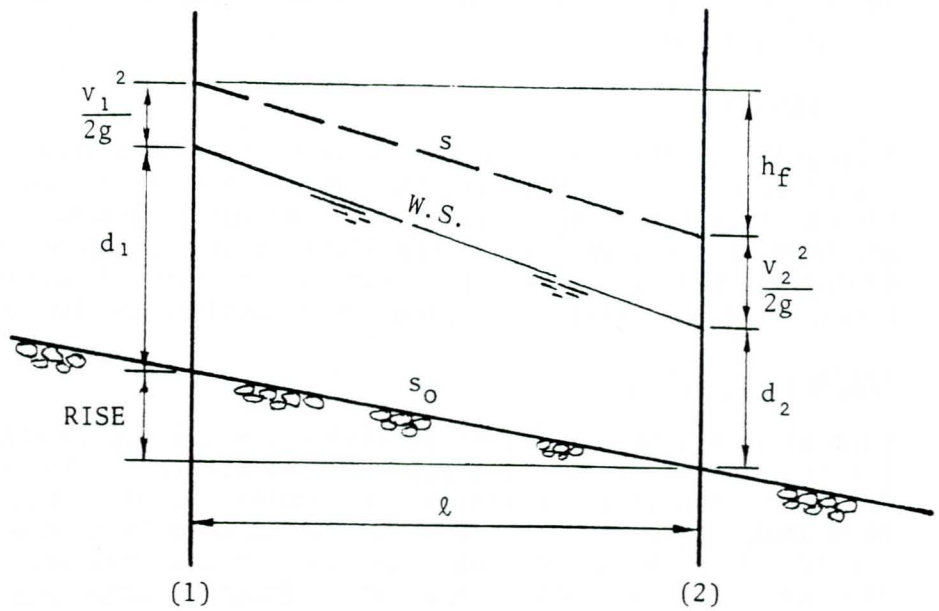

Figure 1. Energy in varied flow

From Figure 1.

$$\text{RISE} + d_1 + \frac{v_1^2}{2g} = d_2 + \frac{v_2^2}{2g} + h_f$$

The total head loss, h_f, between sections 1 and 2 is equal to the rate of friction loss, s, times the distance, ℓ, between sections 1 and 2 or

$$h_f = s\ell$$

$$s = \frac{1}{\ell}\left[(d_1 - d_2) + \frac{Q^2}{2g}\left(\frac{1}{a_1^2} - \frac{1}{a_2^2}\right) + \text{RISE}\right] \quad (1)$$

It is further assumed that conversion losses in the transitions and the correction for non-uniform velocity distribution are negligible; thus they are ignored. The rate of friction loss, s, between sections 1 and 2 is taken as the arithmetical average of the instantaneous rate of friction loss of section 1, (s_1), and section 2, (s_2), or

$$s = \frac{1}{2}(s_1 + s_2)$$

From Manning's Formula

$$s_1 = \left(\frac{nQ}{1.486}\right)^2 \frac{p_1^{4/3}}{a_1^{10/3}}$$

$$s_2 = \left(\frac{nQ}{1.486}\right)^2 \frac{p_2^{4/3}}{a_2^{10/3}}$$

$$s = \frac{1}{2}\left(\frac{nQ}{1.486}\right)^2 \left[\frac{p_1^{4/3}}{a_1^{10/3}} + \frac{p_2^{4/3}}{a_2^{10/3}}\right] \text{- - - - - - - - - - - - - - - - -} \quad (2)$$

Setting equation (1) equal to equation (2)

$$d_1 + \frac{Q^2}{2a_1^2}\left[\frac{1}{g} - \ell\left(\frac{n}{1.486}\right)^2 \left(\frac{p_1}{a_1}\right)^{4/3}\right]$$

$$= d_2 - \text{RISE} + \frac{Q^2}{2a_2^2}\left[\frac{1}{g} + \ell\left(\frac{n}{1.486}\right)^2 \left(\frac{p_2}{a_2}\right)^{4/3}\right] \text{- - - -} \quad (3)$$

Computations

The computation of the water surface profile merely determines the depth of flow at one end of a computational reach when the depth of the other end is known. Thus, the length of a computational reach is equal to the distance between any two consecutive sections. In the case of subcritical flow where computation of WSP is in an upstream direction, the depth at section 2 (see Figure 1) is known; thus, every term on the right hand side of equation (3) is known. The depth at section 1, d_1, is determined by assuming a depth, d_1, and stepping d_1 until equation (3) is balanced within the degree of accuracy desired. The degree of accuracy may be achieved when the computational reaches are "sufficiently short." The lengths of computational reaches used in the computer program are set equal to the distance between preselected consecutive sections of the riprap structure divided by ten. In other words, the length between any two preselected consecutive sections is divided into ten equal sub-lengths; each sub-length contains two subsections where WSP is computed. The depths at these subsections are computed to an accuracy of $\pm$ 0.001 ft, but they are not part of the output. Only depths at preselected sections are output.

A flow chart of the procedure used in the WSP computer program is given in Figure 2. Water surface profile computation commences at the most downstream section of the riprap structure. The program examines to see if the starting depth, DS, is equal to or greater than critical depth corresponding to the discharge, Q. If the starting depth is less than critical depth, critical depth will be used as the starting depth. Computations proceed in an upstream direction. The computer examines whether subcritical flows exist. When the flow is critical or supercritical, computation ceases and a message, "CRITICAL DEPTH," will be printed to indicate that critical depth will be used as the starting depth for the next upstream computational reach. This process continues upstream until flow

changes back to subcritical at some section of the downstream transition or until the most downstream section of the prismatic channel has been reached.

If the flow changes back to subcritical before reaching the prismatic channel, both of the following computations occur:

1. Computation of WSP continues upstream for subcritical flow and
2. A message, "SUPERCRICAL FLOW," will be printed to indicate that computation of WSP is in a downstream direction for supercritical flow; using critical depth as the starting depth and commencing at the last preselected section where flow changes back to subcritical flow to the preselected section where supercritical flow first occurred.

However, if the flow did not change back to subcritical flow when the prismatic channel is reached, both of the following computations occur:

1. A message, "SUPERCRITICAL FLOW," will be printed to indicate that computation of WSP is in a downstream direction for supercritical flow. Using critical depth as the starting depth and commencing at the most downstream section of the prismatic channel, compute WSP to the preselected section in the downstream transition where supercritical flow first occurred and
2. Compute the WSP in an upstream direction commencing at the most downstream section of the prismatic channel using critical depth as the starting depth. Flow will approach normal depth in the prismatic channel.

The critical slope, $s_{c,Q}$, is associated with a discharge, Q, and when the discharge is changed, the critical slope is changed. The critical slope usually increases as the discharge decreases. Therefore, for discharges less than or equal to the design discharge, the lowest possible depth at the most downstream section of the prismatic channel is critical depth; flow in the prismatic channel will never be supercritical. The WSP in the prismatic channel and the upstream transition will approach normal depth in an upstream direction.

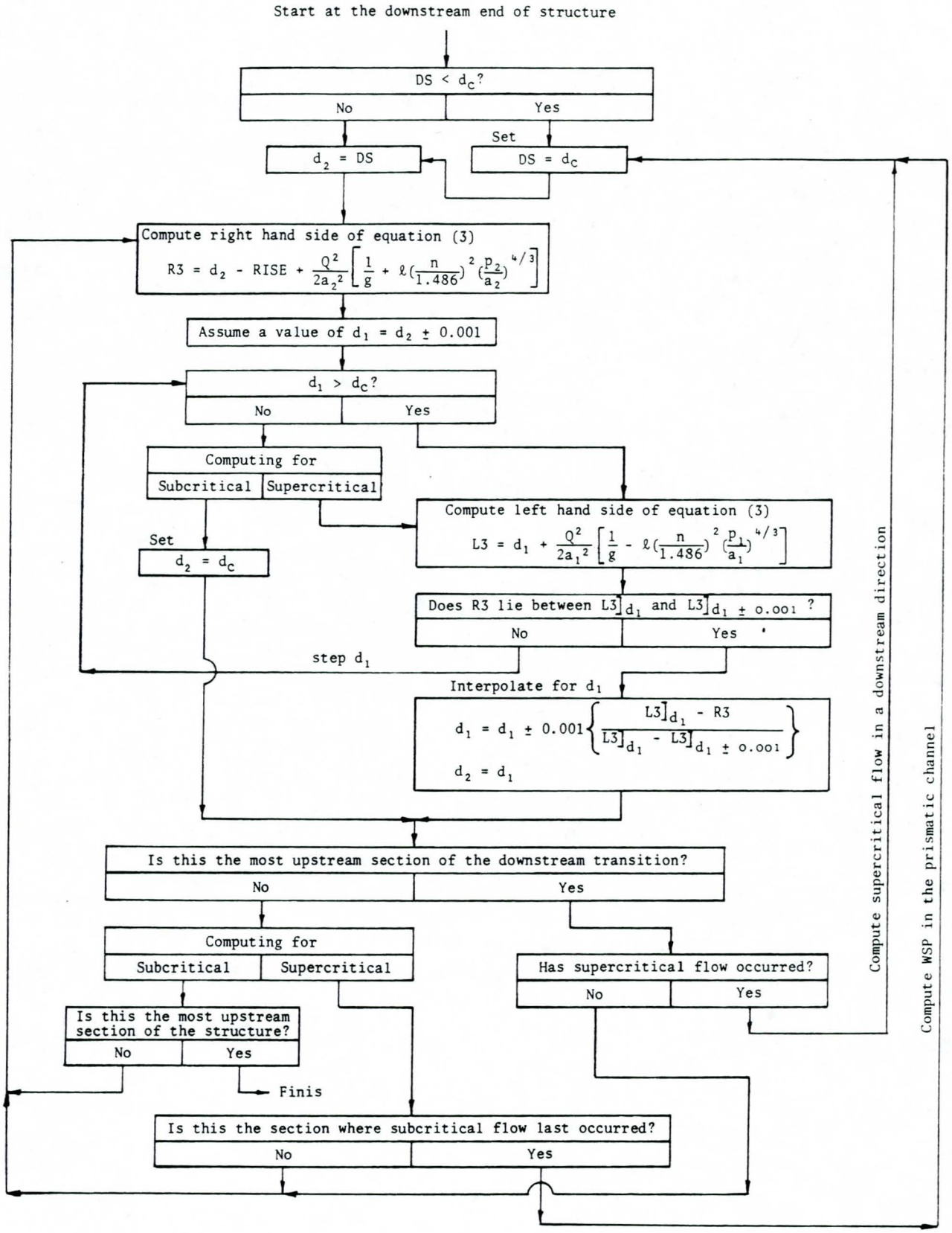

Figure 2. Flow chart of procedure used in computer program to compute WSP

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Computer Program

A computer program has been prepared which computes water surface profiles, maximum tractive stresses and other hydraulic parameters for the purpose of comparing and analyzing the design of a riprap gradient control structure obtained from TR-59. The program examines if the flow is subcritical, critical, or supercritical. The water surface profile corresponding to a discharge will be computed for subcritical as well as supercritical flow. It will readily show the effect on the profile and tractive stress of changes in: the tailwater condition, D_{50} size of riprap, or Manning's roughness coefficient.

Input Data

Each computer job requires two lines of heading information. Each line consists of 80 or less alphanumeric characters. This information must be placed ahead of the other input data and is used for identification.

The line arrangement of input data and their order are given in Table 1. All values indicated must be included except the value of n, see below.

Line No.	Order of Input Parameters						
0	Q	n	D_{50}	DIV	CONV	ZL	ZR
1	DS	BSD	R_1	R_2	R_3	R_4	R_5
2	R_6	R_7	R_8	R_9	R_{10}	-	-
3	ZU	BU	LPC	SN	THETA	-	-
4	BSU	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}
5	R_{17}	R_{18}	R_{19}	R_{20}	-	-	-

Table 1. Input Data

Line 0

Q ≡ Discharge for which WSP is desired, cfs

n ≡ Manning's coefficient of roughness. $n = 0.0395\ D_{50}^{1/6}$ unless user specified

D_{50} ≡ Size of rock in riprap of which 50 percent by weight is finer, ft

DIV ≡ Rate of divergence of the bottom width of the downstream transition, ft/ft

CONV ≡ Rate of convergence of the bottom width of the downstream transition, ft/ft

ZL ≡ Side slope of the left bank at the ends of riprap structure (looking downstream), ft/ft

ZR ≡ Side slope of the right bank of the ends of riprap structure, ft/ft

Lines 1 and 2

DS	≡	Starting depth at the most downstream end of the riprap structure, ft
BSD	≡	Bottom width at the most downstream end of the riprap structure, ft
$R_j = [RISE]_j$	≡	The vertical distance from the bottom of the channel, at the downstream end of the transition, to the bottom of the channel at any section j in the transition, ft. The subscript, j, is numbered from 1 to 10 inclusive; 1 being the first preselected section upstream from the most downstream end section of the transition and 10 being the 10th or the last section (most upstream end section) of the transition. The values of $(RISE)_j$ are obtained from the computer output design of TR-59.

Line 3

ZU	≡	Side slope of the prismatic channel, ft/ft
BU	≡	Bottom width of the prismatic channel, ft
LPC	≡	Length of the prismatic channel, ft
SN	≡	Slope of the prismatic channel, ft/ft
THETA	≡	Angle of repose of the riprap, degrees

Lines 4 and 5

BSU	≡	Bottom width of the most upstream end of the riprap structure, ft
$R_j = [RISE]_j$	≡	See definition above; except that j is numbered from 11 to 20 for the upstream transition, ft

Output Data

The alphanumeric heading information in the first two lines of input is printed in each computer run. The printed alphanumeric information is followed by the data used for analyzing the design.

The output data for the WSP, parameters, and dimensions of the structure are given in the following order:

1. Downstream Transition
2. Prismatic Channel
3. Upstream Transition.

The headings used for the output for the transitions and prismatic channel are:

LENGTH FT	≡	Length from the downstream end of the transition/prismatic channel to any section j of the transition/prismatic channel, ft
RISE FT	≡	The vertical distance from the bottom of the channel, at the downstream end of the transition/prismatic channel, to the bottom of the channel at any section j in the transition/prismatic channel, ft

WIDTH FT ≡ The bottom width at any section j, ft

ZL ≡ The left side slope (looking downstream) at any section j, ft/ft

ZR ≡ The right side slope at any section j, ft/ft

DEPTH FT ≡ The depth at any section j, ft

NORMAL DEPTH ≡ The normal depth at any section j, ft

CRITICAL DEPTH ≡ The critical depth at any section j, ft

VELOCITY FT/SEC ≡ The velocity at any section j, ft/sec

FRIC SLOPE FT/FT ≡ The instantaneous slope of the energy grade line at any section j, ft/ft

TAUBM LB/SQ.FT = (CTAUB)(γ)(RN)(SN) ≡ The maximum tractive stress along the riprap lining on the bottom of any section j, lb/ft^2

FS BOTTOM = $\frac{4\ D_{50}}{TAUBM}$ ≡ Factor of safety of the riprap lining on the bottom of any section j

TAUSM LB/SQ.FT = (CTAUS)(γ)(RN)(SN) ≡ The maximum tractive stress along the riprap lining on the side slope of any section j, lb/ft^2

FS SIDES = $\frac{K\ 4\ D_{50}}{TAUSM}$ ≡ Factor of safety of the riprap lining on the side slope of any section j

TAUO LB/SQ.FT ≡ Mode 4 type structure only (see TR-59); the average tractive stress at any section j in the transition. The maximum tractive stress cannot be obtained, because the value of $C_{\tau b}$ or $C_{\tau s}$ is unknown for trapezoidal cross sections having unequal side slopes, lb/ft^2

In computing the normal depth of flow in the various sections of the riprap structure, the bottom slope, s_o, used in the computations are as follows:

1. Downstream Transition
   a. the slope of the most downstream section has not been defined, therefore normal depth cannot be computed
   b. the average slope of the upstream and downstream computational reach is used to compute DN for all sections except end sections
   c. the slope of the prismatic channel is used to compute DN for the most upstream section
2. Prismatic Channel - the slope of the prismatic channel is used to compute DN for all sections of the prismatic channel

3. Upstream Transition

   a. the slope of the prismatic channel is used to compute DN for the most downstream section

   b. the average slope of the upstream and downstream computational reach is used to compute DN for all sections except end sections

   c. the slope of the most upstream section has not been defined, therefore normal depth cannot be computed.

Example

Given: The riprap structure design used in this example is taken from Example No. 2 of TR-59. This example is repeated in this supplement on pages 14 and 15.

Required:

1. Determine the stability and factor of safety of the riprap structure for the design discharge if the tailwater depth was 6.7 ft instead of 7.0 ft.

2. Determine the stability of the riprap structure for the following discharge-tailwater conditions:

   a. Q = 2600 cfs, DS = 6.75 ft

   b. Q = 2400 cfs, DS = 6.50 ft

   c. Q = 2000 cfs, DS = 6.00 ft.

3. Determine the stability, factor of safety, and capacity of the riprap structure if the design D_{50} = 1.0' was not used in the construction, but the following D_{50} sizes were used.

   a. D_{50} = 1.25 ft

   b. D_{50} = 0.75 ft.

4. Determine the stability, factor of safety, and capacity of the riprap structure if the following CN values were used instead of 0.0395 in the equation $n = CN(D_{50})^{1/6}$

   a. CN = 0.042

   b. CN = 0.035.

5. Determine if the following discharge-tailwater combinations would actually control the design

   a. Q = 2650 cfs, DS = 5.5 ft

   b. Q = 2550 cfs, DS = 6.75 ft.

Solution:

1. The water surface profile elevation, corresponding to the design discharge and a lower starting depth of 6.7 ft, will be lower than the original design where DS = 7.0 ft was used. Therefore, the velocity and tractive stresses will be increased in the downstream transition and the downstream end of the prismatic channel. From the WSP computer output (page 20):

   TAUBM = 4.046 lb/ft^2

   TAUSM = 3.391 lb/ft^2

Example No. 2 (From TR-59)

Given:

Design discharge, Q = 2750 cfs
Side slopes, ZU = 2.5 and ZS = 3.0
Riprap size, D50 = 1.0 ft
Bottom width, BS = 100.0 ft
Starting depth, DS = 7.0 ft
Factor of safety, FS = 1.25

Required:

Design a riprap structure and determine the length of the structure if the total vertical drop desired for gradient control is 6.0 ft.

Solution:

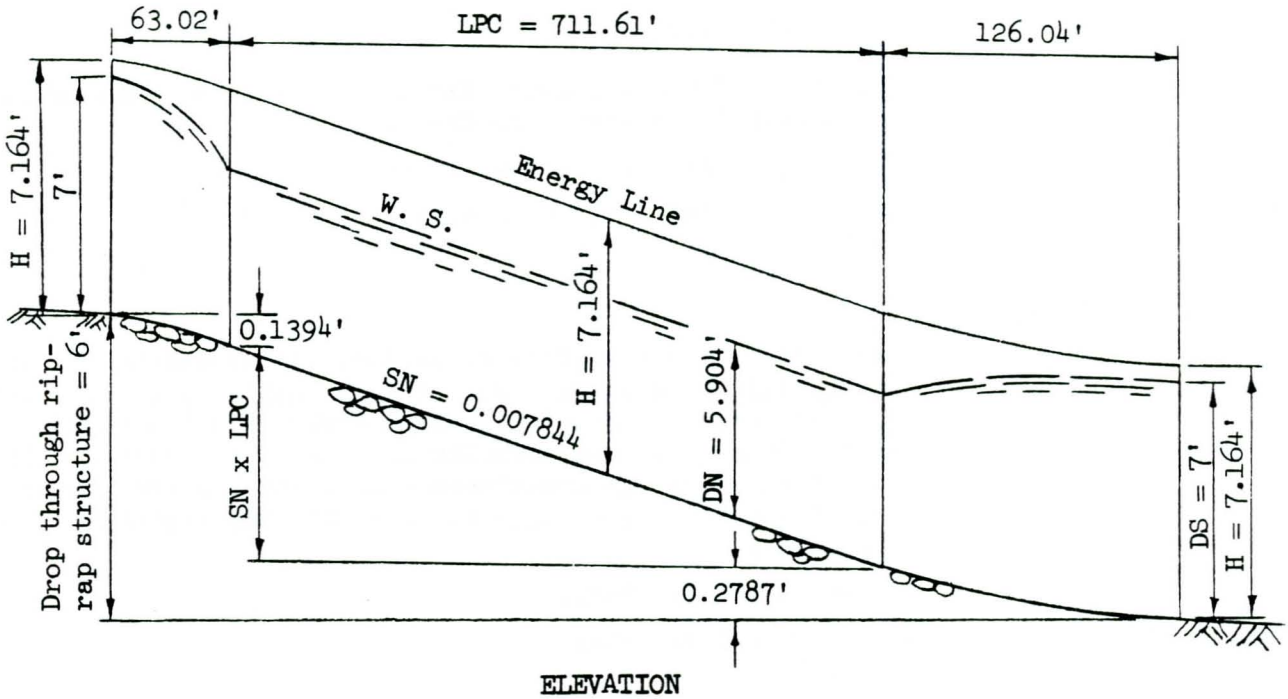
The design obtained from the computer using mode 2 is given on the next page.

The vertical drop in the prismatic channel is equal to the drop through the riprap structure minus the vertical drop contained in both transitions. The length of the prismatic channel, LPC, is equal to the vertical drop in the prismatic channel divided by the bottom slope of the prismatic channel, or

$$LPC = \frac{6.0 - 0.2787 - 0.1394}{0.007844} = 711.61 \text{ ft}$$

The total length of the structure is equal to the length of the prismatic channel plus the lengths of both transitions or

the total length = 711.61 + 126.04 + 63.02 = 900.67 ft



ELEVATION

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 2
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS H= 7.164 FT ZS= 3.00 FT/FT
BS= 100.000 FT DS= 7.000 FT VS= 3.247 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT CS= 0.7000 THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT. CN= 0.0395 CONV= 2.000
FS= 1.250 EXPN= 0.1667 DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	3.00	7.000	0.278	3.247	7.03E-04
12.60	0.0095	93.70	2.95	6.979	0.322	3.448	8.03E-04
25.21	0.0204	87.40	2.90	6.954	0.377	3.677	9.27E-04
37.81	0.0331	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.0480	74.79	2.80	6.883	0.533	4.247	1.28E-03
63.02	0.0658	68.49	2.75	6.833	0.646	4.611	1.55E-03
75.62	0.0876	62.19	2.70	6.767	0.799	5.051	1.91E-03
88.23	0.1150	55.89	2.65	6.677	1.011	5.598	2.43E-03
100.83	0.1507	49.58	2.60	6.545	1.325	6.309	3.23E-03
113.44	0.2002	43.28	2.55	6.334	1.838	7.305	4.62E-03
126.04	0.2787	36.98	2.50	5.904	2.910	9.003	7.84E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 1.000 FT SN= 0.007844 SC= 0.014965 CTAUB = 1.339
CSU= 0.5242 HN= 7.164 FT HC= 6.920 FT TAUBM= 2.910 LB/SQ.FT.
FSU= 1.25 DN= 5.904 FT DC= 4.943 FT TAUBA= 3.200 LB/SQ.FT.
BU= 36.98 FT VN= 9.00 FPS N= 0.0395 CTAUS = 1.122
ZU= 2.50 RN= 4.44 FT K= 0.7621 TAUSM= 2.439 LB/SQ.FT.
KPS= 8.77E+03 TAUSA= 2.439 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	36.98	2.50	5.904	2.910	9.003	7.84E-03
6.30	0.0393	43.28	2.55	6.334	1.838	7.305	4.62E-03
12.60	0.0640	49.58	2.60	6.545	1.325	6.309	3.23E-03
18.91	0.0819	55.89	2.65	6.677	1.011	5.598	2.43E-03
25.21	0.0955	62.19	2.70	6.767	0.799	5.051	1.91E-03
31.51	0.1064	68.49	2.75	6.833	0.646	4.611	1.55E-03
37.81	0.1154	74.79	2.80	6.883	0.533	4.247	1.28E-03
44.11	0.1228	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.1292	87.40	2.90	6.954	0.377	3.677	9.27E-04
56.72	0.1346	93.70	2.95	6.979	0.322	3.448	8.03E-04
63.02	0.1394	100.00	3.00	7.000	0.278	3.247	7.03E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.15 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.05 FT

From the original design (page 15):

TAUBA = 3.200 lb/ft^2

TAUSA = 2.439 lb/ft^2

The maximum tractive stress for both the bottom and side slopes of the channel is greater than their allowable tractive stress, i.e.,

TAUBM > TAUBA

TAUSM > TAUSA

Factor of safety: From the computer output (page 20) or may be computed as follows:

bottom; $FS = \frac{C_{50}D_{50}}{TAUBM} = \frac{4.0(1.0)}{4.046} = 0.99 < 1.25$ N.G.

side slopes; $FS = \frac{K\ C_{50}D_{50}}{TAUSM} = \frac{0.7621(4.0)(1.0)}{3.391} = 0.90 < 1.25$ N.G.

For the design discharge, the lowest tailwater condition should be used for the design. Therefore, the structure should be redesigned using the lower starting depth. The redesign is given on page 21.

2. a. The computer output is given on page 22.

TAUBM = 2.922 < 3.2 = TAUBA OK

FS = 1.37 > 1.25 OK

TAUSM = 2.449 ≃ 2.439 = TAUSA OK

FS = 1.24 ≃ 1.25 OK

b. The computer output is given on page 23.

TAUBM = 2.701 < 3.2 = TAUBA OK

TAUSM = 2.263 < 2.439 = TAUSA OK

FS > 1.25 OK

c. The computer output is given on page 24.

TAUBM = 2.436 < 3.2 = TAUBA OK

TAUSM = 2.042 < 2.439 = TAUSA OK

FS > 1.25 OK

The original design is considered stable for this rating curve.

3. a. Since the riprap size D_{50} = 1.25' was used instead of the design D_{50} = 1.0 ft, Manning's roughness coefficient, n, is increased. Thus, the water surface elevation throughout the entire structure will be higher. However, the increase in depths are considered small in this case, and the usual freeboard provided will be adequate.

Since a larger riprap size was used, stability will not be a problem. From WSP computer output (page 25):

TAUBM = 3.092 lb/ft^2

TAUSM = 2.591 lb/ft^2

$$TAUBA = \frac{C_{50}D_{50}}{FS} = \frac{4(1.25)}{1.25} = 4 > 3.092 = TAUBM \qquad OK$$

$$TAUSA = \frac{K\ C_{50}D_{50}}{FS} = 0.7621(4) = 3.05 > 2.591 = TAUSM \qquad OK$$

Factor of safety for bottom

FS = 1.62 > 1.25 OK

Factor of safety for side slopes

FS = 1.47 > 1.25 OK

b. Since the smaller size riprap D_{50} = 0.75' was used, the value of n is decreased. Thus, the water surface profile elevation throughout the entire structure will be lower so that capacity will not be a problem.

Since a smaller riprap size was used, stability may be a problem and the factor of safety will be decreased. From WSP computer output (page 26):

TAUBM = 2.835 lb/ft^2

TAUSM = 2.376 lb/ft^2

$$TAUBA = \frac{C_{50}D_{50}}{FS} = \frac{4(0.75)}{1.25} = 2.4 < 2.835 = TAUBM \qquad N.G.$$

$$TAUSA = \frac{K\ C_{50}D_{50}}{FS} = \frac{0.7621(4)(0.75)}{1.25} = 1.83 < 2.376 = TAUSM \qquad N.G.$$

Factor of safety for bottom

FS = 1.06 < 1.25 N.G.

Factor of safety for side slopes

FS = 0.96 < 1.25 N.G.

4. a. Since the value of CN = 0.042 was used instead of 0.0395, Manning's roughness coefficient is increased. Thus the water surface profile elevation throughout the entire structure will be higher. (See DEPTH column of WSP computer output, page 27).

From Example Design No. 2 (page 15) the maximum allowable tractive stress for the bottom and side slopes are:

TAUBA = 3.200 lb/ft^2

TAUSA = 2.439 lb/ft^2

From the WSP computer output (page 27) the maximum tractive stress occurred at the most downstream end of the prismatic channel.

TAUBM = 3.260 > 3.200 = TAUBA

TAUSM = 2.686 > 2.439 = TAUSA N.G.

Factor of safety at bottom

FS = 1.25

Factor of safety at side slopes

FS < 1.25

If the factor of safety = 1.25 is desired, the structure should be redesigned using the higher CN value.

b. The smaller value of CN = 0.035 would result in a smaller value of n. Thus, the water surface profile elevation throughout the entire structure will be lower. (See DEPTH column of WSP computer output, page 28). The maximum tractive stress occurred at the upstream end of the prismatic channel.

TAUBM = 2.724 < 3.200 = TAUBA OK

TAUSM = 2.282 < 2.439 = TAUSA OK

Factor of safety at the bottom

FS = 1.47 > 1.25 OK

Factor of safety at the side slopes

FS = 1.34 > 1.25 OK

5. a. The WSP computer output is given on page 29. Computation of water surface profile commences at the most downstream section, Sta. 0.0, in an upstream direction with a starting depth of 5.5 ft. Flow remains subcritical to Sta. 100.83, but supercritical flow occurred before reaching Sta. 113.44. Therefore, computation ceases and critical depth of 4.454 ft was used as the starting depth for the next computational reach. However, flow remains supercritical to the most upstream section (Sta. 126.04) of the downstream transition.

Computation of water surface profile for supercritical flow in a downstream direction using d_c = 4.835 ft as the starting depth commencing at Sta. 126.04 to Sta. 100.83 where subcritical flow last occurred. Note that actually a hydraulic jump occurs between Sta. 113.44 and Sta. 100.83.

Computation of water surface profile in an upstream direction resumes commencing at Sta. 126.04 using critical depth as the starting depth. The WSP approaches normal depth in the prismatic channel and the upstream transition.

In this case, the tailwater is considered to be decreasing very rapidly with a small decrease in discharge. The lesser discharge

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causes higher tractive stresses than the design discharge. For example, at Sta. 113.44;

TAUBM = 6.304 > 1.838 = TAU

TAUSM = 5.304 > 1.838 = TAU

where TAU is the maximum tractive stress at Sta. 113.44 for the design discharge-tailwater condition (see page 15).

Thus, the lesser discharge actually controls the design.

b. As can be seen from the WSP computer output given on page 30, this discharge-tailwater condition does not control the design and the original design is good for this condition.

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

SPECIAL ANALYSIS PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - JANUARY 23, 1978

PARAMETERS USED IN THE WSP ANALYSIS

Q = 2750.00 CFS N = 0.0395 D50 = 1.00 FT DIV = 4.00 CONV = 2.00 SN = 0.007844 THETA = 35.0 DEGREES

DOWNSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	100.00	3.00	3.00	6.700	******	2.784	3.418	0.000820	0.305	13.12	0.266	12.55
12.60	0.0095	93.70	2.95	2.95	6.678	6.964	2.899	3.631	0.000938	0.355	11.27	0.308	10.75
25.21	0.0204	87.40	2.90	2.90	6.651	6.934	3.027	3.875	0.001084	0.417	9.60	0.361	9.13
37.81	0.0331	81.09	2.85	2.85	6.618	6.901	3.170	4.157	0.001269	0.494	8.09	0.426	7.67
50.42	0.0480	74.79	2.80	2.80	6.577	6.862	3.330	4.486	0.001508	0.593	6.74	0.509	6.36
63.02	0.0658	68.49	2.75	2.75	6.523	6.805	3.511	4.878	0.001826	0.723	5.53	0.618	5.20
75.62	0.0876	62.19	2.70	2.70	6.451	6.727	3.717	5.355	0.002267	0.898	4.45	0.765	4.16
88.23	0.1150	55.89	2.65	2.65	6.350	6.623	3.954	5.956	0.002911	1.146	3.49	0.972	3.24
100.83	0.1507	49.58	2.60	2.60	6.200	6.465	4.230	6.751	0.003931	1.522	2.63	1.286	2.43
113.44	0.2002	43.28	2.55	2.55	5.945	6.172	4.555	7.915	0.005820	2.170	1.84	1.826	1.69
126.04	0.2787	36.98	2.50	2.50	5.211	5.904	4.943	10.554	0.012370	4.046	0.99	3.391	0.90

PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.211	5.904	4.943	10.554	0.012370	4.046	0.99	3.391	0.90
71.20	0.5585	36.98	2.50	2.50	5.717	5.904	4.943	9.381	0.008822	3.170	1.26	2.656	1.15
142.40	1.1170	36.98	2.50	2.50	5.827	5.904	4.943	9.155	0.008229	3.013	1.33	2.525	1.21
213.60	1.6755	36.98	2.50	2.50	5.870	5.904	4.943	9.070	0.008012	2.955	1.35	2.476	1.23
284.80	2.2340	36.98	2.50	2.50	5.888	5.904	4.943	9.033	0.007920	2.930	1.37	2.456	1.24
356.00	2.7925	36.98	2.50	2.50	5.897	5.904	4.943	9.017	0.007879	2.919	1.37	2.446	1.25
427.20	3.3510	36.98	2.50	2.50	5.900	5.904	4.943	9.009	0.007860	2.914	1.37	2.442	1.25
498.40	3.9094	36.98	2.50	2.50	5.902	5.904	4.943	9.006	0.007851	2.912	1.37	2.440	1.25
569.60	4.4679	36.98	2.50	2.50	5.903	5.904	4.943	9.004	0.007848	2.911	1.37	2.439	1.25
640.80	5.0264	36.98	2.50	2.50	5.903	5.904	4.943	9.004	0.007846	2.910	1.37	2.439	1.25
712.00	5.5849	36.98	2.50	2.50	5.904	5.904	4.943	9.003	0.007845	2.910	1.37	2.439	1.25

UPSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.904	5.904	4.943	9.003	0.007845	2.910	1.37	2.439	1.25
6.30	0.0393	43.28	2.55	2.55	6.331	6.172	4.555	7.309	0.004628	1.841	2.17	1.549	1.99
12.60	0.0640	49.58	2.60	2.60	6.542	6.465	4.230	6.312	0.003238	1.327	3.02	1.121	2.78
18.91	0.0819	55.89	2.65	2.65	6.674	6.626	3.954	5.601	0.002435	1.012	3.95	0.858	3.67
25.21	0.0955	62.19	2.70	2.70	6.764	6.735	3.717	5.053	0.001914	0.799	5.00	0.681	4.68
31.51	0.1064	68.49	2.75	2.75	6.830	6.796	3.511	4.613	0.001550	0.647	6.18	0.553	5.81
37.81	0.1154	74.79	2.80	2.80	6.880	6.856	3.330	4.249	0.001285	0.534	7.50	0.458	7.08
44.11	0.1228	81.09	2.85	2.85	6.920	6.901	3.170	3.942	0.001084	0.446	8.96	0.385	8.49
50.42	0.1292	87.40	2.90	2.90	6.951	6.934	3.027	3.679	0.000928	0.378	10.59	0.327	10.07
56.72	0.1346	93.70	2.95	2.95	6.976	6.964	2.899	3.450	0.000805	0.323	12.40	0.280	11.83
63.02	0.1394	100.00	3.00	3.00	6.997	******	2.784	3.248	0.000704	0.278	14.39	0.242	13.77

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DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - - JANUARY 23, 1978

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS H= 6.882 FT ZS= 3.00 FT/FT
BS= 100.000 FT DS= 6.700 FT VS= 3.418 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT CS= 0.7000 THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT. CN= 0.0395 CONV= 2.000
FS= 1.250 EXPN= 0.1667 DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	3.00	6.700	0.305	3.418	8.20E-04
11.98	0.0105	94.01	2.95	6.678	0.353	3.622	9.32E-04
23.95	0.0225	88.02	2.90	6.651	0.411	3.853	1.07E-03
35.93	0.0363	82.03	2.85	6.618	0.483	4.118	1.24E-03
47.91	0.0525	76.05	2.80	6.577	0.574	4.426	1.46E-03
59.89	0.0718	70.06	2.75	6.525	0.691	4.789	1.75E-03
71.86	0.0951	64.07	2.70	6.457	0.847	5.226	2.14E-03
83.84	0.1241	58.08	2.65	6.365	1.061	5.765	2.70E-03
95.82	0.1615	52.09	2.60	6.233	1.374	6.461	3.54E-03
107.80	0.2125	46.10	2.55	6.024	1.878	7.428	4.98E-03
119.77	0.2919	40.11	2.50	5.603	2.910	9.069	8.27E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 1.000 FT SN= 0.008275 SC= 0.015036 CTAUB = 1.306
CSU= 0.5503 HN= 6.882 FT HC= 6.678 FT TAUBM= 2.910 LB/SQ.FT.
FSU= 1.25 DN= 5.603 FT DC= 4.746 FT TAUBA= 3.200 LB/SQ.FT.
BU= 40.11 FT VN= 9.07 FPS N= 0.0395 CTAUS = 1.095
ZU= 2.50 RN= 4.31 FT K= 0.7621 TAUSM= 2.438 LB/SQ.FT.
KPS= 8.49E+03 TAUSA= 2.439 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	40.11	2.50	5.603	2.910	9.069	8.27E-03
5.99	0.0397	46.10	2.55	6.024	1.878	7.428	4.98E-03
11.98	0.0652	52.09	2.60	6.233	1.374	6.461	3.54E-03
17.97	0.0839	58.08	2.65	6.365	1.061	5.765	2.70E-03
23.95	0.0984	64.07	2.70	6.457	0.847	5.226	2.14E-03
29.94	0.1100	70.06	2.75	6.525	0.691	4.789	1.75E-03
35.93	0.1197	76.05	2.80	6.577	0.574	4.426	1.46E-03
41.92	0.1278	82.03	2.85	6.618	0.483	4.118	1.24E-03
47.91	0.1347	88.02	2.90	6.651	0.411	3.853	1.07E-03
53.90	0.1407	94.01	2.95	6.678	0.353	3.622	9.32E-04
59.89	0.1459	100.00	3.00	6.700	0.305	3.418	8.20E-04

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TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.15 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.05 FT

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WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

SPECIAL ANALYSIS PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - JANUARY 23, 1978

PARAMETERS USED IN THE WSP ANALYSIS

Q = 2600.00 CFS N = 0.0395 D50 = 1.00 FT DIV = 4.00 CONV = 2.00 SN = 0.007844 THETA = 35.0 DEGREES

DOWNSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	100.00	3.00	3.00	6.750	******	2.684	3.203	0.000714	0.268	14.91	0.234	14.26
12.60	0.0095	93.70	2.95	2.95	6.730	6.745	2.796	3.402	0.000816	0.312	12.82	0.271	12.23
25.21	0.0204	87.40	2.90	2.90	6.705	6.717	2.920	3.629	0.000942	0.366	10.93	0.317	10.39
37.81	0.0331	81.09	2.85	2.85	6.675	6.685	3.058	3.891	0.001101	0.433	9.23	0.373	8.75
50.42	0.0480	74.79	2.80	2.80	6.636	6.648	3.213	4.196	0.001305	0.519	7.71	0.446	7.27
63.02	0.0658	68.49	2.75	2.75	6.587	6.594	3.388	4.557	0.001576	0.631	6.34	0.540	5.95
75.62	0.0876	62.19	2.70	2.70	6.523	6.519	3.588	4.995	0.001948	0.781	5.12	0.665	4.78
88.23	0.1150	55.89	2.65	2.65	6.434	6.419	3.818	5.541	0.002483	0.992	4.03	0.841	3.75
100.83	0.1507	49.58	2.60	2.60	6.304	6.267	4.086	6.252	0.003310	1.304	3.07	1.102	2.83
113.44	0.2002	43.28	2.55	2.55	6.094	5.985	4.402	7.254	0.004755	1.819	2.20	1.530	2.02
126.04	0.2787	36.98	2.50	2.50	5.652	5.726	4.780	9.001	0.008227	2.922	1.37	2.449	1.24

PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.652	5.726	4.780	9.001	0.008227	2.922	1.37	2.449	1.24
71.20	0.5585	36.98	2.50	2.50	5.693	5.726	4.780	8.917	0.008008	2.865	1.40	2.401	1.27
142.40	1.1170	36.98	2.50	2.50	5.711	5.726	4.780	8.882	0.007917	2.842	1.41	2.381	1.28
213.60	1.6755	36.98	2.50	2.50	5.719	5.726	4.780	8.866	0.007877	2.831	1.41	2.373	1.28
284.80	2.2340	36.98	2.50	2.50	5.723	5.726	4.780	8.859	0.007859	2.827	1.42	2.369	1.29
356.00	2.7925	36.98	2.50	2.50	5.724	5.726	4.780	8.855	0.007851	2.824	1.42	2.367	1.29
427.20	3.3510	36.98	2.50	2.50	5.725	5.726	4.780	8.854	0.007847	2.823	1.42	2.366	1.29
498.40	3.9094	36.98	2.50	2.50	5.725	5.726	4.780	8.853	0.007846	2.823	1.42	2.366	1.29
569.60	4.4679	36.98	2.50	2.50	5.726	5.726	4.780	8.853	0.007845	2.823	1.42	2.365	1.29
640.80	5.0264	36.98	2.50	2.50	5.726	5.726	4.780	8.853	0.007844	2.823	1.42	2.365	1.29
712.00	5.5849	36.98	2.50	2.50	5.726	5.726	4.780	8.853	0.007844	2.823	1.42	2.365	1.29

UPSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.726	5.726	4.780	8.853	0.007844	2.823	1.42	2.365	1.29
6.30	0.0393	43.28	2.55	2.55	6.140	5.985	4.402	7.185	0.004628	1.784	2.24	1.501	2.06
12.60	0.0640	49.58	2.60	2.60	6.344	6.267	4.086	6.203	0.003235	1.283	3.12	1.084	2.88
18.91	0.0819	55.89	2.65	2.65	6.471	6.422	3.818	5.501	0.002432	0.978	4.09	0.829	3.80
25.21	0.0955	62.19	2.70	2.70	6.559	6.527	3.588	4.962	0.001910	0.771	5.19	0.657	4.85
31.51	0.1064	68.49	2.75	2.75	6.623	6.584	3.388	4.528	0.001547	0.623	6.42	0.533	6.03
37.81	0.1154	74.79	2.80	2.80	6.671	6.643	3.213	4.170	0.001282	0.513	7.80	0.440	7.36
44.11	0.1228	81.09	2.85	2.85	6.709	6.685	3.058	3.867	0.001081	0.428	9.34	0.369	8.85
50.42	0.1292	87.40	2.90	2.90	6.739	6.717	2.920	3.608	0.000925	0.362	11.05	0.313	10.51
56.72	0.1346	93.70	2.95	2.95	6.763	6.745	2.796	3.383	0.000802	0.309	12.96	0.268	12.36
63.02	0.1394	100.00	3.00	3.00	6.783	******	2.685	3.185	0.000702	0.265	15.07	0.232	14.41

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

SPECIAL ANALYSIS PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - JANUARY 23, 1978

PARAMETERS USED IN THE WSP ANALYSIS

Q = 2400.00 CFS N = 0.0395 D50 = 1.00 FT DIV = 4.00 CONV = 2.00 SN = 0.007844 THETA = 35.0 DEGREES

DOWNSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	100.00	3.00	3.00	6.500	******	2.549	3.090	0.000694	0.247	16.16	0.216	15.46
12.60	0.0095	93.70	2.95	2.95	6.481	6.444	2.655	3.283	0.000793	0.288	13.87	0.251	13.23
25.21	0.0204	87.40	2.90	2.90	6.457	6.417	2.773	3.502	0.000916	0.339	11.80	0.293	11.22
37.81	0.0331	81.09	2.85	2.85	6.429	6.387	2.904	3.755	0.001070	0.402	9.95	0.346	9.43
50.42	0.0480	74.79	2.80	2.80	6.393	6.354	3.052	4.050	0.001270	0.483	8.29	0.414	7.82
63.02	0.0658	68.49	2.75	2.75	6.346	6.303	3.219	4.400	0.001533	0.587	6.81	0.502	6.40
75.62	0.0876	62.19	2.70	2.70	6.285	6.232	3.410	4.824	0.001894	0.729	5.49	0.620	5.13
88.23	0.1150	55.89	2.65	2.65	6.201	6.138	3.631	5.351	0.002413	0.926	4.32	0.785	4.01
100.83	0.1507	49.58	2.60	2.60	6.079	5.994	3.888	6.037	0.003213	1.219	3.28	1.030	3.03
113.44	0.2002	43.28	2.55	2.55	5.883	5.726	4.192	6.999	0.004603	1.698	2.36	1.429	2.16
126.04	0.2787	36.98	2.50	2.50	5.481	5.480	4.556	8.640	0.007839	2.700	1.48	2.262	1.35

PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.481	5.480	4.556	8.640	0.007839	2.700	1.48	2.262	1.35
71.20	0.5585	36.98	2.50	2.50	5.480	5.480	4.556	8.641	0.007842	2.700	1.48	2.263	1.35
142.40	1.1170	36.98	2.50	2.50	5.480	5.480	4.556	8.641	0.007843	2.701	1.48	2.263	1.35
213.60	1.6755	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35
284.80	2.2340	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35
356.00	2.7925	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35
427.20	3.3510	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35
498.40	3.9094	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35
569.60	4.4679	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35
640.80	5.0264	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35
712.00	5.5849	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35

UPSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.480	5.480	4.556	8.642	0.007844	2.701	1.48	2.263	1.35
6.30	0.0393	43.28	2.55	2.55	5.875	5.726	4.192	7.012	0.004627	1.704	2.35	1.434	2.15
12.60	0.0640	49.58	2.60	2.60	6.070	5.994	3.888	6.049	0.003231	1.224	3.27	1.034	3.02
18.91	0.0819	55.89	2.65	2.65	6.191	6.141	3.631	5.362	0.002427	0.930	4.30	0.789	4.00
25.21	0.0955	62.19	2.70	2.70	6.275	6.240	3.410	4.833	0.001905	0.731	5.47	0.623	5.11
31.51	0.1064	68.49	2.75	2.75	6.336	6.294	3.219	4.409	0.001542	0.590	6.78	0.504	6.37
37.81	0.1154	74.79	2.80	2.80	6.382	6.348	3.052	4.058	0.001277	0.484	8.26	0.416	7.79
44.11	0.1228	81.09	2.85	2.85	6.418	6.388	2.904	3.763	0.001077	0.404	9.91	0.348	9.39
50.42	0.1292	87.40	2.90	2.90	6.446	6.417	2.773	3.509	0.000921	0.340	11.76	0.294	11.18
56.72	0.1346	93.70	2.95	2.95	6.470	6.444	2.655	3.289	0.000798	0.290	13.82	0.251	13.18
63.02	0.1394	100.00	3.00	3.00	6.489	******	2.549	3.096	0.000698	0.248	16.10	0.217	15.41

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

SPECIAL ANALYSIS PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - JANUARY 23, 1978

PARAMETERS USED IN THE WSP ANALYSIS

Q = 2000.00 CFS N = 0.0395 D50 = 1.00 FT DIV = 4.00 CONV = 2.00 SN = 0.007844 THETA = 35.0 DEGREES

DOWNSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	100.00	3.00	3.00	6.000	******	2.264	2.825	0.000637	0.204	19.61	0.178	18.76
12.60	0.0095	93.70	2.95	2.95	5.983	5.804	2.359	3.002	0.000728	0.237	16.88	0.206	16.11
25.21	0.0204	87.40	2.90	2.90	5.962	5.781	2.464	3.204	0.000841	0.280	14.31	0.242	13.60
37.81	0.0331	81.09	2.85	2.85	5.937	5.756	2.582	3.437	0.000983	0.333	12.01	0.287	11.38
50.42	0.0480	74.79	2.80	2.80	5.906	5.728	2.715	3.708	0.001165	0.401	9.97	0.344	9.41
63.02	0.0658	68.49	2.75	2.75	5.865	5.684	2.865	4.030	0.001406	0.490	8.16	0.419	7.66
75.62	0.0876	62.19	2.70	2.70	5.812	5.623	3.038	4.418	0.001736	0.610	6.56	0.520	6.13
88.23	0.1150	55.89	2.65	2.65	5.739	5.541	3.237	4.901	0.002209	0.777	5.15	0.659	4.78
100.83	0.1507	49.58	2.60	2.60	5.634	5.414	3.470	5.526	0.002931	1.024	3.91	0.865	3.61
113.44	0.2002	43.28	2.55	2.55	5.469	5.174	3.747	6.390	0.004161	1.422	2.81	1.197	2.58
126.04	0.2787	36.98	2.50	2.50	5.148	4.956	4.081	7.794	0.006837	2.209	1.81	1.851	1.65

PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.148	4.956	4.081	7.794	0.006837	2.209	1.81	1.851	1.65
71.20	0.5585	36.98	2.50	2.50	5.048	4.956	4.081	7.988	0.007340	2.324	1.72	1.947	1.57
142.40	1.1170	36.98	2.50	2.50	4.997	4.956	4.081	8.090	0.007611	2.385	1.68	1.998	1.53
213.60	1.6755	36.98	2.50	2.50	4.974	4.956	4.081	8.137	0.007741	2.414	1.66	2.023	1.51
284.80	2.2340	36.98	2.50	2.50	4.964	4.956	4.081	8.158	0.007800	2.427	1.65	2.034	1.50
356.00	2.7925	36.98	2.50	2.50	4.959	4.956	4.081	8.168	0.007825	2.432	1.64	2.038	1.50
427.20	3.3510	36.98	2.50	2.50	4.957	4.956	4.081	8.172	0.007836	2.435	1.64	2.040	1.49
498.40	3.9094	36.98	2.50	2.50	4.956	4.956	4.081	8.173	0.007841	2.436	1.64	2.041	1.49
569.60	4.4679	36.98	2.50	2.50	4.956	4.956	4.081	8.174	0.007843	2.436	1.64	2.042	1.49
640.80	5.0264	36.98	2.50	2.50	4.956	4.956	4.081	8.174	0.007844	2.436	1.64	2.042	1.49
712.00	5.5849	36.98	2.50	2.50	4.956	4.956	4.081	8.174	0.007844	2.436	1.64	2.042	1.49

UPSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	4.956	4.956	4.081	8.174	0.007844	2.436	1.64	2.042	1.49
6.30	0.0393	43.28	2.55	2.55	5.310	5.174	3.747	6.629	0.004628	1.533	2.61	1.290	2.39
12.60	0.0640	49.58	2.60	2.60	5.485	5.414	3.470	5.711	0.003225	1.094	3.66	0.924	3.37
18.91	0.0819	55.89	2.65	2.65	5.595	5.543	3.237	5.055	0.002418	0.827	4.84	0.701	4.50
25.21	0.0955	62.19	2.70	2.70	5.670	5.629	3.038	4.552	0.001895	0.647	6.18	0.551	5.78
31.51	0.1064	68.49	2.75	2.75	5.724	5.676	2.865	4.148	0.001532	0.519	7.71	0.443	7.25
37.81	0.1154	74.79	2.80	2.80	5.765	5.723	2.715	3.815	0.001268	0.423	9.45	0.364	8.91
44.11	0.1228	81.09	2.85	2.85	5.797	5.756	2.582	3.534	0.001068	0.351	11.40	0.302	10.80
50.42	0.1292	87.40	2.90	2.90	5.823	5.781	2.464	3.294	0.000913	0.294	13.61	0.254	12.94
56.72	0.1346	93.70	2.95	2.95	5.843	5.804	2.359	3.085	0.000790	0.249	16.09	0.216	15.35
63.02	0.1394	100.00	3.00	3.00	5.860	******	2.264	2.903	0.000691	0.217	18.45	0.189	17.65

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

SPECIAL ANALYSIS PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - - JANUARY 23, 1978

PARAMETERS USED IN THE WSP ANALYSIS

Q = 2750.00 CFS N = 0.0410 D50 = 1.25 FT DIV = 4.00 CONV = 2.00 SN = 0.007844 THETA = 35.0 DEGREES

DOWNSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	100.00	3.00	3.00	7.000	******	2.784	3.247	0.000758	0.299	16.72	0.261	15.99
12.60	0.0095	93.70	2.95	2.95	6.980	7.113	2.899	3.447	0.000865	0.347	14.40	0.302	13.74
25.21	0.0204	87.40	2.90	2.90	6.955	7.082	3.027	3.676	0.000998	0.406	12.31	0.351	11.71
37.81	0.0331	81.09	2.85	2.85	6.925	7.048	3.170	3.938	0.001165	0.480	10.42	0.413	9.87
50.42	0.0480	74.79	2.80	2.80	6.887	7.008	3.330	4.244	0.001380	0.573	8.72	0.492	8.23
63.02	0.0658	68.49	2.75	2.75	6.839	6.949	3.511	4.606	0.001663	0.695	7.19	0.594	6.76
75.62	0.0876	62.19	2.70	2.70	6.774	6.868	3.717	5.044	0.002050	0.858	5.83	0.731	5.45
88.23	0.1150	55.89	2.65	2.65	6.686	6.761	3.954	5.588	0.002605	1.085	4.61	0.920	4.28
100.83	0.1507	49.58	2.60	2.60	6.558	6.599	4.230	6.293	0.003457	1.420	3.52	1.200	3.25
113.44	0.2002	43.28	2.55	2.55	6.353	6.300	4.555	7.277	0.004925	1.965	2.54	1.654	2.33
126.04	0.2787	36.98	2.50	2.50	5.934	6.025	4.943	8.944	0.008294	3.092	1.62	2.591	1.47

PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.934	6.025	4.943	8.944	0.008294	3.092	1.62	2.591	1.47
71.20	0.5585	36.98	2.50	2.50	5.981	6.025	4.943	8.853	0.008054	3.027	1.65	2.536	1.50
142.40	1.1170	36.98	2.50	2.50	6.004	6.025	4.943	8.811	0.007945	2.997	1.67	2.511	1.52
213.60	1.6755	36.98	2.50	2.50	6.014	6.025	4.943	8.791	0.007894	2.983	1.68	2.499	1.52
284.80	2.2340	36.98	2.50	2.50	6.019	6.025	4.943	8.781	0.007869	2.976	1.68	2.494	1.53
356.00	2.7925	36.98	2.50	2.50	6.022	6.025	4.943	8.776	0.007856	2.972	1.68	2.491	1.53
427.20	3.3510	36.98	2.50	2.50	6.023	6.025	4.943	8.774	0.007850	2.971	1.68	2.489	1.53
498.40	3.9094	36.98	2.50	2.50	6.024	6.025	4.943	8.772	0.007847	2.970	1.68	2.489	1.53
569.60	4.4679	36.98	2.50	2.50	6.024	6.025	4.943	8.772	0.007846	2.969	1.68	2.488	1.53
640.80	5.0264	36.98	2.50	2.50	6.024	6.025	4.943	8.771	0.007845	2.969	1.68	2.488	1.53
712.00	5.5849	36.98	2.50	2.50	6.024	6.025	4.943	8.771	0.007845	2.969	1.68	2.488	1.53

UPSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	6.024	6.025	4.943	8.771	0.007845	2.969	1.68	2.488	1.53
6.30	0.0393	43.28	2.55	2.55	6.417	6.300	4.555	7.186	0.004748	1.914	2.61	1.611	2.39
12.60	0.0640	49.58	2.60	2.60	6.618	6.599	4.230	6.222	0.003345	1.387	3.60	1.172	3.33
18.91	0.0819	55.89	2.65	2.65	6.745	6.764	3.954	5.527	0.002525	1.061	4.71	0.900	4.38
25.21	0.0955	62.19	2.70	2.70	6.833	6.876	3.717	4.991	0.001988	0.840	5.95	0.715	5.56
31.51	0.1064	68.49	2.75	2.75	6.898	6.939	3.511	4.558	0.001613	0.681	7.35	0.582	6.90
37.81	0.1154	74.79	2.80	2.80	6.947	7.002	3.330	4.200	0.001338	0.562	8.90	0.482	8.40
44.11	0.1228	81.09	2.85	2.85	6.985	7.048	3.170	3.898	0.001130	0.470	10.63	0.405	10.07
50.42	0.1292	87.40	2.90	2.90	7.016	7.082	3.027	3.638	0.000968	0.398	12.56	0.345	11.94
56.72	0.1346	93.70	2.95	2.95	7.041	7.113	2.899	3.412	0.000839	0.341	14.68	0.296	14.01
63.02	0.1394	100.00	3.00	3.00	7.062	******	2.784	3.214	0.000735	0.293	17.04	0.256	16.30

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

SPECIAL ANALYSIS PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - JANUARY 23, 1978

PARAMETERS USED IN THE WSP ANALYSIS

Q = 2750.00 CFS N = 0.0377 D50 = 0.75 FT DIV = 4.00 CONV = 2.00 SN = 0.007844 THETA = 35.0 DEGREES

DOWNSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	100.00	3.00	3.00	7.000	******	2.784	3.247	0.000639	0.252	11.89	0.220	11.38
12.60	0.0095	93.70	2.95	2.95	6.978	6.777	2.899	3.448	0.000730	0.293	10.24	0.254	9.77
25.21	0.0204	87.40	2.90	2.90	6.952	6.748	3.027	3.678	0.000843	0.343	8.75	0.297	8.32
37.81	0.0331	81.09	2.85	2.85	6.919	6.716	3.170	3.942	0.000985	0.405	7.40	0.349	7.01
50.42	0.0480	74.79	2.80	2.80	6.878	6.679	3.330	4.251	0.001169	0.485	6.18	0.416	5.84
63.02	0.0658	68.49	2.75	2.75	6.826	6.624	3.511	4.616	0.001412	0.589	5.10	0.503	4.79
75.62	0.0876	62.19	2.70	2.70	6.758	6.549	3.717	5.059	0.001745	0.728	4.12	0.620	3.85
88.23	0.1150	55.89	2.65	2.65	6.664	6.448	3.954	5.611	0.002224	0.923	3.25	0.783	3.02
100.83	0.1507	49.58	2.60	2.60	6.527	6.295	4.230	6.331	0.002967	1.213	2.47	1.024	2.28
113.44	0.2002	43.28	2.55	2.55	6.306	6.011	4.555	7.346	0.004267	1.690	1.77	1.422	1.63
126.04	0.2787	36.98	2.50	2.50	5.842	5.751	4.943	9.125	0.007407	2.719	1.10	2.279	1.00

PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.842	5.751	4.943	9.125	0.007407	2.719	1.10	2.279	1.00
71.20	0.5585	36.98	2.50	2.50	5.791	5.751	4.943	9.228	0.007648	2.784	1.08	2.333	0.98
142.40	1.1170	36.98	2.50	2.50	5.768	5.751	4.943	9.275	0.007761	2.813	1.07	2.357	0.97
213.60	1.6755	36.98	2.50	2.50	5.758	5.751	4.943	9.296	0.007809	2.826	1.06	2.368	0.97
284.80	2.2340	36.98	2.50	2.50	5.754	5.751	4.943	9.304	0.007830	2.831	1.06	2.373	0.96
356.00	2.7925	36.98	2.50	2.50	5.752	5.751	4.943	9.308	0.007838	2.834	1.06	2.375	0.96
427.20	3.3510	36.98	2.50	2.50	5.752	5.751	4.943	9.309	0.007842	2.835	1.06	2.375	0.96
498.40	3.9094	36.98	2.50	2.50	5.751	5.751	4.943	9.310	0.007843	2.835	1.06	2.376	0.96
569.60	4.4679	36.98	2.50	2.50	5.751	5.751	4.943	9.310	0.007844	2.835	1.06	2.376	0.96
640.80	5.0264	36.98	2.50	2.50	5.751	5.751	4.943	9.310	0.007844	2.835	1.06	2.376	0.96
712.00	5.5849	36.98	2.50	2.50	5.751	5.751	4.943	9.310	0.007844	2.835	1.06	2.376	0.96

UPSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.751	5.751	4.943	9.310	0.007844	2.835	1.06	2.376	0.96
6.30	0.0393	43.28	2.55	2.55	6.231	6.011	4.555	7.458	0.004456	1.744	1.72	1.467	1.58
12.60	0.0640	49.58	2.60	2.60	6.454	6.295	4.230	6.421	0.003090	1.248	2.40	1.054	2.22
18.91	0.0819	55.89	2.65	2.65	6.591	6.451	3.954	5.689	0.002314	0.949	3.16	0.805	2.94
25.21	0.0955	62.19	2.70	2.70	6.684	6.556	3.717	5.128	0.001814	0.748	4.01	0.637	3.75
31.51	0.1064	68.49	2.75	2.75	6.752	6.615	3.511	4.678	0.001468	0.605	4.96	0.517	4.66
37.81	0.1154	74.79	2.80	2.80	6.803	6.673	3.330	4.307	0.001215	0.498	6.03	0.427	5.69
44.11	0.1228	81.09	2.85	2.85	6.843	6.716	3.170	3.995	0.001025	0.416	7.21	0.358	6.83
50.42	0.1292	87.40	2.90	2.90	6.875	6.748	3.027	3.727	0.000877	0.352	8.53	0.304	8.11
56.72	0.1346	93.70	2.95	2.95	6.901	6.777	2.899	3.494	0.000759	0.300	9.99	0.261	9.53
63.02	0.1394	100.00	3.00	3.00	6.922	******	2.784	3.290	0.000665	0.258	11.61	0.225	11.11

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

SPECIAL ANALYSIS PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - JANUARY 23, 1978

PARAMETERS USED IN THE WSP ANALYSIS

Q = 2750.00 CFS N = 0.0420 D50 = 1.00 FT DIV = 4.00 CONV = 2.00 SN = 0.007844 THETA = 35.0 DEGREES

DOWNSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	100.00	3.00	3.00	7.000	******	2.784	3.247	0.000795	0.314	12.74	0.274	12.19
12.60	0.0095	93.70	2.95	2.95	6.980	7.212	2.899	3.447	0.000908	0.364	10.98	0.316	10.48
25.21	0.0204	87.40	2.90	2.90	6.956	7.180	3.027	3.675	0.001047	0.426	9.39	0.369	8.93
37.81	0.0331	81.09	2.85	2.85	6.927	7.144	3.170	3.937	0.001221	0.503	7.95	0.434	7.53
50.42	0.0480	74.79	2.80	2.80	6.890	7.104	3.330	4.242	0.001446	0.601	6.65	0.516	6.28
63.02	0.0658	68.49	2.75	2.75	6.843	7.044	3.511	4.603	0.001742	0.728	5.49	0.623	5.16
75.62	0.0876	62.19	2.70	2.70	6.780	6.962	3.717	5.039	0.002146	0.899	4.45	0.765	4.16
88.23	0.1150	55.89	2.65	2.65	6.694	6.852	3.954	5.580	0.002724	1.136	3.52	0.963	3.27
100.83	0.1507	49.58	2.60	2.60	6.568	6.688	4.230	6.281	0.003608	1.485	2.69	1.254	2.49
113.44	0.2002	43.28	2.55	2.55	6.367	6.384	4.555	7.256	0.005125	2.050	1.95	1.725	1.79
126.04	0.2787	36.98	2.50	2.50	5.961	6.104	4.943	8.891	0.008558	3.205	1.25	2.686	1.13

PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.961	6.104	4.943	8.891	0.008558	3.206	1.25	2.686	1.13
71.20	0.5585	36.98	2.50	2.50	6.035	6.104	4.943	8.751	0.008180	3.101	1.29	2.599	1.17
142.40	1.1170	36.98	2.50	2.50	6.070	6.104	4.943	8.687	0.008010	3.054	1.31	2.559	1.19
213.60	1.6755	36.98	2.50	2.50	6.087	6.104	4.943	8.656	0.007928	3.031	1.32	2.540	1.20
284.80	2.2340	36.98	2.50	2.50	6.095	6.104	4.943	8.640	0.007887	3.020	1.32	2.530	1.20
356.00	2.7925	36.98	2.50	2.50	6.100	6.104	4.943	8.632	0.007866	3.014	1.33	2.526	1.21
427.20	3.3510	36.98	2.50	2.50	6.102	6.104	4.943	8.628	0.007856	3.011	1.33	2.523	1.21
498.40	3.9094	36.98	2.50	2.50	6.103	6.104	4.943	8.626	0.007850	3.009	1.33	2.522	1.21
569.60	4.4679	36.98	2.50	2.50	6.104	6.104	4.943	8.625	0.007847	3.008	1.33	2.521	1.21
640.80	5.0264	36.98	2.50	2.50	6.104	6.104	4.943	8.624	0.007846	3.008	1.33	2.521	1.21
712.00	5.5849	36.98	2.50	2.50	6.104	6.104	4.943	8.624	0.007845	3.008	1.33	2.521	1.21

UPSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	6.104	6.104	4.943	8.624	0.007845	3.008	1.33	2.521	1.21
6.30	0.0393	43.28	2.55	2.55	6.475	6.384	4.555	7.103	0.004821	1.961	2.04	1.650	1.87
12.60	0.0640	49.58	2.60	2.60	6.670	6.688	4.230	6.160	0.003412	1.426	2.80	1.205	2.59
18.91	0.0819	55.89	2.65	2.65	6.795	6.855	3.954	5.477	0.002581	1.093	3.66	0.927	3.40
25.21	0.0955	62.19	2.70	2.70	6.881	6.970	3.717	4.948	0.002035	0.866	4.62	0.738	4.31
31.51	0.1064	68.49	2.75	2.75	6.945	7.034	3.511	4.521	0.001652	0.703	5.69	0.601	5.35
37.81	0.1154	74.79	2.80	2.80	6.993	7.098	3.330	4.167	0.001372	0.580	6.89	0.498	6.50
44.11	0.1228	81.09	2.85	2.85	7.031	7.145	3.170	3.868	0.001159	0.486	8.23	0.419	7.80
50.42	0.1292	87.40	2.90	2.90	7.061	7.180	3.027	3.610	0.000993	0.412	9.71	0.356	9.23
56.72	0.1346	93.70	2.95	2.95	7.086	7.212	2.899	3.386	0.000861	0.352	11.35	0.306	10.83
63.02	0.1394	100.00	3.00	3.00	7.106	******	2.784	3.190	0.000754	0.304	13.16	0.265	12.60

LIBRARY

WATER SURFACE PROFILES AND TRACTIVE STRESSES FOR RIPRAP GRADIENT CONTROL STRUCTURES

SPECIAL ANALYSIS PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
DESIGN UNIT, ENGINEERING DIVISION, HYATTSVILLE, MARYLAND
EXAMPLE DESIGN NO. 1 - - - - - - - - - JANUARY 23, 1978

PARAMETERS USED IN THE WSP ANALYSIS

Q = 2750.00 CFS N = 0.0350 D50 = 1.00 FT DIV = 4.00 CONV = 2.00 SN = 0.007844 THETA = 35.0 DEGREES

DOWNSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	100.00	3.00	3.00	7.000	******	2.784	3.247	0.000552	0.218	18.35	0.190	17.56
12.60	0.0095	93.70	2.95	2.95	6.977	6.500	2.899	3.449	0.000631	0.253	15.79	0.220	15.07
25.21	0.0204	87.40	2.90	2.90	6.949	6.473	3.027	3.680	0.000730	0.297	13.48	0.257	12.82
37.81	0.0331	81.09	2.85	2.85	6.915	6.443	3.170	3.945	0.000854	0.351	11.40	0.302	10.80
50.42	0.0480	74.79	2.80	2.80	6.872	6.408	3.330	4.256	0.001013	0.420	9.52	0.361	8.99
63.02	0.0658	68.49	2.75	2.75	6.817	6.357	3.511	4.624	0.001226	0.510	7.84	0.436	7.36
75.62	0.0876	62.19	2.70	2.70	6.745	6.286	3.717	5.071	0.001518	0.632	6.33	0.538	5.91
88.23	0.1150	55.89	2.65	2.65	6.647	6.191	3.954	5.629	0.001940	0.803	4.98	0.681	4.63
100.83	0.1507	49.58	2.60	2.60	6.503	6.045	4.230	6.360	0.002597	1.058	3.78	0.894	3.49
113.44	0.2002	43.28	2.55	2.55	6.271	5.774	4.555	7.399	0.003764	1.482	2.70	1.247	2.47
126.04	0.2787	36.98	2.50	2.50	5.768	5.526	4.943	9.275	0.006706	2.431	1.65	2.037	1.50

PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.768	5.526	4.943	9.275	0.006706	2.431	1.65	2.037	1.50
71.20	0.5585	36.98	2.50	2.50	5.622	5.526	4.943	9.584	0.007364	2.602	1.54	2.180	1.40
142.40	1.1170	36.98	2.50	2.50	5.559	5.526	4.943	9.723	0.007675	2.681	1.49	2.247	1.36
213.60	1.6755	36.98	2.50	2.50	5.536	5.526	4.943	9.774	0.007789	2.710	1.48	2.271	1.34
284.80	2.2340	36.98	2.50	2.50	5.529	5.526	4.943	9.790	0.007827	2.719	1.47	2.279	1.34
356.00	2.7925	36.98	2.50	2.50	5.527	5.526	4.943	9.795	0.007839	2.722	1.47	2.281	1.34
427.20	3.3510	36.98	2.50	2.50	5.526	5.526	4.943	9.797	0.007843	2.723	1.47	2.282	1.34
498.40	3.9094	36.98	2.50	2.50	5.526	5.526	4.943	9.797	0.007844	2.724	1.47	2.282	1.34
569.60	4.4679	36.98	2.50	2.50	5.526	5.526	4.943	9.797	0.007844	2.724	1.47	2.282	1.34
640.80	5.0264	36.98	2.50	2.50	5.526	5.526	4.943	9.798	0.007844	2.724	1.47	2.282	1.34
712.00	5.5849	36.98	2.50	2.50	5.526	5.526	4.943	9.798	0.007844	2.724	1.47	2.282	1.34

UPSTREAM TRANSITION

LENGTH FT	RISE FT	WIDTH FT	ZL	ZR	DEPTH FT	NORMAL DEPTH	CRITICAL DEPTH	VELOCITY FT/SEC	FRIC SLOPE FT/FT	TAUBM LB/SQ.FT	FS BOTTOM	TAUSM LB/SQ.FT	FS SIDES
0.0	0.0	36.98	2.50	2.50	5.526	5.526	4.943	9.798	0.007844	2.724	1.47	2.282	1.34
6.30	0.0393	43.28	2.55	2.55	6.102	5.774	4.555	7.659	0.004157	1.592	2.51	1.340	2.30
12.60	0.0640	49.58	2.60	2.60	6.341	6.045	4.230	6.564	0.002846	1.129	3.54	0.953	3.27
18.91	0.0819	55.89	2.65	2.65	6.485	6.193	3.954	5.804	0.002120	0.854	4.68	0.724	4.35
25.21	0.0955	62.19	2.70	2.70	6.582	6.293	3.717	5.225	0.001657	0.671	5.96	0.572	5.57
31.51	0.1064	68.49	2.75	2.75	6.652	6.348	3.511	4.764	0.001337	0.541	7.39	0.463	6.94
37.81	0.1154	74.79	2.80	2.80	6.705	6.403	3.330	4.384	0.001106	0.445	8.99	0.382	8.48
44.11	0.1228	81.09	2.85	2.85	6.746	6.443	3.170	4.064	0.000931	0.371	10.77	0.320	10.20
50.42	0.1292	87.40	2.90	2.90	6.778	6.473	3.027	3.790	0.000796	0.314	12.75	0.271	12.13
56.72	0.1346	93.70	2.95	2.95	6.805	6.500	2.899	3.552	0.000689	0.268	14.95	0.232	14.26
63.02	0.1394	100.00	3.00	3.00	6.826	******	2.784	3.344	0.000603	0.230	17.38	0.201	16.63