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GRAPHICAL SOLUTION FOR THE HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

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.

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GRAPHICAL SOLUTION FOR THE HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

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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 $\equiv$ Acceleration of gravity, ft/sec^2

H $\equiv$ Specific energy head corresponding to the design discharge, Q, ft

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

LDT $\equiv$ Length of downstream transition, ft

LPC $\equiv$ Length of prismatic channel, ft

LUT $\equiv$ Length of upstream transition, ft

m $\equiv$ Number of equal parts that the transition length is divided into for computational purposes

n $\equiv$ Manning's coefficient of roughness

Q $\equiv$ Design discharge through the riprap structure, cfs

RISE $\equiv$ 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

RISE$]_j$ $\equiv$ 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 $\equiv$ Energy gradient, ft/ft

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

s_j $\equiv$ Energy gradient at any section j in the transition, ft/ft

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

s_o $\equiv$ Slope of channel bottom, ft/ft

v $\equiv$ Velocity corresponding to the design discharge, Q, ft/sec

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

ZS $\equiv$ 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

τ_{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

τ_{sc} = K τ_{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.

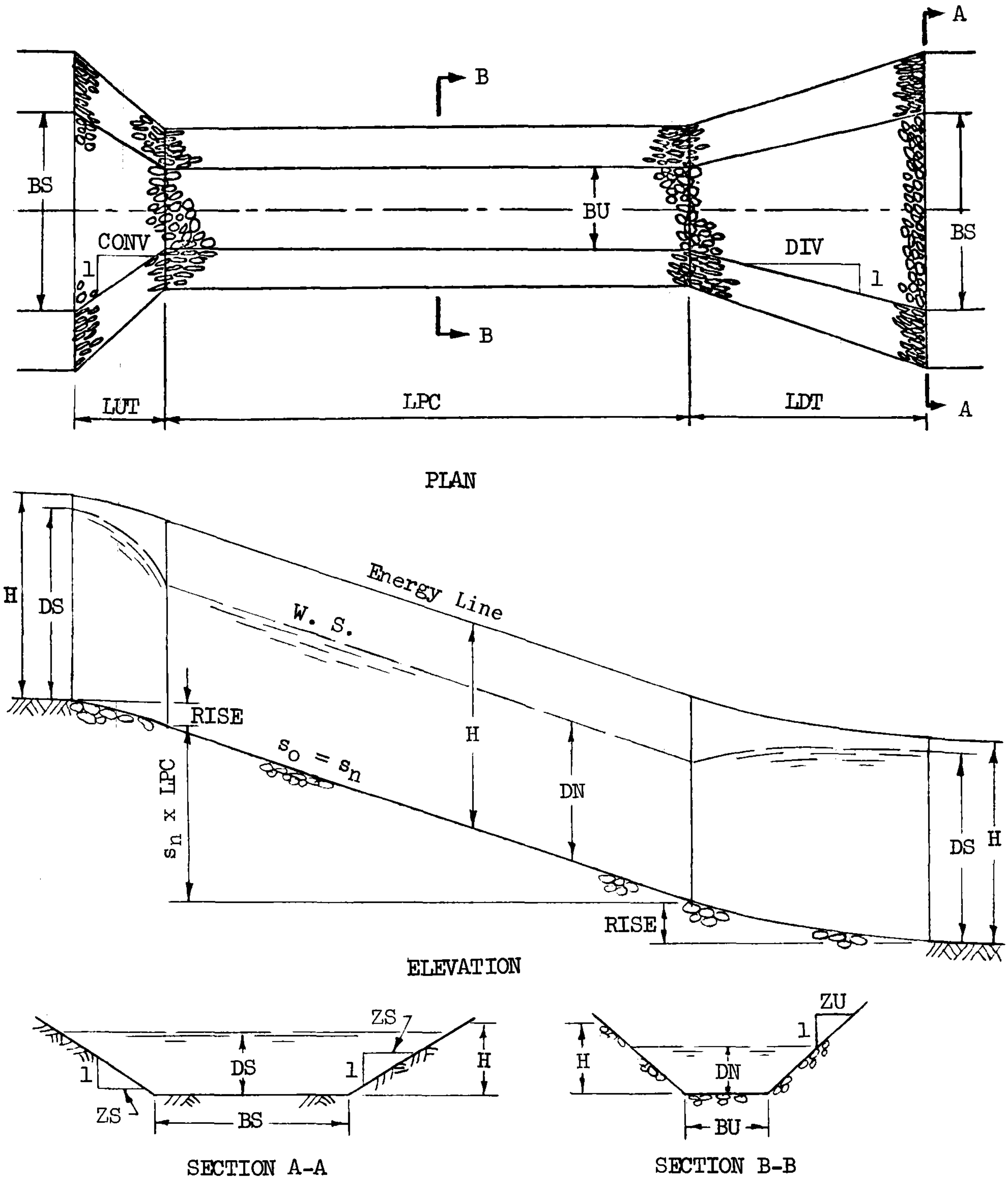


Figure 1. Riprap gradient control structure

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.

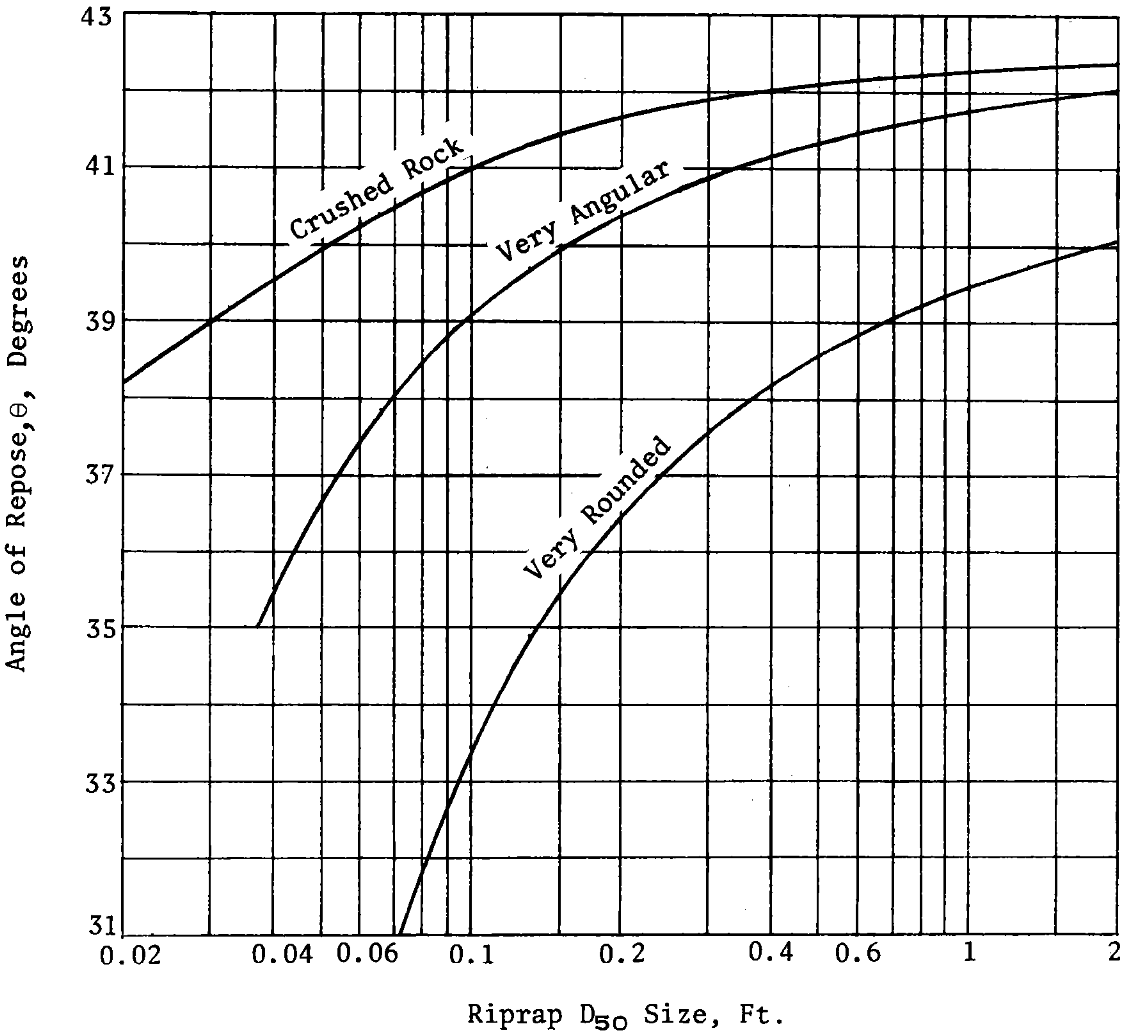


Figure 2. Riprap angle of repose for riprap shape and D_{50} size (taken from Figure 24 of NCHRP Report 108[1])

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

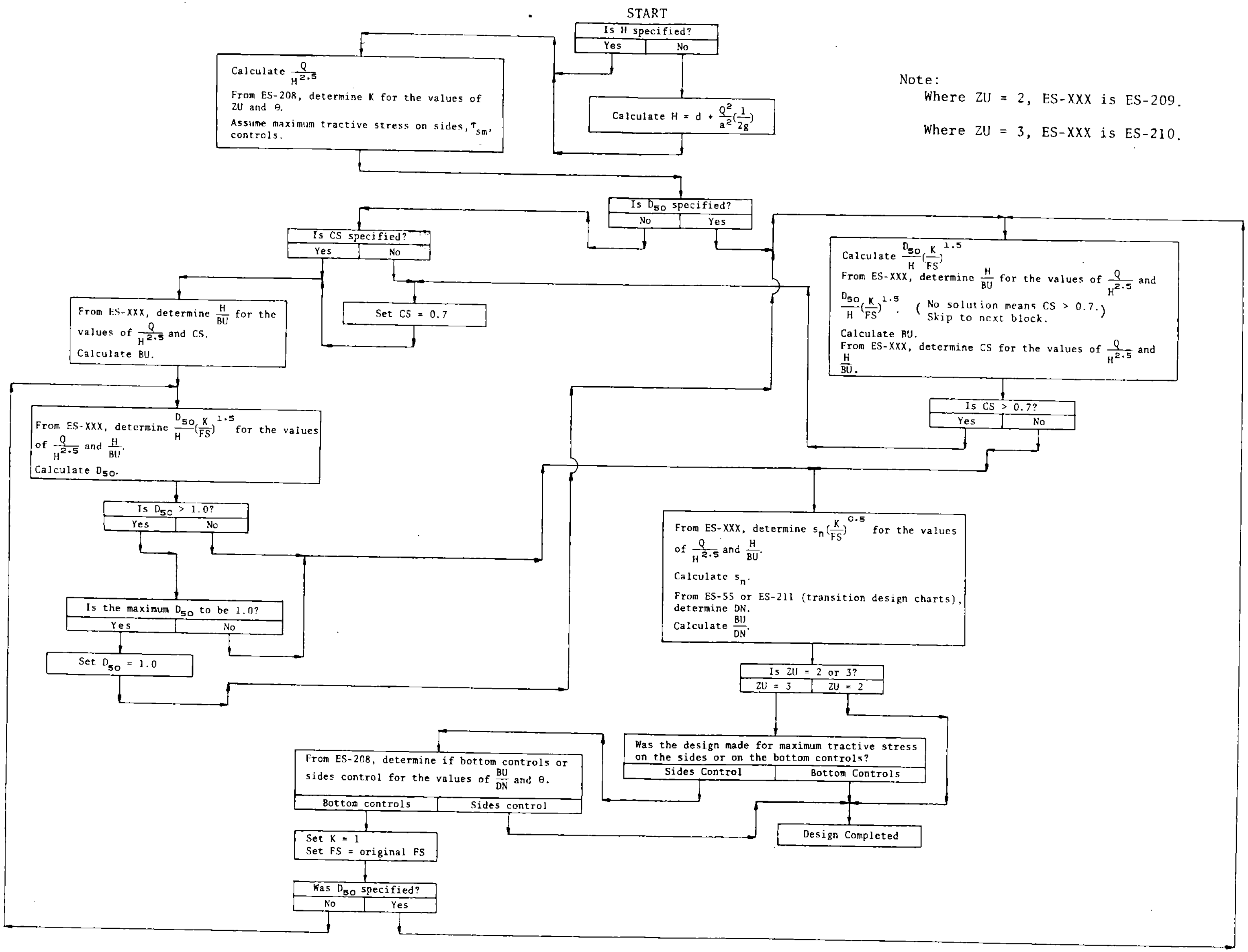


Figure 3. Flow chart for graphical solution of prismatic channel

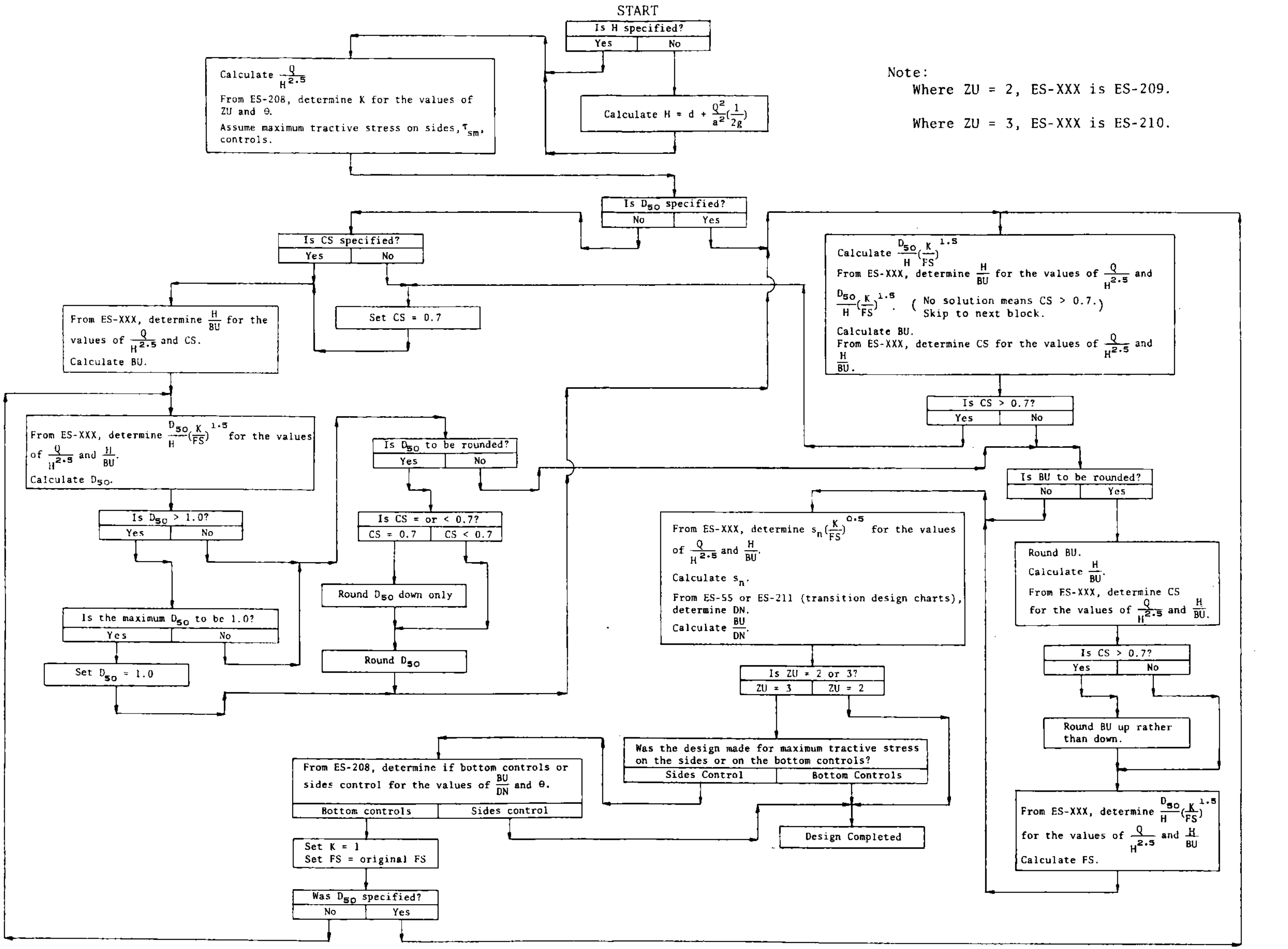


Figure 4. Flow chart for graphical solution of prismatic channel with rounding of BU and/or D_{50}

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 $CONV(\frac{BS-BU}{2})$. 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 $DIV(\frac{BS-BU}{2})$.

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
$H = 4.8$ ft
$ZU = 2$
$CS = 0.7$
$\theta = 39^o$
$FS = 1.5$

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 $\frac{D_{50}}{H}(\frac{K}{FS})^{1.5} = 0.085$.

Then

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

Set D_{50} to 1.0 ft.

Then

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

Example No. 2

Given:

Q = 2500 cfs
ZU = 3
H = 6.5 ft

D_{50} = 1.25 ft (trial value)
θ = 35°
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 θ = 35°, 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 θ = 35° 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 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 $\frac{D_{50}}{H}(\frac{K}{FS})^{1.5} = 0.031$, 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 $s_n(\frac{K}{FS})^{0.5} = 0.0025$.

Then

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

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 $\theta = 42^{o}$, maximum tractive stress on the bottom controls. Therefore, the charts for maximum tractive stress on the bottom, τ_{bm}, controls must be used to determine 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
D_{50} = 0.75 ft	structure = 3.0 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 $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$

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

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

Then

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

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

Use ES-208, plot of K vs. θ.
For ZU = 3 and θ = 35°, read K = 0.834.

Then

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

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

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

For θ = 35° 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 $\frac{D_{50}}{H}(\frac{K}{FS})^{1.5} = 0.069$, 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 $\frac{D_{50}}{H}(\frac{K}{FS})^{1.5} = 0.06$

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

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

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

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

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

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)	$s\left(\frac{b^5}{z^3 Q^2}\right)\left(\frac{b}{D_{50}}\right)^{1/3}$	$\left(\frac{b}{D_{50}}\right)^{1/3}$	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)	$s\left(\frac{b^5}{z^3 Q^2}\right)\left(\frac{b}{D_{50}}\right)^{1/3}$	$\left(\frac{b}{D_{50}}\right)^{1/3}$	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 = $\frac{2.84}{s_n}$

$= \frac{2.84}{0.0067}$

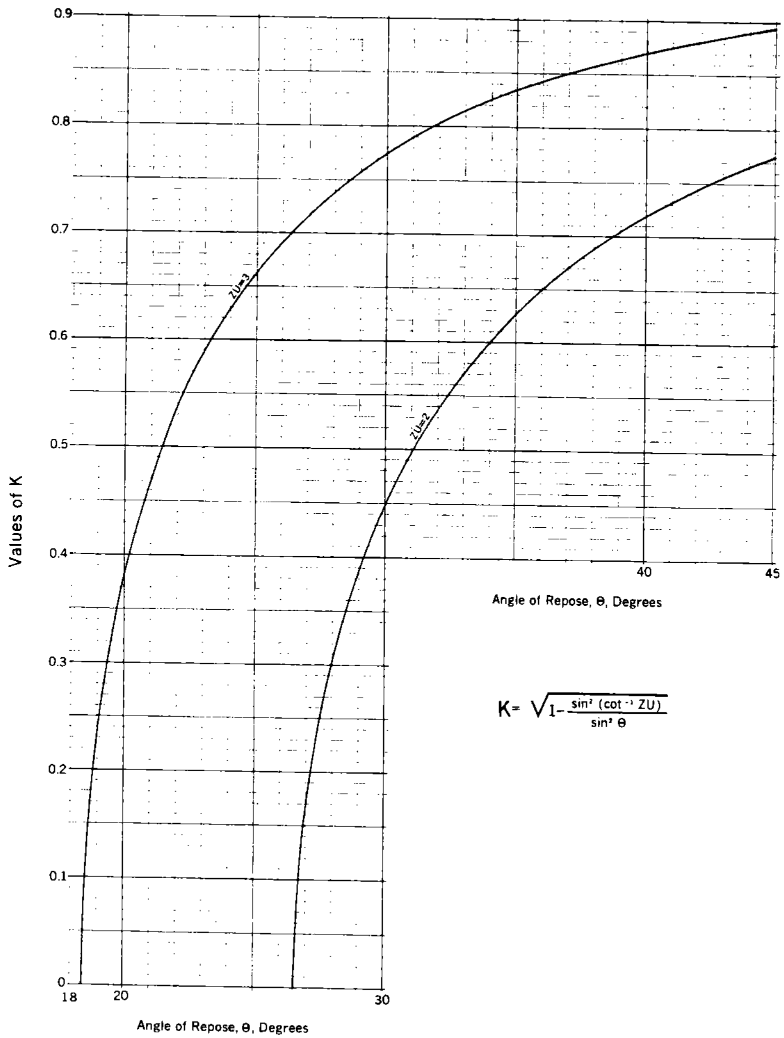
= 424 ft

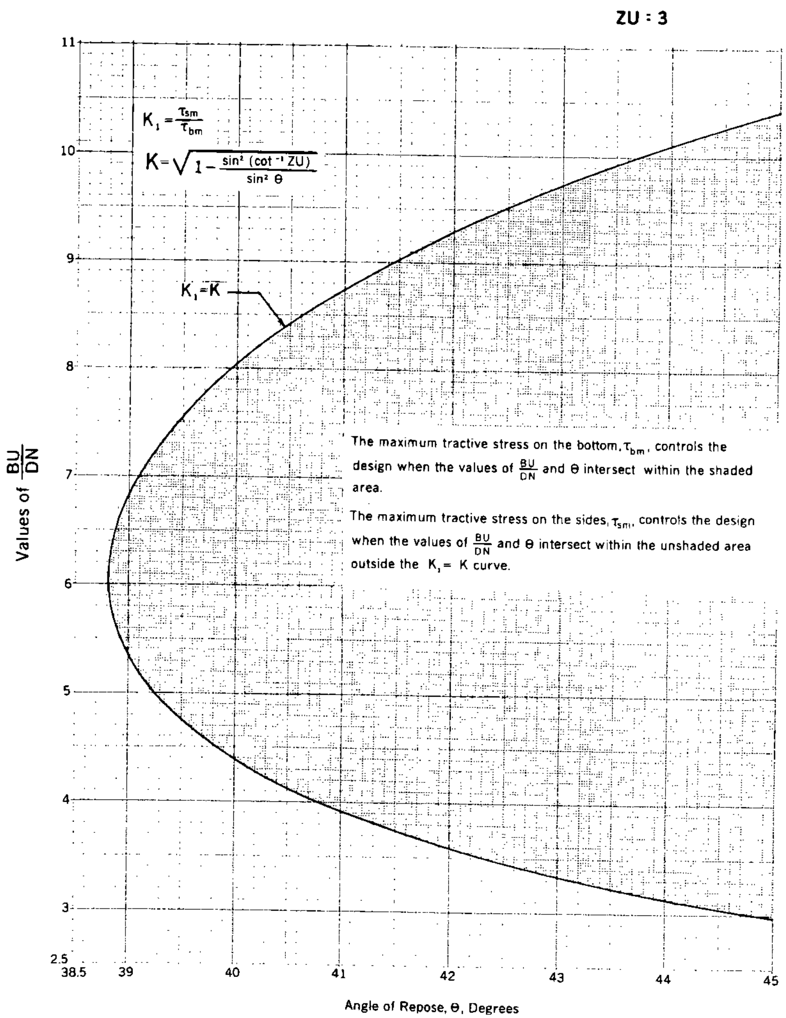
Total length of riprap structure = Length of upstream transition + Length of downstream transition + LPC

Total length = 16 + 32 + 424 = 472 ft

☆U.S. Government Printing Office : 1987 -180-917/60046

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





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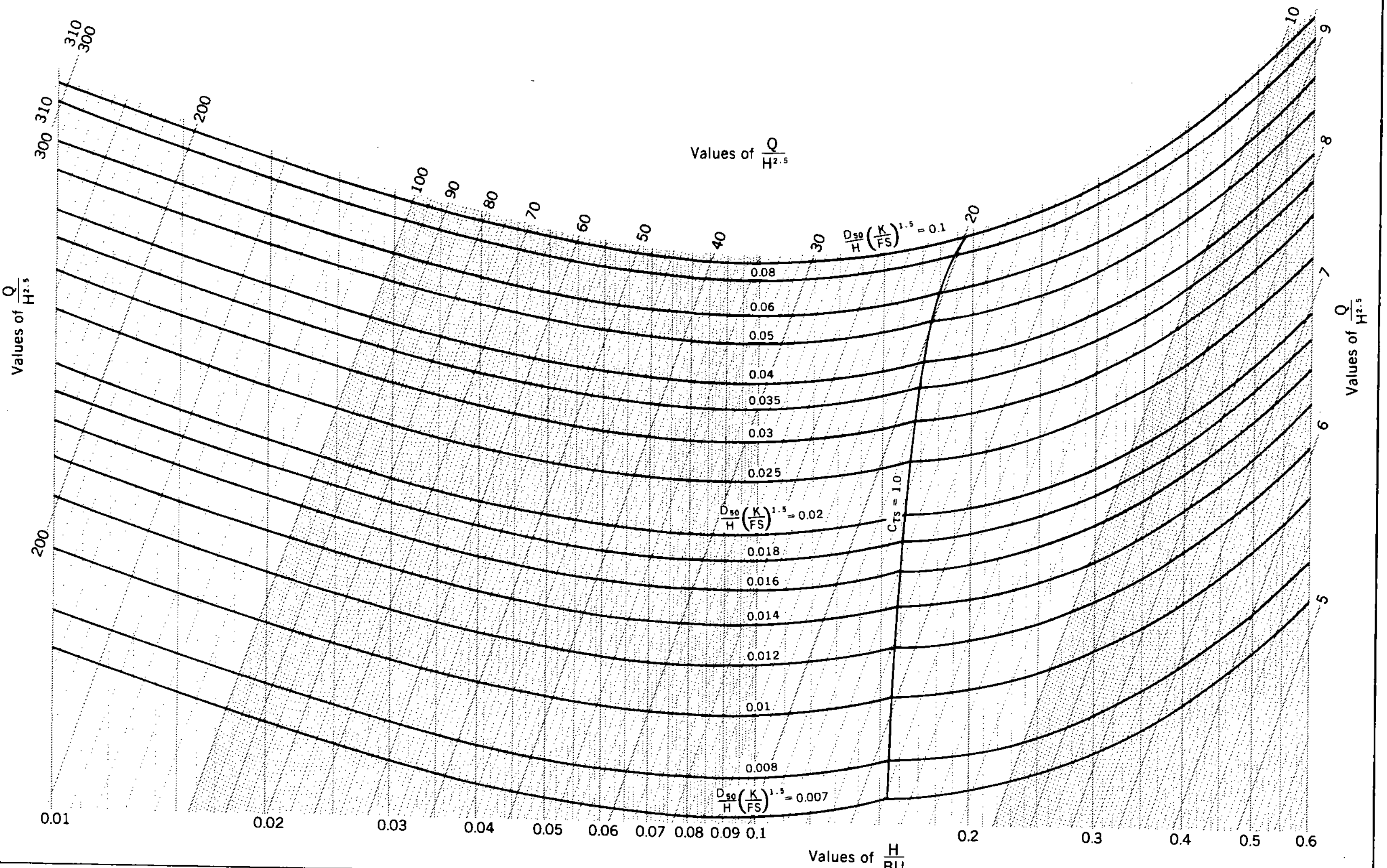
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$ curves

ZU = 2



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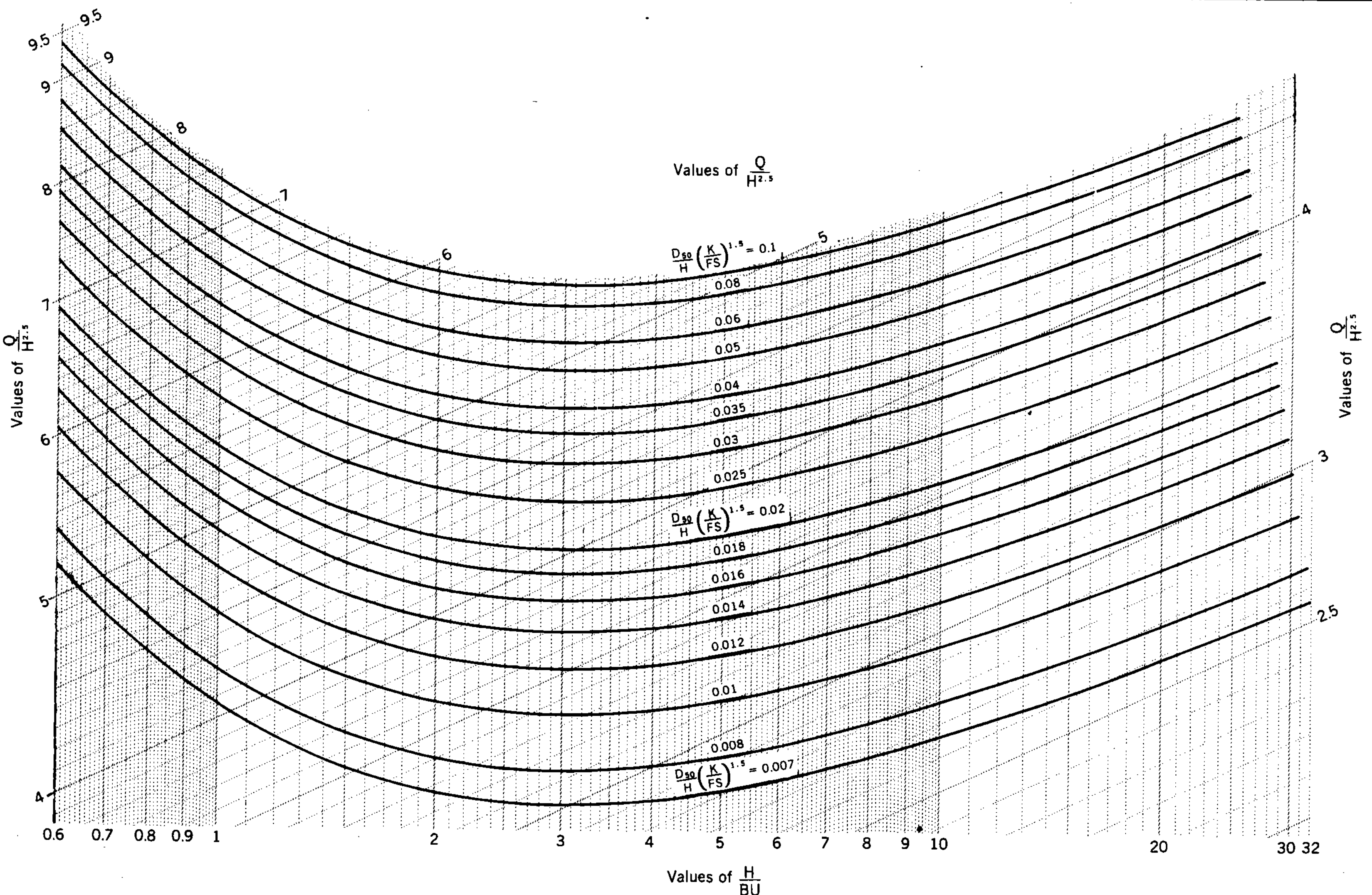
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$ curves

ZU = 2



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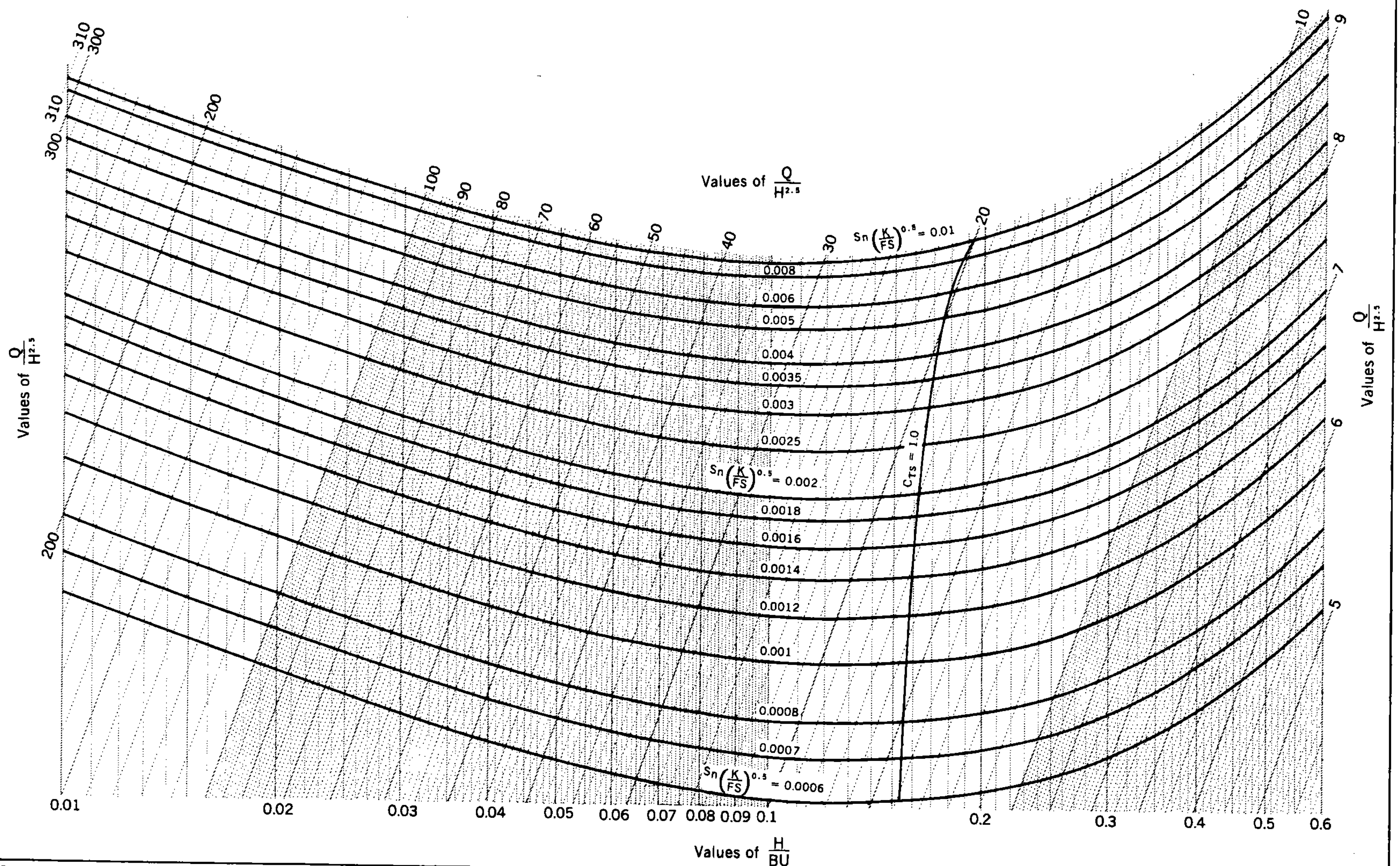
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $S_n\left(\frac{K}{FS}\right)^{0.5}$ curves

ZU = 2



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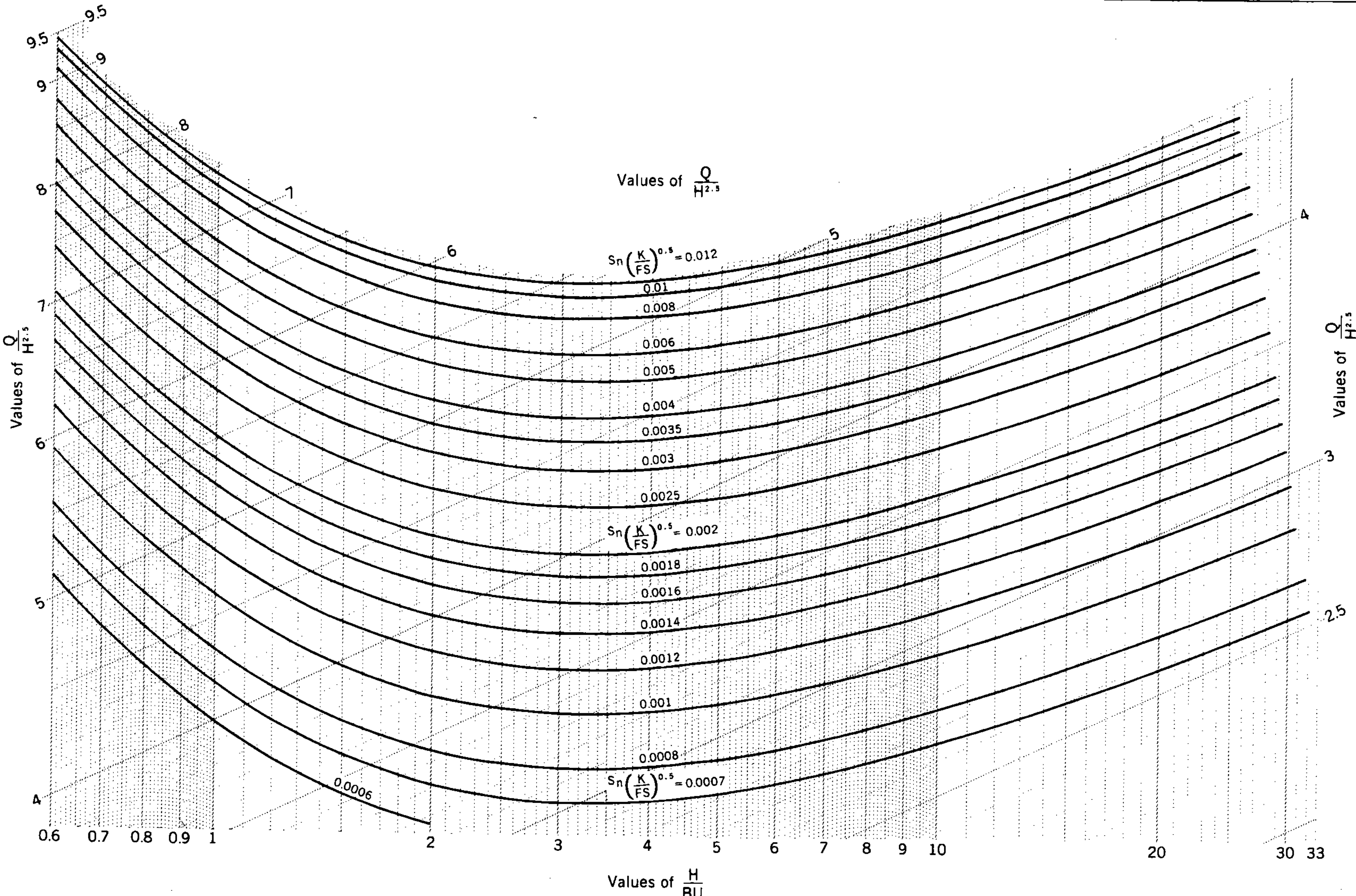
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $Sn\left(\frac{K}{FS}\right)^{0.5}$ curves

ZU = 2



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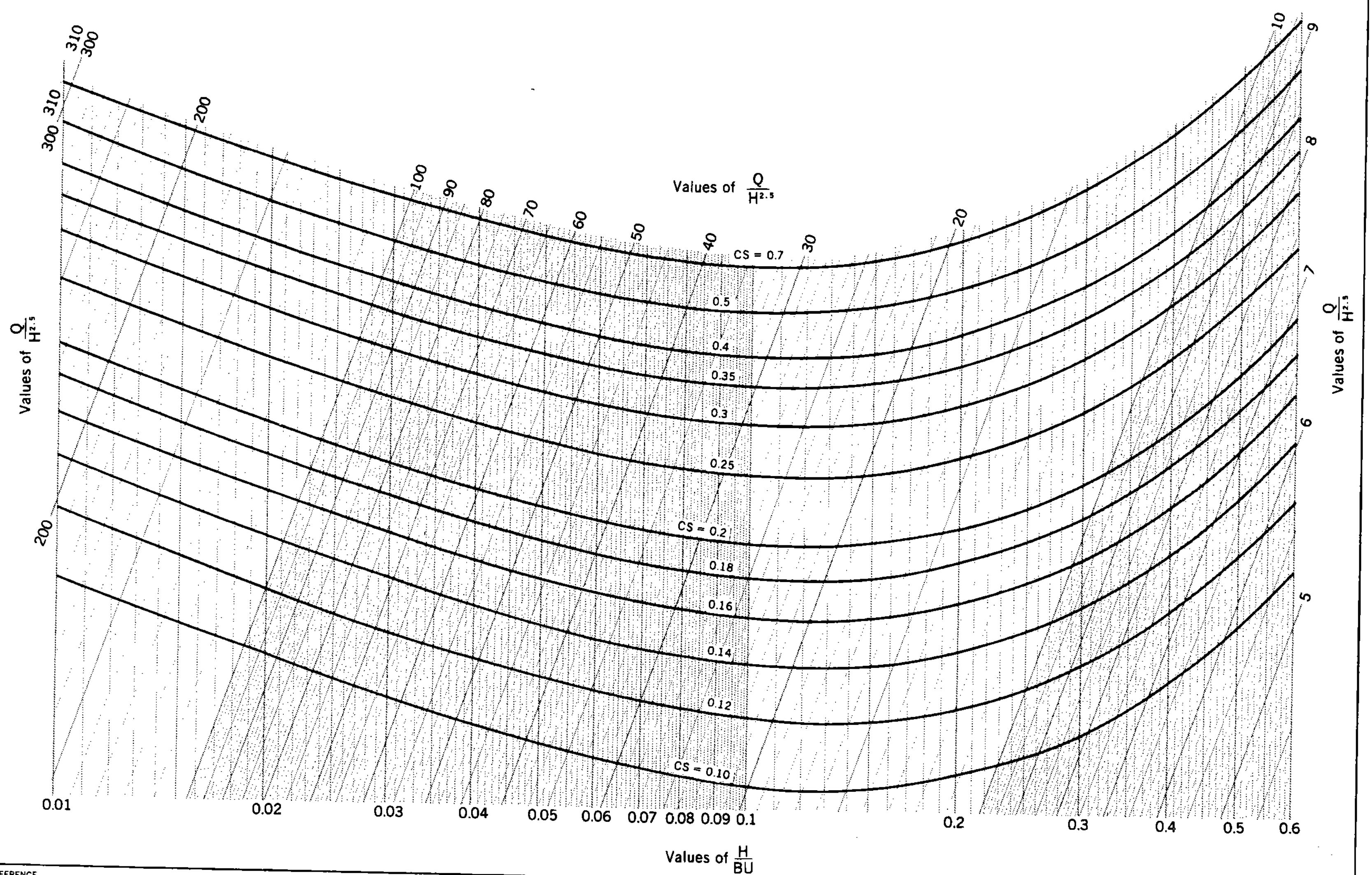
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with CS curves

ZU = 2



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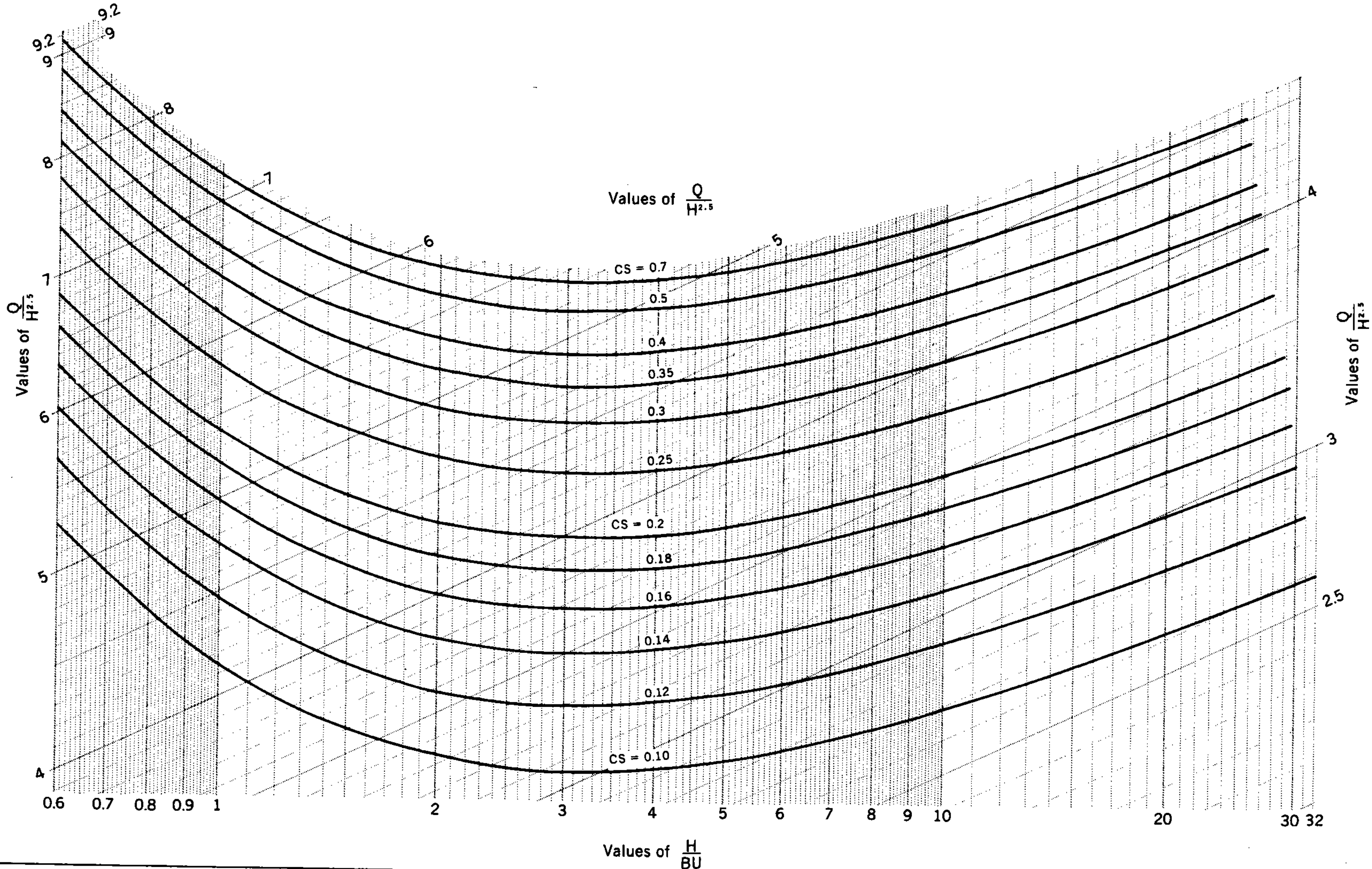
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with CS curves

ZU = 2



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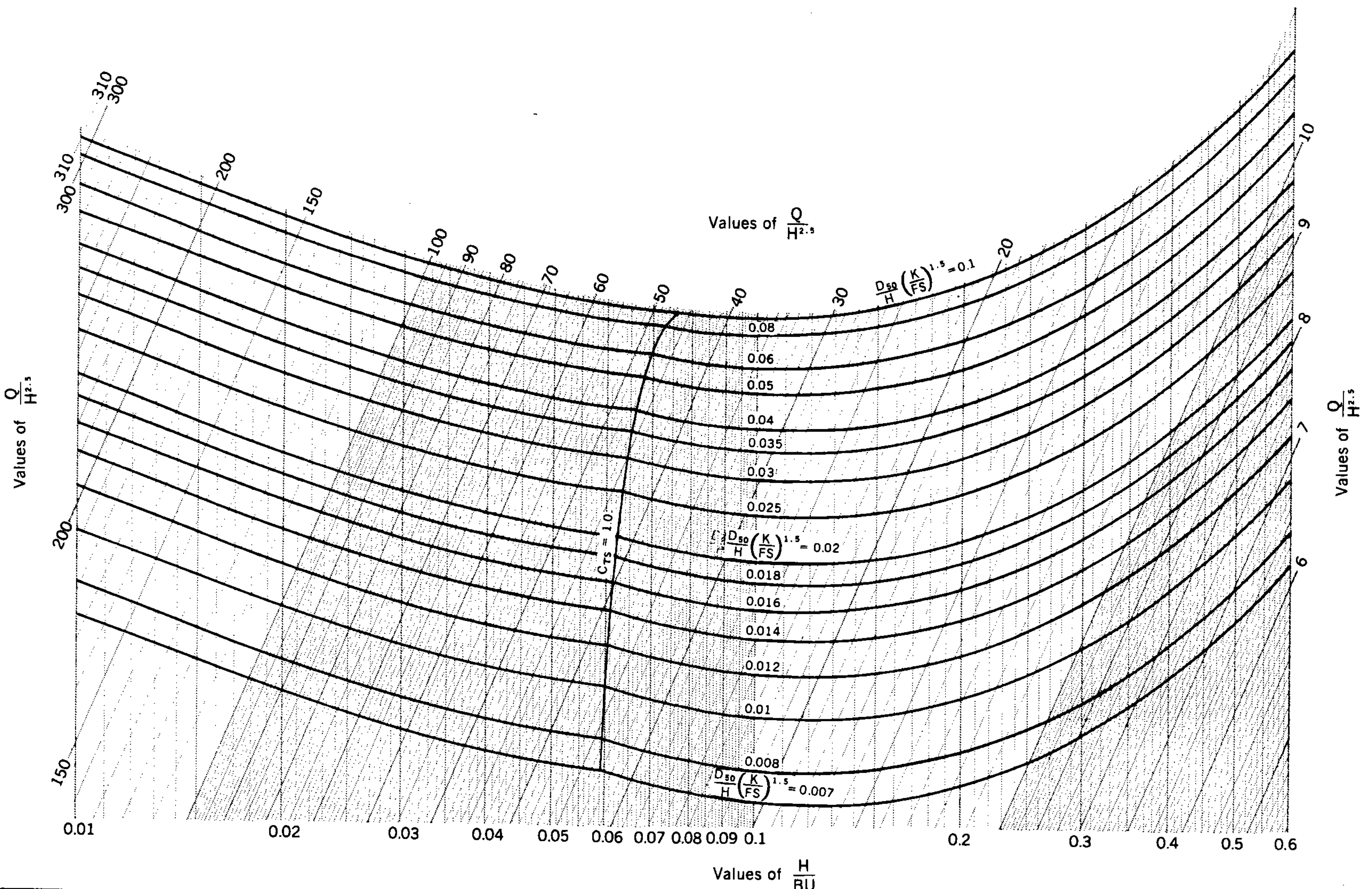
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$ curves

ZU = 3
τ_{sm} controls



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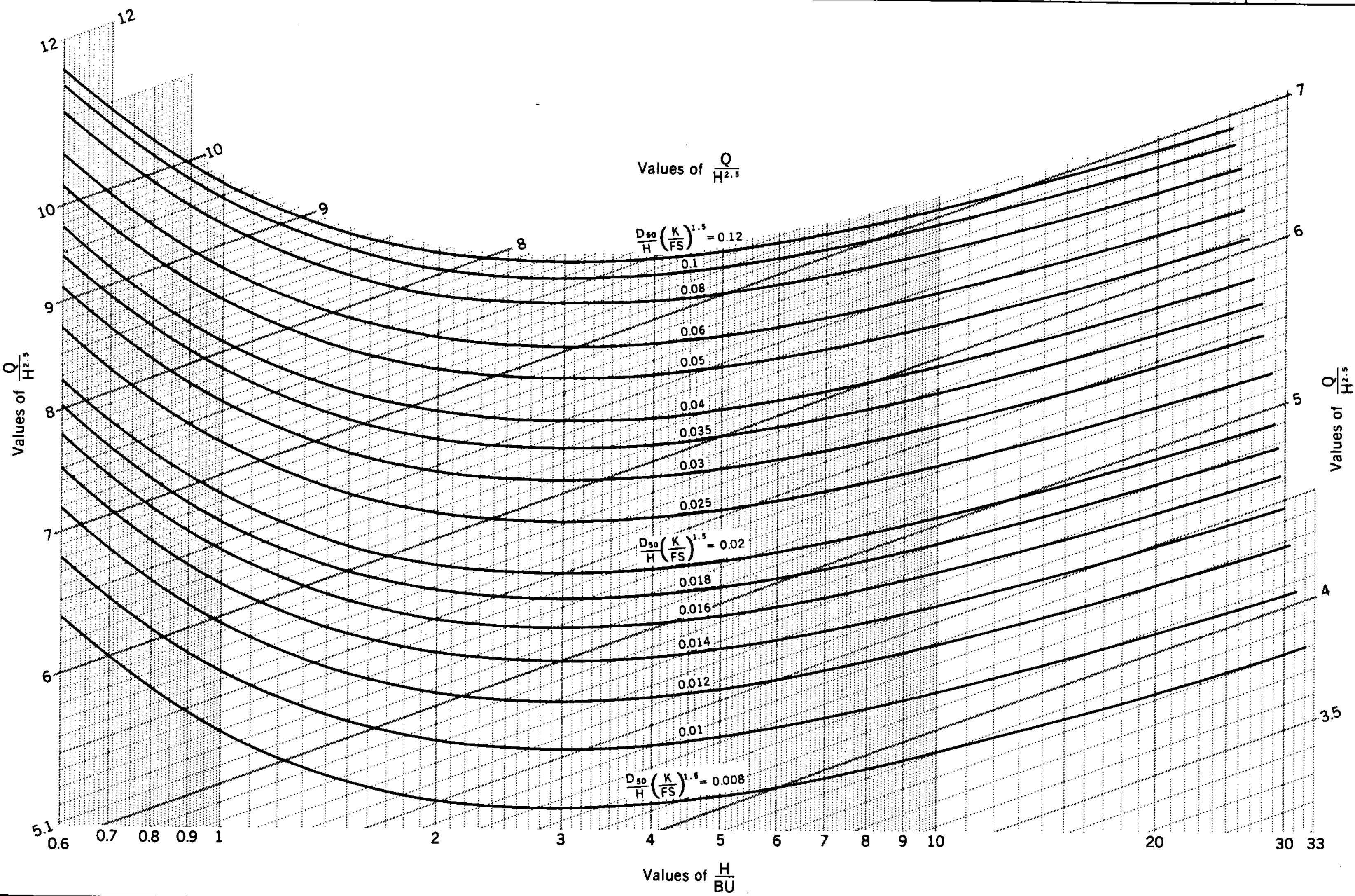
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{K}{FS}\right)^{1.5}$ curves

ZU = 3
τ_{sm} controls



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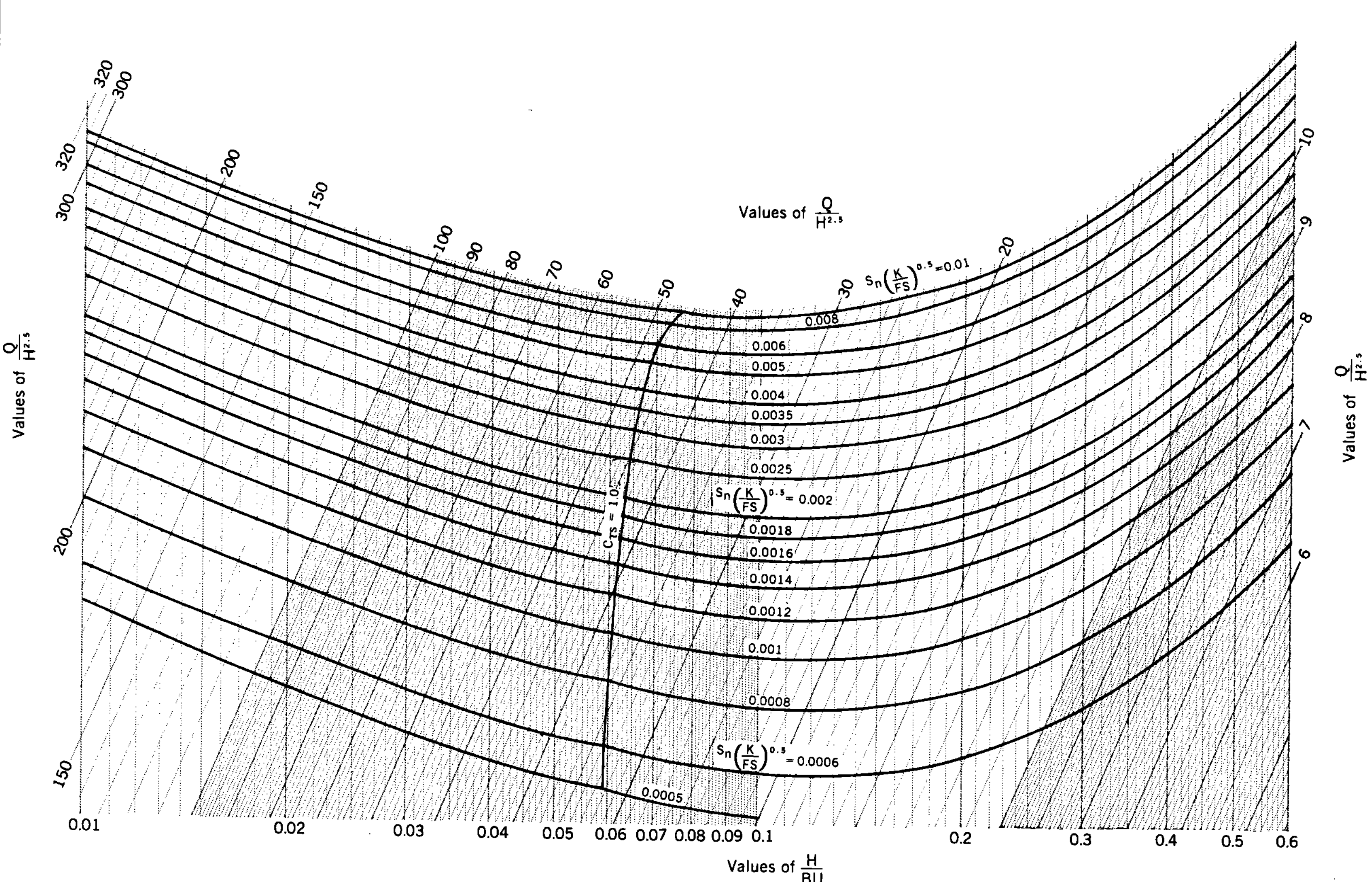
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $Sn\left(\frac{K}{FS}\right)^{0.5}$ curves

ZU = 3
τ_{sm} controls



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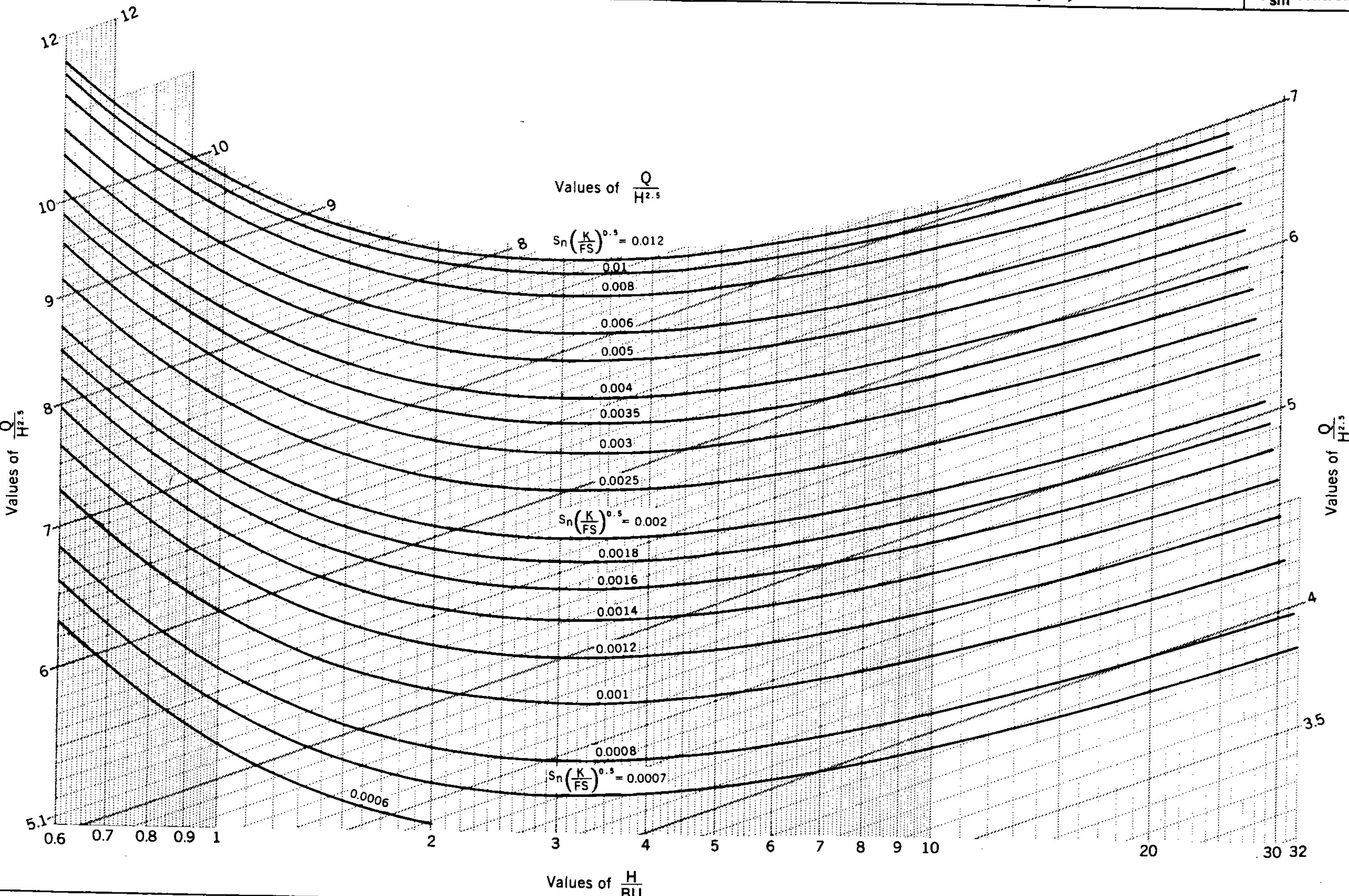
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $S_n\left(\frac{K}{FS}\right)^{0.5}$ curves

ZU = 3
τ_{sm} controls



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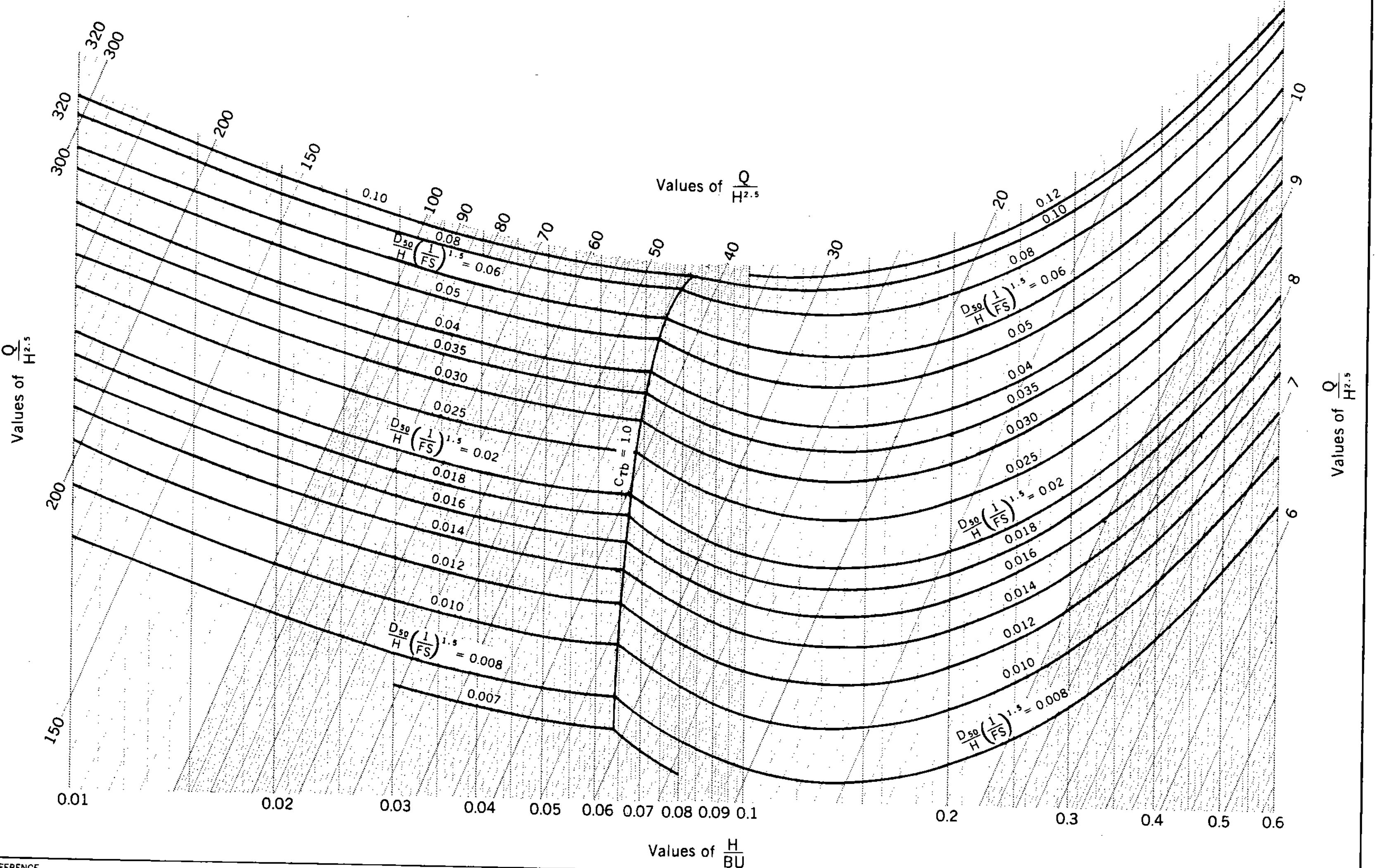
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{1}{FS}\right)^{1.5}$ curves

ZU = 3
τ_{bm} controls



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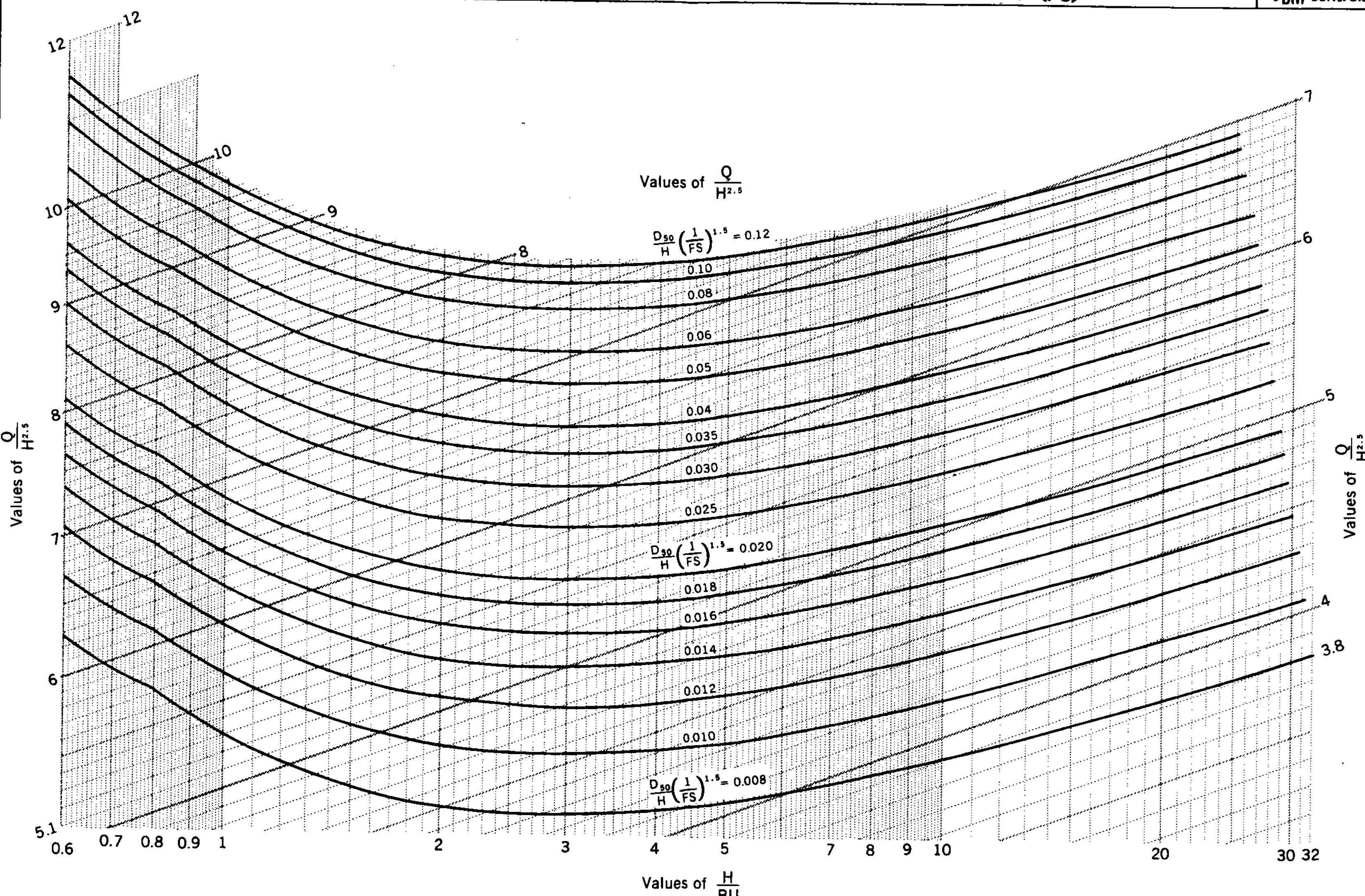
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $\frac{D_{50}}{H}\left(\frac{1}{FS}\right)^{1.5}$ curves

ZU = 3
τ_{bm} controls



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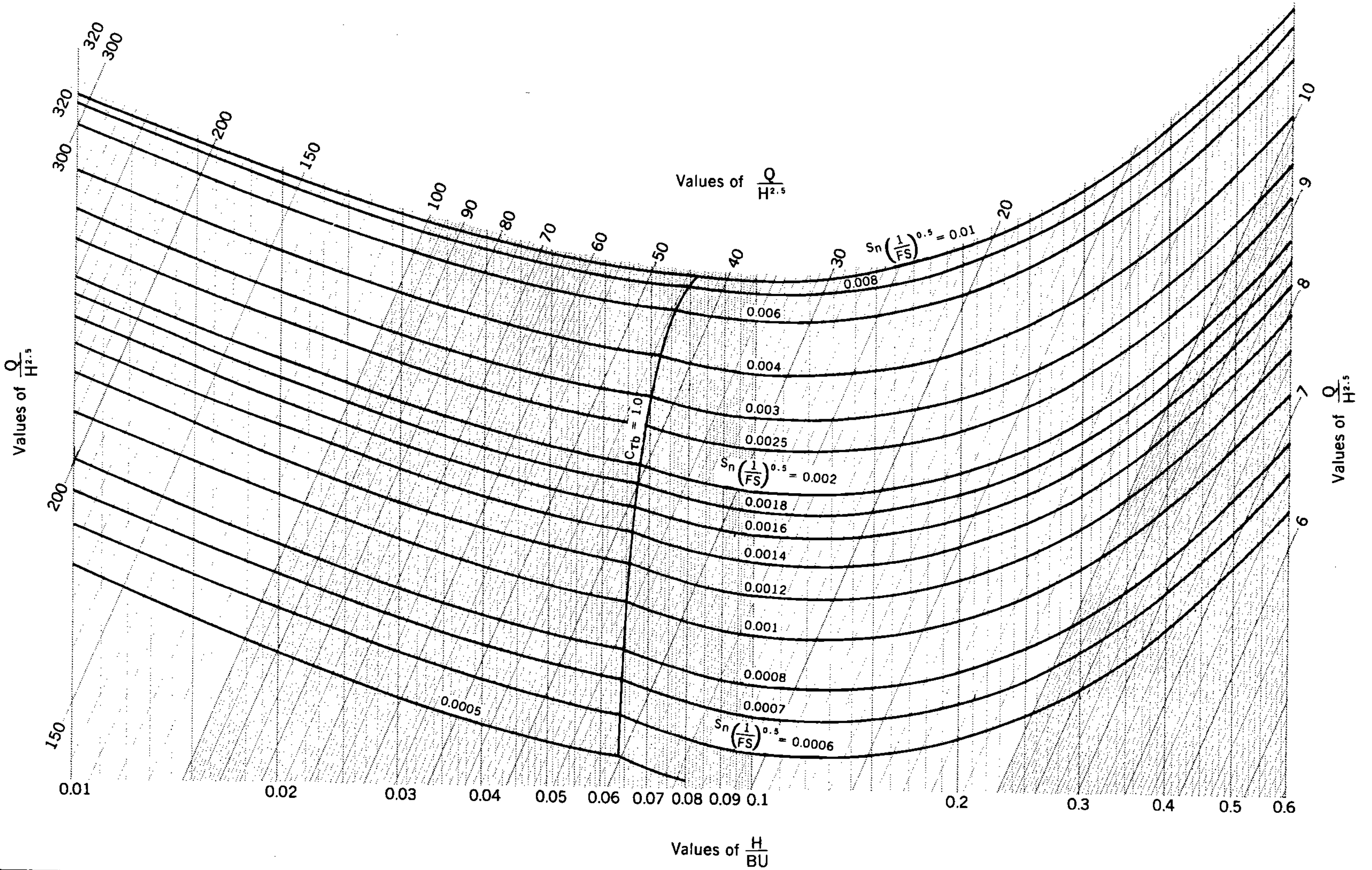
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $S_n\left(\frac{1}{FS}\right)^{0.5}$ curves

ZU = 3

τ_{bm} controls



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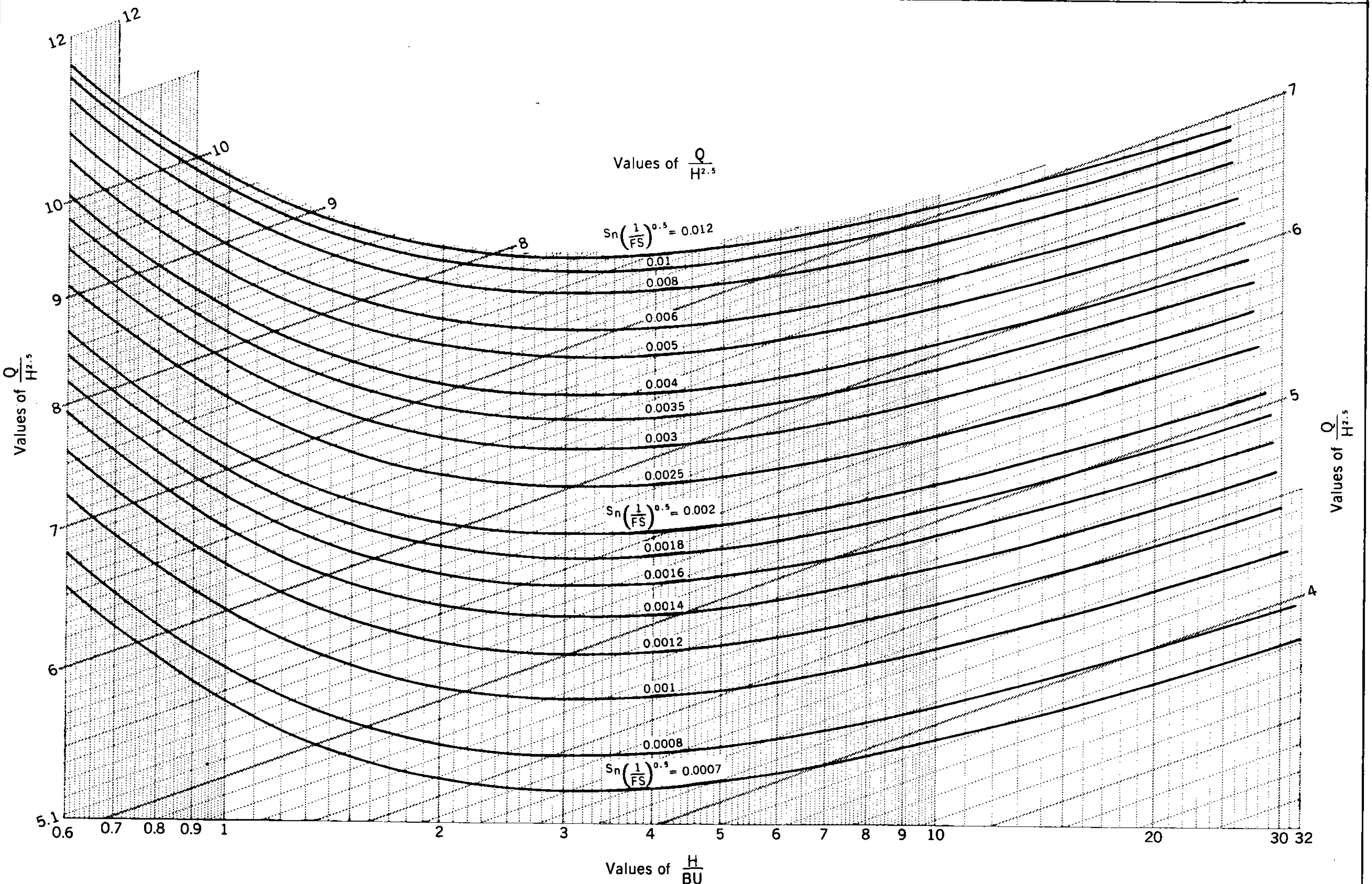
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with $Sn\left(\frac{1}{FS}\right)^{0.5}$ curves

ZU = 3
τ_{bm} controls



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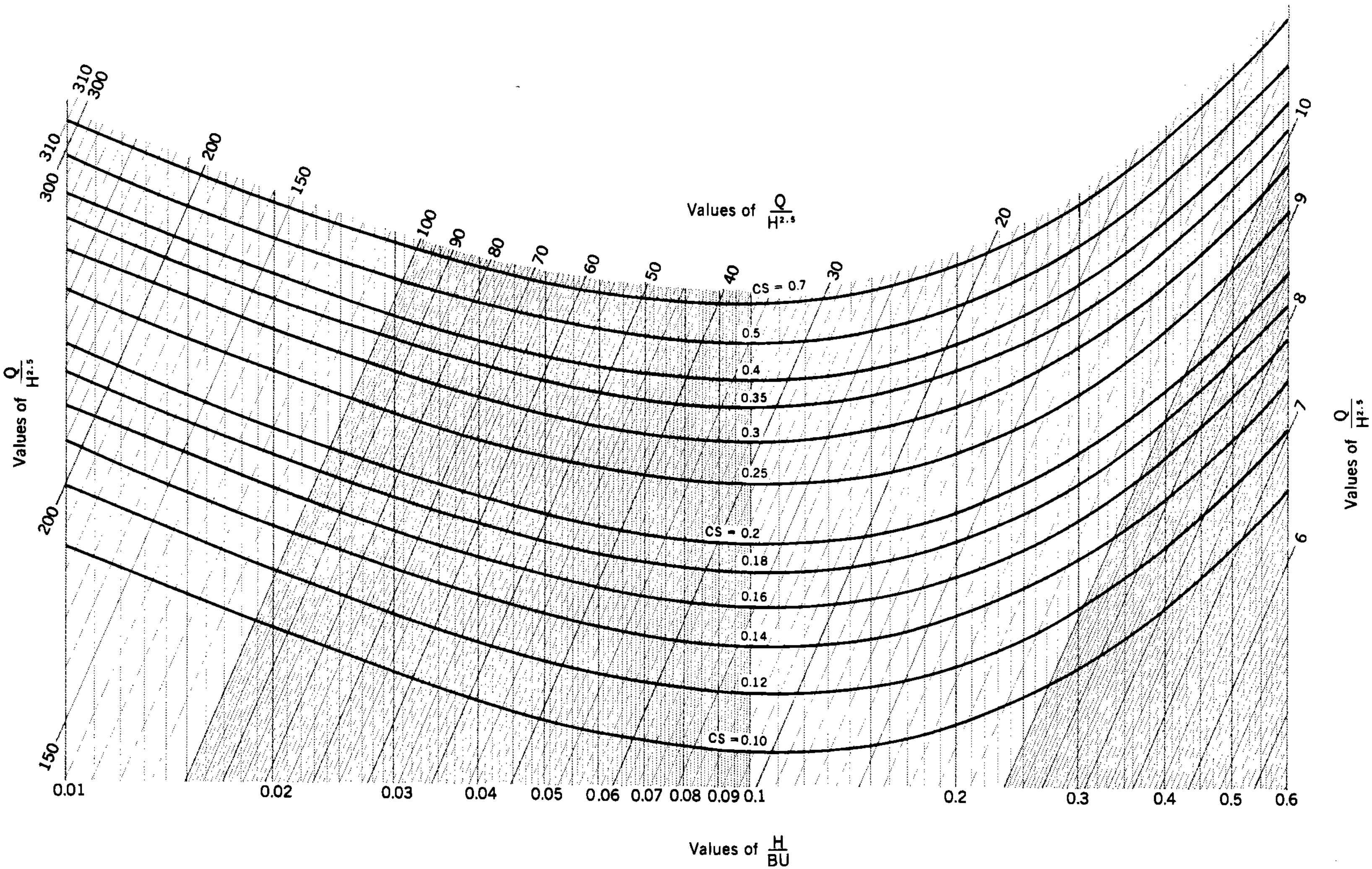
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with CS curves

ZU = 3



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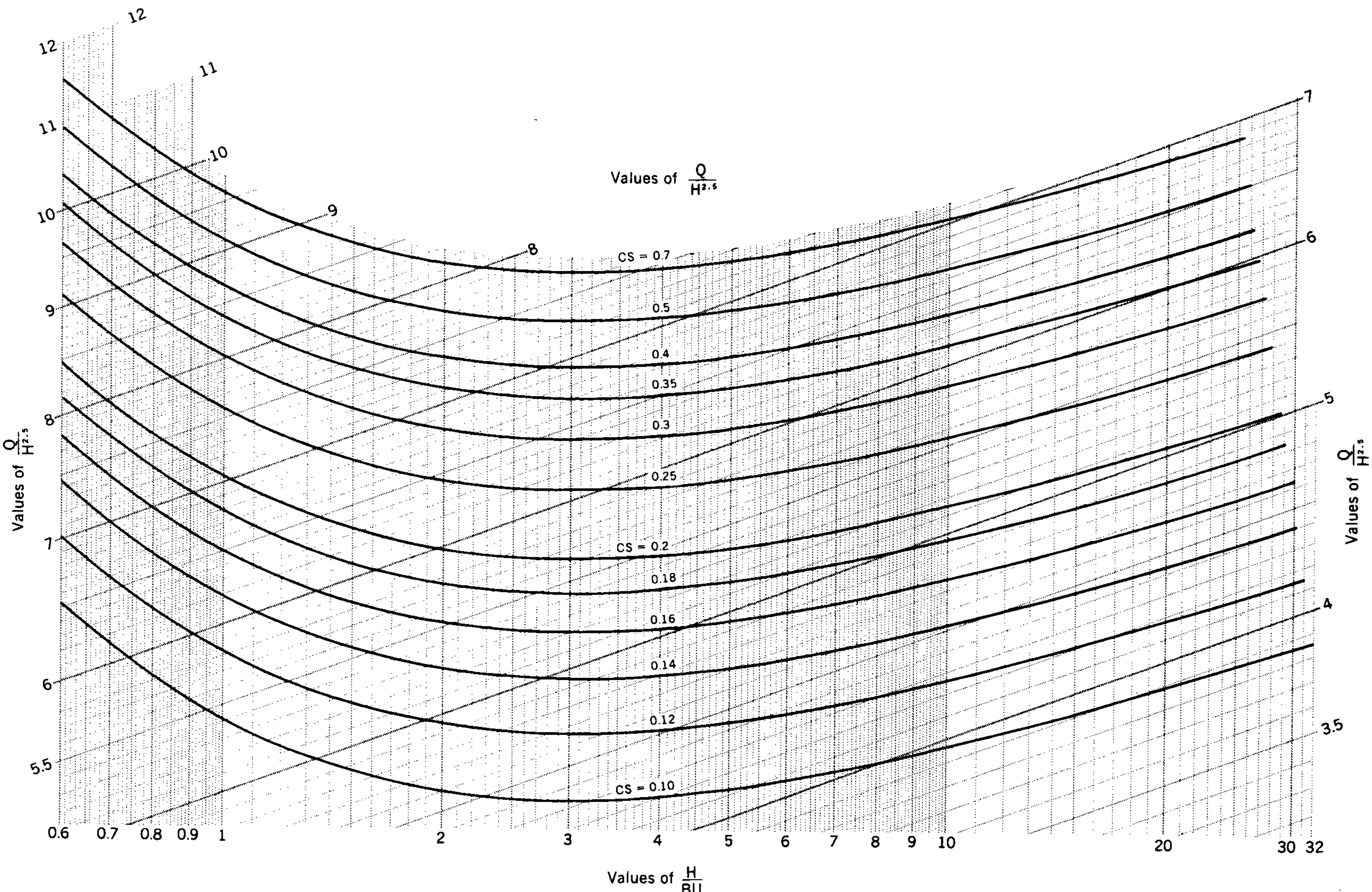
RIPRAP GRADIENT CONTROL STRUCTURES: PRISMATIC CHANNELS; $\frac{Q}{H^{2.5}}$ vs $\frac{H}{BU}$ with CS curves

ZU = 3



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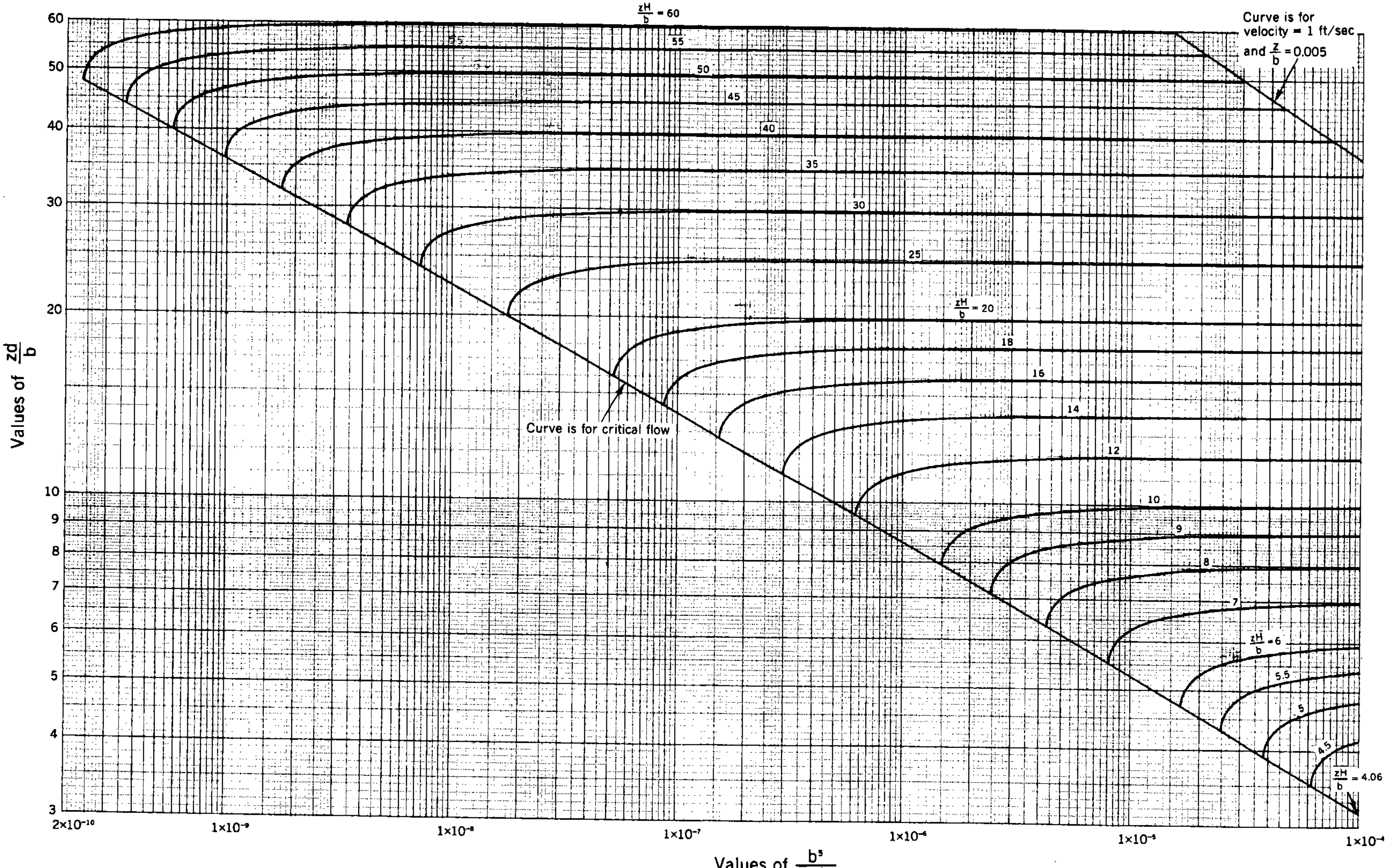
RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs $\frac{b^5}{z^3Q^2}$ with $\frac{zH}{b}$ curves



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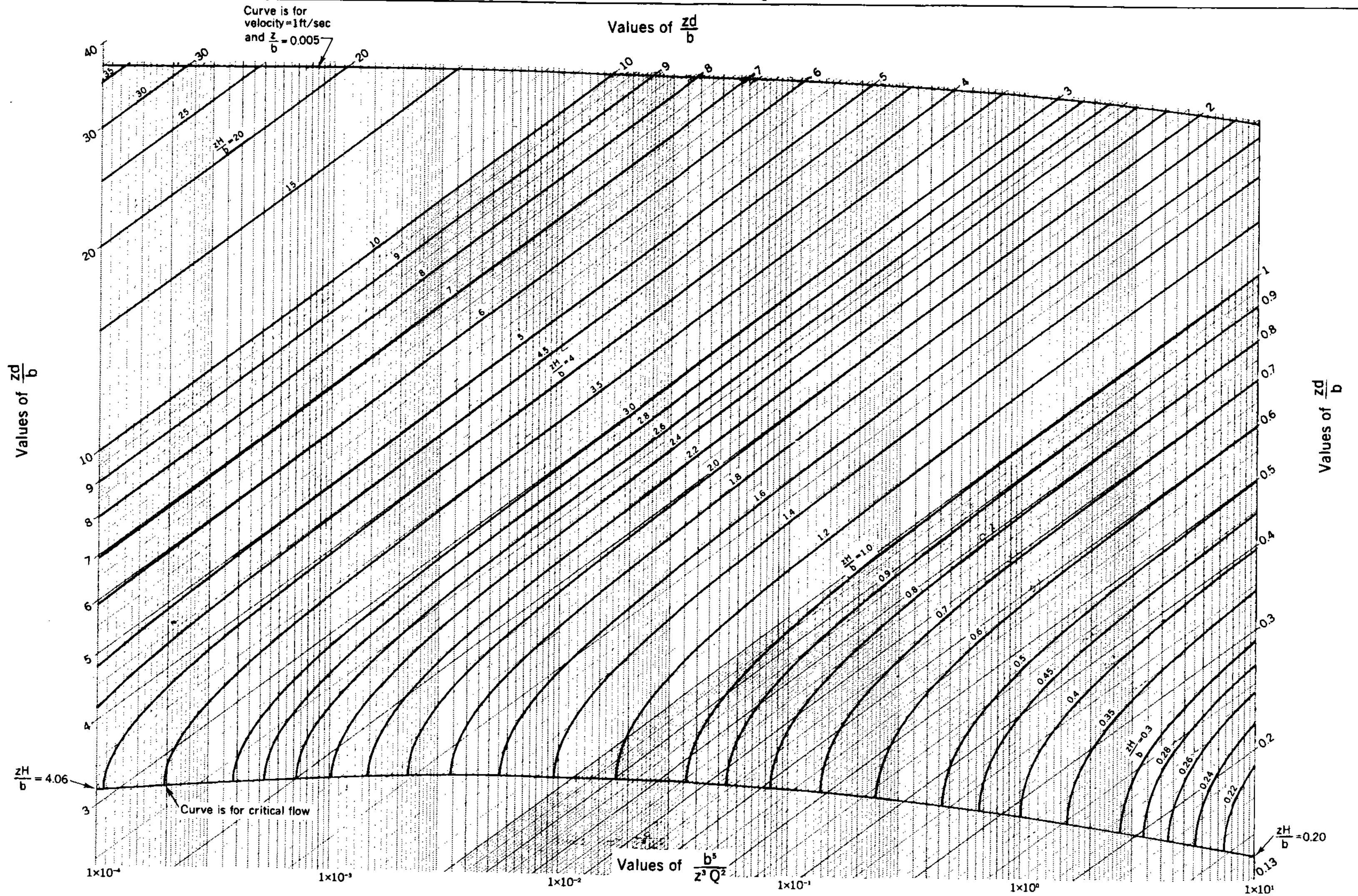
RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs $\frac{b^5}{z^3Q^2}$ with $\frac{zH}{b}$ curves



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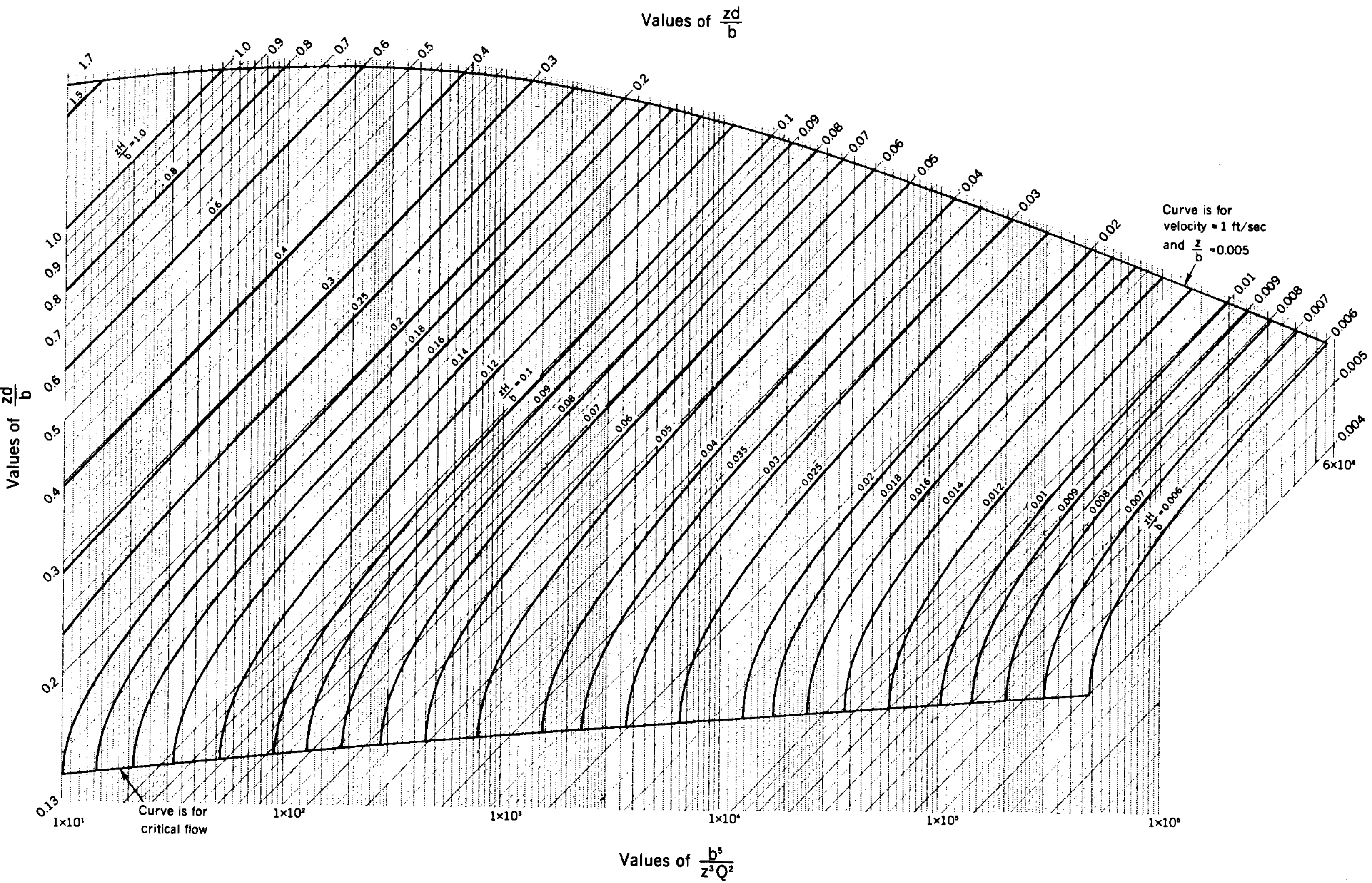
RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs $\frac{b^5}{z^3Q^2}$ with $\frac{zH}{b}$ curves



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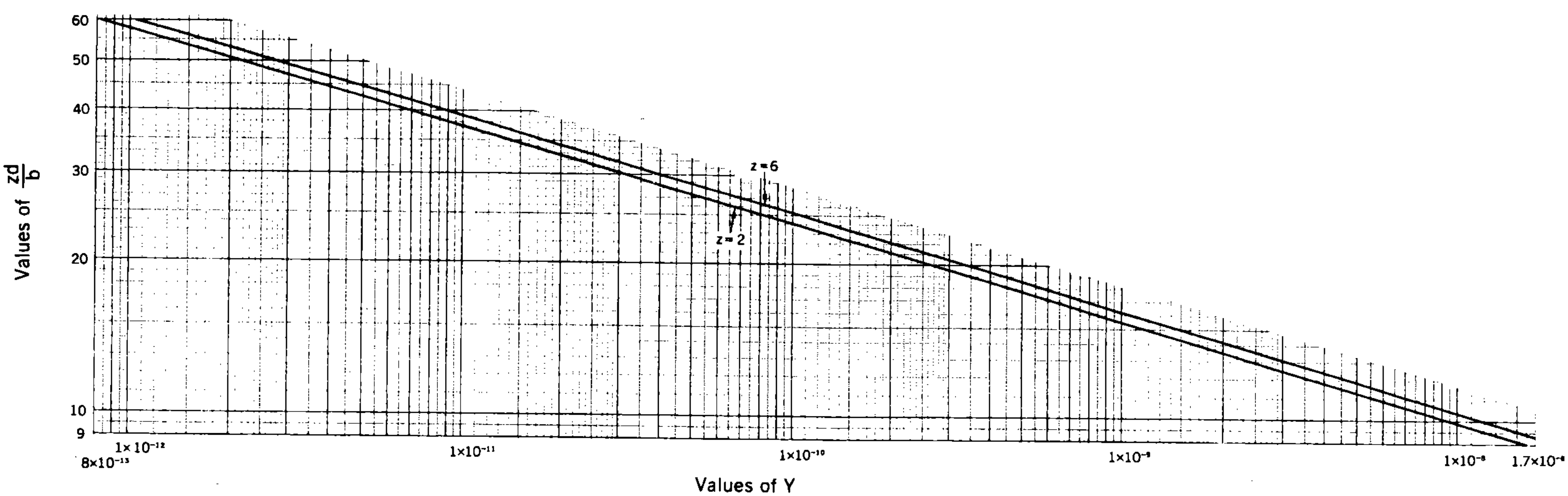
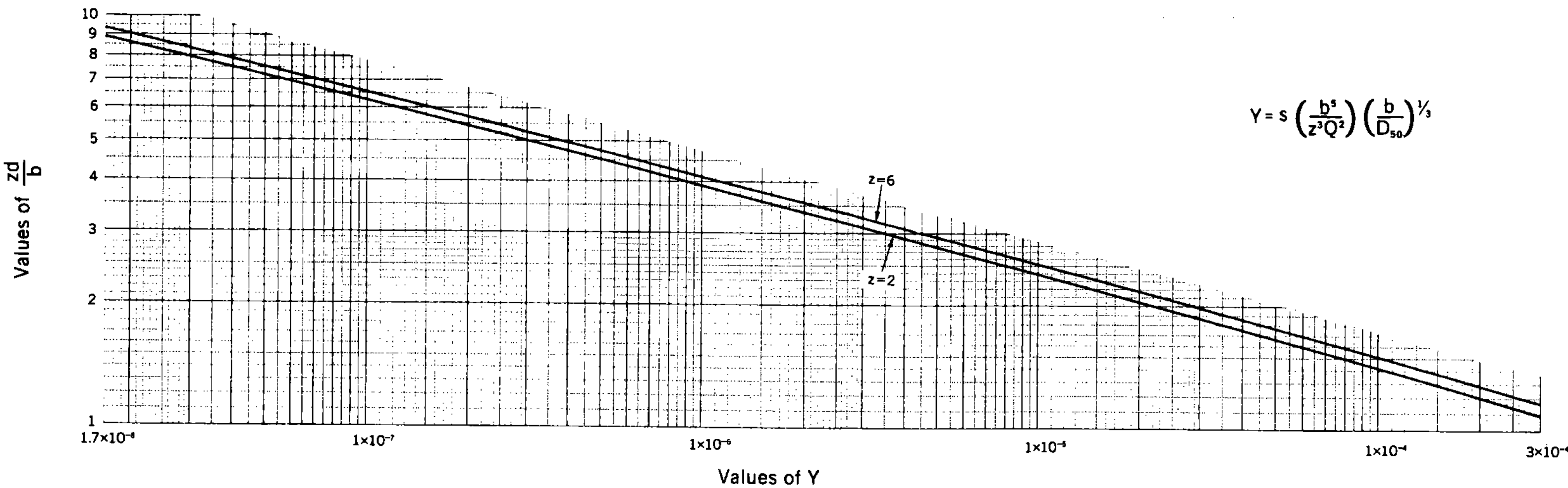
RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs Y with z curves





$$Y = s\left(\frac{b^5}{z^3Q^2}\right)\left(\frac{b}{D_{50}}\right)^{1/3}$$

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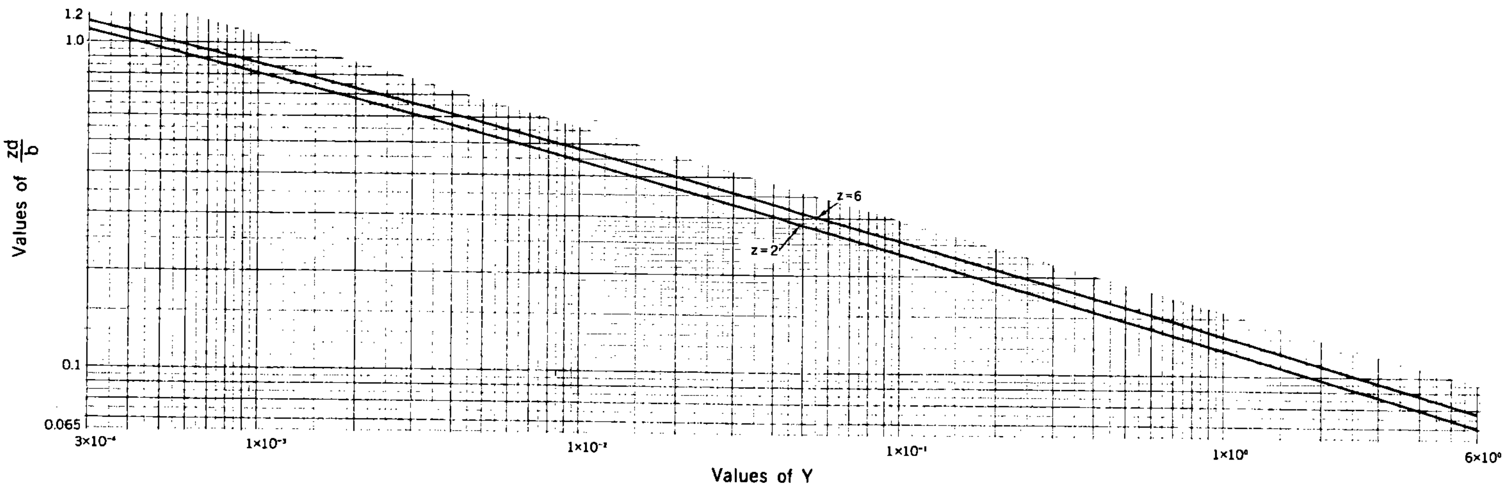
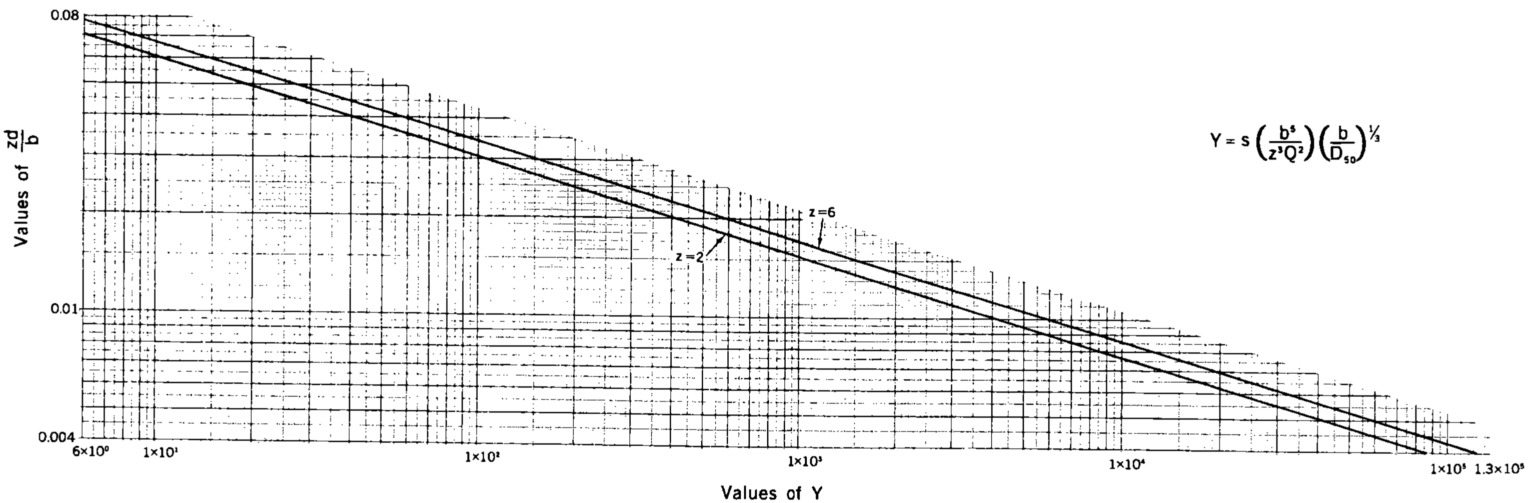
RIPRAP GRADIENT CONTROL STRUCTURES: TRANSITIONS; $\frac{zd}{b}$ vs Y with z curves





$$Y = s\left(\frac{b^5}{z^3Q^2}\right)\left(\frac{b}{D_{50}}\right)^{1/3}$$

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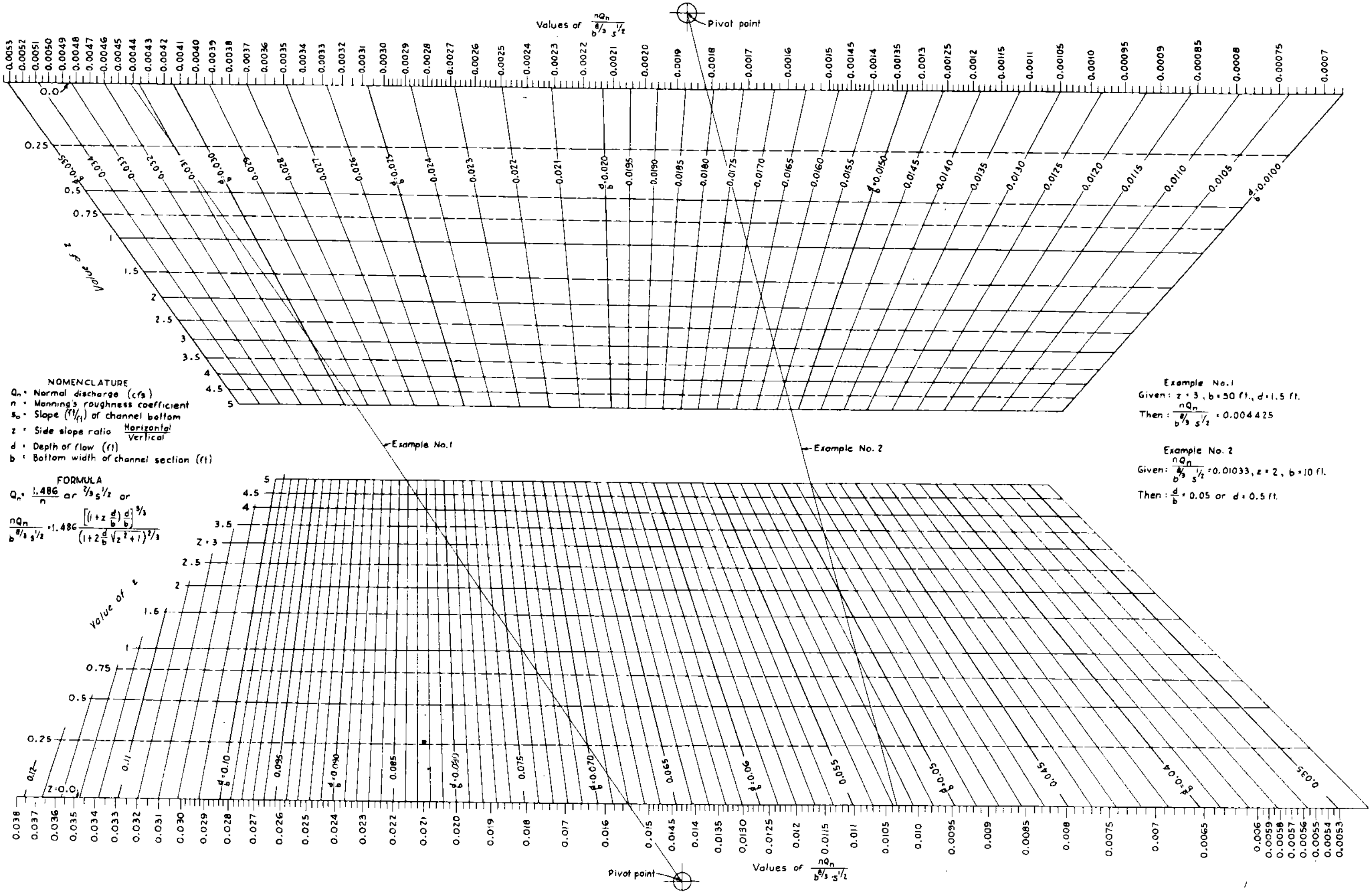
HYDRAULICS: UNIFORM DEPTHS AND DISCHARGES IN TRAPEZOIDAL AND RECTANGULAR CHANNELS



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. 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.

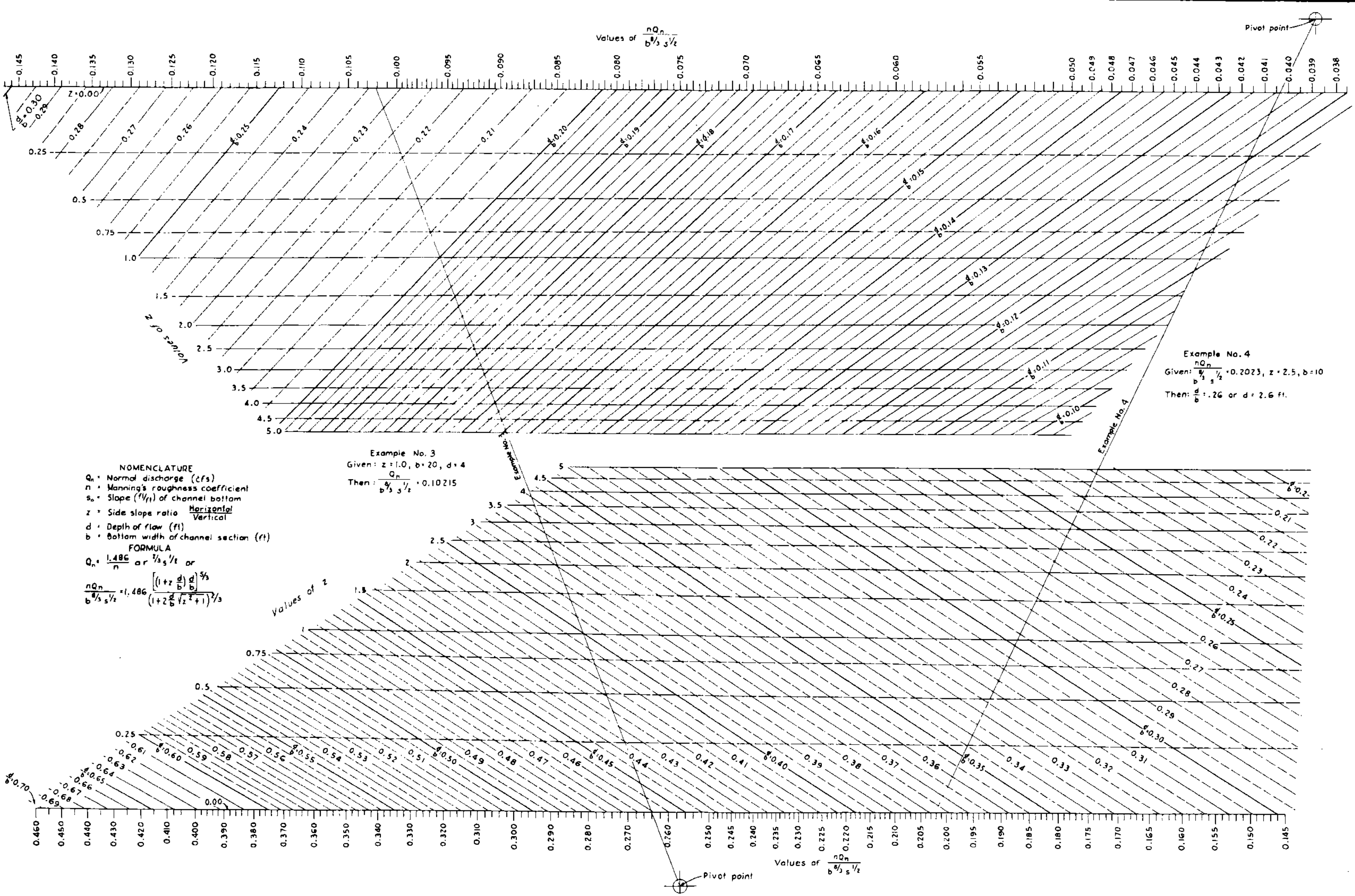
REFERENCE This nomogram was developed by Paul D. Doubt of the Design Section.

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

$Q_n = \frac{1.486}{n} a r^{2/3} s^{1/2}$ 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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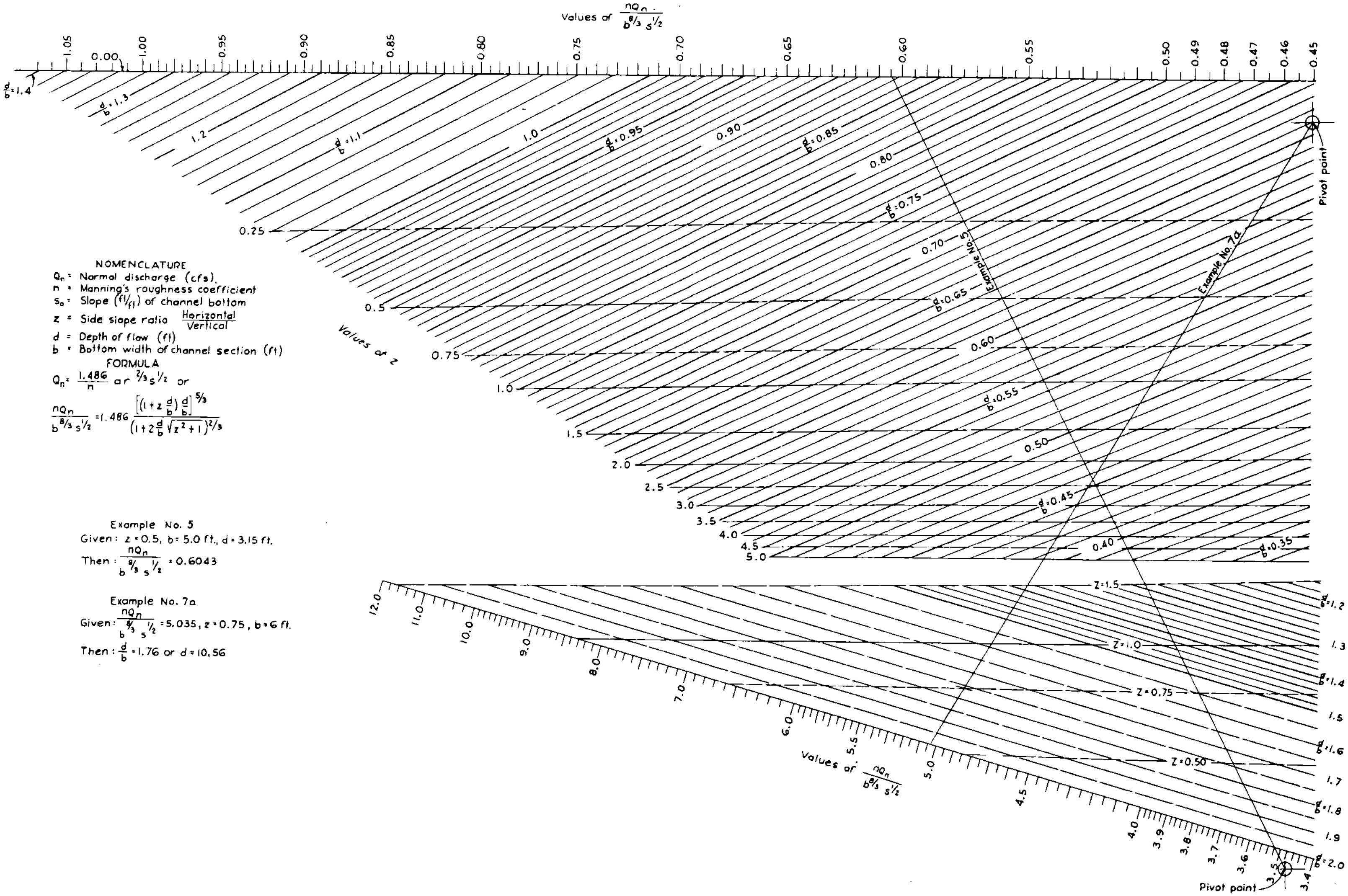
SHEET 2 OF 4

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

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

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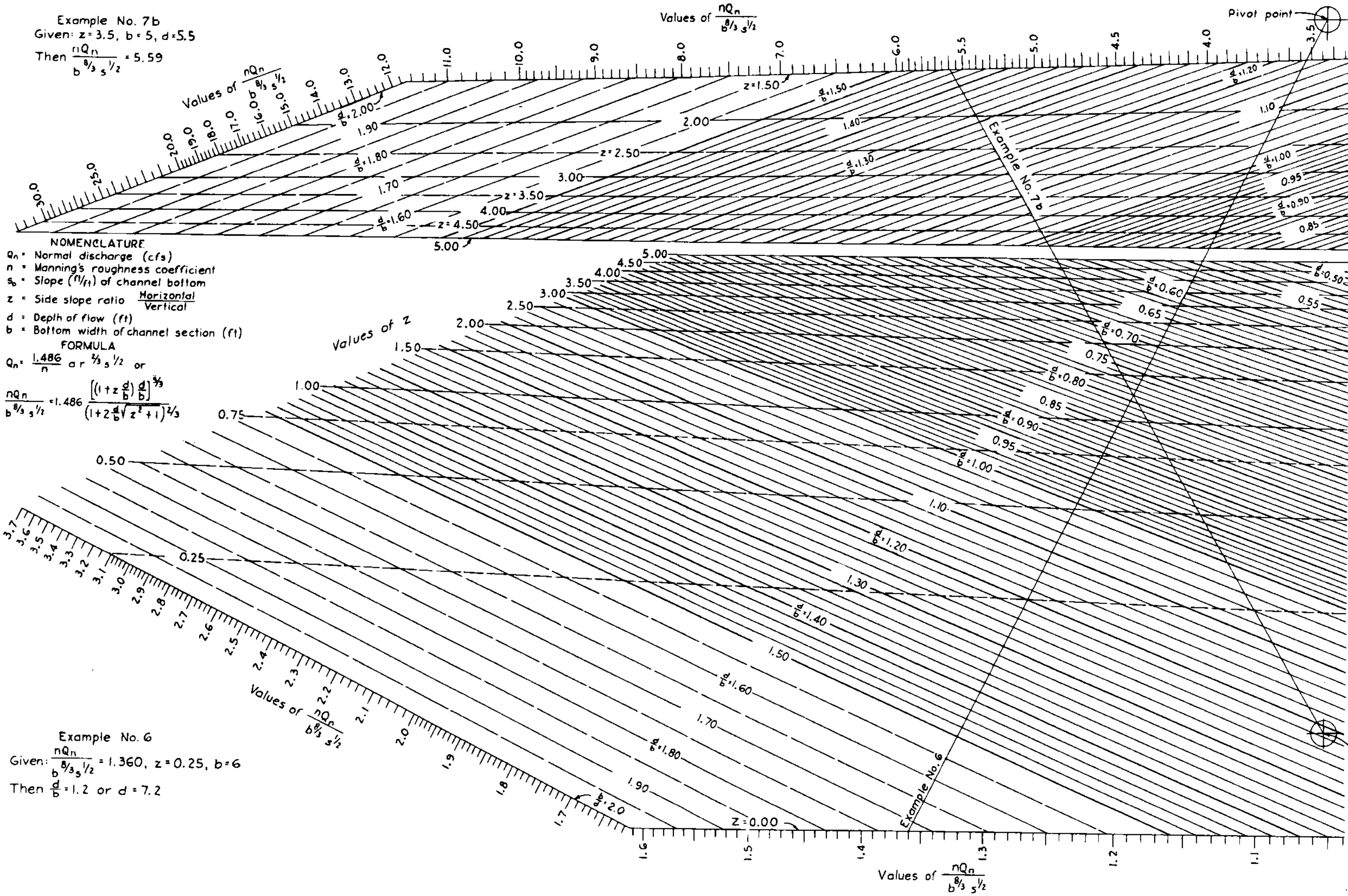
HYDRAULICS: UNIFORM DEPTHS AND DISCHARGES IN TRAPEZOIDAL AND RECTANGULAR CHANNELS

Example No. 7b
Given: z = 3.5, b = 5, d = 5.5
Then $\frac{nQ_n}{b^{8/3} s^{1/2}} = 5.59$



NOMENCLATURE
Q_n = Normal discharge (cfs)
n = Manning's roughness coefficient
s_o = Slope (ft/ft) of channel bottom
z = Side slope ratio $\frac{Horizontal}{Vertical}$
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

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

Example No. 6
Given: $\frac{nQ_n}{b^{8/3} s^{1/2}} = 1.360$, z = 0.25, b = 6
Then $\frac{d}{b} = 1.2$ or d = 7.2

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

Revised 8-17-53

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