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HYDRAULICS OF BROAD-CRESTED SPILLWAYS

PREFACE

This technical release is the first of a series of technical releases envisioned by the Design Branch. The series pertains to the proportioning of earth dams. The main objective of this technical release is to provide a simple procedure for the explicit determination of spillway width while satisfying stability and any capacity requirements.

This technical release is concerned with various aspects for the dimensioning of broad-crested emergency spillways and provides tools for these evaluations. Means are furnished for determining the magnitudes of errors involved in using various approximate procedures and relations. The evaluation of the required emergency spillway capacity is not considered herein.

A number of future technical releases will be concerned with the determination of

a. required spillway capacity,

b. optimum dam at a site, and

c. optimum configuration of structures in a watershed.

Values of parameters used in the preparation of the ES-drawings were obtained by the use of a digital computer. The several programs required for this work were written in FORTRAN IV by the Design Unit. The programs were compiled and executed on IBM 360 equipment by the Washington Data Processing Center, Statistical Reporting Service, USDA.

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NOMENCLATURE

a_c ≡ cross-sectional area of spillway at critical depth, ft^2

b ≡ bottom width of spillway, ft

b' ≡ bottom width of spillway, ft (see page 17)

b'' ≡ bottom width of spillway, ft (see ES-173, sheet 4)

d ≡ depth of flow, ft

d_c ≡ critical depth, ft

d_c' ≡ critical depth, ft (see page 17)

$d_{c,Q}$ ≡ critical depth corresponding to a discharge, Q, ft

$d_{c,Q/4}$ ≡ critical depth corresponding to a discharge, Q/4, ft

$d_{n,Q}$ ≡ normal depth corresponding to a discharge, Q, ft

$d_{n,Q/4}$ ≡ normal depth corresponding to a discharge, Q/4, ft

d_x ≡ depth of flow at section x, ft (see ES-158, sheet 9)

g ≡ acceleration of gravity, ft/sec^2

h_f ≡ friction head loss, ft-lb/lb = ft

h_{f_1} ≡ friction head loss, ft (see Table 3, page 9)

$h_{f,b}$ ≡ friction head loss in a spillway length, L, and bottom width, b, ft

$h_{f,n}$ ≡ friction head loss in a spillway length, L, and Manning's roughness coefficient, n, ft

h_{f_o} ≡ friction head loss, ft (see Table 3, page 9)

$h_{f,z}$ ≡ friction head loss in a spillway length, L, and side slope, z, ft

$h_f]_{Ref}$ ≡ friction head loss in a spillway length, L; bottom width, b = 100 ft; side slope, z = 2; and Manning's roughness coefficient, n = 0.04, ft

Δh_f = $\Delta h_{f,b} + \Delta h_{f,n} + \Delta h_{f,z}$, ft (see ES-179, Example 2)

$\Delta h_{f,b}$ = $h_{f,b} - h_{f,b=100}$, ft

$\Delta h_{f,n}$ = $h_{f,n} - h_{f,n=0.04}$, ft

$\Delta h_{f,z}$ = $h_{f,z} - h_{f,z=2}$, ft

H_e ≡ specific energy head, ft

$H_e]_2$ ≡ specific energy head at section 2, ft (see ES-158, Example 2)

H_{ec} ≡ critical specific energy head, ft

H_{ec}' ≡ critical specific energy head, ft (see page 17)

$H_{ec}]_{z,b}$ ≡ critical specific energy head for a spillway with side slope, z, and bottom width, b, ft

H_p ≡ energy head of the water in the reservoir above the spillway crest, ft

$H_p]_b$ ≡ energy head of the water in the reservoir above the crest of a spillway with a bottom width, b, ft

$H_p]_n$ ≡ energy head of the water in the reservoir over the crest of a spillway with a Manning's roughness coefficient, n, ft

$H_p]_z$ ≡ energy head of the water in the reservoir over the crest of a spillway with side slope, z, ft

ℓ_c ≡ station at the control section (see ES-158, sheet 9)

ℓ_c' ≡ station at fictitious control section (see ES-158, Example 2)

ℓ_x ≡ station at section x (see ES-158, sheet 9)

L ≡ length of the spillway upstream from the control section, ft

L_o ≡ length of horizontal portion of spillway, ft (see Table 3, page 9)

m ≡ variable integer exponent (see ES-173)

n ≡ Manning's roughness coefficient

q ≡ discharge per foot of spillway bottom width, cfs/ft

Q ≡ discharge, cfs

Q_c ≡ critical discharge, cfs

Q_c' ≡ critical discharge, cfs (see page 17)

Q_c'' ≡ critical discharge, cfs (see ES-173, sheet 4)

$Q_{c,d}$ ≡ critical discharge corresponding to a depth, d, cfs

s_c ≡ critical slope, ft/ft

$s_{c,Q}$ ≡ critical slope corresponding to a discharge, Q, ft/ft

$s_{c,Q/4}$ ≡ critical slope corresponding to a discharge, Q/4, ft/ft

$s_{c,Q/4}]_{z,b}$ ≡ critical slope corresponding to a discharge, Q/4, for a spillway with side slope, z, and bottom width, b, ft/ft

s_o ≡ slope of spillway bottom, ft/ft

T_c ≡ top width of a_c, ft

v ≡ mean velocity of flow, ft/sec

v_c ≡ critical velocity, ft/sec

v_p ≡ permissible velocity, ft/sec

z ≡ side slope of the spillway expressed as horizontal distance divided by vertical distance, ft/ft

z' ≡ side slope of the spillway, ft/ft (see page 17)

TECHNICAL RELEASE

NUMBER 39

HYDRAULICS OF BROAD-CRESTED SPILLWAYS

Introduction

This technical release pertains to the hydraulics of broad-crested spillways, both trapezoidal and rectangular. Such spillways usually function as emergency spillways and may be earth, vegetated, rock, or structural.

Broad-crested spillways may or may not have a control section. Although this technical release is primarily directed toward the evaluation of certain parameters for a spillway having a control section, it contains information concerning the hydraulics of a spillway without a control section.

In this discussion, the inlet channel of a spillway having a control section is considered to have a bottom profile composed of a horizontal slope extending from the control section to the reservoir or of a horizontal slope immediately upstream from the control section and a negative slope (or slopes) extending from the horizontal section to the reservoir. Moreover, only spillways of the same bottom width and side slopes throughout their lengths are considered.

The symbol s_o will be used to designate the various bottom slopes of either the inlet or the exit channel of the spillway. Wherever s_o is used, the text or drawing indicates the particular slope under consideration.

This technical release considers spillways having a wide range of values of:

1. spillway bottom widths, b, ($25 \text{ ft} \leq b \leq 400 \text{ ft}$);
2. side slopes, z, ($0 \leq z \leq 4$);
3. Manning's roughness coefficient, n, ($0.02 \leq n \leq 0.08$); and
4. inlet channel lengths, L.

Procedures are presented for:

1. the evaluation of the permissible critical specific energy head, H_{ec}, corresponding to a permissible velocity, v_p, and exit channel bottom slope, s_o;
2. the evaluation of the head, H_p, in the reservoir over the crest of the spillway corresponding to the critical specific energy head, H_{ec};
3. the evaluation of the required spillway bottom width, b, corresponding to the critical specific energy head, H_{ec}, and the required discharge, Q; and
4. the evaluation of the critical slope, $s_{c,Q/4}$, corresponding to the discharge Q/4 where Q is the discharge corresponding to H_{ec}.

The procedures yield answers quickly and with sufficient accuracy for final design. Since results can be obtained quickly, the procedures can be used equally advantageously for planning.

Although numerous ES-drawings are presented in this technical release, the usual spillway design requires the use of only one sheet from each of the ES-drawings 170, 171, and 174. Other graphs and ES-drawings have been included for two reasons;

1. to aid in the evaluation of design parameters for spillways of unusual dimensions, and
2. to provide a method of establishing the magnitude of error incurred by the various approximations employed.

A subsequent technical release will give procedures for evaluating, prior to the determination of the spillway width, b, the required capacity, Q, corresponding to a head, H_p, over the crest. This evaluation involves reservoir routing.

Relation of H_p vs H_{ec} is nearly independent of Q and b

Usually, a spillway has a control section. When a spillway has a control section, the depth of flow and the specific energy head at the control section for a discharge, Q, are equal to the critical depth and the critical specific energy head corresponding to Q, respectively. The critical specific energy head, H_{ec}, is the minimum specific energy head for the discharge, Q. Thus, for the discharge, Q, the specific energy head, H_e, at any section upstream (or downstream) from the control section is greater than H_{ec}. Moreover, it can be shown that the friction head loss, h_f, in conveying the discharge, Q, from the reservoir to the control section is the difference in the head, H_p, over the crest and the critical specific energy head, H_{ec}, i.e.

$$h_f \fallingdotseq H_p - H_{ec} \tag{1}$$

Writers discussing the hydraulics of spillways have often related H_p to either the parameter $q = \frac{Q}{b}$ or the parameter $d_{c,Q}$. Since the relation of H_{ec} vs H_p is more nearly independent of the values of Q and b than the relation of q vs H_p or $d_{c,Q}$ vs H_p, this technical release uses H_{ec} as the fundamental parameter instead of q or $d_{c,Q}$. Insight into the reason for the near independence of the relation of H_{ec} vs H_p with respect to Q and b, as compared to the relation of either q vs H_p or $d_{c,Q}$ vs H_p, can be obtained by observing

$$H_p = d_{c,Q} + \frac{Q^2}{2g\ a_c^2} + h_f = H_{ec} + h_f \tag{2}$$

From Eq. (2) it is evident that for a given H_{ec}, the value of H_p is affected by the parameters which affect h_f; for a given $d_{c,Q}$, the value of H_p is affected by the parameters which affect the critical velocity head, $\frac{Q^2}{2g\ a_c^2}$, and h_f; and for a given q, the value of H_p is affected by the parameters which affect $d_{c,Q}$, $\frac{Q^2}{2g\ a_c^2}$, and h_f.

The near independence of the relation of H_{ec} vs H_p from Q and b is desirable since either Q, b, or both are often unknown prior to a reservoir routing. Although the relation of H_{ec} vs H_p is nearly independent of Q and b, one should observe there is a definite relation of H_{ec}, Q, and b.

Reference Section (b = 100 ft, z = 2, n = 0.04)

Many of the parameters needed in spillway design can be readily evaluated for a preselected cross section. Writers have often evaluated parameters for spillways on the basis of a preselected cross section of infinite width. In this technical release a preselected spillway cross section of b = 100 ft and z = 2 with n = 0.04 was chosen as more nearly representative of actual spillways. This preselected cross section is called the Reference Section.

Using the Reference Section it is possible to obtain values of certain parameters which are approximately correct for the actual cross section. The values of these parameters can be easily refined if thought desirable.

Principal Graphs

Some parameters for the Reference Section can be evaluated by the four principal drawings described below.

1. Permissible H_{ec} vs exit channel bottom slope, s_o, with a family of permissible velocity, v_p-curves. (ES-170)
2. H_p vs H_{ec} with a family of spillway length, L-curves, for selected bottom profiles. (ES-171)
3. Critical slope, $s_{c,Q/4}$ vs H_{eQ}. (ES-172)
4. Q vs H_{ec} with families of spillway bottom widths, b, and critical depths, $d_{c,Q}$. (ES-174)

Additional graphs are included to show the effects on these parameters when b, z, or n differs from that of the Reference Section.

Permissible H_{ec} for Various s_o and v_p (ES-170)

Velocities in structural spillways and spillways constructed in competent rock often are not of magnitudes which require attention. An earth or a vegetated spillway can have velocities in its exit channel of magnitudes which cause instability and require some forethought during design. The graphs of ES-170 pertain to this aspect of spillway design.

The values given by ES-170 are the result of determining the critical specific energy head, H_{ec}, corresponding to a discharge, Q, which is equal to the normal discharge having a velocity of v_p in an exit channel defined by the parameters s_o, n, z, and b. This H_{ec} is the permissible H_{ec} or the permissible critical specific energy head corresponding to the permissible velocity, v_p, and exit channel bottom slope, s_o.

The value of the permissible H_{ec} is increased by any one or any combination of the following changes in parameters:

1. decreasing s_o,
2. increasing v_p, and
3. increasing n.

The stage-discharge relation of a spillway is required in problems of reservoir routings. This relation is readily obtained through the range of discharges for which the spillway has a control section. In this technical release, when a spillway has a control section this range is frequently taken as Q/4 to Q.

To ensure that a spillway, with $z \geqq 1$, has a control section over the range of discharges from Q/4 to Q (see H_{ec} vs $s_{c,Q/4}$ - ES-172), the slope, s_o, immediately downstream from the control section must be equal to or greater than $s_{c,Q/4}$ and be of sufficient length to prevent tailwater effects at the control section. The maximum values of v_p and n are established by the spillway site. Thus, given v_p and n, a spillway with a control section for the range of discharges being considered has a maximum value of permissible H_{ec} when $s_o = s_{c,Q/4}$. Frequently the value of s_o is not required to be greater than 0.04. Thus, if $s_{c,Q/4} > 0.04$ and s_o is taken as 0.04, the break in grade is not a control section for all discharges in the interval Q/4 to Q.

Table 1 shows, for a spillway having a control section for a range of discharges and for n = 0.04, the minimum values of s_o and the maximum values of permissible H_{ec} corresponding to various values of v_p.

Values of the exit channel bottom slope, s_o, were taken as $s_{c,Q/4}$ except when $s_{c,Q/4} > 0.04$ in which case s_o was taken as 0.04. The values of the permissible H_{ec} and minimum s_o for the Reference Section are shown in the shaded blocks.

Table 2 shows, for a spillway having a control section for the range of discharges and for $n = 0.04$, the value of permissible H_{ec} obtained by using $s_o = s_{c,Q/4}$ of the Reference Section in place of $s_{c,Q/4}$ of a non-Reference Section.

Reference Section

For the Reference Section, the relation of permissible H_{ec}, v_p, and s_o is given by ES-170, sheet 1. The drawing contains a curve which gives the relation of the critical specific energy head, H_{ec}, and the critical slope, $s_{c,Q/4}$, where Q is the discharge corresponding to H_{ec}. This curve was obtained by equating the normal depth of flow, $d_{n,Q/4}$, to the critical depth, $d_{c,Q/4}$, to establish the value of $s_{c,Q/4}$.

Non-Reference Section

n = 0.02. - When $n = 0.02$, the relation of permissible H_{ec}, v_p, and s_o is given by ES-170, sheet 2. The graph permits the evaluation of the permissible H_{ec} for spillways with $n = 0.02$ in the exit channel. The three curves labeled $s_{c,Q/4}$ for $n = 0.02$, $n = 0.03$, and $n = 0.04$ are superimposed on this graph. The values of $n = 0.02$, $n = 0.03$, and $n = 0.04$ were used in determining the normal depth of flow, $d_{n,Q/4}$, which was equated to the critical depth, $d_{c,Q/4}$ to establish the value of $s_{c,Q/4}$ where Q is in correspondence with the critical specific energy head, H_{ec}.

$n \neq 0.04$ or 0.02. - When the value of n is neither 0.04 nor 0.02, the relation of the permissible H_{ec}, v_p, and s_o is given by ES-170, sheet 1 by redesignating the abscissa as $\left[\frac{0.04}{n}\right]^2 s_o$ or sheet 2 by redesignating the abscissa as $\left[\frac{0.02}{n}\right]^2 s_o$.

$z \neq 2$, $b \neq 100$ ft. - The permissible H_{ec} values for intervals of $25 \leq b \leq 400$, $0 \leq z \leq 4$, $2 \leq v_p \leq 15$, and wide ranges of s_o and n can be evaluated by use of the information given in ES-177.

Table 1. Maximum values of permissible H_{ec} where $n = 0.04$ and $s_o = s_{c,Q/4}$ but not > 0.04.

v_p = ft/sec, b = ft, z = ft/ft, H_{ec} = ft, s_o = ft/ft

z	v_p	2			3			4		
	b	25	100	400	25	100	400	25	100	400
0	H_{ec}	0.203	0.202	0.202	0.402	0.398	0.396	0.652	0.643	0.641
	s_o	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
1	H_{ec}	0.203	0.202	0.202	0.402	0.397	0.396	0.652	0.643	0.641
	s_o	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
2	H_{ec}	0.203	0.202	0.202	0.403	0.398	0.397	0.656	0.644	0.641
	s_o	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
3	H_{ec}	0.204	0.202	0.202	0.405	0.398	0.397	0.661	0.645	0.641
	s_o	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
4	H_{ec}	0.205	0.202	0.202	0.407	0.399	0.397	0.666	0.647	0.642
	s_o	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

z	v_p	5			6			7		
	b	25	100	400	25	100	400	25	100	400
0	H_{ec}	0.983	0.970	0.961	1.43	1.41	1.39	1.98	1.92	1.89
	s_o	0.0375	0.0370	0.0369	0.0337	0.0327	0.0326	0.0306	0.0297	0.0295
1	H_{ec}	1.00	0.970	0.970	1.46	1.42	1.39	2.01	1.92	1.90
	s_o	0.0366	0.0370	0.0367	0.0324	0.0325	0.0325	0.0293	0.0294	0.0293
2	H_{ec}	1.01	0.975	0.975	1.48	1.42	1.40	2.05	1.92	1.90
	s_o	0.0364	0.0369	0.0367	0.0321	0.0325	0.0324	0.0288	0.0294	0.0293
3	H_{ec}	1.03	0.983	0.970	1.52	1.43	1.41	2.12	1.94	1.92
	s_o	0.0360	0.0367	0.0367	0.0316	0.0323	0.0324	0.0284	0.0291	0.0292
4	H_{ec}	1.05	0.989	0.977	1.55	1.43	1.41	2.19	1.98	1.92
	s_o	0.0358	0.0366	0.0366	0.0313	0.0322	0.0322	0.0280	0.0290	0.0291

z	v_p	8			9			10		
	b	25	100	400	25	100	400	25	100	400
0	H_{ec}	2.62	2.50	2.48	3.36	3.19	3.15	4.23	3.94	3.89
	s_o	0.0283	0.0272	0.0270	0.0267	0.0252	0.0249	0.0252	0.0236	0.0233
1	H_{ec}	2.65	2.52	2.48	3.42	3.20	3.15	4.31	3.99	3.89
	s_o	0.0269	0.0268	0.0268	0.0249	0.0248	0.0248	0.0233	0.0231	0.0231
2	H_{ec}	2.75	2.54	2.48	3.57	3.24	3.19	4.51	4.04	3.91
	s_o	0.0263	0.0268	0.0268	0.0242	0.0246	0.0247	0.0225	0.0229	0.0230
3	H_{ec}	2.86	2.57	2.49	3.74	3.29	3.19	4.71	4.07	3.93
	s_o	0.0257	0.0265	0.0267	0.0237	0.0245	0.0247	0.0219	0.0228	0.0230
4	H_{ec}	2.95	2.60	2.50	3.83	3.32	3.19	4.95	4.18	3.95
	s_o	0.0254	0.0264	0.0267	0.0232	0.0242	0.0247	0.0214	0.0225	0.0230

Table 2. Maximum values of permissible H_{ec} where $n = 0.04$ and $s_o = s_{c,Q/4}\Big]_{z=2,\,b=100}$ but not > 0.04.

v_p = ft/sec, b = ft, z = ft/ft, H_{ec} = ft, s_o = ft/ft

z	v_p	2			3			4		
	b	25	100	400	25	100	400	25	100	400
0	H_{ec}	0.203	0.202	0.202	0.402	0.398	0.396	0.652	0.643	0.641
	s_o									
1	H_{ec}	0.203	0.202	0.202	0.402	0.397	0.396	0.652	0.643	0.641
	s_o									
2	H_{ec}	0.203	0.202	0.202	0.403	0.398	0.397	0.656	0.644	0.641
	s_o		0.04			0.04			0.04	
3	H_{ec}	0.204	0.202	0.202	0.405	0.398	0.397	0.661	0.645	0.641
	s_o									
4	H_{ec}	0.205	0.202	0.202	0.407	0.399	0.397	0.666	0.647	0.642
	s_o									

z	v_p	5			6			7		
	b	25	100	400	25	100	400	25	100	400
0	H_{ec}	0.990	0.970	0.962	1.46	1.42	1.40	2.02	1.93	1.90
	s_o									
1	H_{ec}	0.995	0.972	0.970	1.45	1.42	1.39	2.00	1.92	1.90
	s_o									
2	H_{ec}	1.01	0.975	0.975	1.47	1.42	1.39	2.04	1.92	1.90
	s_o		0.0369			0.0325			0.0294	
3	H_{ec}	1.02	0.979	0.970	1.49	1.42	1.40	2.08	1.93	1.91
	s_o									
4	H_{ec}	1.03	0.982	0.972	1.52	1.43	1.40	2.12	1.97	1.92
	s_o									

z	v_p	8			9			10		
	b	25	100	400	25	100	400	25	100	400
0	H_{ec}	2.71	2.52	2.49	3.51	3.22	3.17	4.49	4.00	3.92
	s_o									
1	H_{ec}	2.67	2.52	2.48	3.45	3.21	3.16	4.36	4.00	3.91
	s_o									
2	H_{ec}	2.72	2.54	2.48	3.55	3.24	3.19	4.47	4.04	3.92
	s_o		0.0268			0.0246			0.0229	
3	H_{ec}	2.78	2.56	2.50	3.65	3.27	3.19	4.58	4.06	3.94
	s_o									
4	H_{ec}	2.86	2.58	2.50	3.75	3.32	3.20	4.75	4.15	3.95
	s_o									

Approximate values of permissible H_{ec}, when $25 \leqq b \leqq 400$ and $0 \leqq z \leqq 4$, may be obtained from ES-170, sheet 1. When they are so obtained, the maximum error can be ascertained from Table 1 for $2 \leqq v_p \leqq 10$. For example; if $b = 30$, $z = 3$ and $v_p = 6.0$, ES-170 gives maximum permissible $H_{ec} = 1.42$ ft. Table 1 shows that maximum permissible H_{ec} is less than 1.52 ft since $25 < (b = 30) < 100$. The error in the maximum permissible H_{ec} is less than 0.1 ft. The error in obtaining the maximum permissible H_{ec} from ES-170, sheet 1 is the greatest for the higher values of v_p and lower values of b.

H_{ec} vs H_p for Various Lengths, L (ES-171)

Except for the higher values of v_p and the lower values of s_o, the relation of the permissible H_{ec} and the corresponding nexus of parameters (v_p, s_o, b, z, n) used in design of an earth or a vegetated spillway is nearly independent of Q and b. The relation of H_{ec} and H_p is also nearly independent of Q and b.

Reference Section

For an H_{ec} and a length of spillway upstream from the control section, the corresponding value of H_p is obtained from ES-171. The drawing considers only spillways having the Reference Section. Each sheet is for a bottom profile as specified by the case number.

Effect of bottom profiles. - For a spillway with the Reference Section and of length, L, the effect of varying the bottom profile on the value of H_p corresponding to a particular value of H_{ec} can be ascertained from the various sheets of ES-171. Table 3 gives the values of friction head loss, h_f, for spillways of various bottom profiles when the spillway length is 400 ft and $H_{ec} = 4$ ft.

Table 3. Values and the distribution of friction head loss, h_f, for spillways of various bottom profiles

H_{ec} = 4.0 ft   L = 400 ft   n = 0.04   z = 2   b = 100 ft

Case	H_p, ft	h_f, ft	L_o, ft	h_{f_o}, ft	h_{f_1}, ft
2	4.62	0.62	30	0.28	0.34
3	4.47	0.47	30	0.28	0.19
4	4.71	0.71	50	0.40	0.31
5	4.58	0.58	50	0.40	0.18
6	4.91	0.91	100	0.65	0.26
7	4.79	0.79	100	0.65	0.14
8	4.61	0.61	50	0.40	0.21
9	4.53	0.53	50	0.40	0.13

L_o ≡ length of horizontal portion of spillway - ft

h_f ≡ total friction head loss in L, $h_f = h_{f_o} + h_{f_1}$ - ft

h_{f_o} ≡ friction head loss in L_o - ft

h_{f_1} ≡ friction head loss in L - L_o - ft

The value of H_p varies between the extreme values of 4.47 ft (Case 3) and 4.91 ft (Case 6).

The friction head loss, h_f, varies between 0.47 ft and 0.91 ft. The major portion of the friction head loss, as is often true, occurs in conveying the discharge through the horizontal part of the spillway. For Case 3 and Case 6, the head loss, h_{f_o}, required to convey the discharge through the horizontal portion of the spillway is h_{f_o} = 0.28 ft and h_{f_o} = 0.65 ft, respectively. For Cases 3 and 6, h_{f_o} is over 50 percent of the total head loss in the 400 ft long spillway. In Case 3 the head loss upstream of the horizontal part of the spillway is h_{f_1} = 0.19 ft while in Case 6 this head loss is h_{f_1} = 0.26 ft.

The left-most curve of ES-171 labeled either L = 30, 50, or 100 is related to the upstream section of the horizontal part of the spillway. At any particular H_{ec}, the ratio of the distance from the left-most curve to the line for L = 0 to the distance from the curve for the spillway length, L, to the line for L = 0 is the ratio $\frac{h_{f_o}}{h_f}$. For example, using Case 6 and $H_{ec} = 4.0$ ft, the values of H_p at L = 100 ft and L = 400 ft are 4.65 ft and 4.91 ft. Thus $\frac{h_{f_o}}{h_f} = \frac{0.65}{0.91} = 71$ percent.

The ratio of the distance from the curves for L = 100 ft and L = 400 ft to the line for L = 0 is also 71 percent at $H_{ec} = 4.0$. These graphs give visually the proportion $\frac{h_{f_o}}{h_f}$.

From Table 3 one can observe that the variation in the depth of the forebay upstream from the horizontal portion of the spillway often has a negligible influence on the H_p value. For example, when L = 400 ft and $H_{ec} = 4.0$ ft, the H_p value for Case 8 is 0.10 ft smaller than the H_p value for Case 4.

H_{ec} vs H_p for bottom profiles differing from those in ES-171. - The relation of H_{ec} vs H_p for spillways with bottom profiles differing from those given by ES-171 may be approximated by the use of ES-171; however, if a closer evaluation is desired, the relation may be obtained from the basic information given in ES-158 and ES-159.

ES-158 and ES-159 are for spillways with the Reference Section. The drawings, ES-158 and ES-159, can be used in determining the relation of H_{ec} vs H_p for spillways not having a control section.

Non-Reference Section

The friction head loss, h_f, occurring in a spillway having a non-Reference Section and a bottom profile of either Case 1 or Case 2, as defined by ES-171, may be obtained from ES-176. In ES-176, the effect on the friction head loss is considered when the parameters n, b, and z are varied in the following ranges:

1. $0.02 \leq n \leq 0.08$,
2. $25 \leq b \leq 400$, and
3. $1 \leq z \leq 4$.

Observe that for some curves in ES-176 the maximum h_f exists at values of $H_{ec} < 15$ ft. For example, see ES-176, sheet 2, the curve labeled n = 0.04, L = 30 ft shows a maximum for h_f at $H_{ec} < 15$ ft. The first reaction by some is that this curve might be in error, since erroneously, "More water can be conveyed at less friction loss for $H_{ec} = 10$ ft than for $H_{ec} = 5$ ft." One should recall that although the units of h_f are generally given and viewed as feet, h_f is actually a rate of energy loss per pound of water being conveyed, i.e. ft-lb/lb. Normally, hydraulic computations involving energy relations are made on the basis of per pound of water and the term total energy loss usually refers to the total energy loss for each pound of water. The total energy loss through the spillway in one second of time for all the pounds of water being conveyed is actually 62.4 Q h_f.

Effect of Manning's n. - From ES-176, sheets 1-3, one can observe that the value of Manning's roughness coefficient, n, has considerable effect on the value of h_f and hence H_p. Sheets 1, 2, and 3 of ES-176 can be used for the evaluation of the friction head loss, h_f, when $n \neq 0.04$.

When $n \neq 0.04$ and $s_o = 0$, the abscissa, $(\ell_c - \ell_x)$, of ES-158, sheet 1 may be redesignated

$$\frac{n^2(\ell_c - \ell_x)}{0.0016} \qquad (3)$$

to evaluate the depth of flow at a section a distance, $(\ell_c - \ell_x)$, upstream from a control section. A similar redesignation of the abscissas of the sheets 2-8 of ES-158 would be incorrect.

Effect of bottom width, b. - As previously mentioned, for a particular value of H_{ec}, the value of b within the interval of $25 \leqq b \leqq 400$ has minor effect on the value of H_p. For Cases 1 and 2, the value of h_f can be ascertained from ES-176, sheets 4 and 5 for any b within the interval $25 \leqq b \leqq 400$.

Figure 1 shows, for z = 2 and Case 1, the maximum values of $(H_p]_b - H_p]_{b=100})$ for b = 25 ft and 400 ft, for the interval $0.45 \leqq H_{ec} \leqq 15$ and for various spillway lengths, L. For Case 1, the maximum error in taking $H_p]_b = H_p]_{100}$ is less than 0.10 ft within the region $25 \leqq b \leqq 400$, $30 \leqq L \leqq 1000$, and $0.45 \leqq H_{ec} \leqq 15$.

Figure 2 shows, for z = 2 and Case 2, the maximum error in taking $H_p]_b = H_p]_{100}$ is less than 0.04 ft within the region $25 \leqq b \leqq 400$, $30 \leqq L \leqq 750$, and $0.45 \leqq H_{ec} \leqq 15$.

<u>Effect of side slope, z.</u> - For a particular value of H_{ec}, the value of z, within the interval $1 \leq z \leq 4$, has a minor effect on the value of H_p. For Cases 1 and 2, the value of h_f can be ascertained for any z, within the interval $1 \leq z \leq 4$, from ES-176, sheets 6 and 7. Figure 3 shows, for b = 100 and Case 1, the maximum values of $(H_p]_z - H_p]_{z=2})$ for z = 1 and 4 for the intervals $0.45 \leq H_{ec} \leq 4.0$ and $0.45 \leq H_{ec} \leq 15$ and for various spillway lengths, L. Figure 4 shows, for b = 100 and Case 2, the maximum error in taking $H_p]_z = H_p]_2$ is less than 0.09 ft within the region $1 \leq z \leq 4$, $30 \leq L \leq 750$, and $0.45 \leq H_{ec} \leq 15$.

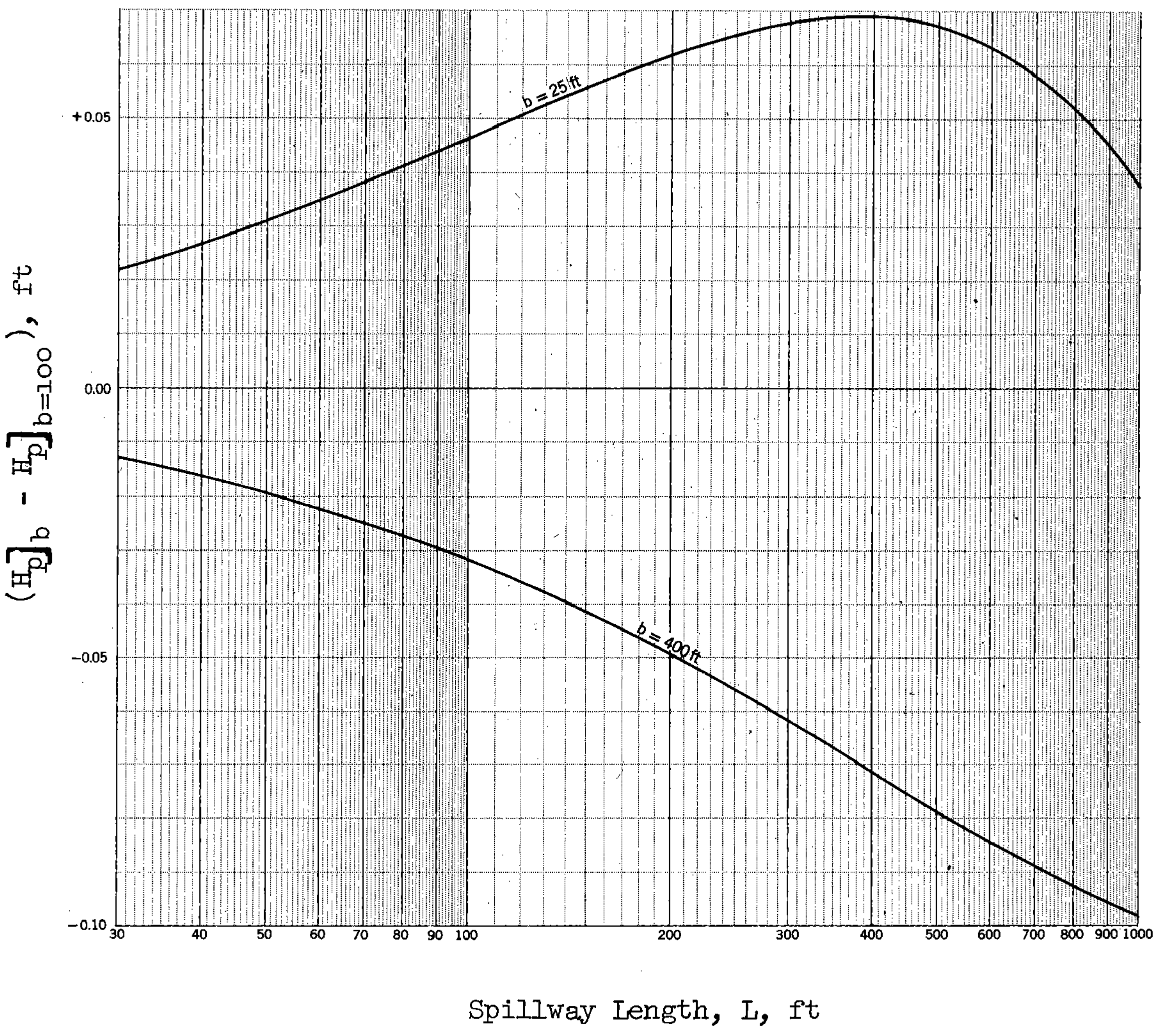

Figure 1. Maximum values of $(H_p]_b - H_p]_{b=100})$ for z = 2 and Case 1 spillways of various lengths and in the interval $0.45 \leq H_{ec} \leq 15.0$

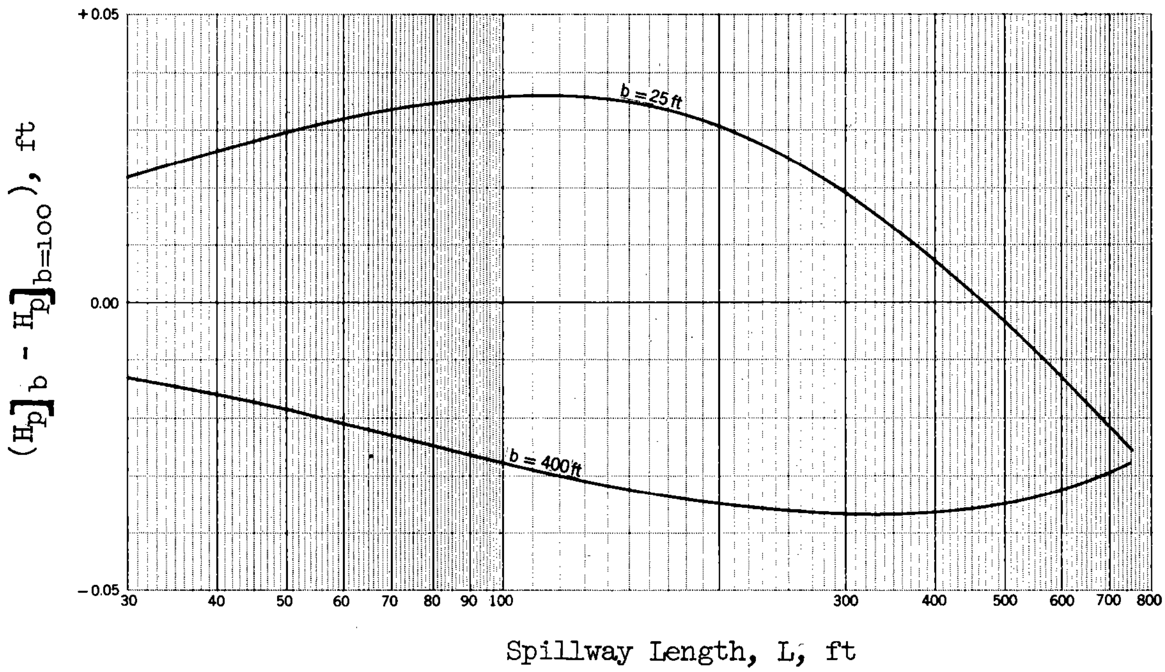

Figure 2. Maximum values of $(H_p]_b - H_p]_{b=100})$ for z = 2 and Case 2 spillways of various lengths and in the interval $0.45 \leq H_{ec} \leq 15.0$

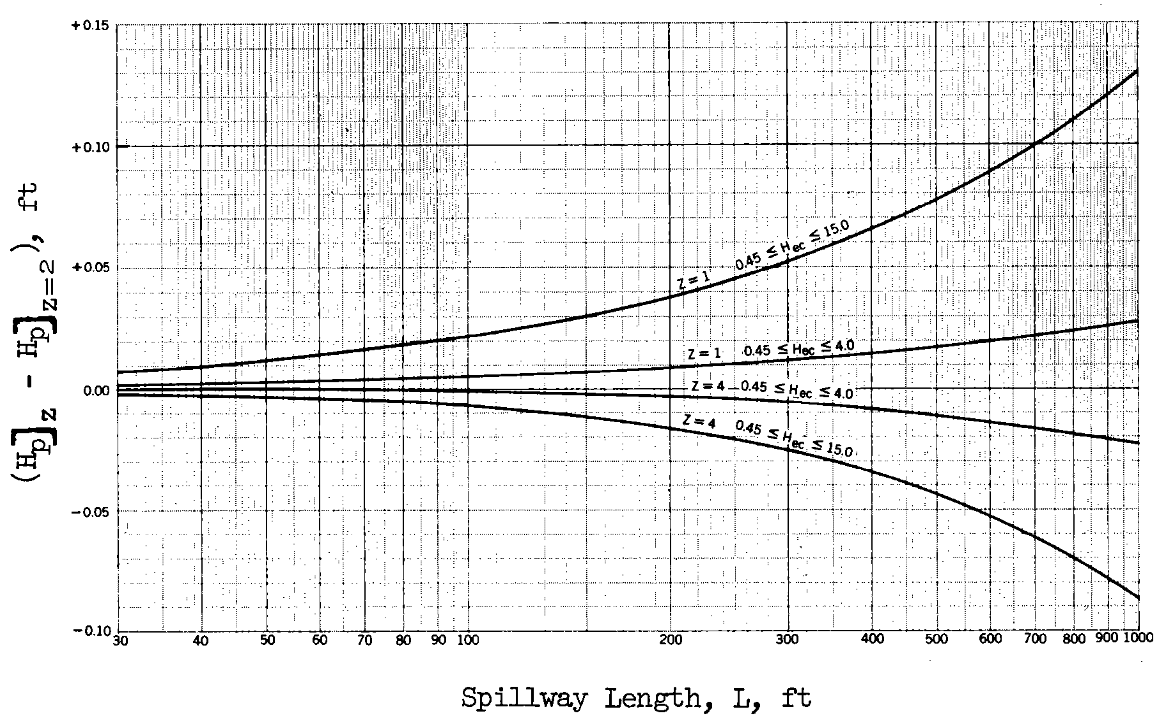

Figure 3. Maximum values of $(H_p]_z - H_p]_{z=2})$ for b = 100 ft and Case 1 spillways of various lengths and in the indicated intervals of H_{ec}

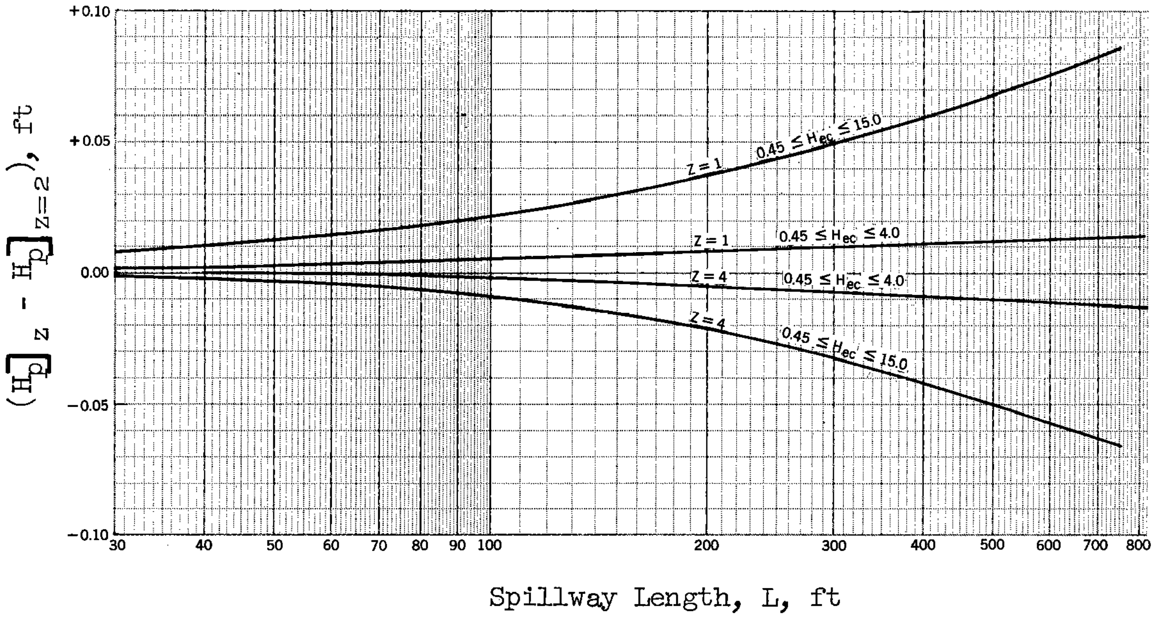

Figure 4. Maximum values of $(H_p]_z - H_p]_{z=2})$ for b = 100 ft and Case 2 spillways of various lengths and in the indicated intervals

Critical Slope Corresponding to Q/4 (ES-172)

A control section exists at a break in grade if;

1. the slope upstream from the break in grade is less than critical slope and is sufficiently long, and
2. the slope downstream from the break in grade is greater than or equal to the critical slope, and is sufficiently long to prevent tailwater effects at the control section.

Critical slope corresponding to the discharge, Q, is defined as that slope which causes the discharge, Q, to be conveyed as uniform flow at a depth equal to critical depth (i.e. $d_{n,Q} = d_{c,Q}$).

The critical slope is associated with a discharge, Q, and when the discharge is changed, the critical slope is changed. Further, the depth of flow at the control section is the critical depth corresponding to the discharge, Q.

For the range of b's, z's and depths of flow being considered in this technical release the critical slope usually decreases as the discharge is increased. When this is true, a control section is ensured for a range of discharges from Q/4 to Q if the slope immediately downstream from the control section is greater than or equal to the critical slope corresponding to Q/4. Symbolically the critical slope corresponding to Q/4 is written $s_{c,Q/4}$ and is in correspondence with H_{ec} where H_{ec} is in correspondence with Q.

Reference Section

For an H_{ec} the corresponding value of $s_{c,Q/4}$ is obtained from ES-172.

Non-Reference Section

A control section is ensured for the range of discharges of Q/4 to Q in the regions

(1) $1 \leq z \leq 4$, $25 \leq b \leq 400$, and $0.45 \leq H_{ec} \leq 15$;

(2) $z = 0$, $40 \leq b \leq 400$, and $0.45 \leq H_{ec} \leq 15$; and the region

(3) $z = 0$, $25 \leq b \leq 400$, and $0.45 \leq H_{ec} \leq 9.8$

by taking the exit channel bottom slope $s_o \geq s_{c,Q/4}$.

When $z = 0$, $b < 40$, and $9.8 \leq H_{ec} \leq 15$, taking $s_o = s_{c,Q/4}$ does not ensure a control section for the range of discharges from Q/4 to Q.

The relation of H_{ec} vs $s_{c,Q/4}$, for the lower values of H_{ec} but greater than 0.45, is nearly independent of Q and b for the range of values $25 \leq b \leq 400$ and $0 \leq z \leq 4$.

Effect of n. - When the value of $n \neq 0.04$, $z = 2$, and $b = 100$, the critical slope, $s_{c,Q/4}$, corresponding to an H_{ec} can be obtained by redesignating the abscissa of ES-172, sheet 1 as $\left[\frac{0.04}{n}\right]^2 s_{c,Q/4}$.

When the value of $n \neq 0.04$, $z = 0$, and $25 \leq b \leq 400$, the critical slope, $s_{c,Q/4}$, corresponding to an H_{ec} can be obtained by redesignating the abscissa of ES-178, sheet 1 as $\left[\frac{0.04}{n}\right]^2 s_{c,Q/4}$.

The value of $s_{c,Q/4}\big]_{z,b}$ for any n can be obtained from ES-178, sheet 2, within the region $1 \leq z \leq 4$, $25 \leq b \leq 400$, and $0.45 \leq H_{ec} \leq 15$.

Effect of b and z. - The value of $s_{c,Q/4}$, as obtained from ES-172, is in error by less than 0.001 within the region $25 \leq b \leq 400$, $2 \leq z \leq 4$, and $0.45 \leq H_{ec} \leq 15.0$.

The value of $s_{c,Q/4}$ for $z = 0$ and within the region $25 \leq b \leq 400$ and $0.45 \leq H_{ec} \leq 15$ is given by sheet 1, ES-178.

The value of $s_{c,Q/4}$ for any n and within the region $25 \leq b \leq 400$, $1 \leq z \leq 4$, and $0.45 \leq H_{ec} \leq 15$ is shown by sheet 2 of ES-178.

Values of $s_{c,Q/4}$, along with $s_{c,Q}$, for the extremes of the region $25 \leq b \leq 400$, $0 \leq z \leq 4$, and $0.45 \leq H_{ec} \leq 15$ are given in Table 4.

Table 4. Corresponding values of H_{ec}, $s_{c,Q/4}$ and $s_{c,Q}$

n = 0.04

H_{ec}, ft	b, ft	z	$s_{c,Q/4}$, ft/ft	$s_{c,Q}$, ft/ft
0.45	25	0	0.04797	0.03593
0.45	400	0	0.04741	0.03488
0.45	25	4	0.04735	0.03529
0.45	400	4	0.04737	0.03484
15	25	0	0.02126	0.02368
15	400	0	0.01511	0.01154
15	25	4	0.01523	0.01259
15	400	4	0.01471	0.01111

H_{ec} vs $Q_{c,d}$ for various bottom widths, b (ES-173, 174, and 175)

The critical discharge, $Q_{c,d}$, corresponding to the critical specific energy head, H_{ec}, and bottom width, b, is shown by ES-173, 174, and 175 when the side slopes are z = 0, 2, and 3, respectively. The corresponding critical depth, $d_{c,Q}$, is also given. Thus, for a broad-crested spillway containing a control section, the discharge, Q, is equal to the critical discharge, $Q_{c,d}$, corresponding to H_{ec}. When the spillway width, b, and the correspondence of H_p and H_{ec} (as given by ES-171) are known for a particular spillway, the correspondence of H_p and Q (i.e. spillway rating) is readily obtained.

The fundamental relations involving H_{ec}, $Q_{c,d}$, b, and z are

$$\frac{(Q_{c,d})^2}{g} = \frac{a_c^3}{T_c} = \frac{\left[(b + zd_{c,Q})\, d_{c,Q}\right]^3}{(b + 2z\, d_{c,Q})} \tag{4}$$

$$H_{ec} = d_{c,Q} + \frac{v_c^2}{2g} \tag{5}$$

$$H_{ec} = \frac{(3b + 5z\, d_{c,Q})d_{c,Q}}{2b + 4z\, d_{c,Q}} \tag{6}$$

For z = 0 the last relation reduces to

$$H_{ec} = \frac{3}{2}\, d_{c,Q} \qquad \text{(when } z = 0) \tag{7}$$

Further,

$$H_{ec} = 0.4717 \left[\frac{Q_{c,d}}{b}\right]^{2/3} \qquad \text{(when } z = 0\text{)} \qquad (8)$$

$$\frac{Q_{c,d}}{b} = 3.087\ H_{ec}^{3/2} \qquad \text{(when } z = 0\text{)} \qquad (9)$$

When $z \neq 0$, 2, or 3

The parameters, z and b, can have considerable effect on the value of $Q_{c,d}$ corresponding to a particular critical specific energy head, H_{ec}.

When the critical discharge corresponding to a given H_{ec}, b, and z is to be determined, a direct solution may be made by solving Eq. (6) for $d_{c,Q}$ and then solving Eq. (4) for $Q_{c,d}$. The solution for H_{ec} corresponding to $Q_{c,d}$, z, and b is implicit. Both of these solutions can be simplified by an approximation. The approximation is; if two trapezoidal sections have equal critical specific energy heads, then the ratio of their corresponding critical discharges is approximately equal to the ratio of their average width at critical depth.[1] When the side slopes of the trapezoidal section are equal, this approximation becomes,

$$\frac{Q_c}{Q_c'} = \frac{b + z\ d_c}{b' + z' d_c'} \qquad \text{(when } H_{ec} = H_{ec}'\text{)} \qquad (10)$$

When the approximation is based on a rectangular section ($z' = 0$) of width $b' = 100'$, obtain from Eq. (7)

$$d_c' = \frac{2}{3} H_{ec}' = \frac{2}{3} H_{ec}$$

and substituting into Eq. (10) in which the approximation $d_c = d_c'$ is used, obtain

$$\frac{Q_c}{Q_c'} = \frac{b + z(\frac{2}{3} H_{ec})}{100} = \frac{1.5b + z\ H_{ec}}{150} \qquad (11)$$

When the approximation is based on a rectangular section of width $b' = 100$ ft, the error in the critical discharge, Q_c, is readily obtained from ES-173, sheet 4, Figure 1.

Examples

Examples are usually given with each ES-drawing in this technical release illustrating the use of the drawing. Two examples are given in ES-179 illustrating the interrelation of the ES-drawings.

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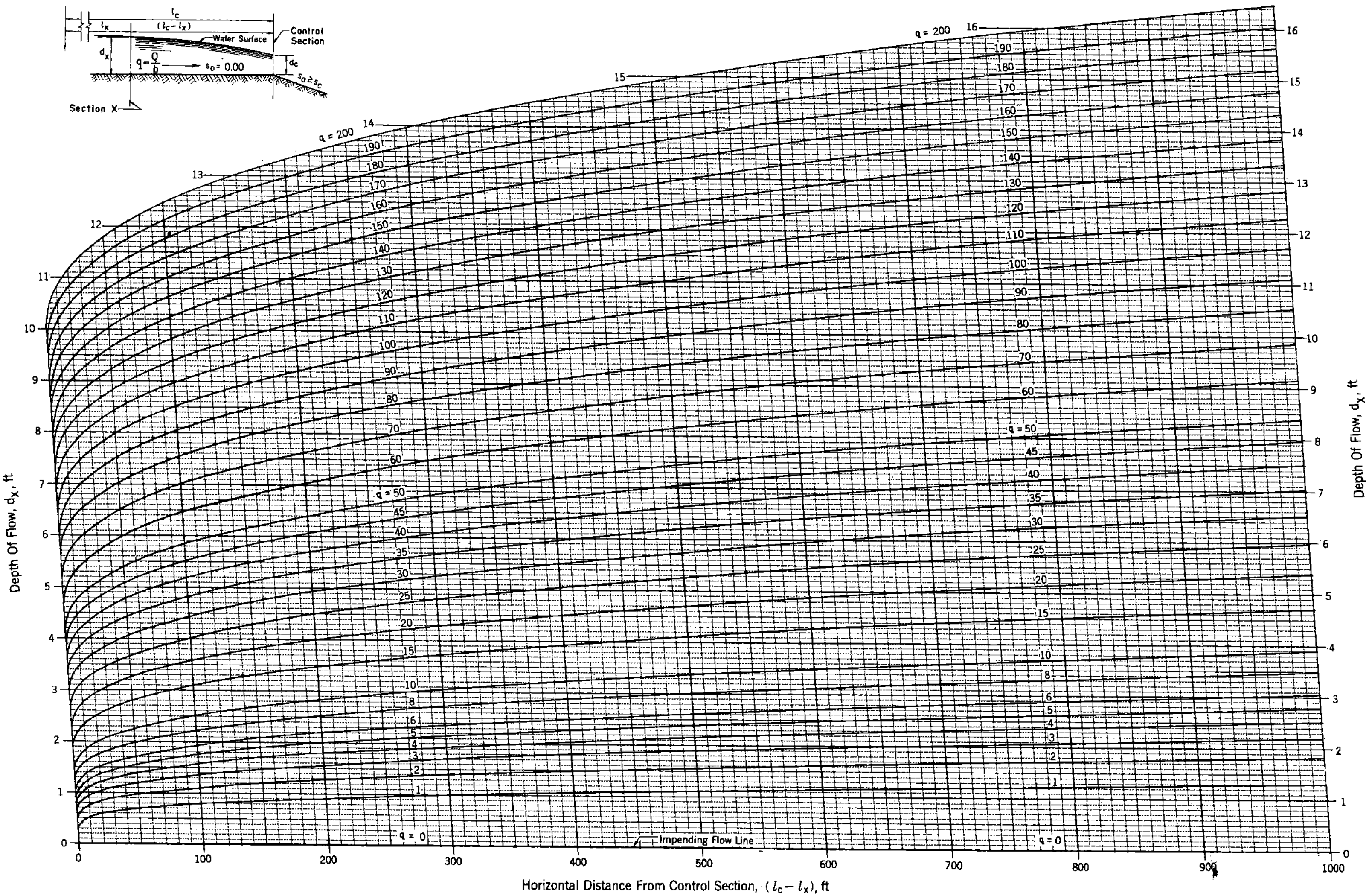
[1]This approximation, in another form, was proposed by Mr. M. M. Culp, Chief, Design Branch, Engineering Division, SCS. See Tentative Technical Release No. 2.

SPILLWAYS: Subcritical Water Surface Profiles

b = 100 ft
z = 2
n = 0.04

$s_o = 0.00$



REFERENCE

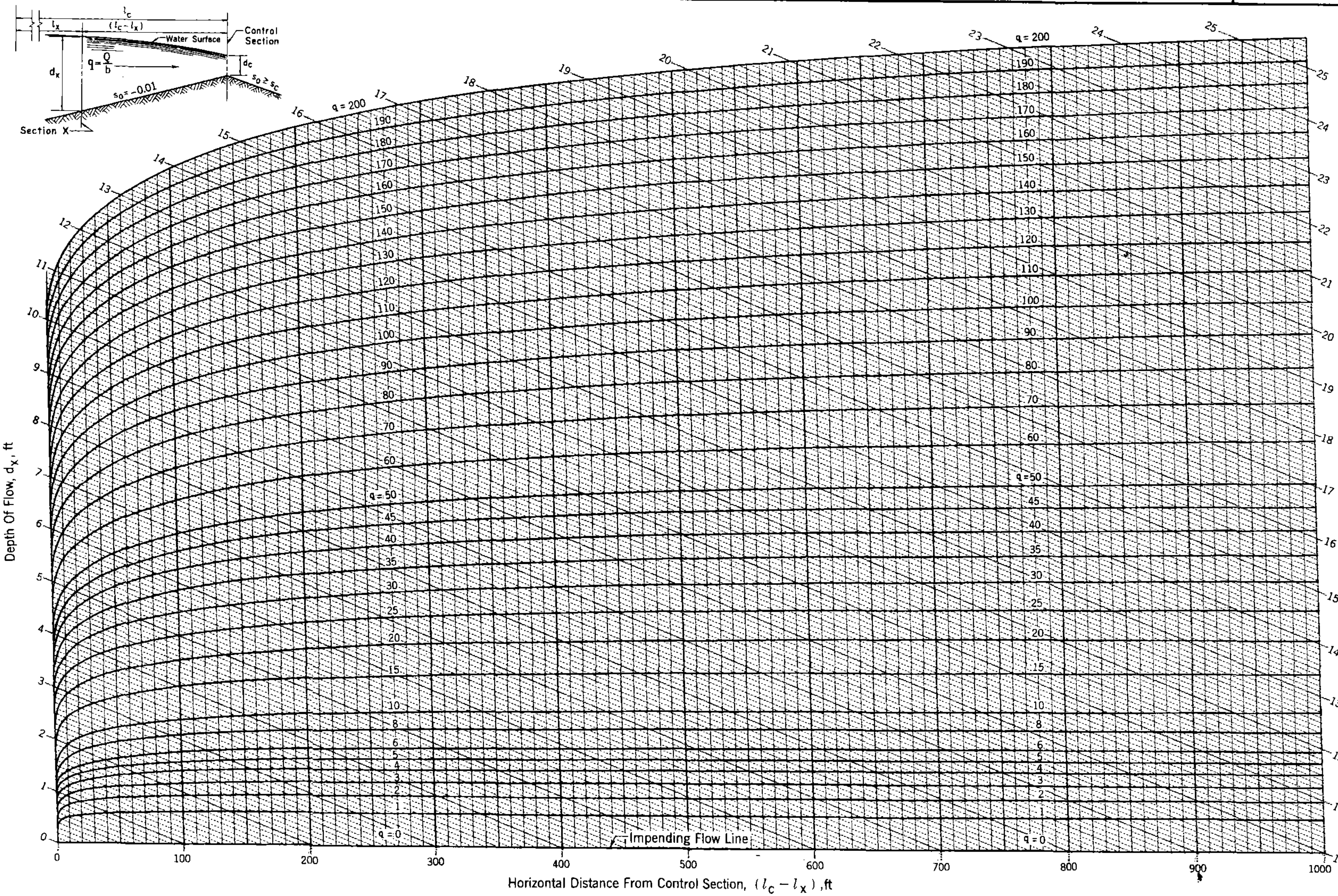
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES- 158
SHEET 1 OF 10
DATE 2-67

SPILLWAYS: Subcritical Water Surface Profiles

b = 100 ft
Z = 2
n = 0.04

$s_o = -0.01$



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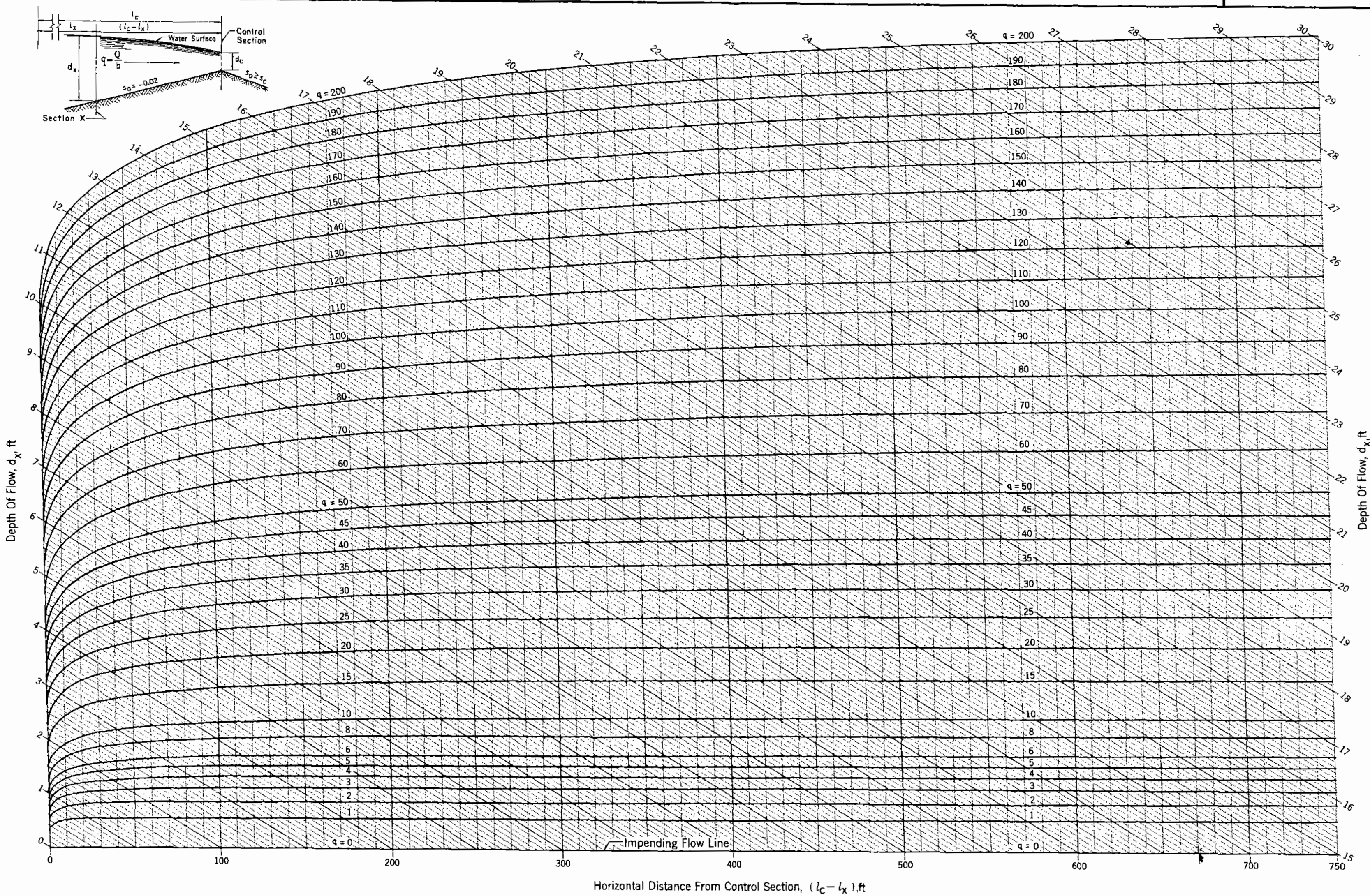
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES- 158
SHEET 2 OF 10
DATE 2-67

SPILLWAYS: Subcritical Water Surface Profiles

b = 100 ft
z = 2
n = 0.04

$S_o = -0.02$



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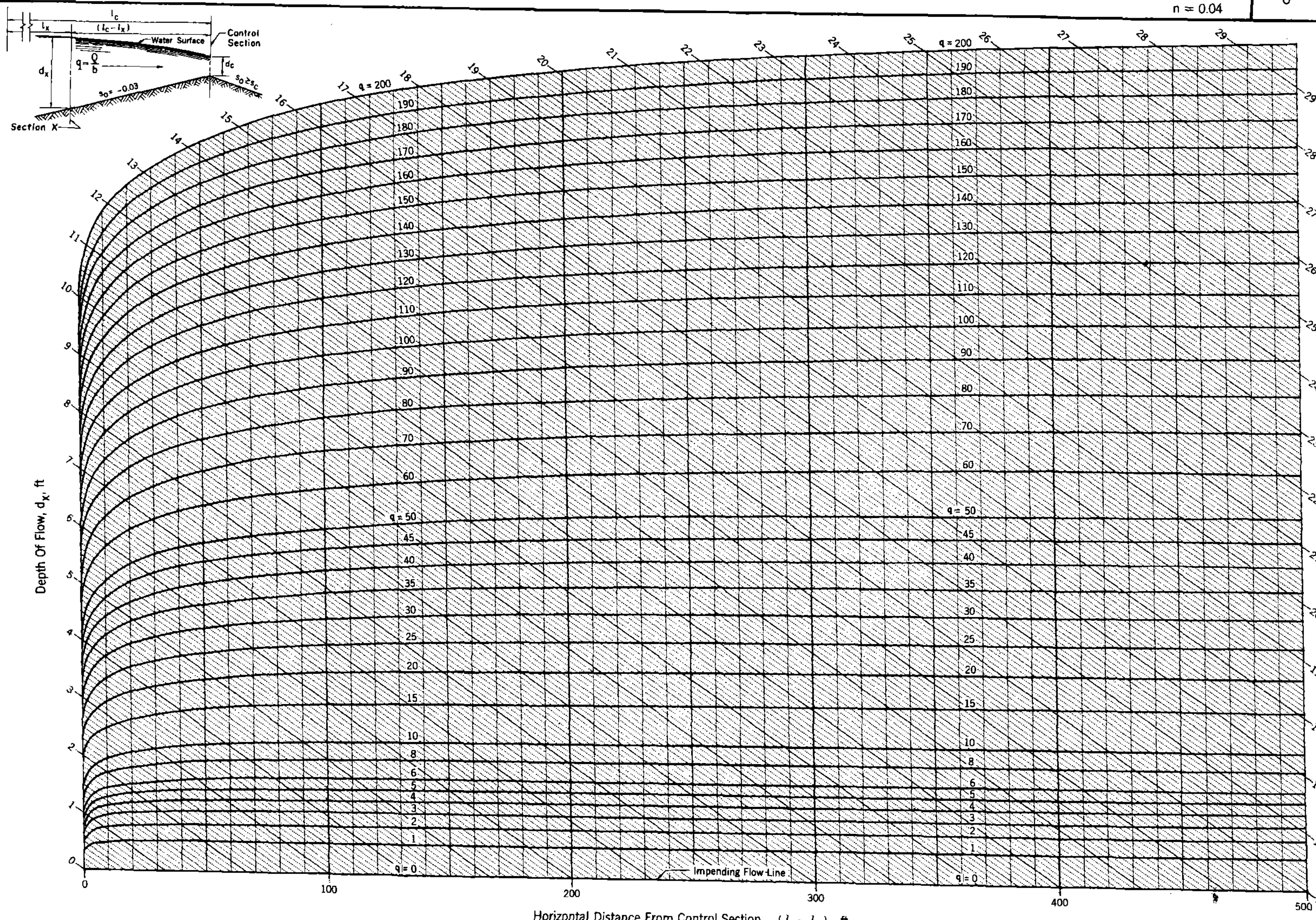
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES- 158
SHEET 3 OF 10
DATE 2-67

SPILLWAYS: Subcritical Water Surface Profiles

b = 100 ft
z = 2
n = 0.04

$s_o = -0.03$



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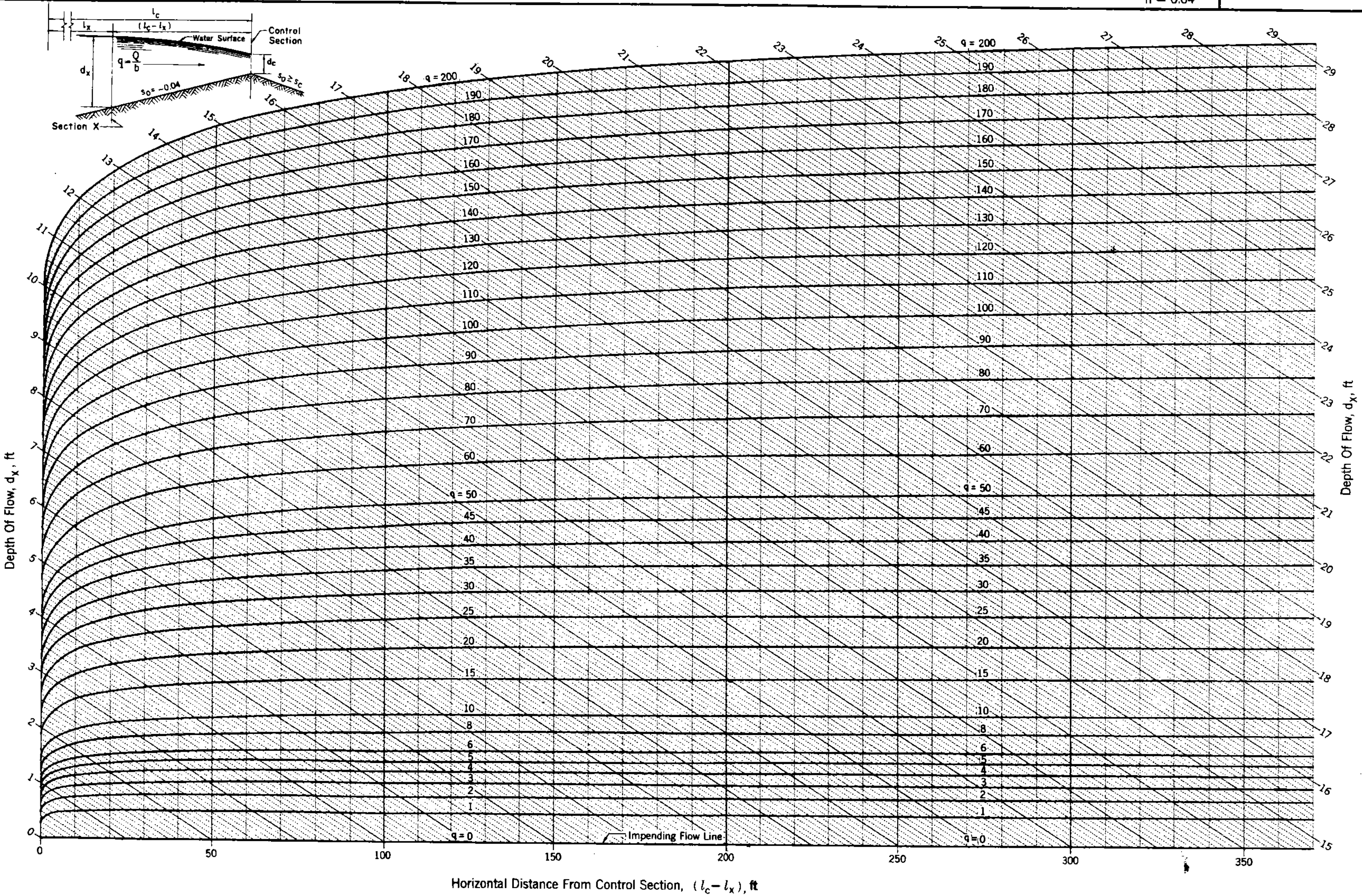
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES- 158
SHEET 4 OF 10
DATE 2-67

SPILLWAYS: Subcritical Water Surface Profiles

b = 100 ft
z = 2
n = 0.04

$s_o = -0.04$



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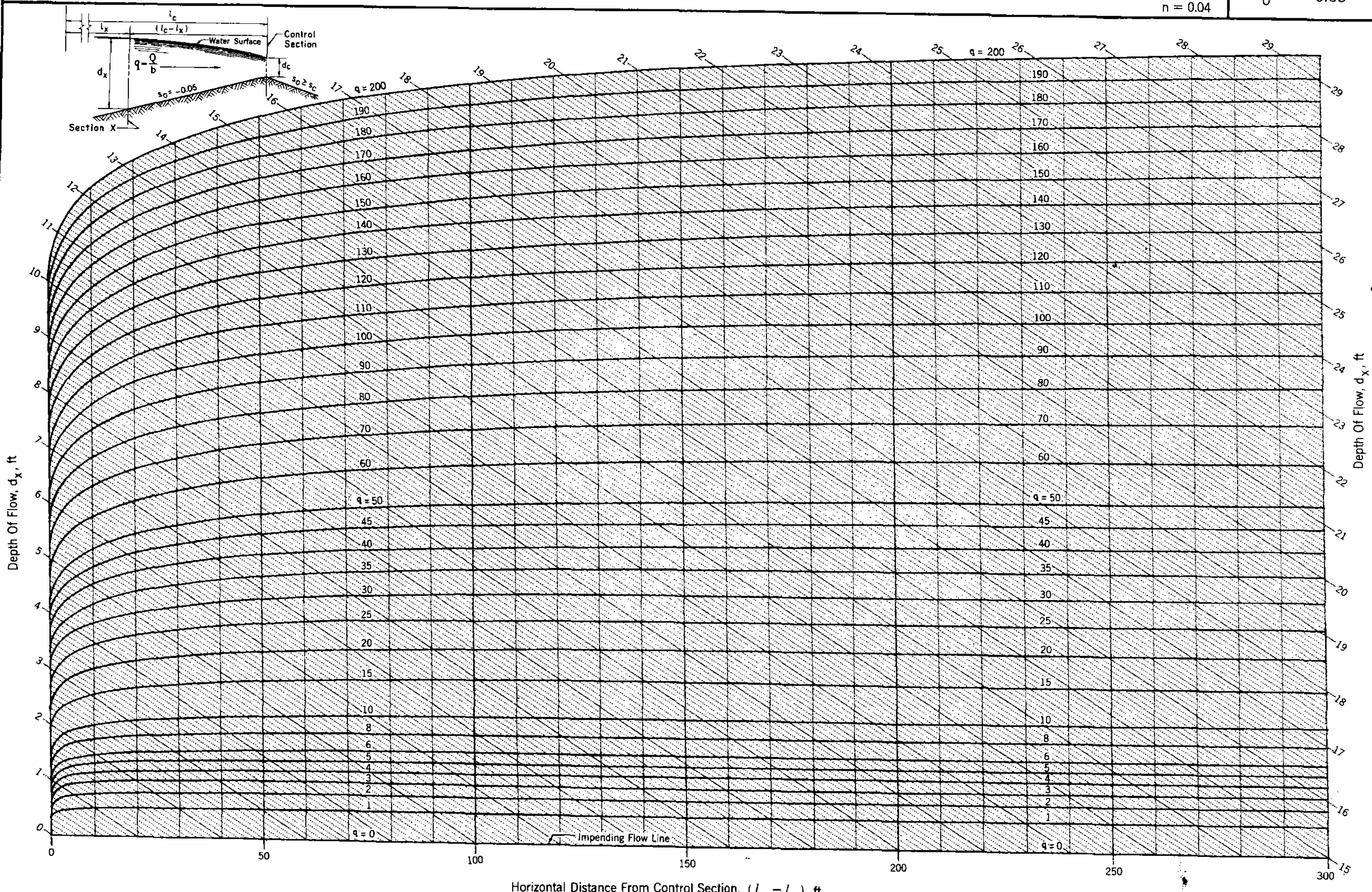
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES- 158
SHEET 5 OF 10
DATE 2-67

SPILLWAYS: Subcritical Water Surface Profiles

b = 100 ft
z = 2
n = 0.04

$s_o = -0.05$



REFERENCE

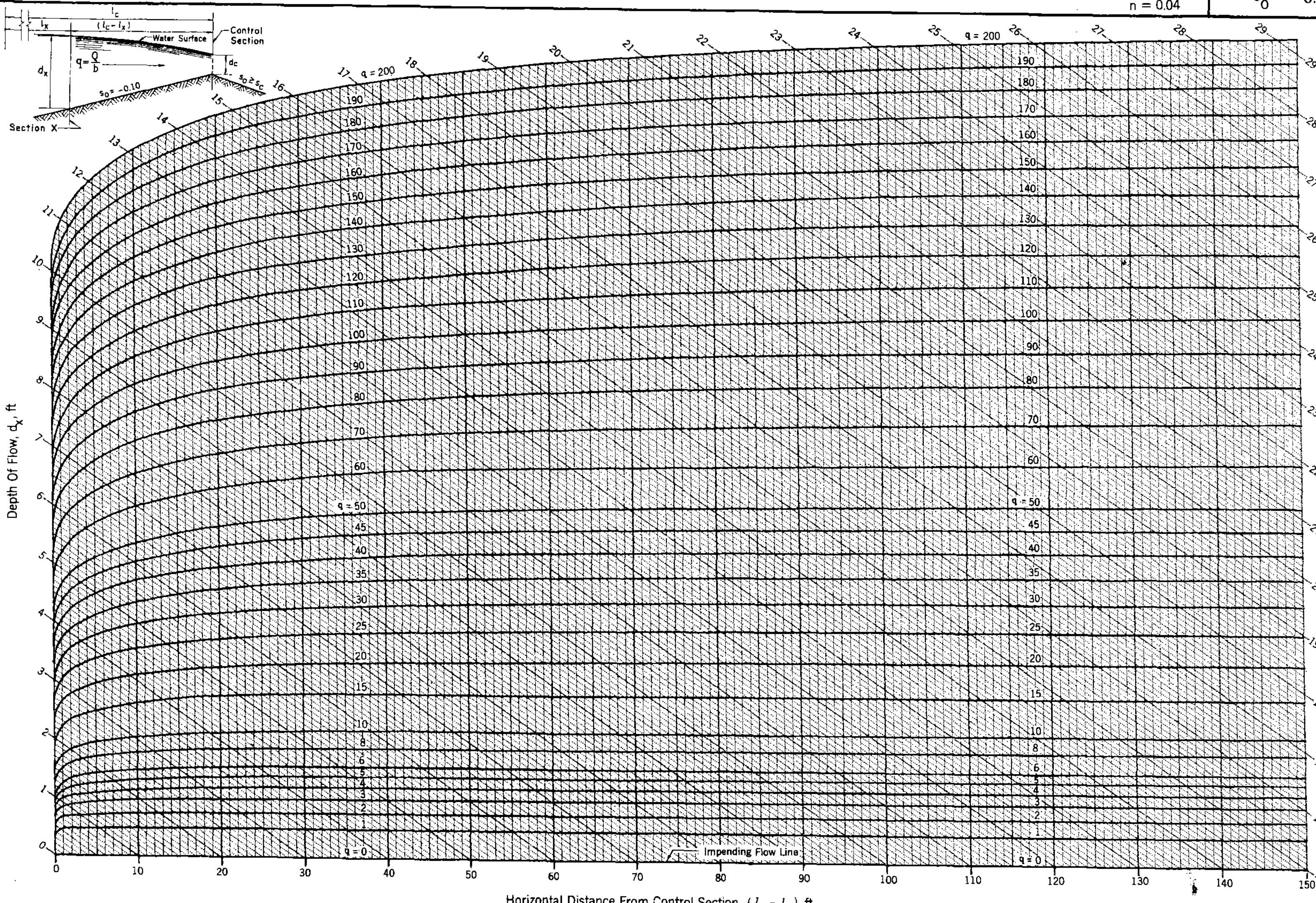
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES- 158
SHEET 6 OF 10
DATE 2-67

SPILLWAYS: Subcritical Water Surface Profiles

b = 100 ft
z = 2
n = 0.04

$s_o = -0.10$



REFERENCE

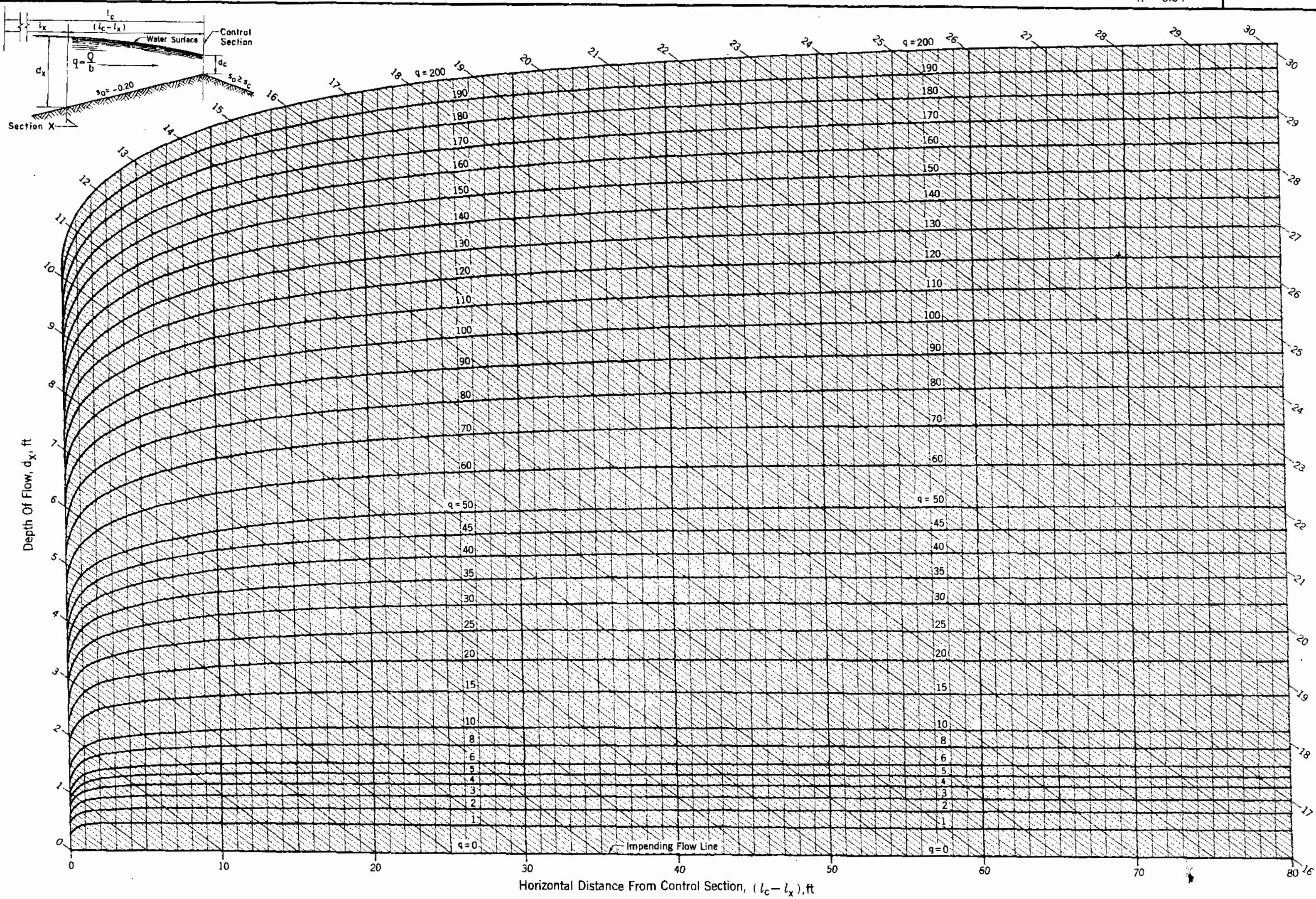
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO. ES- 158
SHEET 7 OF 10
DATE 2-67

SPILLWAYS: Subcritical Water Surface Profiles

b = 100 ft
z = 2
n = 0.04

$s_o = -0.20$



REFERENCE

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

STANDARD DWG. NO.
ES- 158
SHEET 8 OF 10
DATE 2-57

NOMENCLATURE

d_x ≡ depth of flow at section x

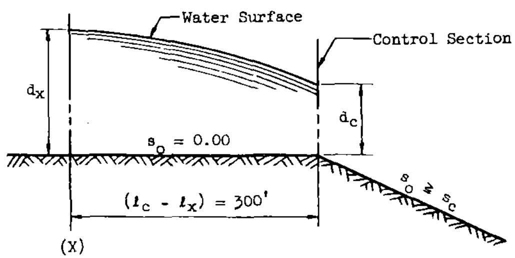
ℓ_c ≡ station at the control section

ℓ_x ≡ station at section x

EXAMPLE 1

Given:
Emergency spillway bottom profile as shown in figure
Q = 3500 cfs
b = 100 ft
z = 2
n = 0.04

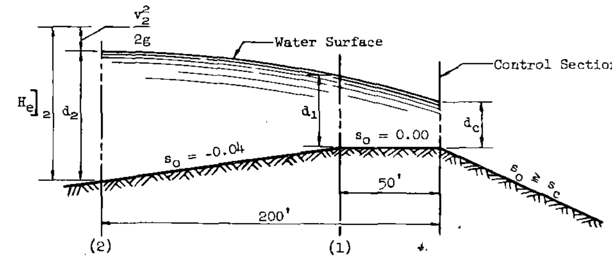
Determine:
The depth of flow, d_x, at section x.



Solution:
Use ES-158, sheet 1.
For $(\ell_c - \ell_x)$ = 300 ft and $q = \frac{Q}{b} = \frac{3500}{100}$ = 35 cfs/ft, read d_x = 5.67 ft.

EXAMPLE 2

Given:
Emergency spillway bottom profile as shown in figure
Q = 5000 cfs
b = 100 ft
z = 2
n = 0.04

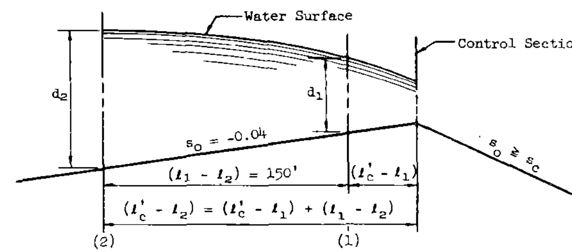


Determine:
I. The depth of flow, d_2, and
II. The specific energy head, $H_e]_2$, at section 2.

Solution:
I. Determine d_2

A. Considering the 50 ft reach of s_o = 0.00 immediately upstream from the control section, use ES-158, sheet 1. For $(\ell_c - \ell_1)$ = 50 ft and $q = \frac{Q}{b} = \frac{5000}{100}$ = 50 cfs/ft, read d_1 = 5.40 ft.

B. Considering the 150 ft reach of s_o = -0.04, use ES-158, sheet 5.
1. For d_1 = 5.40 ft and q = 50 cfs/ft, read $(\ell_c' - \ell_1)$ = 9 ft.



2. For $(\ell_c' - \ell_2)$ = 150 + 9 = 159 ft and q = 50 cfs/ft, read d_2 = 12.57 ft.

II. Determine $H_e]_2$
To obtain the velocity head, $\frac{v_2^2}{2g}$, use ES-159, sheet 1.
For q = 50 cfs/ft and d_2 = 12.57 ft, read $\frac{v_2^2}{2g}$ = 0.16 ft.
Then $H_e]_2 = d_2 + \frac{v_2^2}{2g}$ = 12.57 + 0.16 = 12.73 ft.

EXAMPLE 3

Given:

Emergency spillway bottom profile as shown in figure

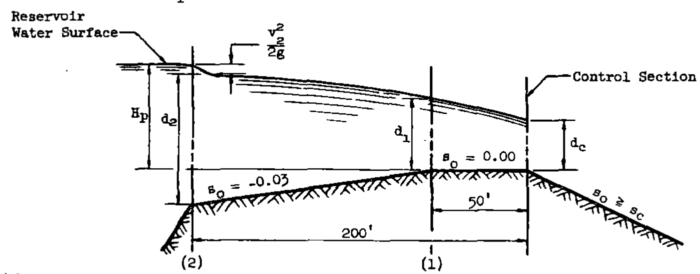
$b = 100$ ft

$z = 2$

$n = 0.04$

Determine:

The rating curve (H_p vs Q relation) for the given emergency spillway.



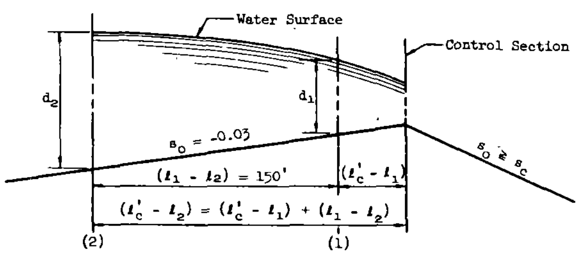
Solution:

I. Determine the depth of flow, d_2

A. Considering the 50 ft reach of $s_o = 0.00$ immediately upstream from the control section, use ES-158, sheet 1. For $(\ell_c - \ell_1) = 50$ ft and for various q values, read d_1 values.

B. Considering the 150 ft reach of $s_o = -0.03$, use ES-158, sheet 4.

1. For the values of d_1 and the corresponding q, read values of $(\ell_c' - \ell_1)$.



2. Then $(\ell_c' - \ell_2) = 150 + (\ell_c' - \ell_1)$. For the values of $(\ell_c' - \ell_2)$ and corresponding q, read d_2 values.

II. Determine the energy head of the water in the reservoir above the spillway crest, H_p.

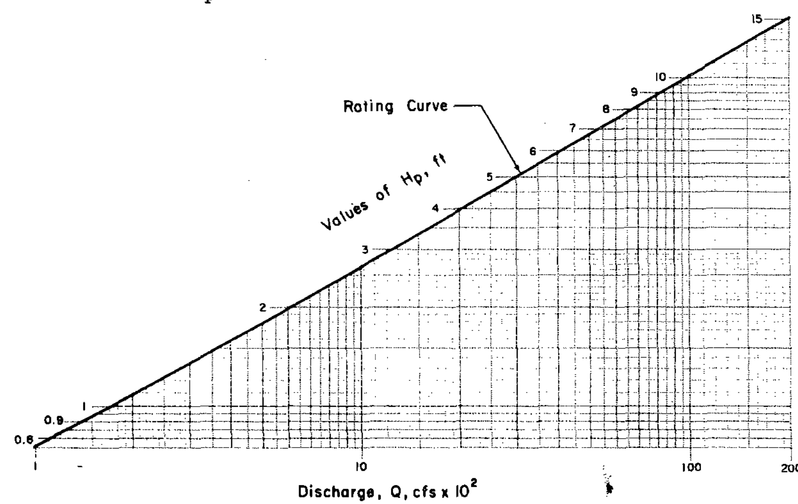
A. To obtain values of velocity head, $\frac{v_2^2}{2g}$, use ES-159.

For the values of d_2 and corresponding q, read $\frac{v_2^2}{2g}$ values.

B. Then $H_p = d_2 + \frac{v_2^2}{2g} - |s_o|(\ell_1 - \ell_2) = d_2 + \frac{v_2^2}{2g} - 0.03(150) = d_2 + \frac{v_2^2}{2g} - 4.50$

q	Q=qb	d_1	$\ell_c' - \ell_1$	$\ell_c' - \ell_2$	d_2	$\frac{v_2^2}{2g}$	H_p
cfs/ft	cfs	ft	ft	ft	ft	ft	ft
1	100	0.70	7	157	5.26	--	0.76
2	200	0.97	8	158	5.58	--	1.08
5	500	1.55	9	159	6.27	0.01	1.78
10	1,000	2.25	10	160	7.13	0.02	2.65
20	2,000	3.26	10	160	8.37	0.06	3.93
50	5,000	5.40	11	161	11.05	0.21	6.76
100	10,000	7.98	11	161	14.18	0.47	10.15
200	20,000	11.78	10	160	18.68	0.94	15.12

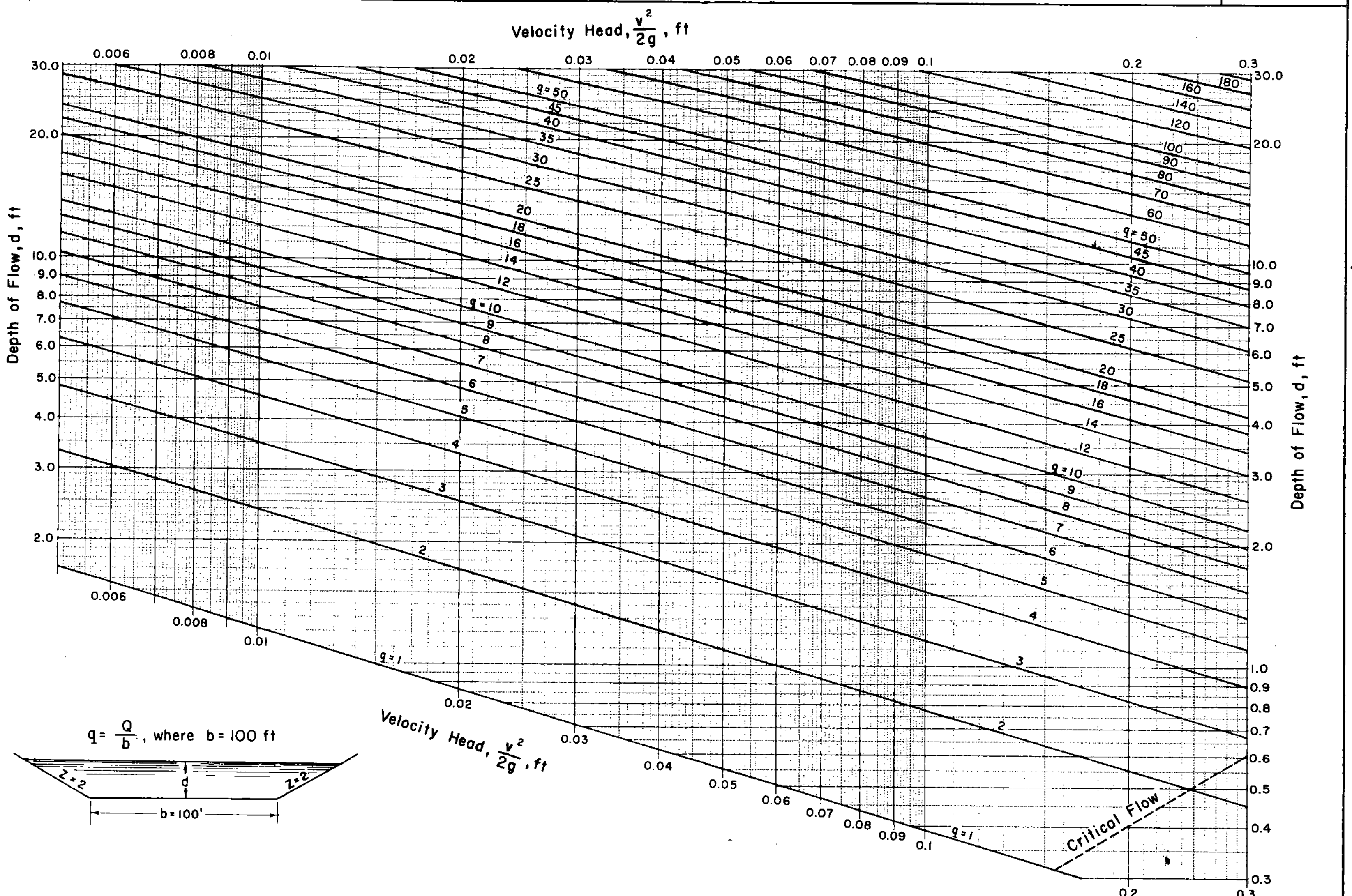
Knowing H_p and Q, plot the rating curve.



REFERENCE

SPILLWAYS: Velocity Head Chart

b = 100 ft
z = 2



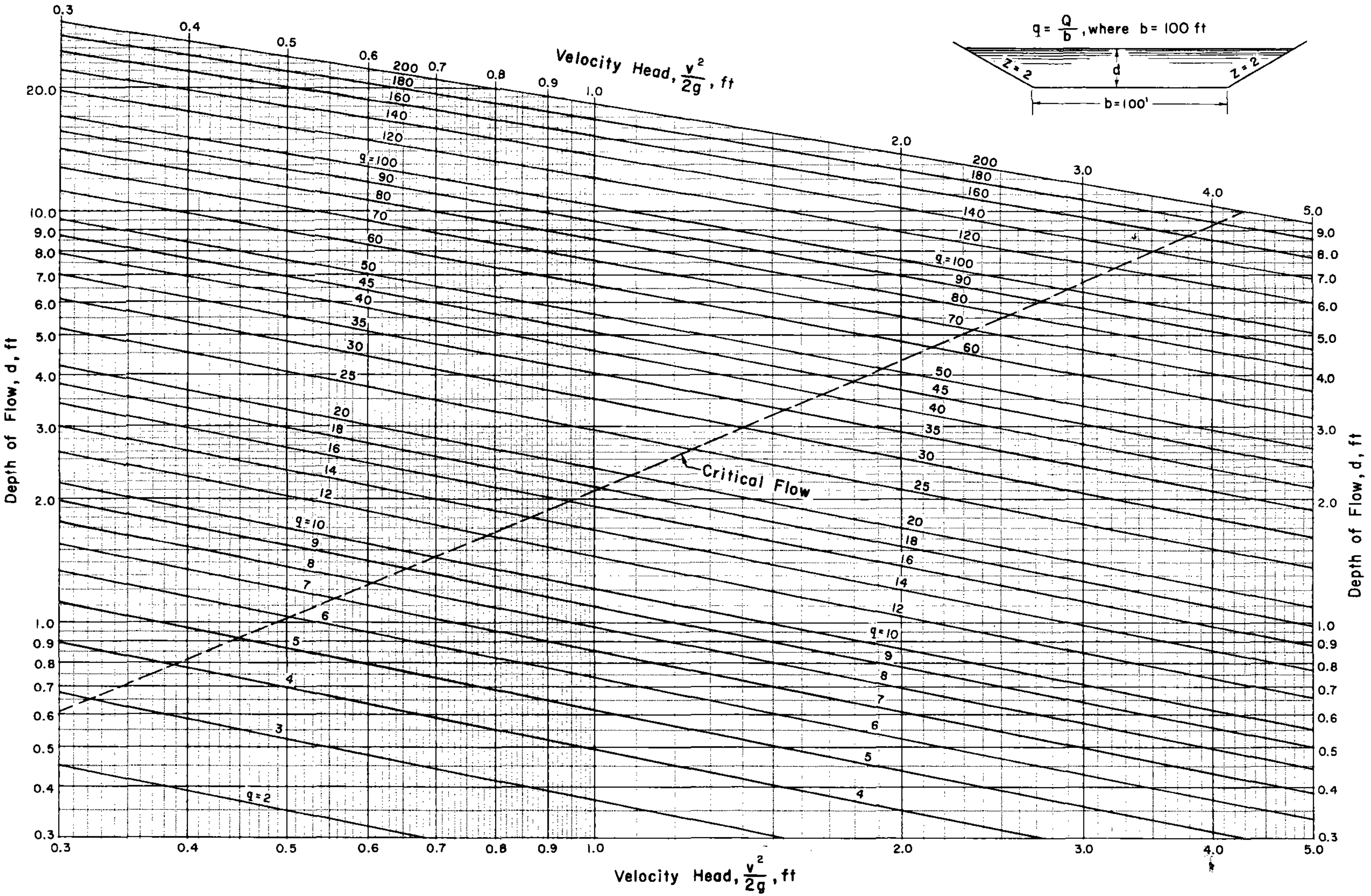
REFERENCE

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

STANDARD DWG. NO.
ES- 159
SHEET 1 OF 2
DATE 2-67

SPILLWAYS: Velocity Head Chart

b = 100 ft
z = 2



REFERENCE

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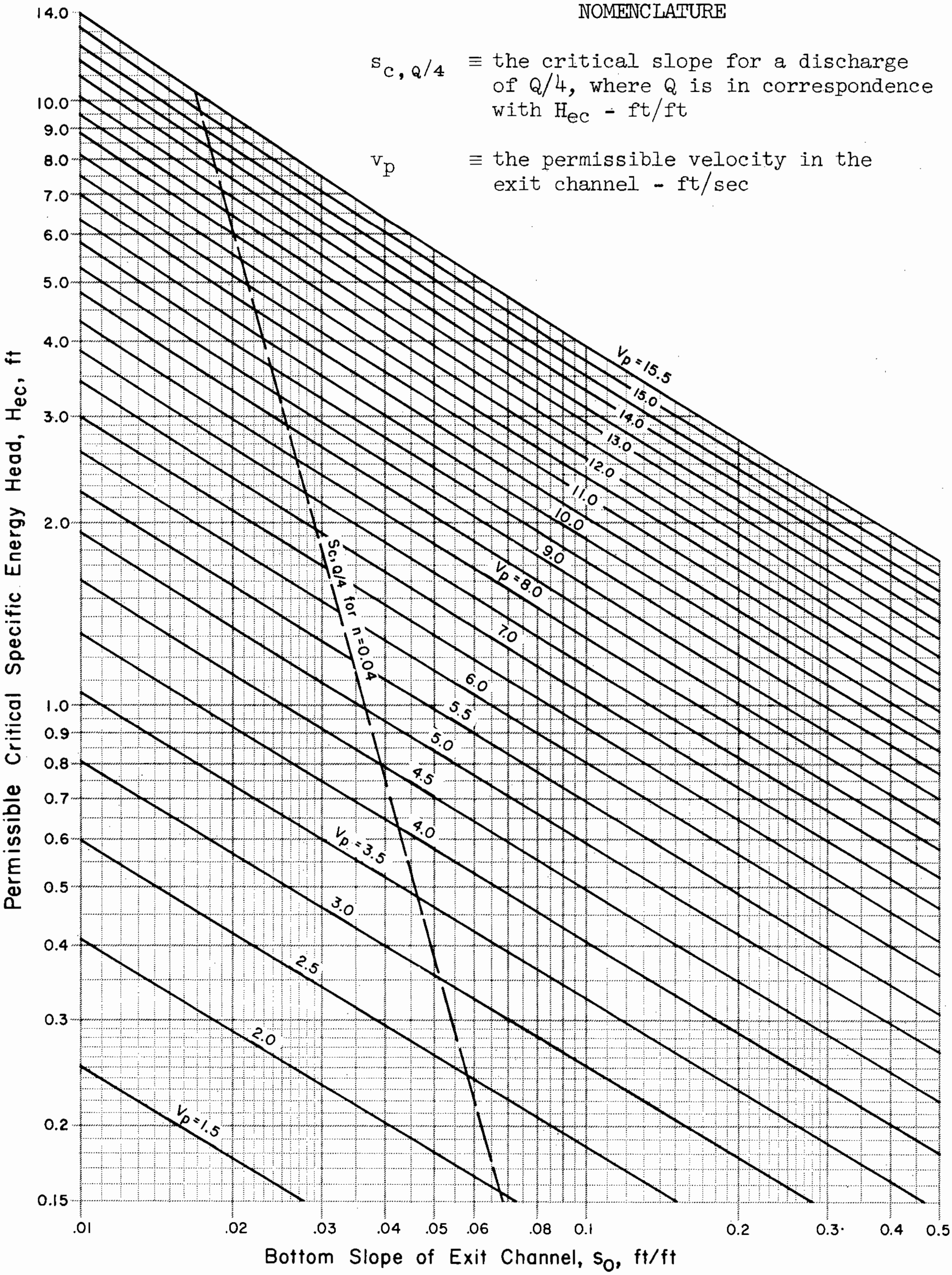
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO. ES- 159
SHEET 2 OF 2
DATE 2-67

SPILLWAYS: Permissible H_{ec} for Various s_o and v_p

b = 100 ft
z = 2
n = 0.04



NOMENCLATURE

$s_{c,Q/4}$ ≡ the critical slope for a discharge of Q/4, where Q is in correspondence with H_{ec} - ft/ft

v_p ≡ the permissible velocity in the exit channel - ft/sec

REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
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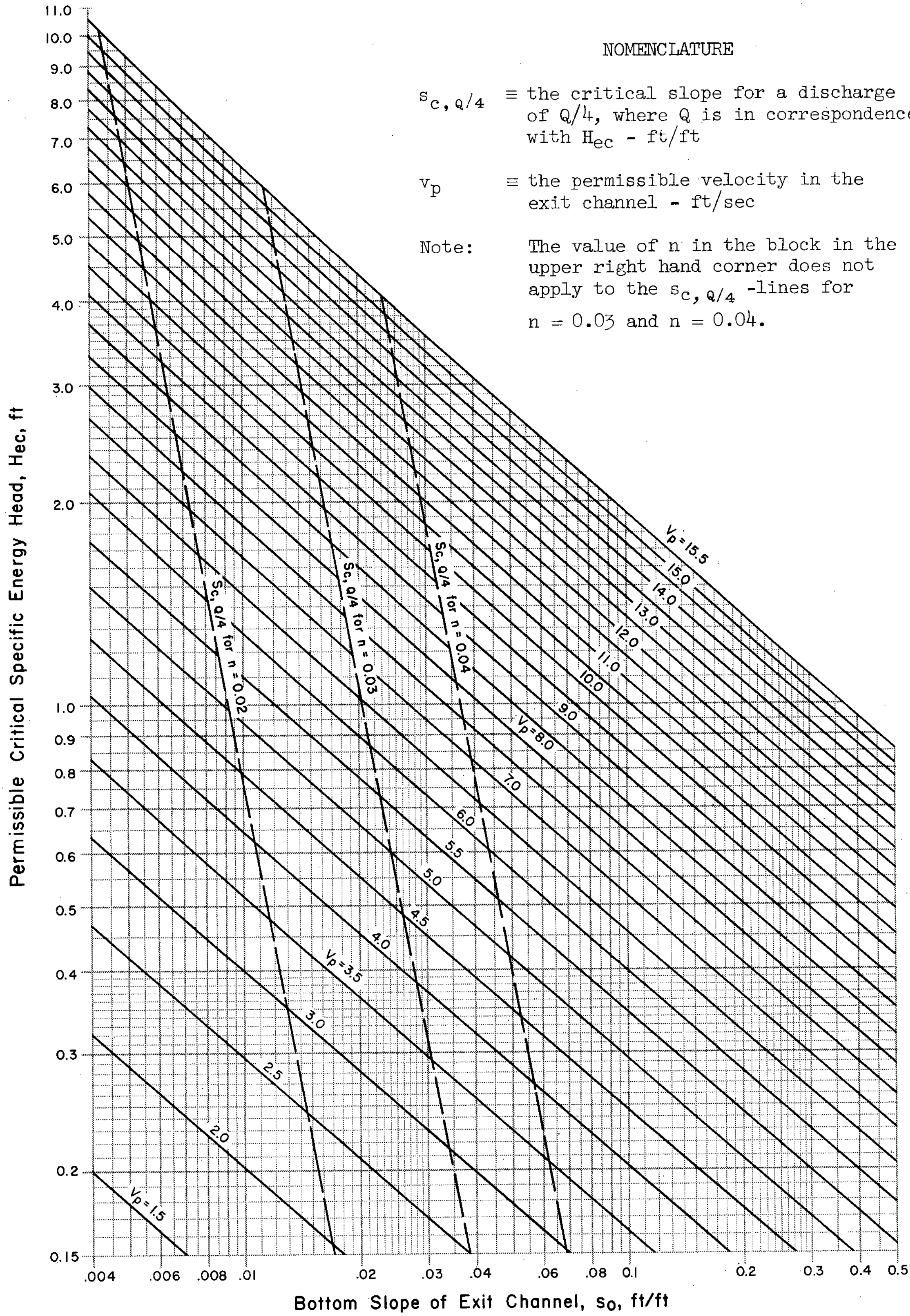
STANDARD DWG. NO.
ES-170
SHEET 1 OF 4
DATE 1-68

SPILLWAYS: Permissible H_{ec} for Various s_o and v_p

b = 100 ft
z = 2
n = 0.02



NOMENCLATURE

$s_{c,\,Q/4}$ ≡ the critical slope for a discharge of Q/4, where Q is in correspondence with H_{ec} - ft/ft

v_p ≡ the permissible velocity in the exit channel - ft/sec

Note: The value of n in the block in the upper right hand corner does not apply to the $s_{c,\,Q/4}$ -lines for n = 0.03 and n = 0.04.

REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
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STANDARD DWG. NO.
ES-170
SHEET 2 OF 4
DATE 1-68

EXAMPLE 1

Given:

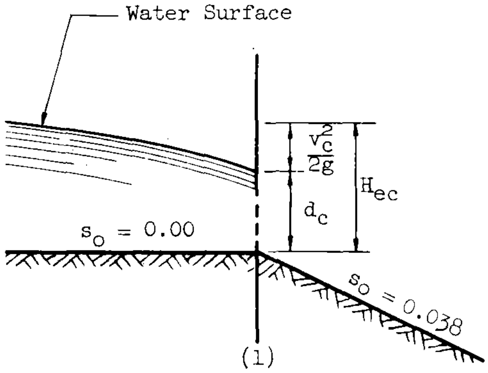
Emergency spillway bottom profile as shown in figure

$z = 2$

$b = 100$ ft

$n = 0.04$

$v_p = 6.5$ ft/sec



Determine:

I. Permissible H_{ec}

II. If the exit channel bottom slope, s_o, is greater than or equal to $s_{c,\,Q/4}$

Solution:

I. Determine permissible H_{ec}

Use ES-170, sheet 1.

For $n = 0.04$, $v_p = 6.5$ ft/sec, and $s_o = 0.038$, read permissible $H_{ec} = 1.5$ ft.

II. Determine if $s_o \geqq s_{c,\,Q/4}$

Use ES-170, sheet 1.

For $H_{ec} = 1.5$ ft, read $s_{c,\,Q/4} = 0.032$.

$s_o > s_{c,\,Q/4}$; therefore, a control section exists at section (1) for discharges in the interval Q/4 to Q.

EXAMPLE 2

Given:

Emergency spillway bottom profile as shown in figure for Example 1 except that the exit channel bottom slope, s_o, is equal to 0.025

$z = 2$

$b = 100$ ft

$v_p = 4.0$ ft/sec

Determine:

I. Permissible H_{ec} when $n = 0.02$

II. If $s_o \geqq s_{c,\,Q/4}$, when the value of n in the exit channel is

A. 0.02

B. 0.03

Solution:

I. Determine permissible H_{ec}
Use ES-170, sheet 2.
For $n = 0.02$, $v_p = 4.0$ ft/sec, and $s_o = 0.025$, read permissible $H_{ec} = 0.41$ ft.

II. Determine if $s_o \geqq s_{c,\,Q/4}$

A. When $n = 0.02$
Use ES-170, sheet 2.
For $n = 0.02$ and $H_{ec} = 0.41$ ft, read
$s_o = 0.0122 = s_{c,\,Q/4}$.

Thus, the exit channel bottom slope, s_o, is greater than $s_{c,\,Q/4}$.

B. When $n = 0.03$
Use ES-170, sheet 2.
For $n = 0.03$ and $H_{ec} = 0.41$ ft, read
$s_o = 0.0275 = s_{c,\,Q/4}$.

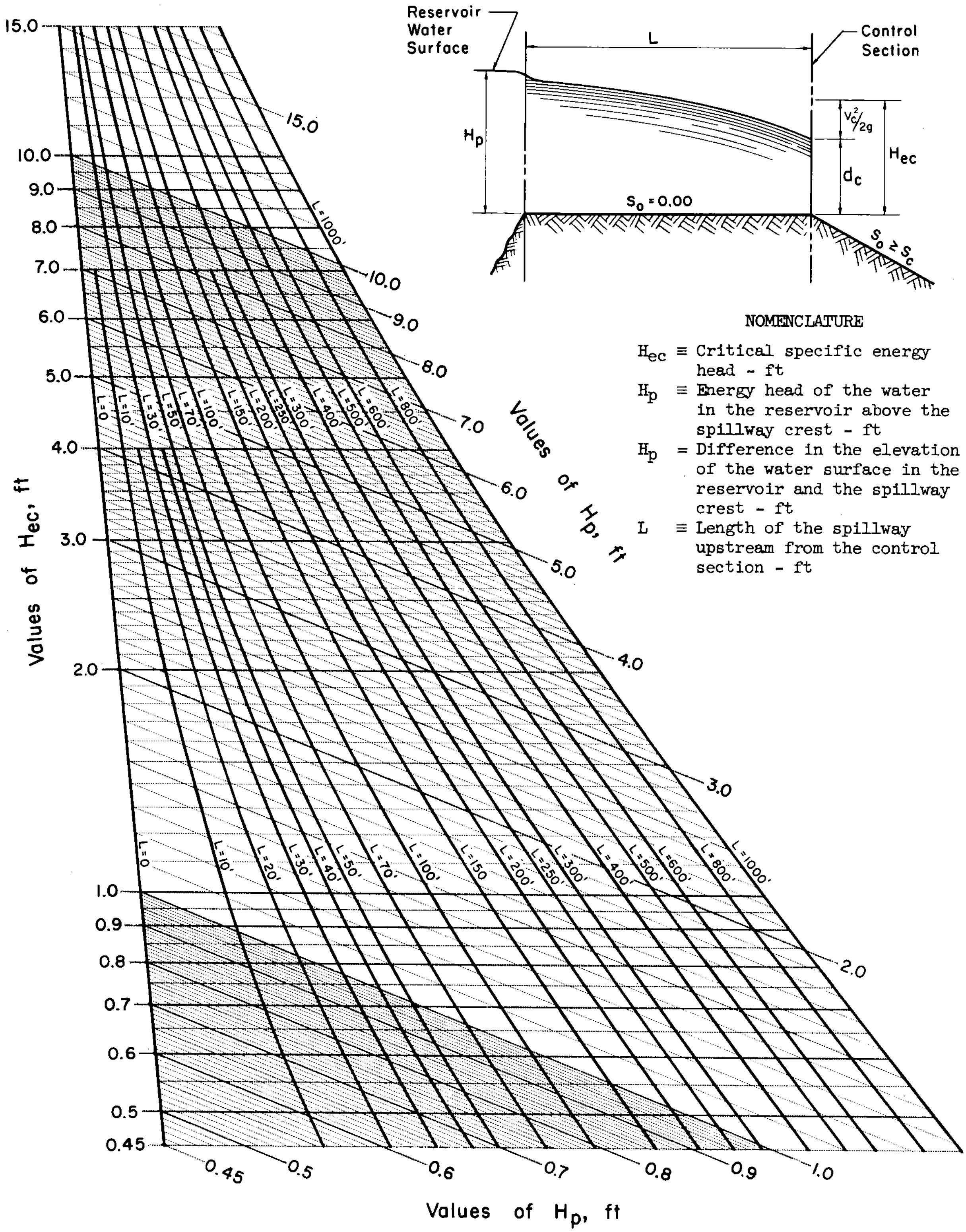
Thus, the exit channel bottom slope, s_o, is smaller than $s_{c,\,Q/4}$.

Therefore, if the value of Manning's n is altered, say by vegetative growth, from a value of 0.02 to 0.03, Section (1) is no longer a control section for all discharges in the interval Q/4 to Q.

SPILLWAYS: H_{ec} vs H_p for Various Lengths, L

b = 100 ft
z = 2
n = 0.04

Case I



NOMENCLATURE

H_{ec} ≡ Critical specific energy head - ft

H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft

H_p = Difference in the elevation of the water surface in the reservoir and the spillway crest - ft

L ≡ Length of the spillway upstream from the control section - ft

REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
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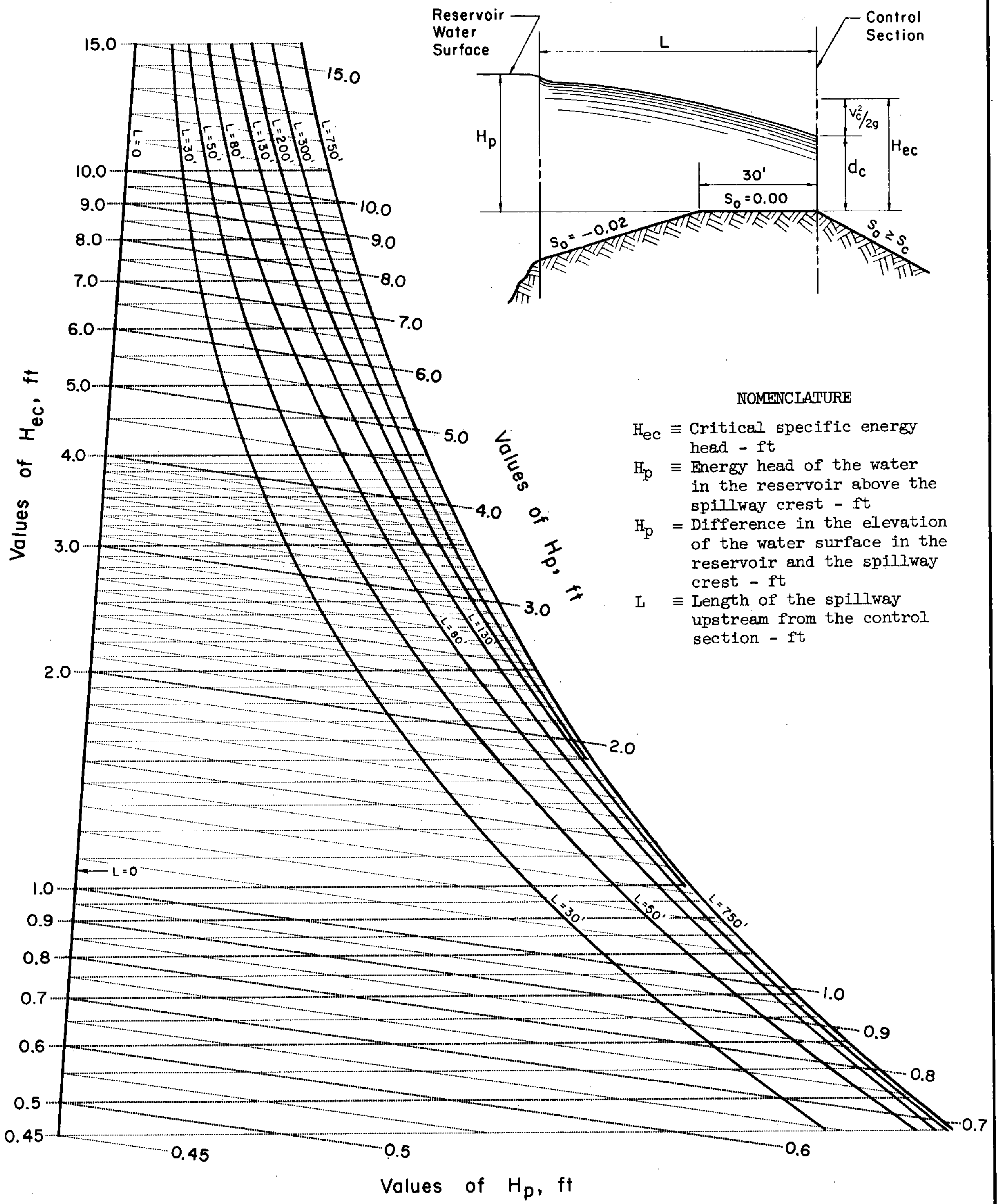
SPILLWAYS: H_{ec} vs H_p for Various Lengths, L | b = 100 ft, z = 2, n = 0.04 | Case 2



NOMENCLATURE

H_{ec} ≡ Critical specific energy head - ft

H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft

H_p = Difference in the elevation of the water surface in the reservoir and the spillway crest - ft

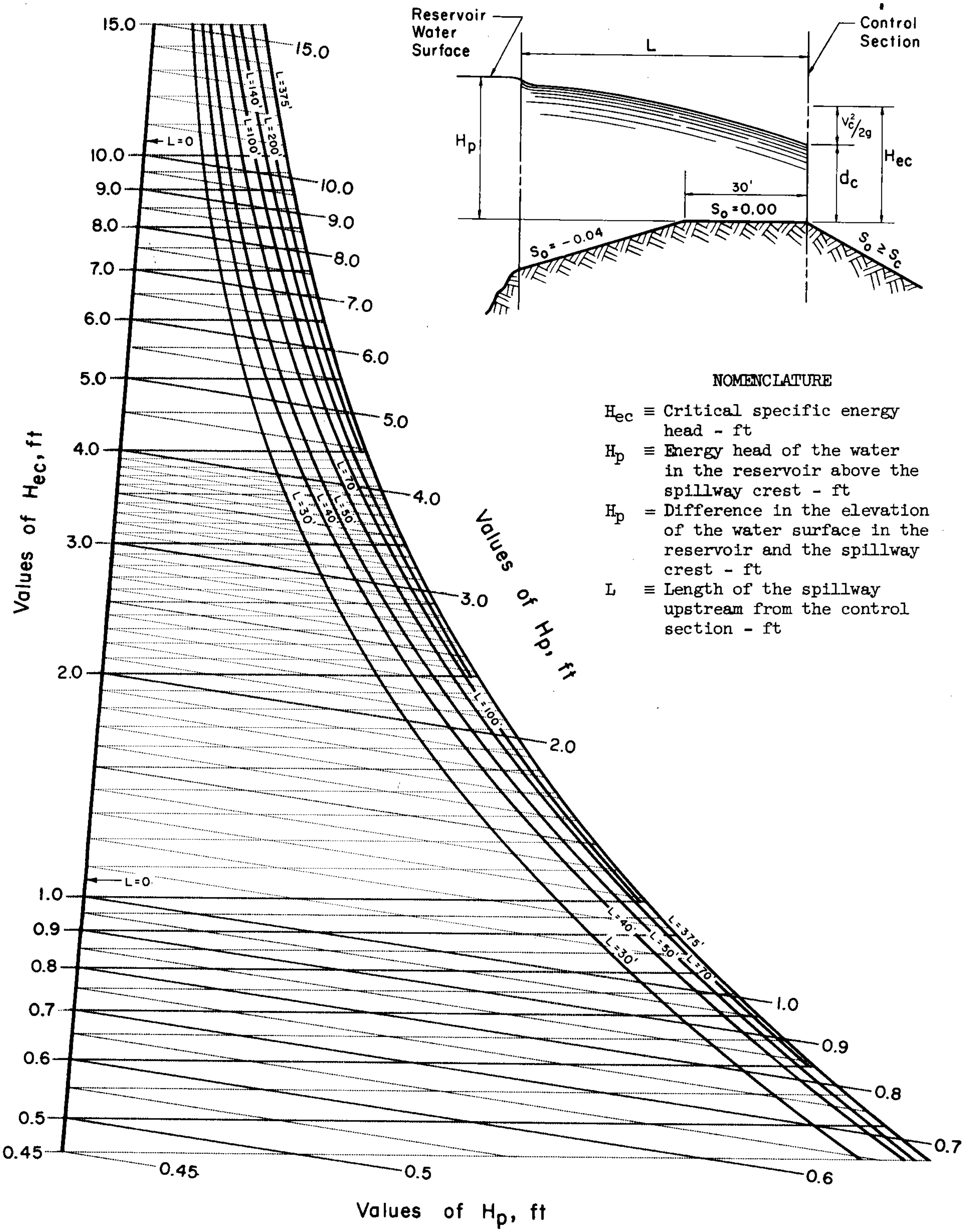
L ≡ Length of the spillway upstream from the control section - ft

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 171 SHEET 2 OF 10 DATE 2-67

SPILLWAYS: H_{ec} vs H_p for Various Lengths, L

b = 100 ft
z = 2
n = 0.04

Case 3



NOMENCLATURE

H_{ec} ≡ Critical specific energy head - ft

H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft

H_p = Difference in the elevation of the water surface in the reservoir and the spillway crest - ft

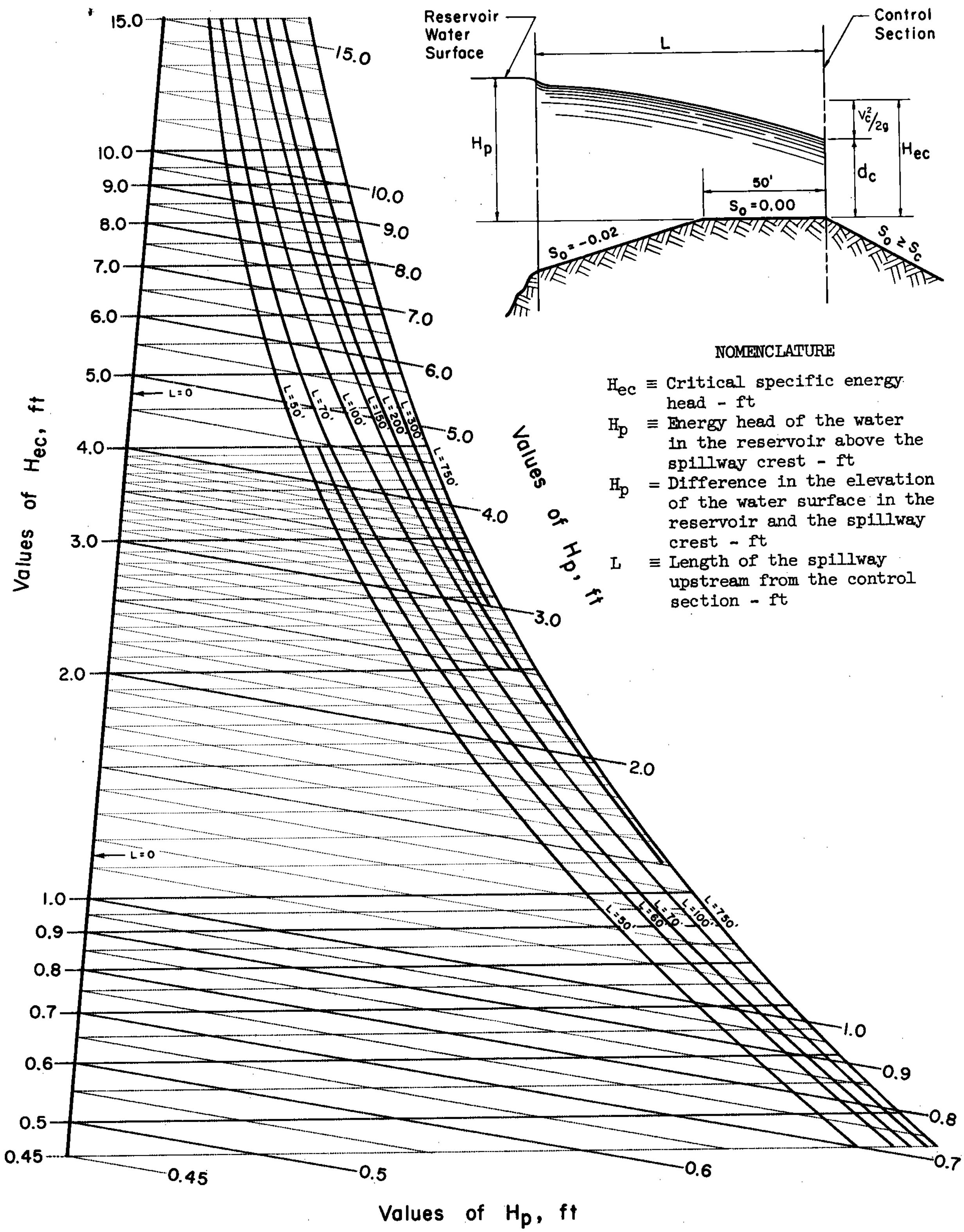
L ≡ Length of the spillway upstream from the control section - ft

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 171 SHEET 3 OF 10 DATE 2-67

SPILLWAYS: H_{ec} vs H_p for Various Lengths, L

b = 100 ft
z = 2
n = 0.04

Case 4



NOMENCLATURE

H_{ec} ≡ Critical specific energy head - ft

H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft

H_p ≡ Difference in the elevation of the water surface in the reservoir and the spillway crest - ft

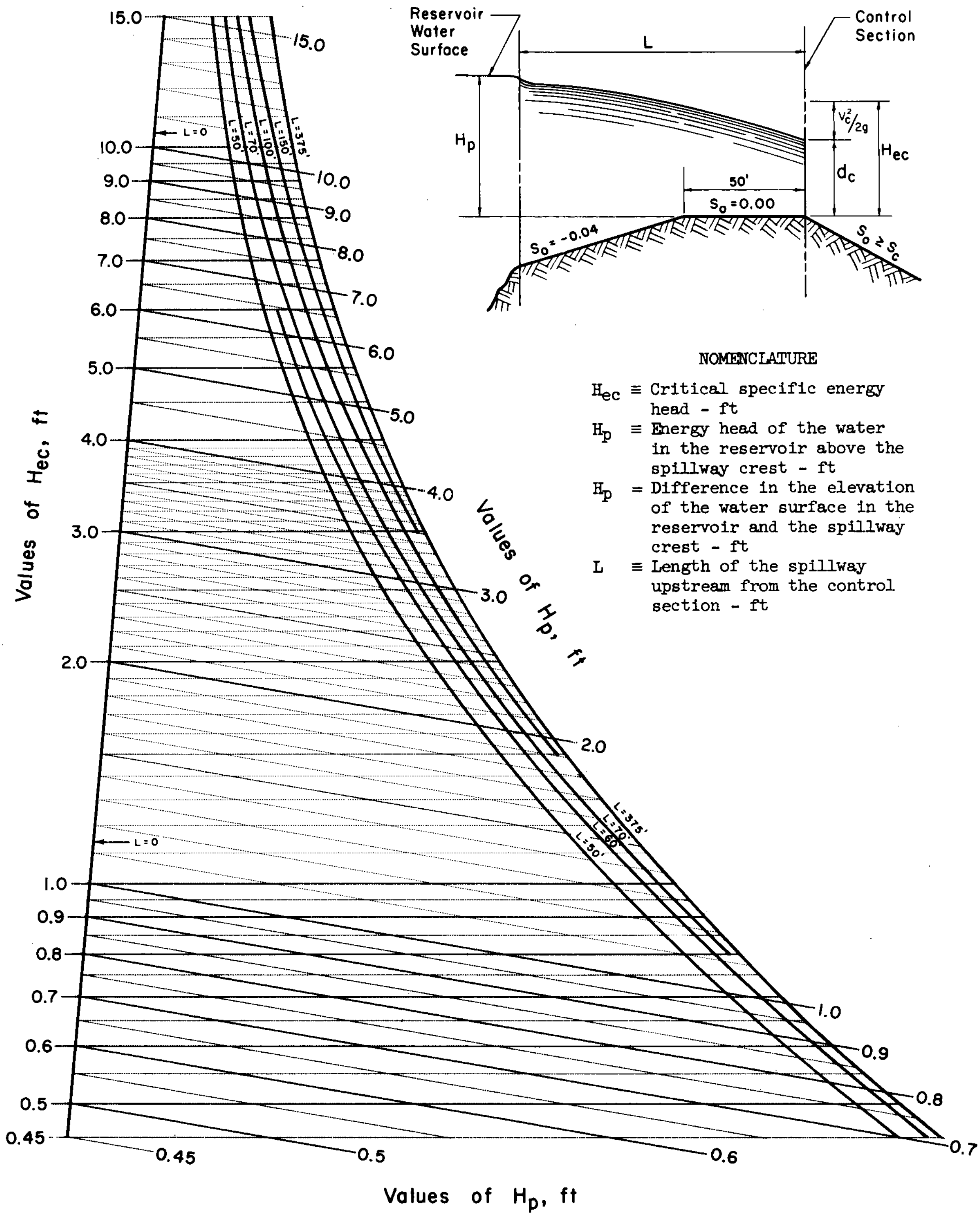
L ≡ Length of the spillway upstream from the control section - ft

REFERENCE

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

STANDARD DWG. NO.
ES- 171
SHEET 4 OF 10
DATE 2-67

SPILLWAYS: H_{ec} vs H_p for Various Lengths, L — b=100 ft, z=2, n=0.04 — Case 5



NOMENCLATURE

H_{ec} ≡ Critical specific energy head - ft

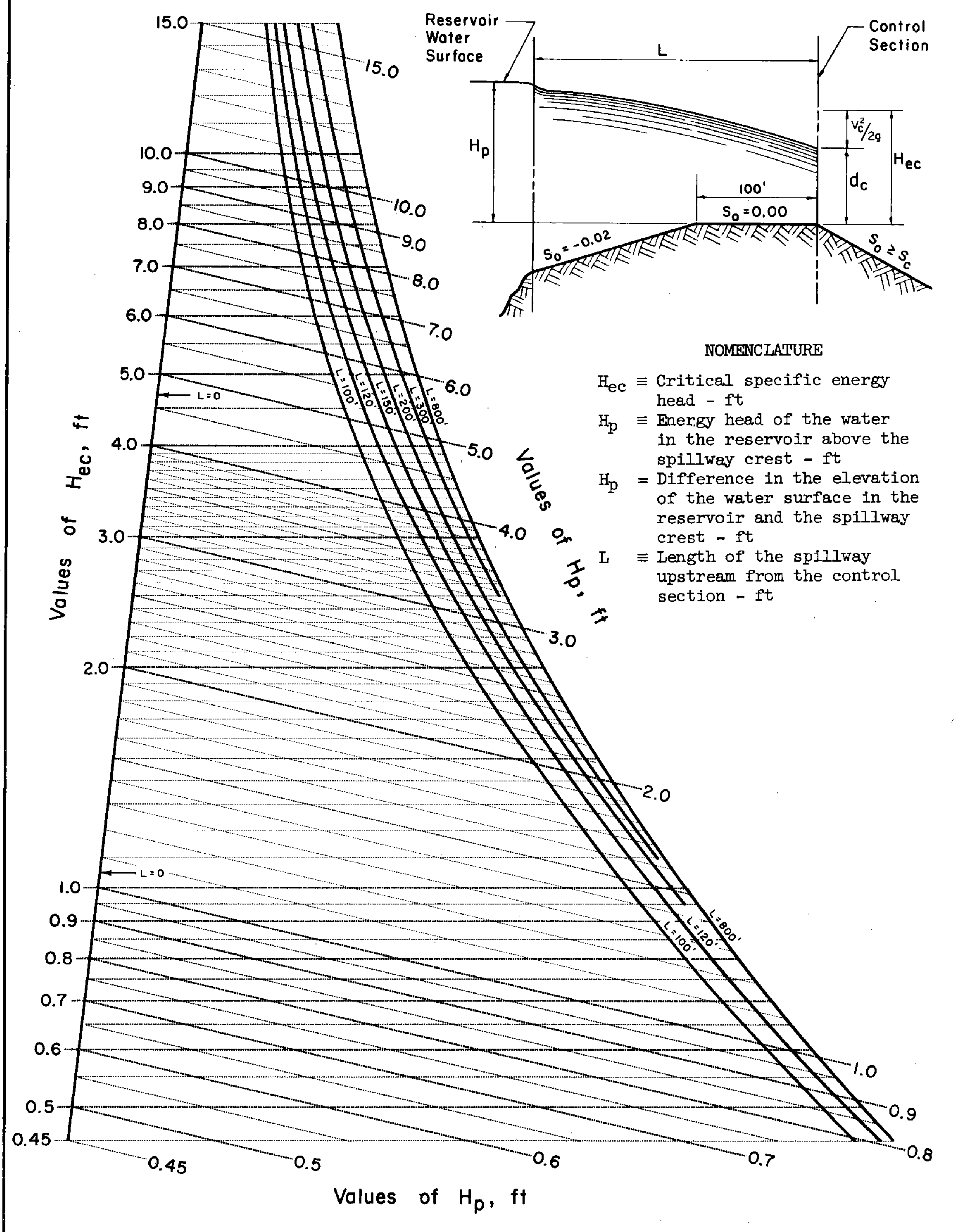
H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft

H_p' = Difference in the elevation of the water surface in the reservoir and the spillway crest - ft

L ≡ Length of the spillway upstream from the control section - ft

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 171 SHEET 5 OF 10 DATE 2-67

SPILLWAYS: H_{ec} vs H_p for Various Lengths, L | b = 100 ft, z = 2, n = 0.04 | Case 6



NOMENCLATURE

H_{ec} ≡ Critical specific energy head - ft

H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft

H_p = Difference in the elevation of the water surface in the reservoir and the spillway crest - ft

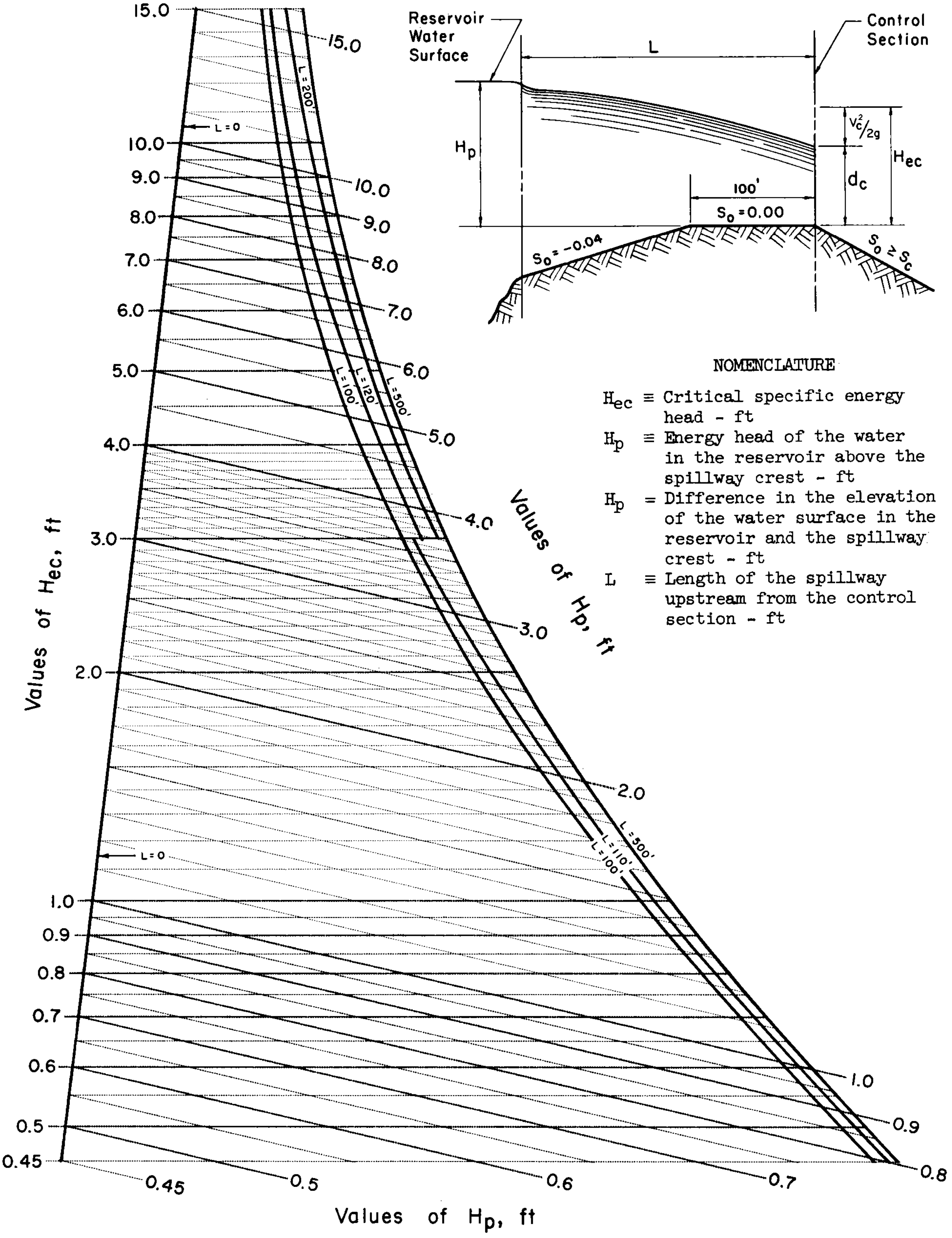
L ≡ Length of the spillway upstream from the control section - ft

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 171 SHEET 6 OF 10 DATE 2-67

SPILLWAYS: H_{ec} vs H_p for Various Lengths, L

b = 100 ft
z = 2
n = 0.04

Case 7



NOMENCLATURE

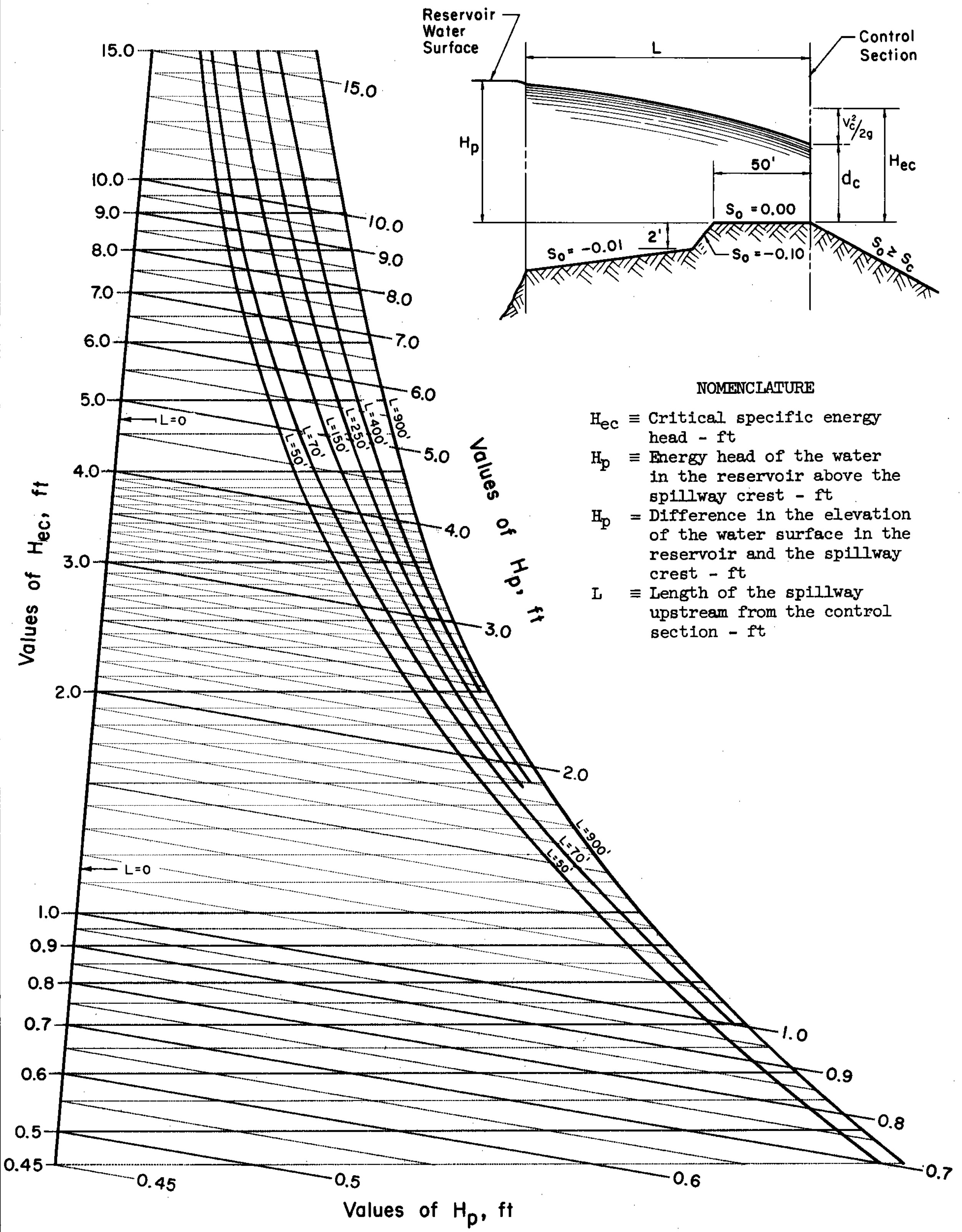
- H_{ec} ≡ Critical specific energy head - ft
- H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft
- H_p = Difference in the elevation of the water surface in the reservoir and the spillway crest - ft
- L ≡ Length of the spillway upstream from the control section - ft

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 171 SHEET 7 OF 10 DATE 2-67

SPILLWAYS: H_{ec} vs H_p for Various Lengths, L

b = 100 ft
z = 2
n = 0.04

Case 8



NOMENCLATURE

H_{ec} ≡ Critical specific energy head - ft

H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft

H_p = Difference in the elevation of the water surface in the reservoir and the spillway crest - ft

L ≡ Length of the spillway upstream from the control section - ft

REFERENCE

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

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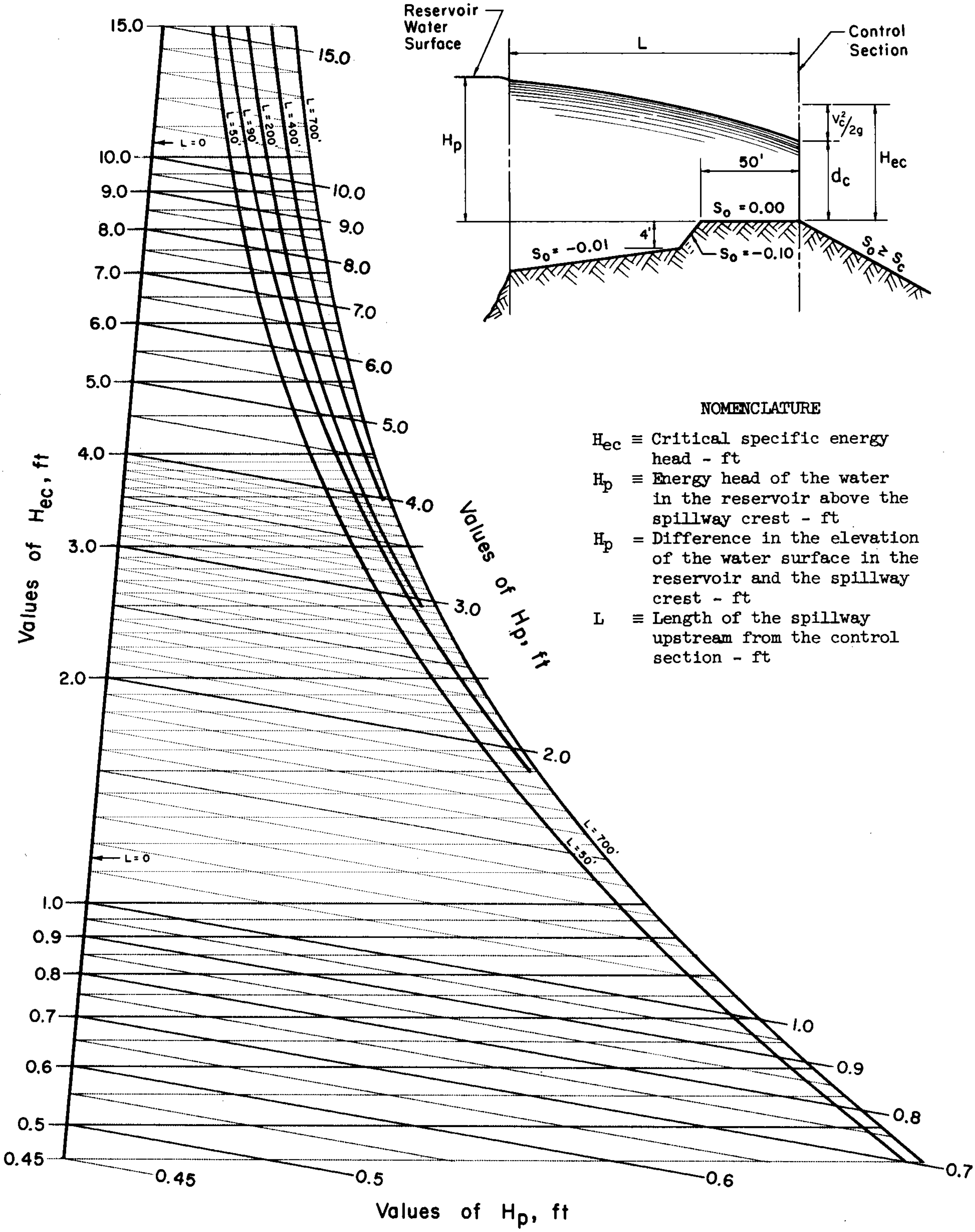
ES- 171
SHEET 8 OF 10
DATE 2-67

SPILLWAYS: H_{ec} vs H_p for Various Lengths, L

b = 100 ft
z = 2
n = 0.04

Case 9



NOMENCLATURE

H_{ec} ≡ Critical specific energy head - ft

H_p ≡ Energy head of the water in the reservoir above the spillway crest - ft

H_p = Difference in the elevation of the water surface in the reservoir and the spillway crest - ft

L ≡ Length of the spillway upstream from the control section - ft

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 171 SHEET 9 OF 10 DATE 2-67

EXAMPLE

Given:

Emergency spillway bottom profile as shown in figure

b = 100 ft

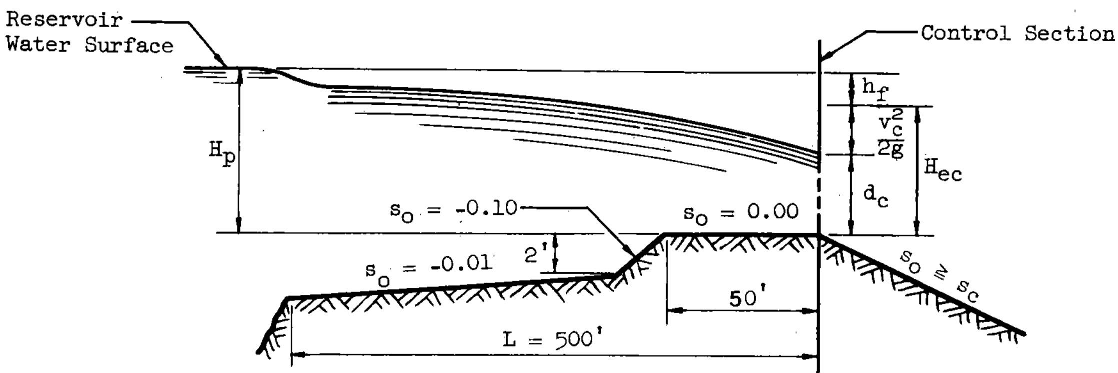
z = 2

n = 0.04

H_{ec} = 3.1 ft

Determine:

1. H_p
2. Friction head loss, h_f, in the distance, L



Case 8

Solution:

1. Determine H_p
   Use ES-171, sheet 8.
   For H_{ec} = 3.1 ft and L = 500 ft, read H_p = 3.66 ft.
2. Compute h_f

   $h_f = H_p - H_{ec} = 3.66 - 3.10 = 0.56$ ft

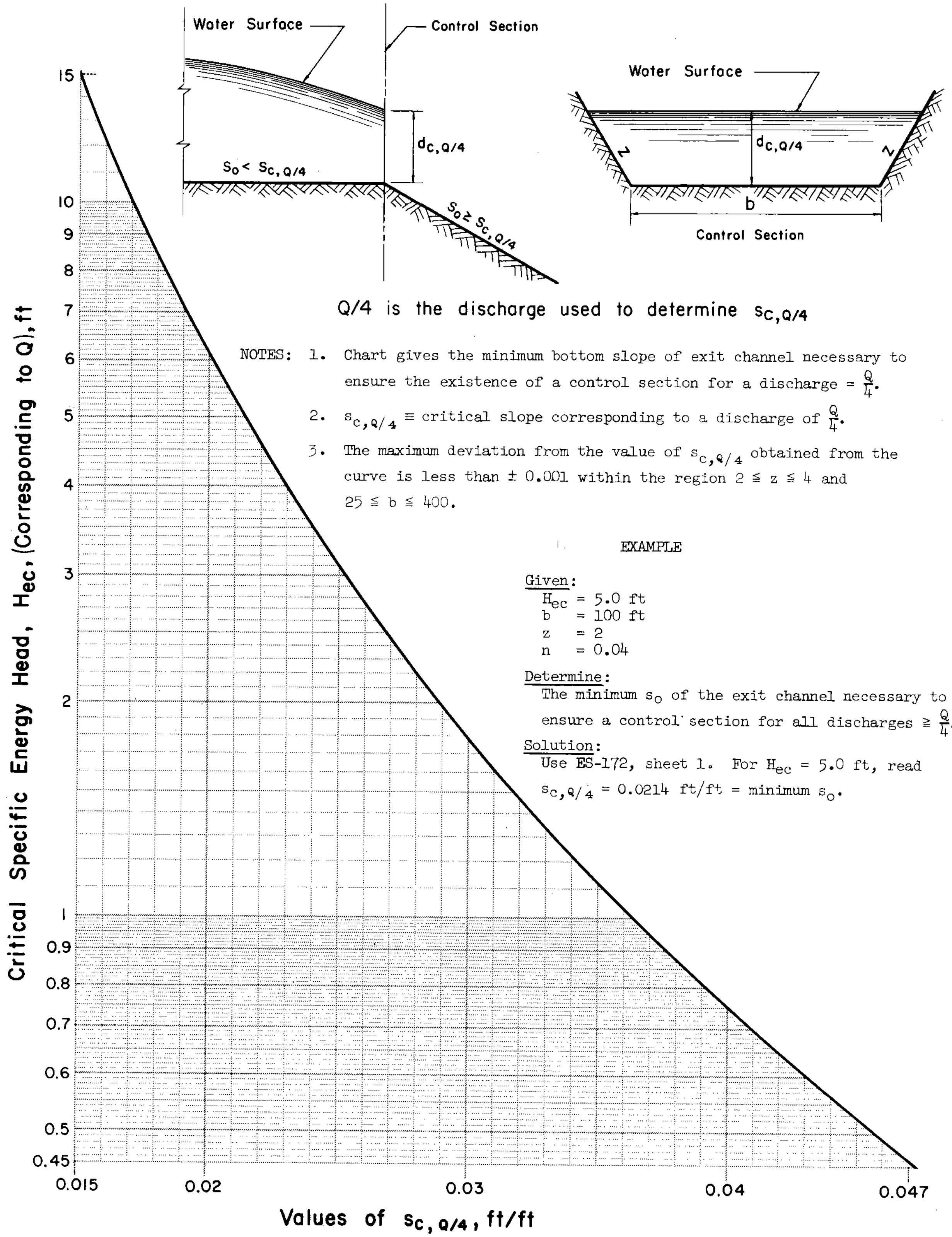
NOTE:

The H_p corresponding to an H_{ec} remains nearly constant regardless of the bottom width (where 25' ≦ b ≦ 400') and side slope of the emergency spillway.

See ES-176 for the effect of n, z, or b on H_p.

SPILLWAYS: Critical Slope Corresponding to Q/4

b = 100'
z = 2
n = 0.04



Q/4 is the discharge used to determine $s_{c,Q/4}$

NOTES:
1. Chart gives the minimum bottom slope of exit channel necessary to ensure the existence of a control section for a discharge = $\frac{Q}{4}$.
2. $s_{c,Q/4} \equiv$ critical slope corresponding to a discharge of $\frac{Q}{4}$.
3. The maximum deviation from the value of $s_{c,Q/4}$ obtained from the curve is less than ± 0.001 within the region $2 \leq z \leq 4$ and $25 \leq b \leq 400$.

EXAMPLE

Given:
H_{ec} = 5.0 ft
b = 100 ft
z = 2
n = 0.04

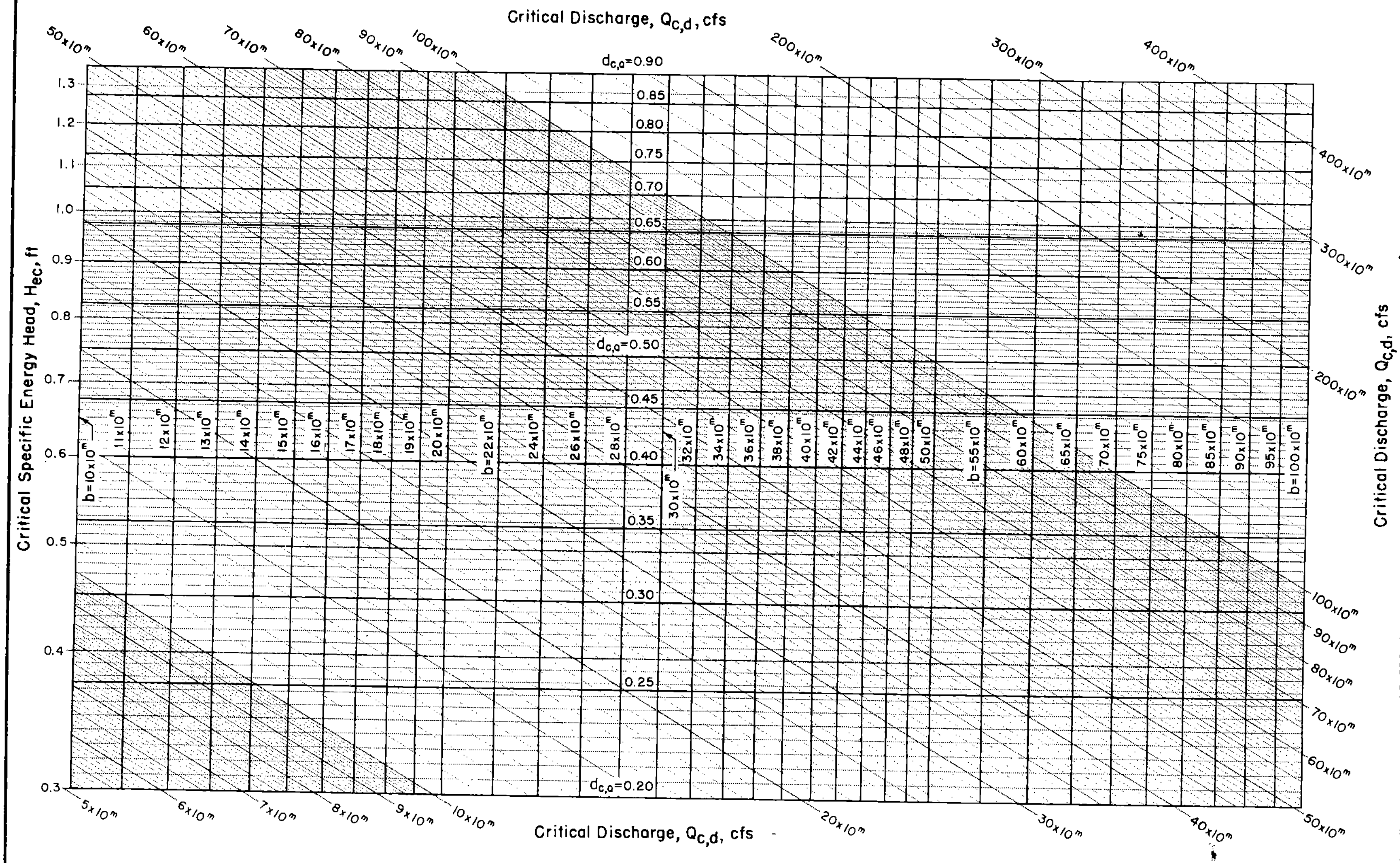
Determine:
The minimum s_o of the exit channel necessary to ensure a control section for all discharges $\geq \frac{Q}{4}$.

Solution:
Use ES-172, sheet 1. For H_{ec} = 5.0 ft, read $s_{c,Q/4}$ = 0.0214 ft/ft = minimum s_o.

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 172 SHEET 1 OF 1 DATE 3-67

HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z=0



REFERENCE

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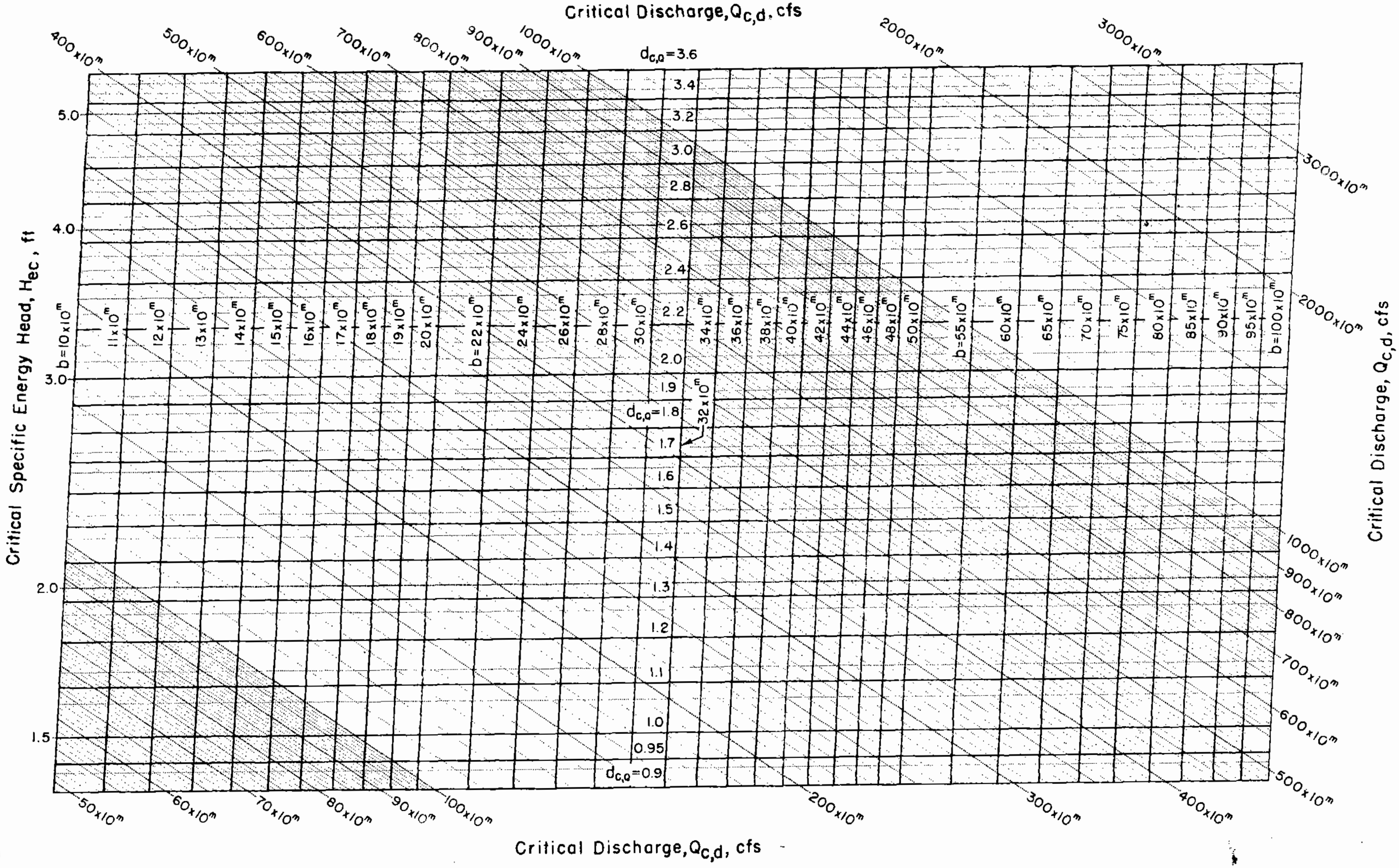
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION · DESIGN UNIT

STANDARD DWG. NO.
ES- 173
SHEET 1 OF 6
DATE 2-67

HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z=0



REFERENCE

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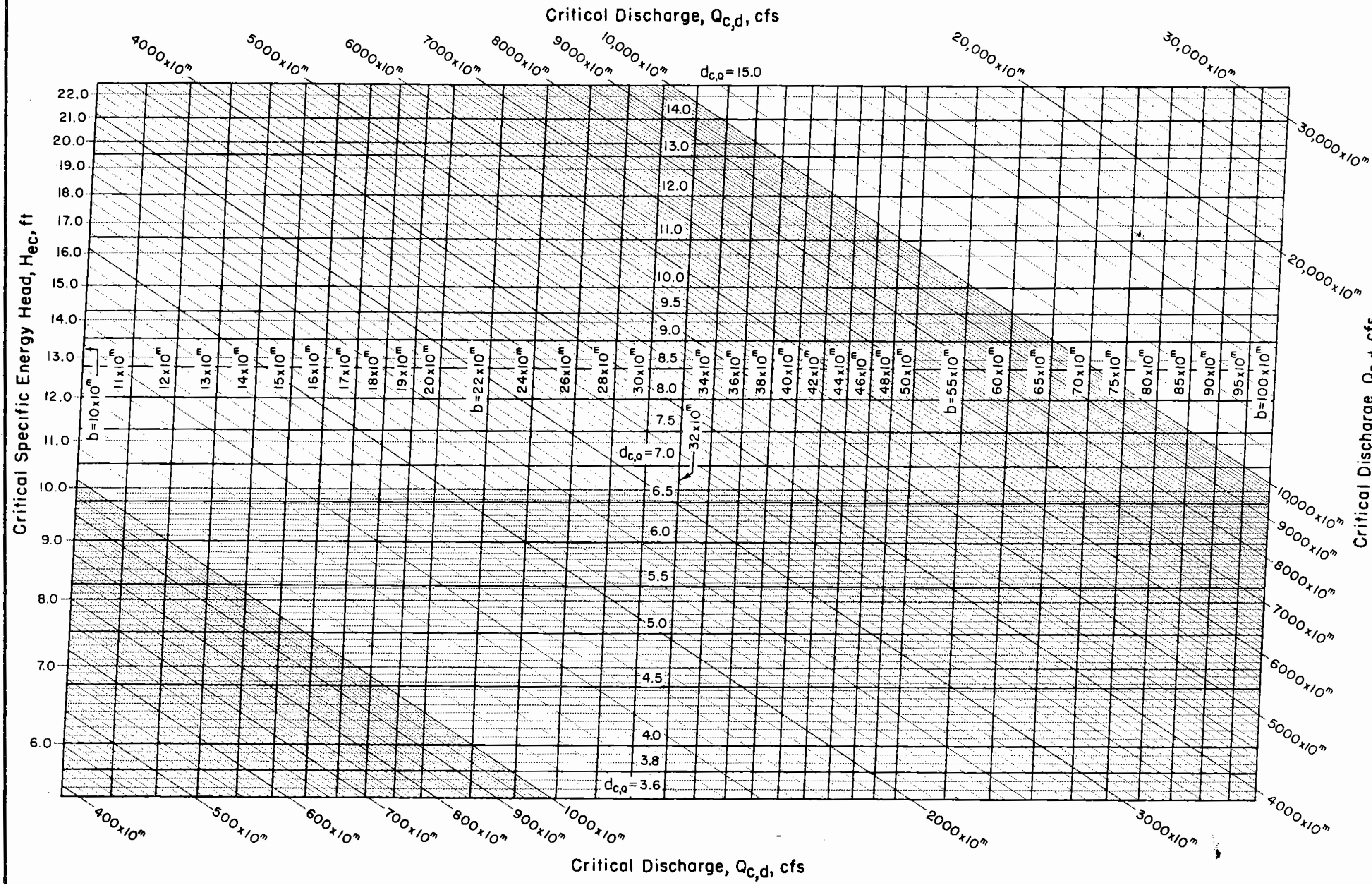
ENGINEERING DIVISION · DESIGN UNIT

STANDARD DWG. NO. ES- 173
SHEET 2 OF 6
DATE 2-67

HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z=0



REFERENCE

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SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES- 173
SHEET 3 OF 6
DATE 2-67

HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b and Side Slopes, z

An approximate relation of critical discharges for a trapezoidal channel and for a channel of bottom width = 100 ft and side slope = 0 having the same H_{ec} as the trapezoidal channel is

$$\frac{Q_c}{Q_c'} = \frac{1.5b + zH_{ec}}{150} \qquad \text{Equation 1}$$

where: Q_c' ≡ the critical discharge for a channel of bottom width = 100 ft and side slope = 0.

H_{ec} ≡ the critical specific energy head corresponding to the critical discharges, Q_c' and Q_c.

A. When Q_c is to be determined,

Q_c ≡ the first approximation of the critical discharge, as obtained from Equation 1, for a channel of bottom width, b, and side slope, z.

B. When b is to be determined,

b ≡ the first approximation of the bottom width, as obtained from Equation 1, associated with a critical discharge, Q_c, and side slope, z.

When a second and closer approximation of critical discharge is required, the following equation may be used.

$$Q_c'' = \frac{Q_c}{1 - \frac{\%\ \text{Error}}{100}} \qquad \text{Equation 2}$$

where: Q_c'' ≡ the second and closer approximation of the critical discharge for a channel of bottom width, b, and side slope, z.

When a second and closer approximation of bottom width is required, the following equation may be used.

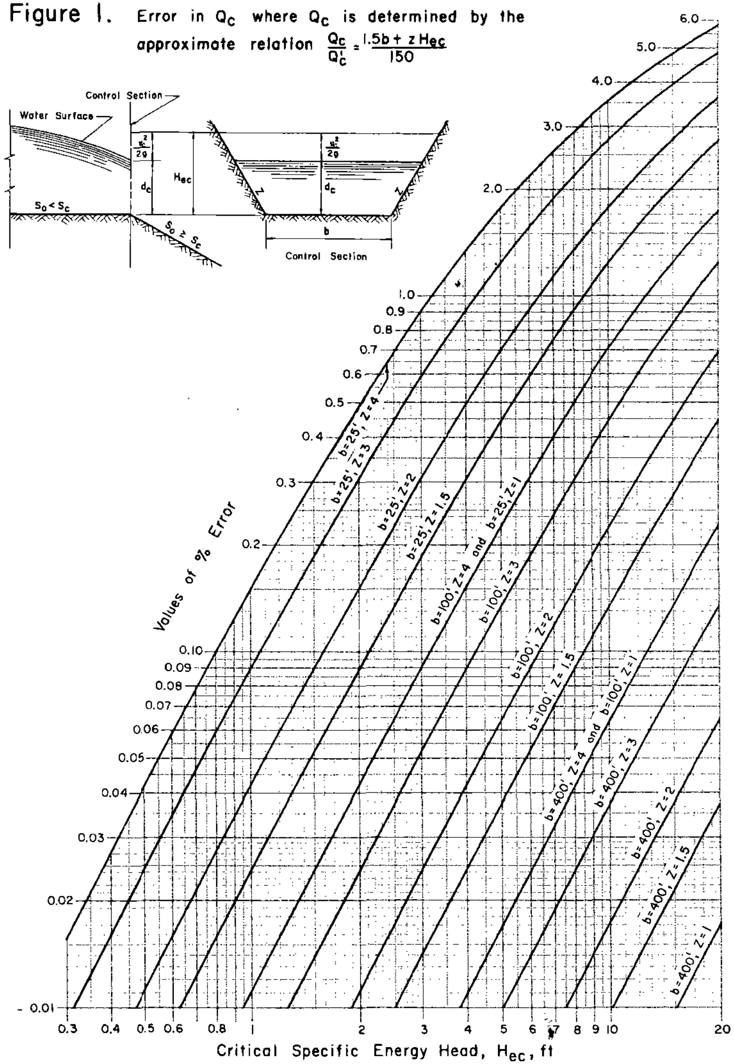
$$b'' = \frac{b}{1 - \frac{\%\ \text{Error}}{100}} \qquad \text{Equation 3}$$

where: b'' ≡ the second and closer approximation of the bottom width associated with a critical discharge, Q_c, and side slope, z.

The value of % Error may be obtained from Figure 1 or from the approximate relation

$$\%\ \text{Error} = 2.27\left[\frac{zH_{ec}}{b}\right]^{1.1 + \left[\text{Log}_{10}\left(\frac{b}{zH_{ec}}\right)\right]\left[0.59 - 0.136\ \text{Log}_{10}\left(\frac{b}{zH_{ec}}\right)\right]} \qquad \text{Equation 4}$$

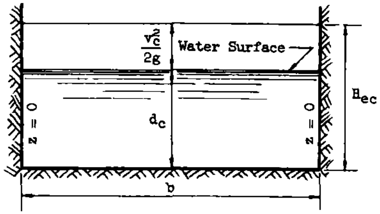
Figure 1. Error in Q_c where Q_c is determined by the approximate relation $\frac{Q_c}{Q_c'} = \frac{1.5b + zH_{ec}}{150}$



REFERENCE

EXAMPLE 1

Given:
H_{ec} = 8.0 ft
z = 0



Control Section

Determine:
I. Critical depth, d_c
II. Bottom width, b, where $Q_{c,d}$ = 200, 2,000, and 20,000 cfs

Solution:
Use ES-173, sheet 3.
I. Determine d_c
For H_{ec} = 8.0 ft, read d_c = 5.3 ft.

II. Determine b
A. Where $Q_{c,d} = 200 = 2{,}000 \times 10^m$; m = -1
For H_{ec} = 8.0 ft and $Q_{c,d}$ = 200, read
$b = 28.5 \times 10^m = 28.5 \times 10^{-1} = 2.85$ ft.

B. Where $Q_{c,d} = 2{,}000 = 2{,}000 \times 10^m$; m = 0
Then $b = 28.5 \times 10^m = 28.5 \times 10^0 = 28.5$ ft

C. Where $Q_{c,d} = 20{,}000 = 2{,}000 \times 10^m$; m = 1
Then $b = 28.5 \times 10^m = 28.5 \times 10^1 = 285$ ft

EXAMPLE 2

Given:
A trapezoidal channel
z = 4
H_{ec} = 4.5 ft
Q_c = 4400 cfs

Determine:
I. The first approximation of the bottom width, b, by the use of Equation 1.
II. The second approximation of the bottom width, b", by the use of Figure 1.

Solution:
I. Determine b
A. Use ES-173, sheet 2.
For H_{ec} = 4.5 ft and b = 100 ft, read Q_c' = 2950 cfs.

B. From Equation 1,

$$b = \frac{100(Q_c)}{Q_c'} - \frac{zH_{ec}}{1.5}$$

$$b = \frac{100(4400)}{2950} - \frac{(4)(4.5)}{1.5}$$

$$b = 149 - 12 = 137 \text{ ft}$$

II. Determine b"
A. Use Figure 1.
For H_{ec} = 4.5 ft, b = 137 ft, and z = 4, estimate % Error = 0.1.

B. Then substituting into Equation 3

$$b'' = \frac{b}{1 - \frac{\%\ \text{Error}}{100}} = \frac{137}{1 - \frac{0.1}{100}} = 137 \text{ ft}$$

REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
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ES- 173

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EXAMPLE 3

Given:
A trapezoidal channel
b = 50 ft
z = 2.5
H_{ec} = 7.5 ft

Determine:
I. The first approximation of the corresponding critical discharge, Q_c, by the use of Equation 1.
II. The second approximation of the corresponding critical discharge, Q_c'',
A. By the use of Figure 1
B. By the use of Equation 4.

Solution:
I. Determine Q_c
Use ES-173, sheet 3.
For H_{ec} = 7.5 ft and b = 100 ft, read Q_c' = 6340 cfs.

From Equation 1

$$Q_c = \left[\frac{1.5b + zH_{ec}}{150}\right] Q_c'$$

Substituting

$$Q_c = \left[\frac{1.5(50) + 2.5(7.5)}{150}\right] 6340 = 3963 \text{ cfs}$$

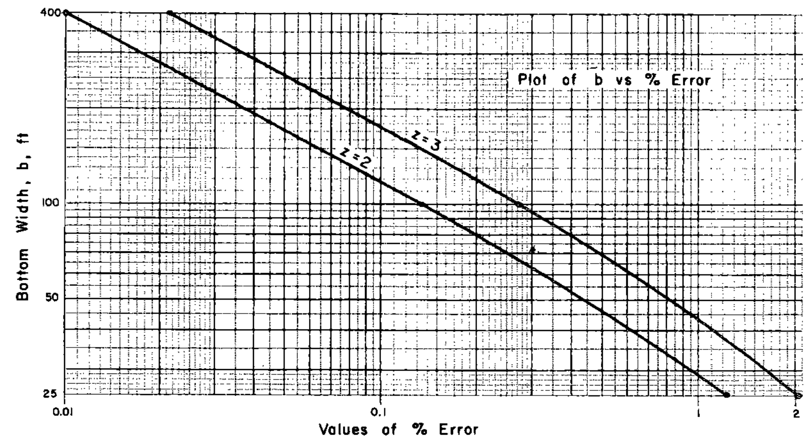
II. Determine Q_c''
A. By use of Figure 1
1. Use Figure 1 to prepare a plot of b vs % Error
For H_{ec} = 7.5 ft,

b = 25 ft, and z = 2 and 3;
b = 100 ft, and z = 2 and 3; and
b = 400 ft, and z = 2 and 3,

read % Error values.

Plot b vs % Error with z = 2 and z = 3 lines.
2. Use plot of b vs % Error to obtain % Error for z = 2.5 and b = 50 ft.
For b = 50 ft and z = 2, read % Error = 0.44.
For b = 50 ft and z = 3, read % Error = 0.80.
Then for b = 50 ft and z = 2.5, % Error = $\frac{0.44 + 0.82}{2}$ = 0.63.
3. Then substituting into Equation 2

$$Q_c'' = \frac{Q_c}{1 - \frac{\% \text{ Error}}{100}} = \frac{3963}{1 - \frac{0.63}{100}} = 3988 \text{ cfs}$$



B. By use of Equation 4
1. Substituting into Equation 4

$$\% \text{ Error} = 2.27 \left[\frac{zH_{ec}}{b}\right]^{1.1 + \left[\text{Log}_{10}\left(\frac{b}{zH_{ec}}\right)\right]\left[0.59 - 0.136 \text{ Log}_{10}\left(\frac{b}{zH_{ec}}\right)\right]}$$

$$= 2.27 \left[\frac{2.5(7.5)}{50}\right]^{1.1 + \left[\text{Log}_{10}\left(\frac{50}{2.5(7.5)}\right)\right]\left[0.59 - 0.136 \text{ Log}_{10}\left(\frac{50}{2.5(7.5)}\right)\right]}$$

$$= 2.27\left[0.375\right]^{1.1 + \left[\text{Log}_{10} 2.667\right]\left[0.59 - 0.136 \text{ Log}_{10} 2.667\right]}$$

$$= 2.27[0.375]^{1.1 + [0.426][0.59 - 0.058]}$$

$$\% \text{ Error} = 2.27[0.375]^{1.327} = 2.27[0.272] = 0.618$$

2. Then substituting into Equation 2

$$Q_c'' = \frac{Q_c}{1 - \frac{\% \text{ Error}}{100}} = \frac{3963}{1 - \frac{0.618}{100}} = 3988 \text{ cfs}$$

HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

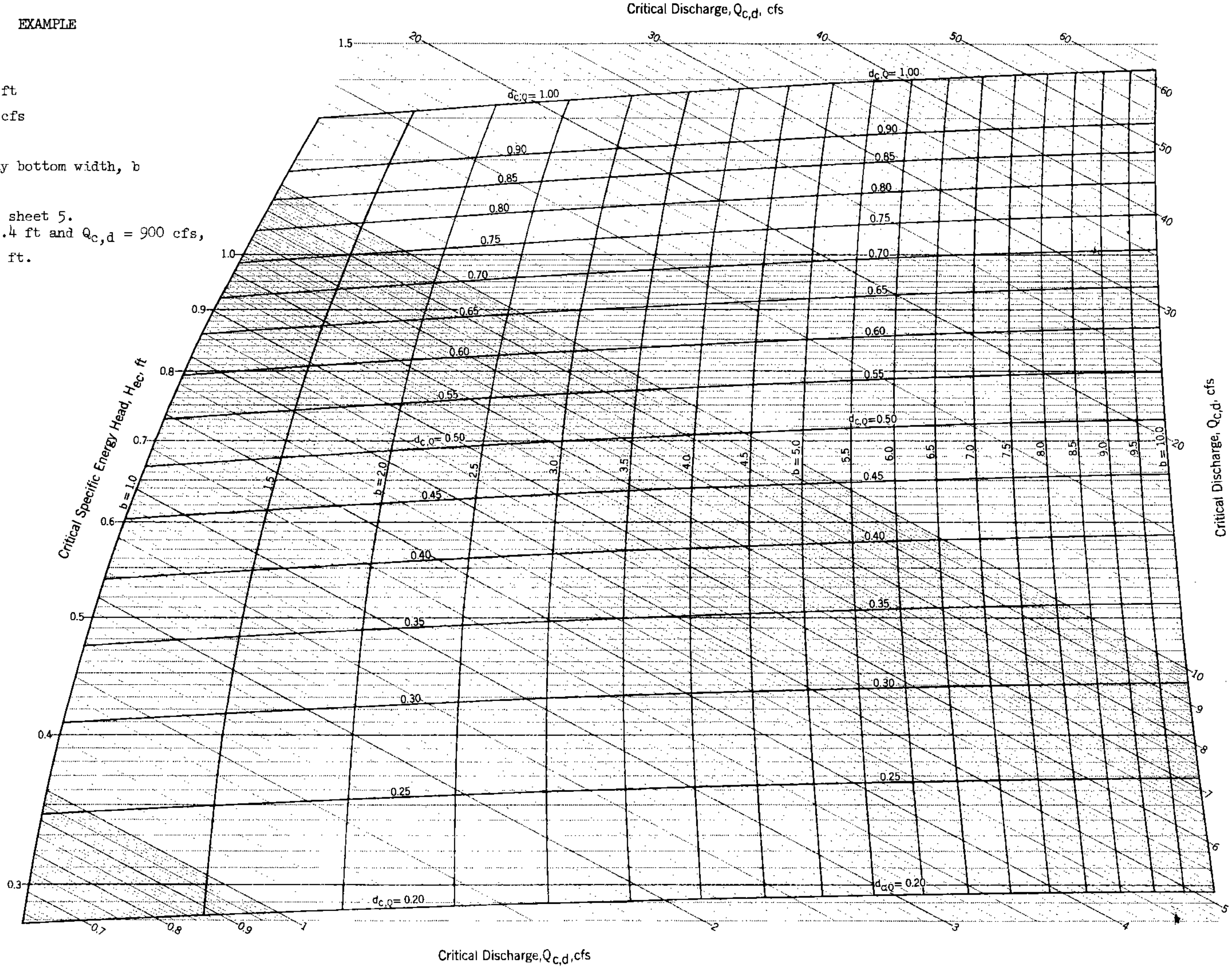
$z = 2$
$1 \text{ ft} \le b \le 10 \text{ ft}$
$0.2 \text{ ft} \le d_{c,Q} \le 1.0 \text{ ft}$

EXAMPLE

Given:
$z = 2$
$H_{ec} = 3.4$ ft
$Q_{c,d} = 900$ cfs

Determine:
The spillway bottom width, b

Solution:
Use ES-174, sheet 5.
For $H_{ec} = 3.4$ ft and $Q_{c,d} = 900$ cfs,
read b = 42 ft.



REFERENCE

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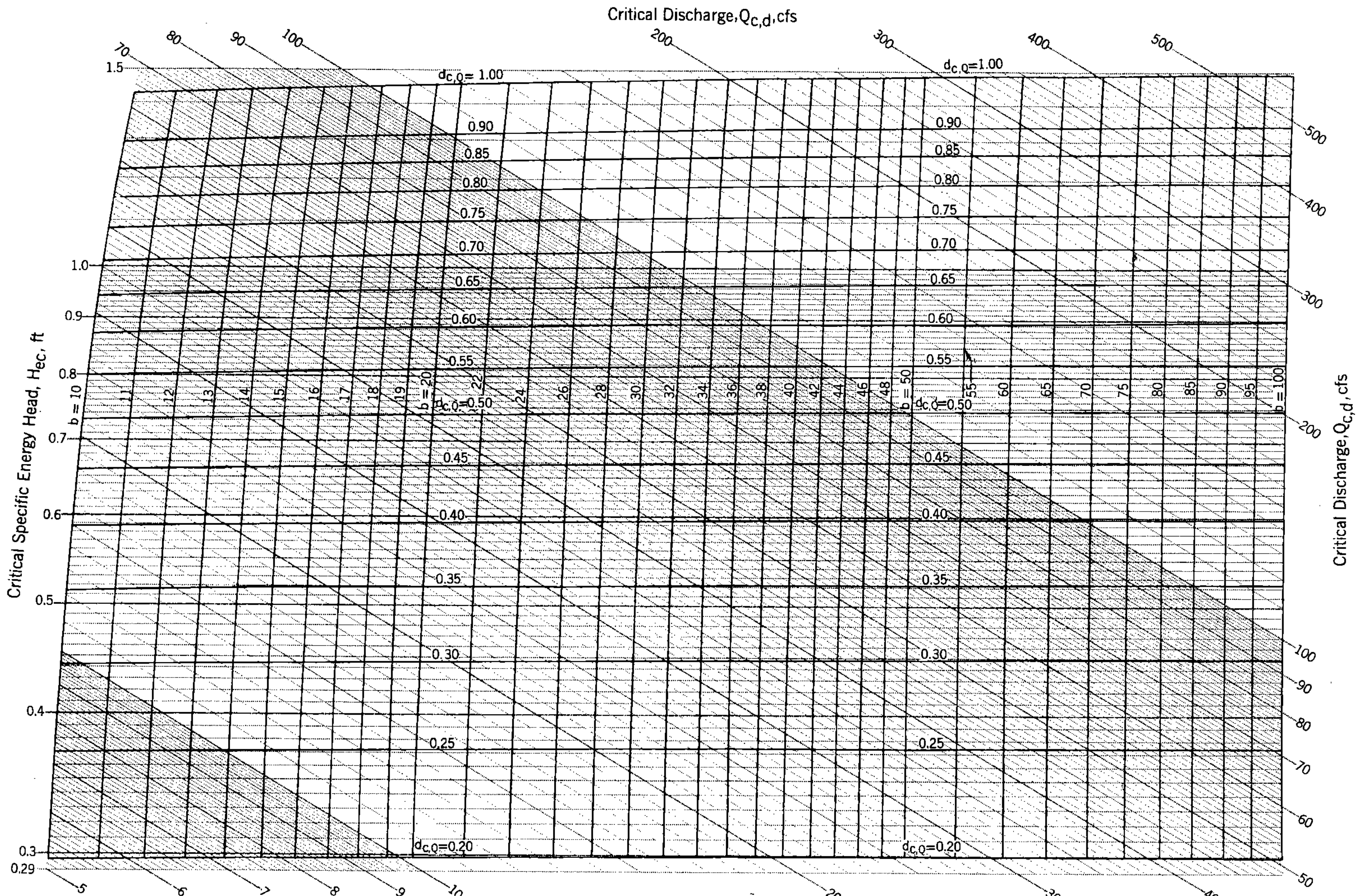
Z = 2
10 ft ≤ b ≤ 100 ft
0.2 ft ≤ $d_{c,Q}$ ≤ 1.0 ft

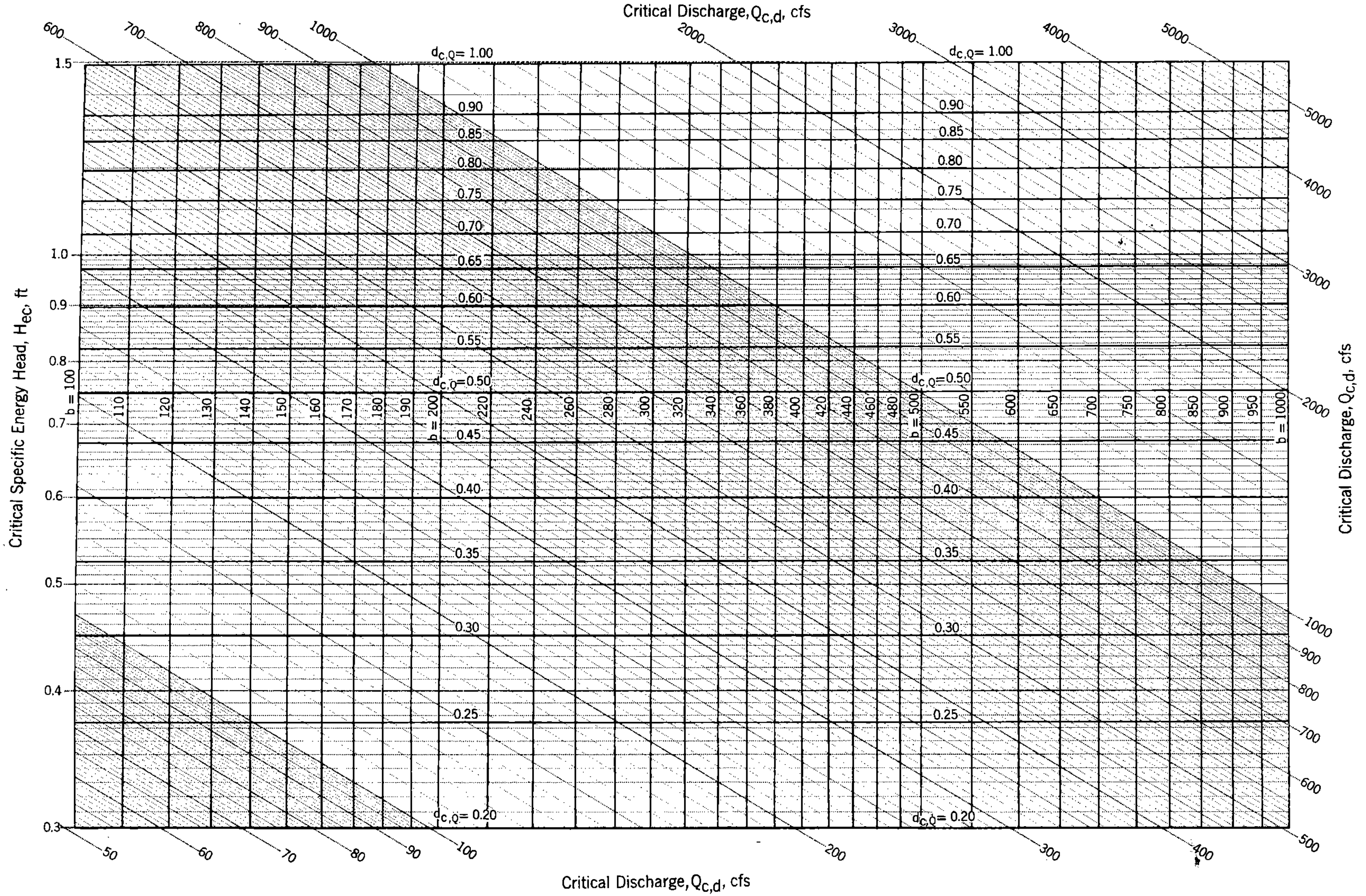


Critical Discharge, $Q_{c,d}$, cfs

REFERENCE

HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

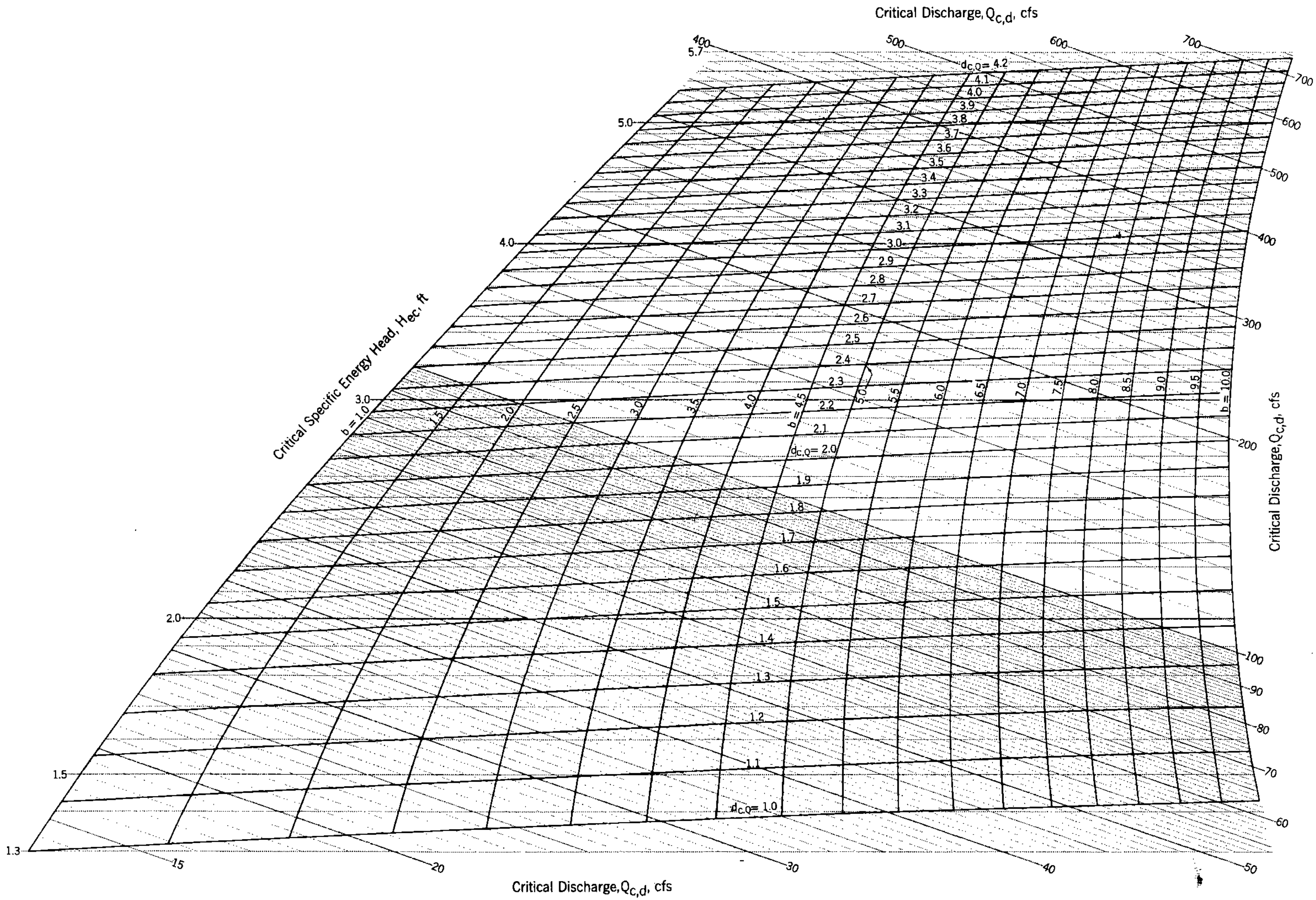
100 ft ≤ b ≤ 1000 ft
0.2 ft ≤ $d_{c,Q}$ ≤ 1.0 ft



REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES - 174 SHEET 3 OF 9 DATE 11-67

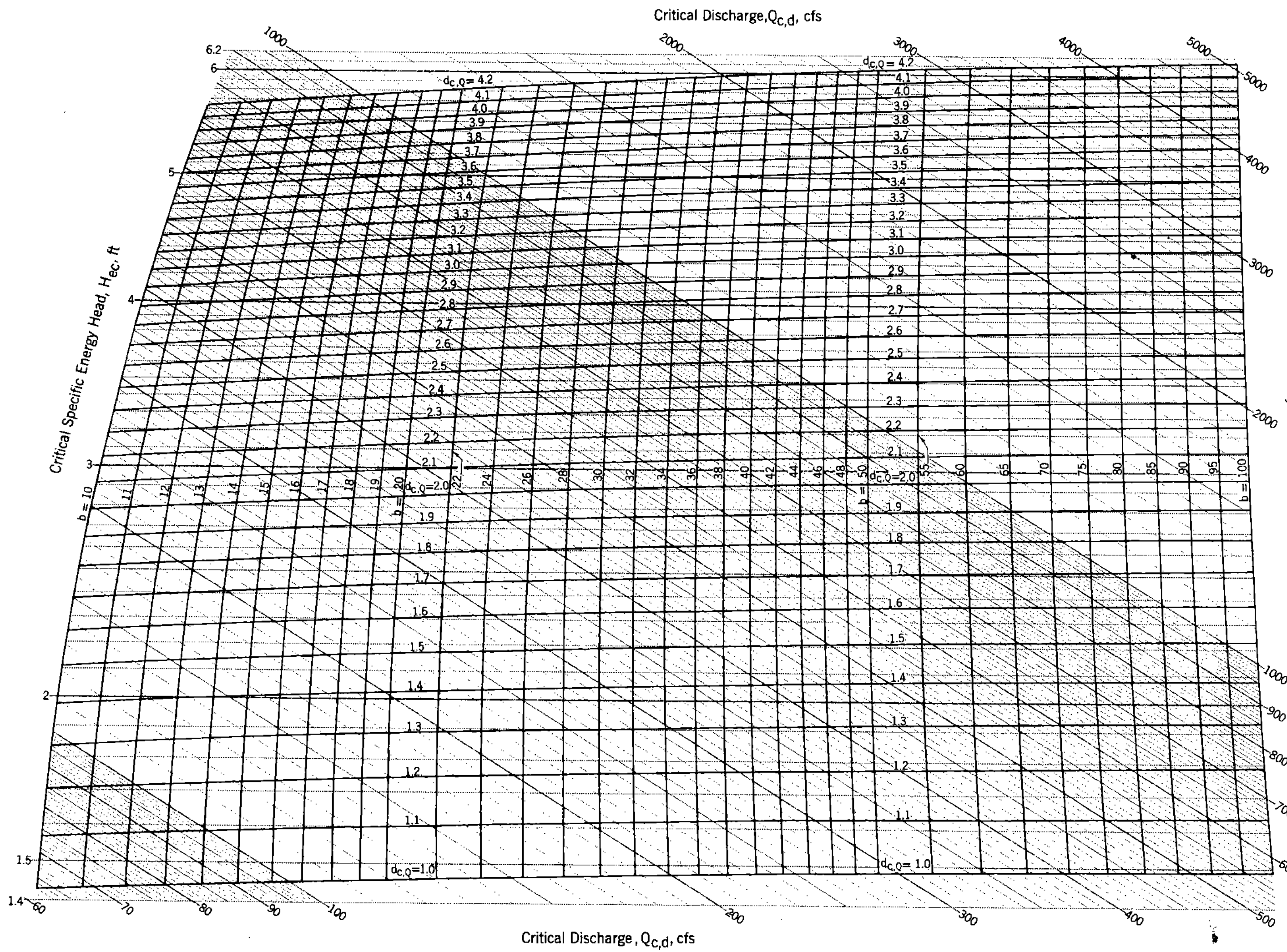
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 2
1 ft ≤ b ≤ 10 ft
1.0 ft ≤ $d_{c,Q}$ ≤ 4.2 ft



HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 2
10 ft ≤ b ≤ 100 ft
1.0 ft ≤ $d_{c,Q}$ ≤ 4.2 ft



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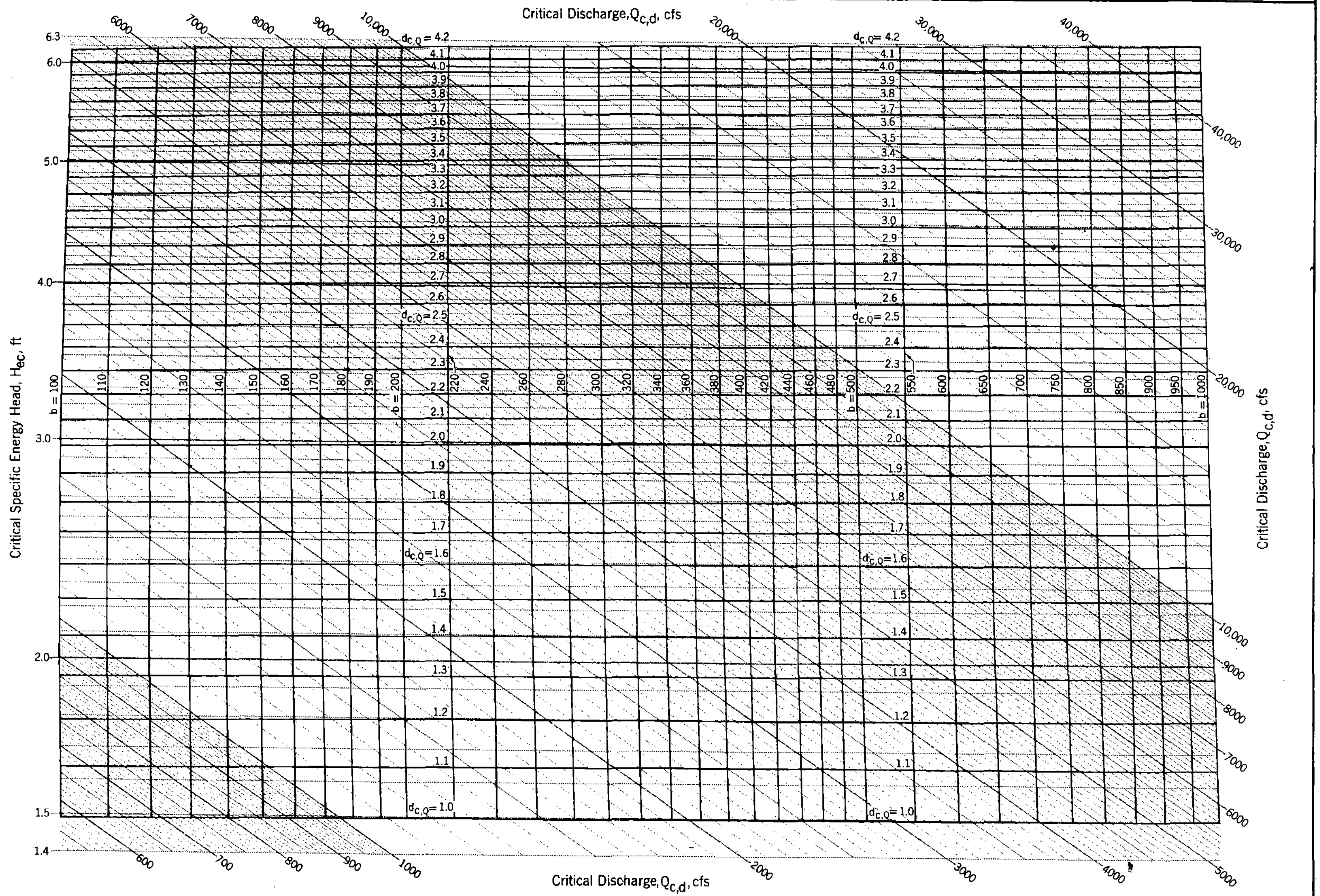
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 2
100 ft ≤ b ≤ 1000 ft
1.0 ft ≤ $d_{c,Q}$ ≤ 4.2 ft



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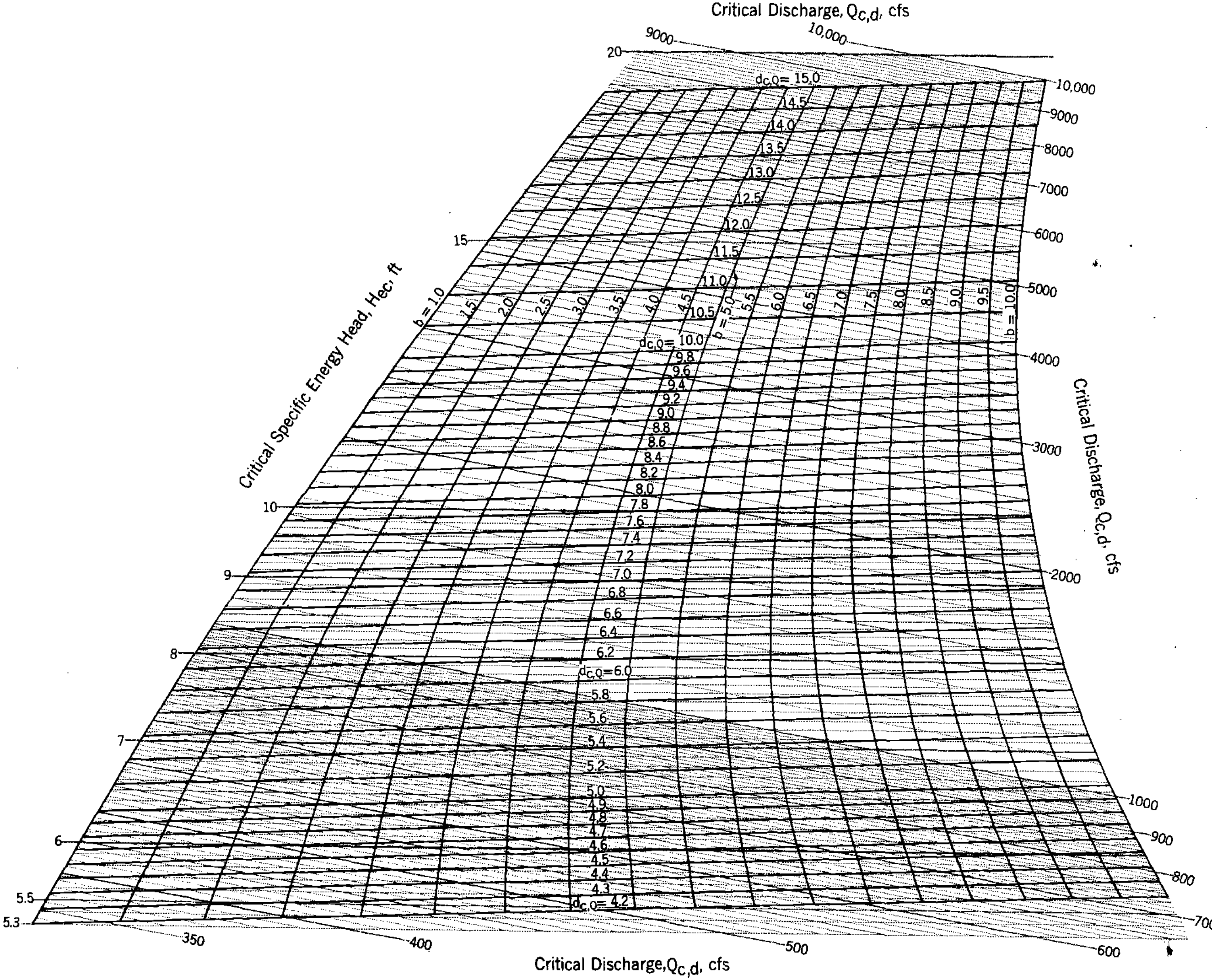
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 2
1 ft ≤ b ≤ 10 ft
4.2 ft ≤ $d_{c,Q}$ ≤ 15 ft



REFERENCE

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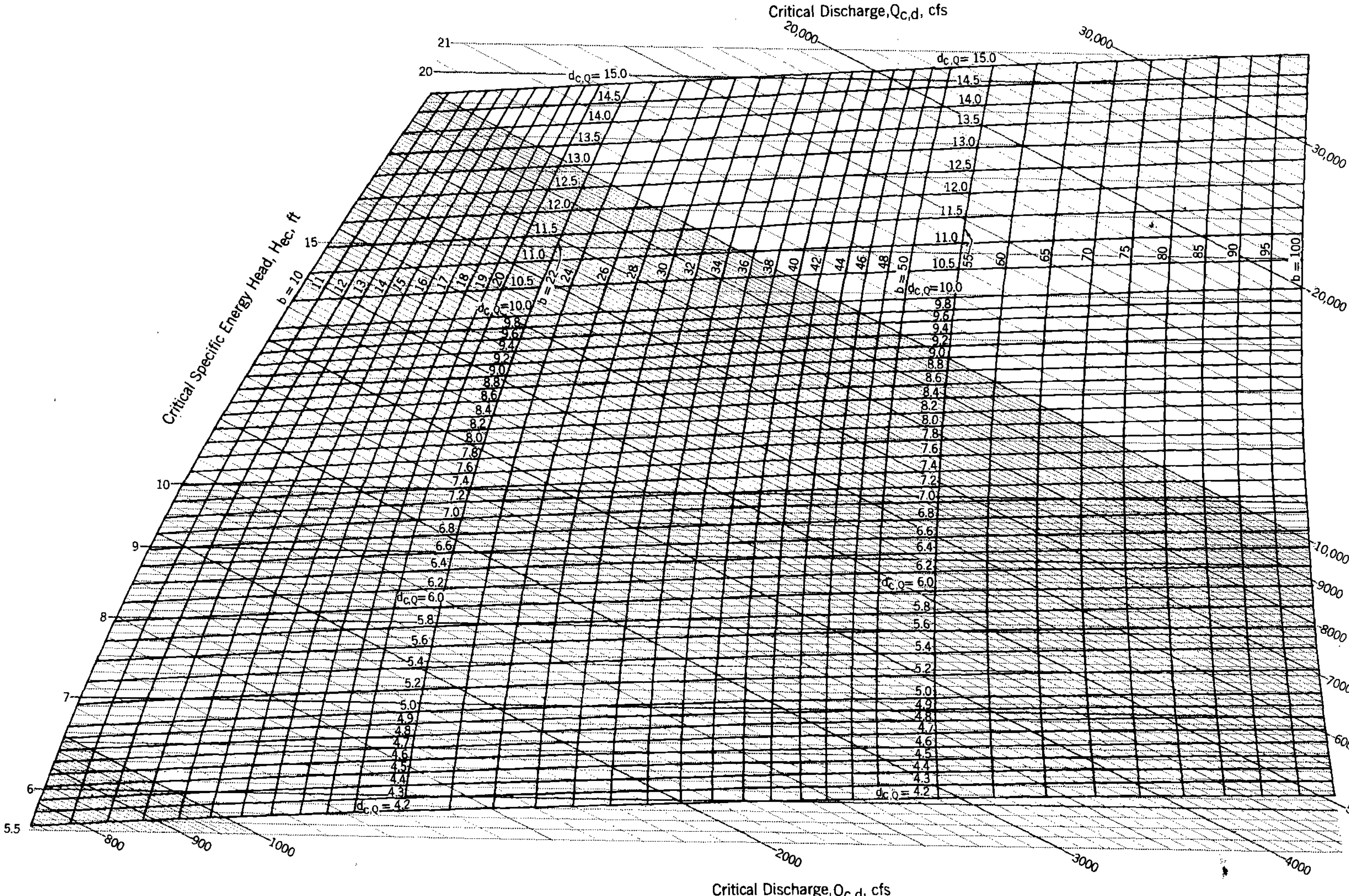
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 2
10 ft ≤ b ≤ 100 ft
4.2 ft ≤ $d_{c,Q}$ ≤ 15 ft



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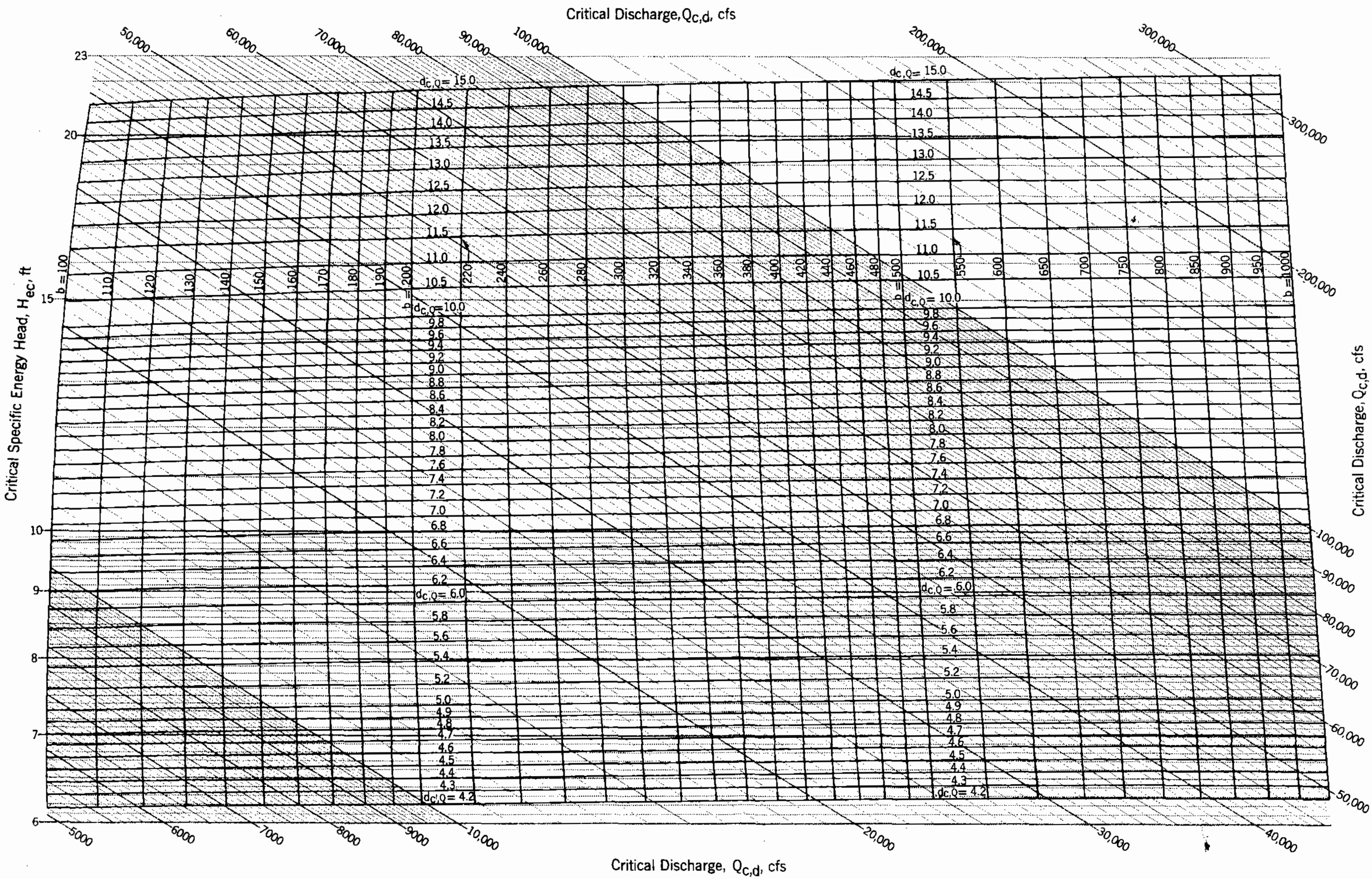
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 2
100 ft ≤ b ≤ 1000 ft
4.2 ft ≤ $d_{c,Q}$ ≤ 15 ft



REFERENCE

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HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

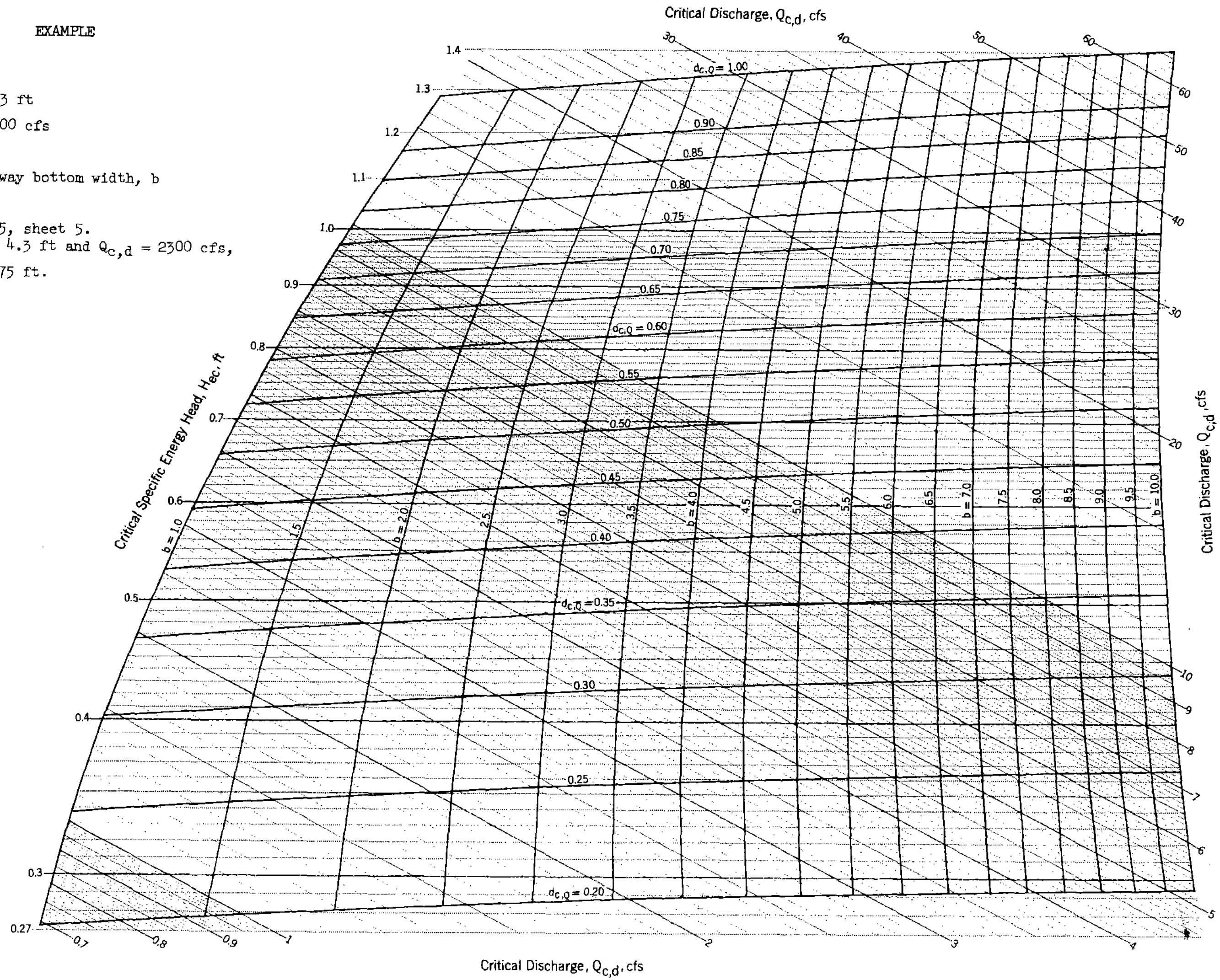
Z = 3
1 ft ≤ b ≤ 10 ft
0.2 ft ≤ $d_{c,Q}$ ≤ 1.0 ft

EXAMPLE

Given:
z = 3
H_{ec} = 4.3 ft
$Q_{c,d}$ = 2300 cfs

Determine:
The spillway bottom width, b

Solution:
Use ES-175, sheet 5.
For H_{ec} = 4.3 ft and $Q_{c,d}$ = 2300 cfs,
read b = 75 ft.



REFERENCE

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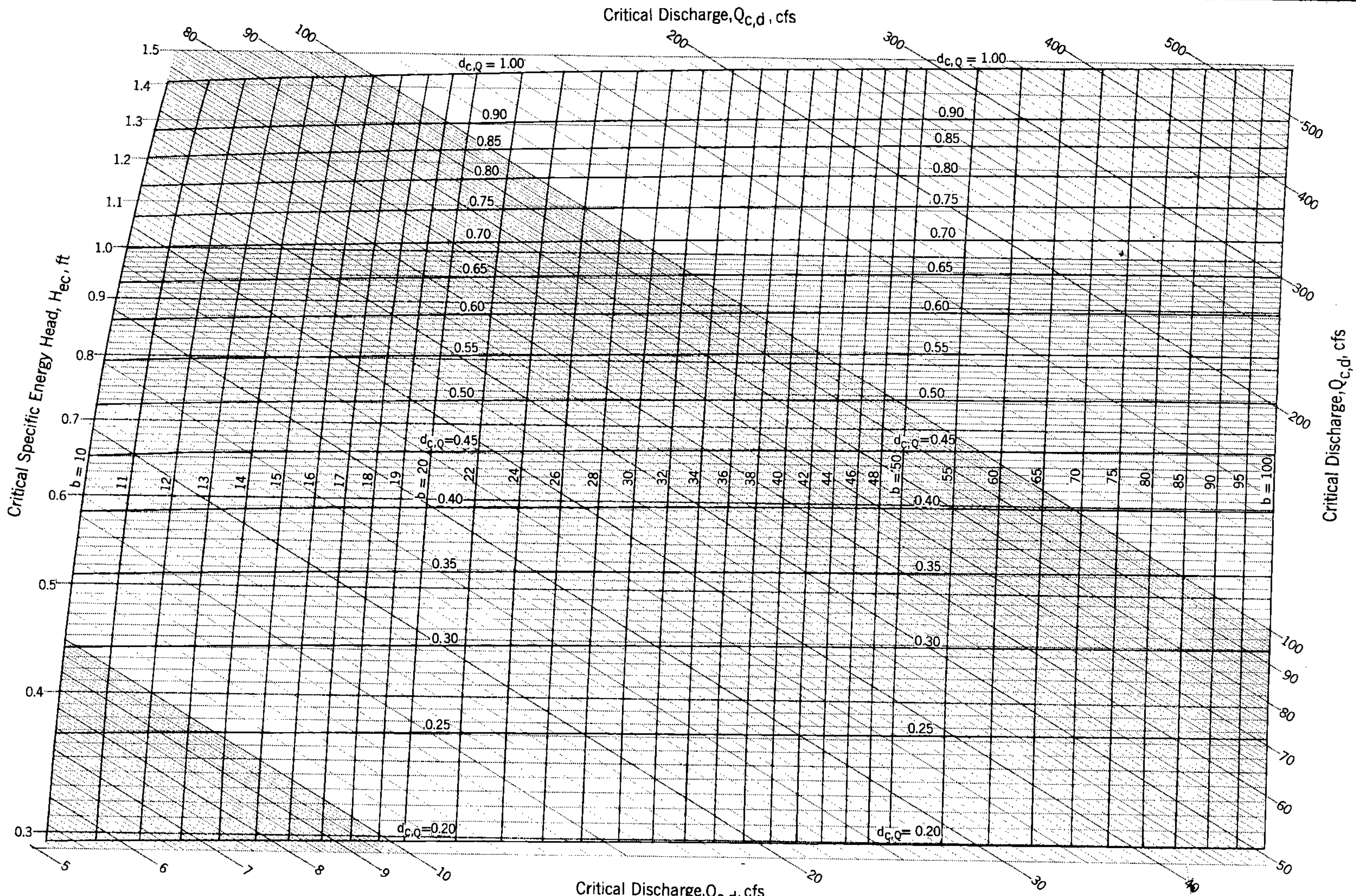
DATE 11-67

HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

10 ft $\leq b \leq$ 100 ft
0.2 ft $\leq d_{c,Q} \leq$ 1.0 ft



REFERENCE

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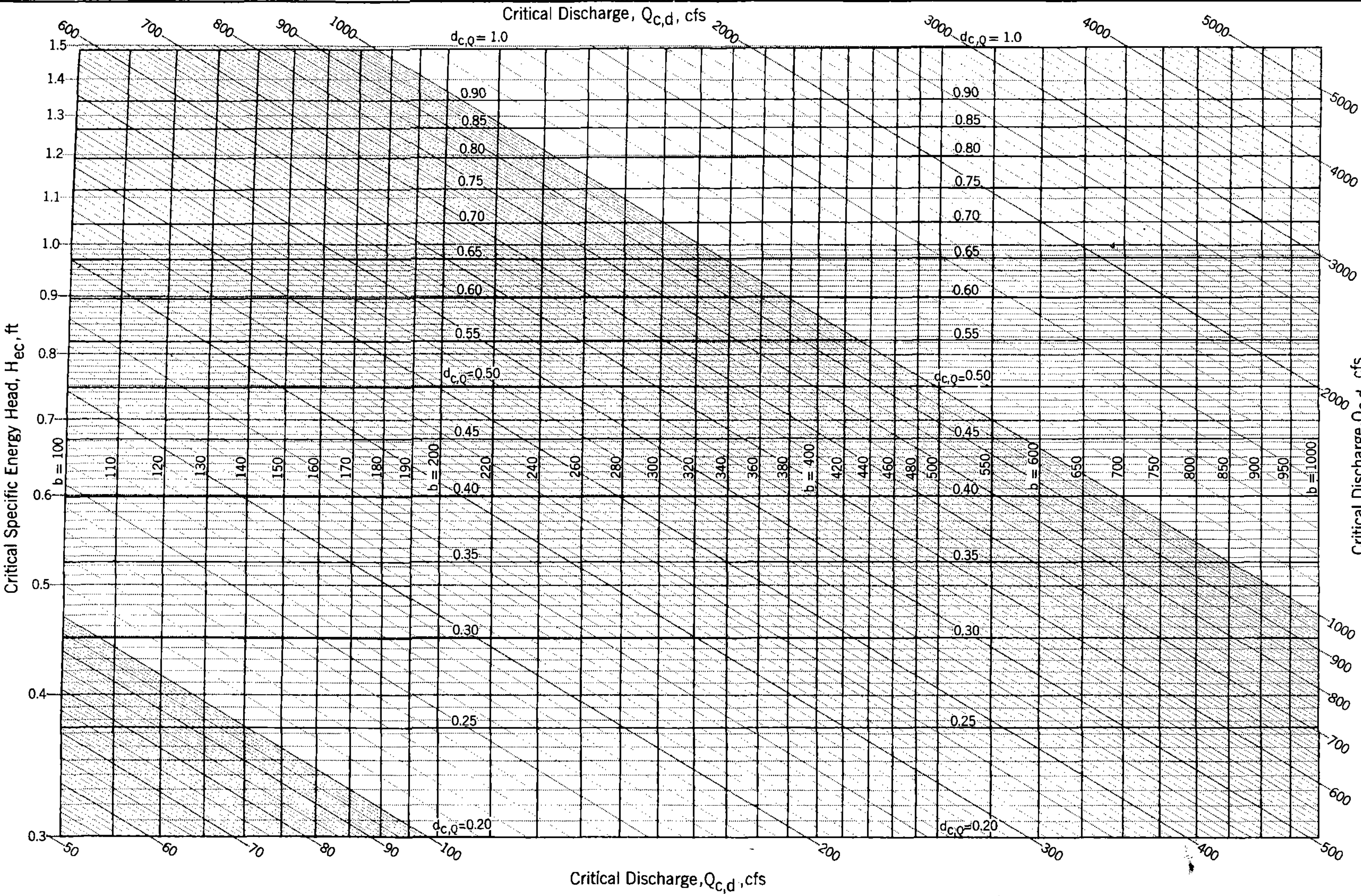
DATE 11-67

HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 3
100 ft ≤ b ≤ 1000 ft
0.2 ft ≤ $d_{c,Q}$ ≤ 1.0 ft



REFERENCE

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ES-175
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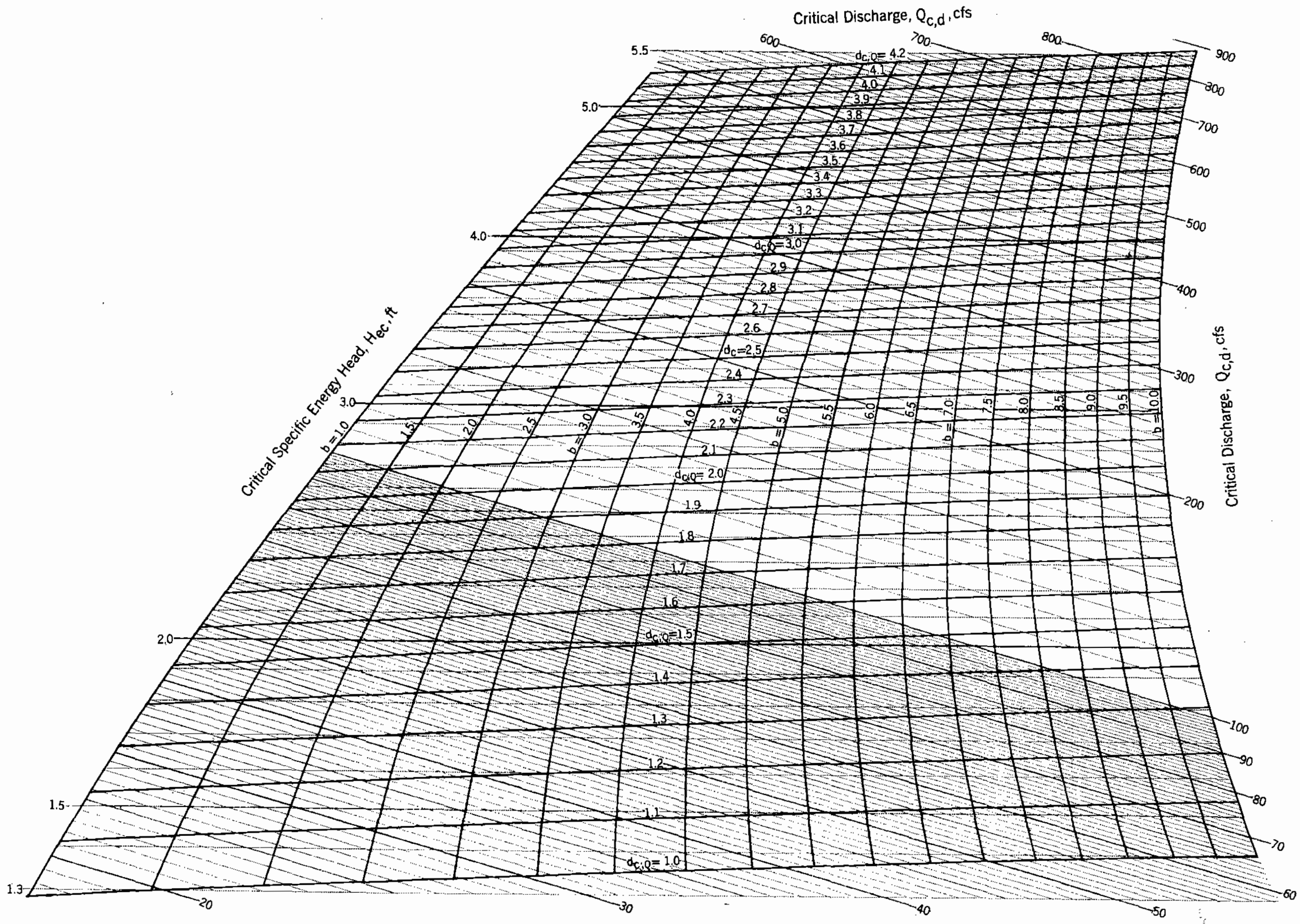
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 3
1 ft ≤ b ≤ 10 ft
1.0 ft ≤ $d_{c,Q}$ ≤ 4.2 ft



REFERENCE

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ES- 175
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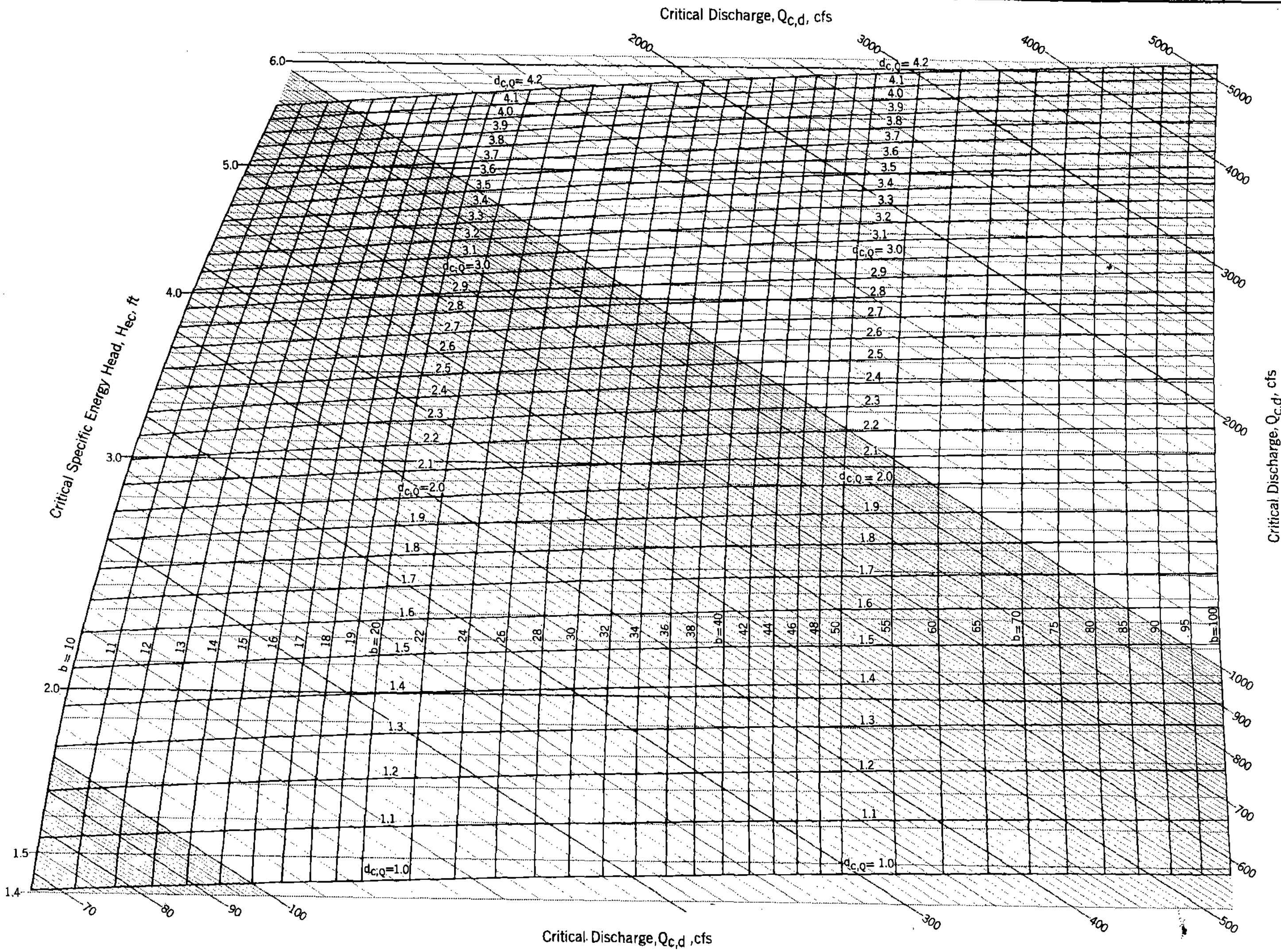
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 3
10 ft ≤ b ≤ 100 ft
1.0 ft ≤ $d_{c,Q}$ ≤ 4.2 ft



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ES - 175
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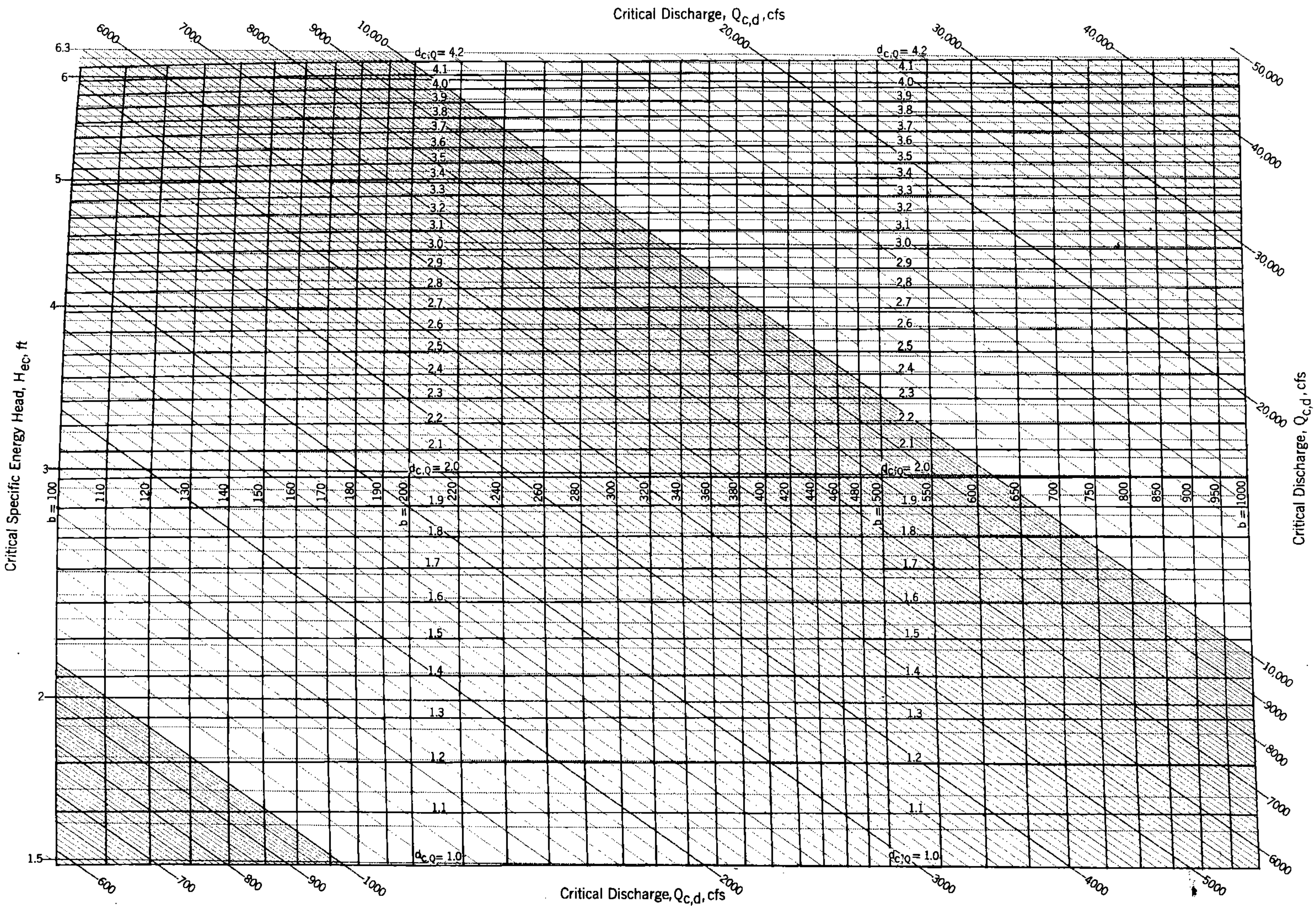
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 3
100 ft ≤ b ≤ 1000 ft
1.0 ft ≤ $d_{c,Q}$ ≤ 4.2 ft



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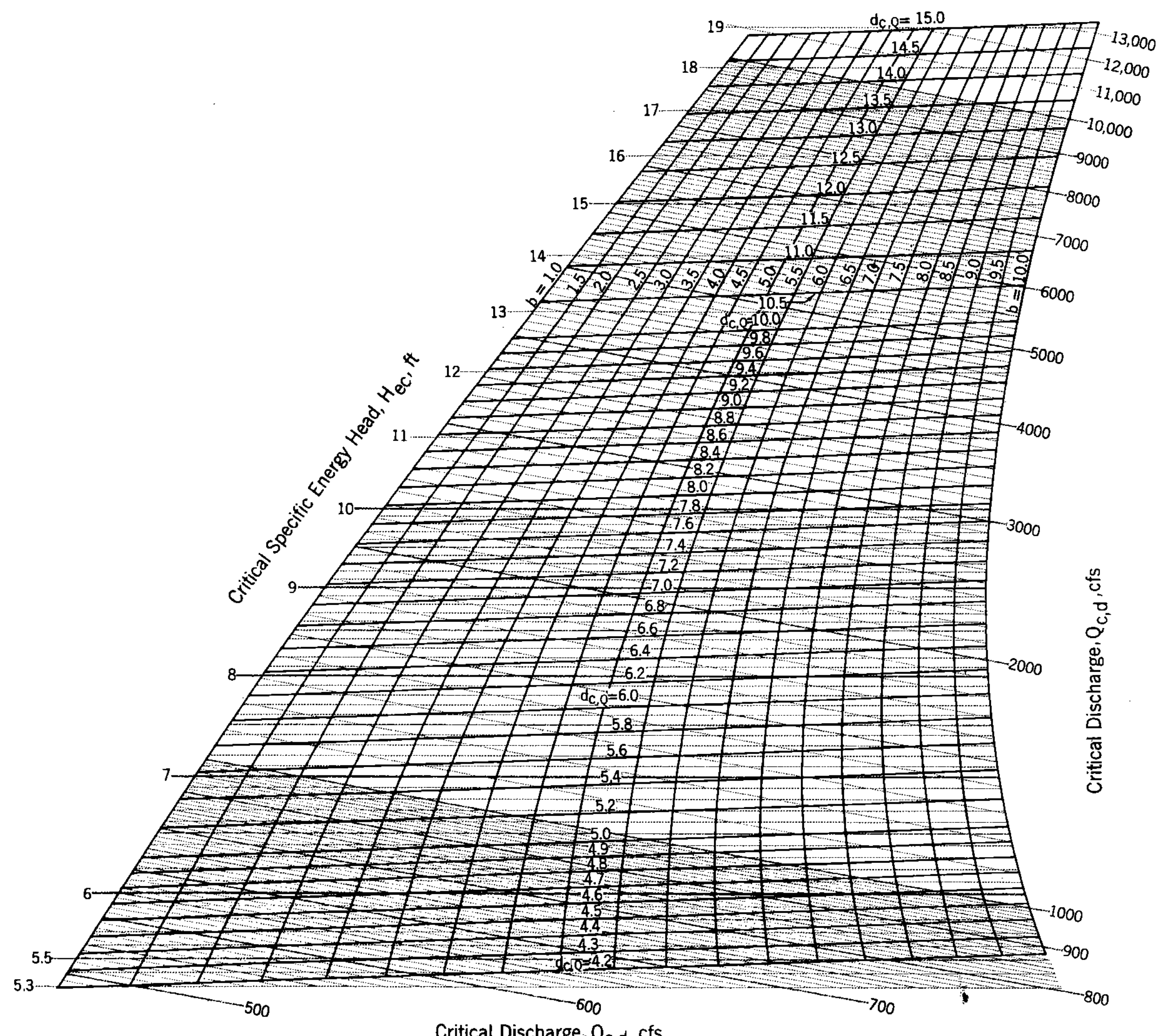
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 3
1 ft ≤ b ≤ 10 ft
4.2 ft ≤ $d_{c,0}$ ≤ 15.0 ft



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ES-175
SHEET 7 OF 9
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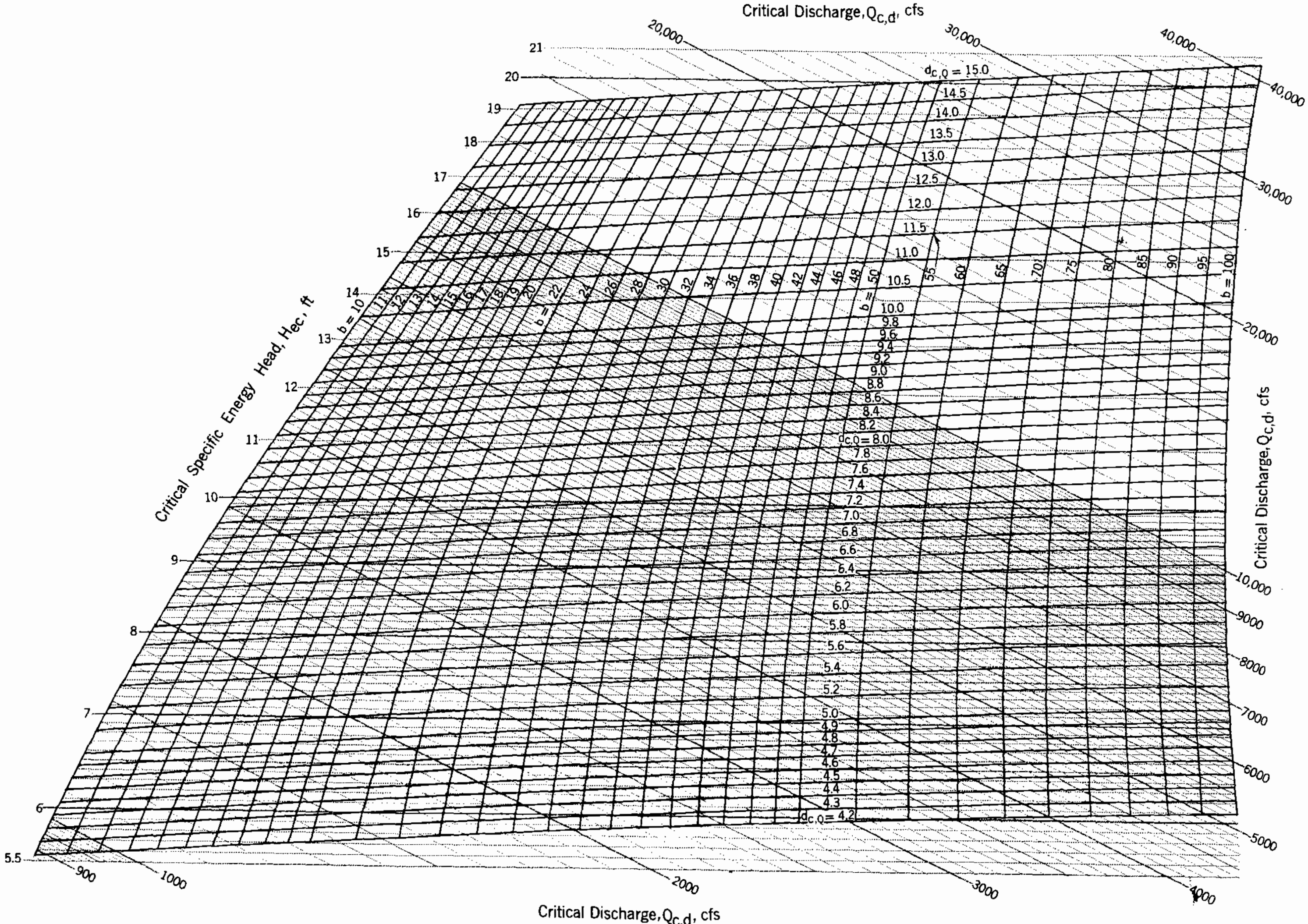
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 3
10 ft ≤ b ≤ 100 ft
4.2 ft ≤ $d_{c,Q}$ ≤ 15 ft



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ES-175
SHEET 8 OF 9
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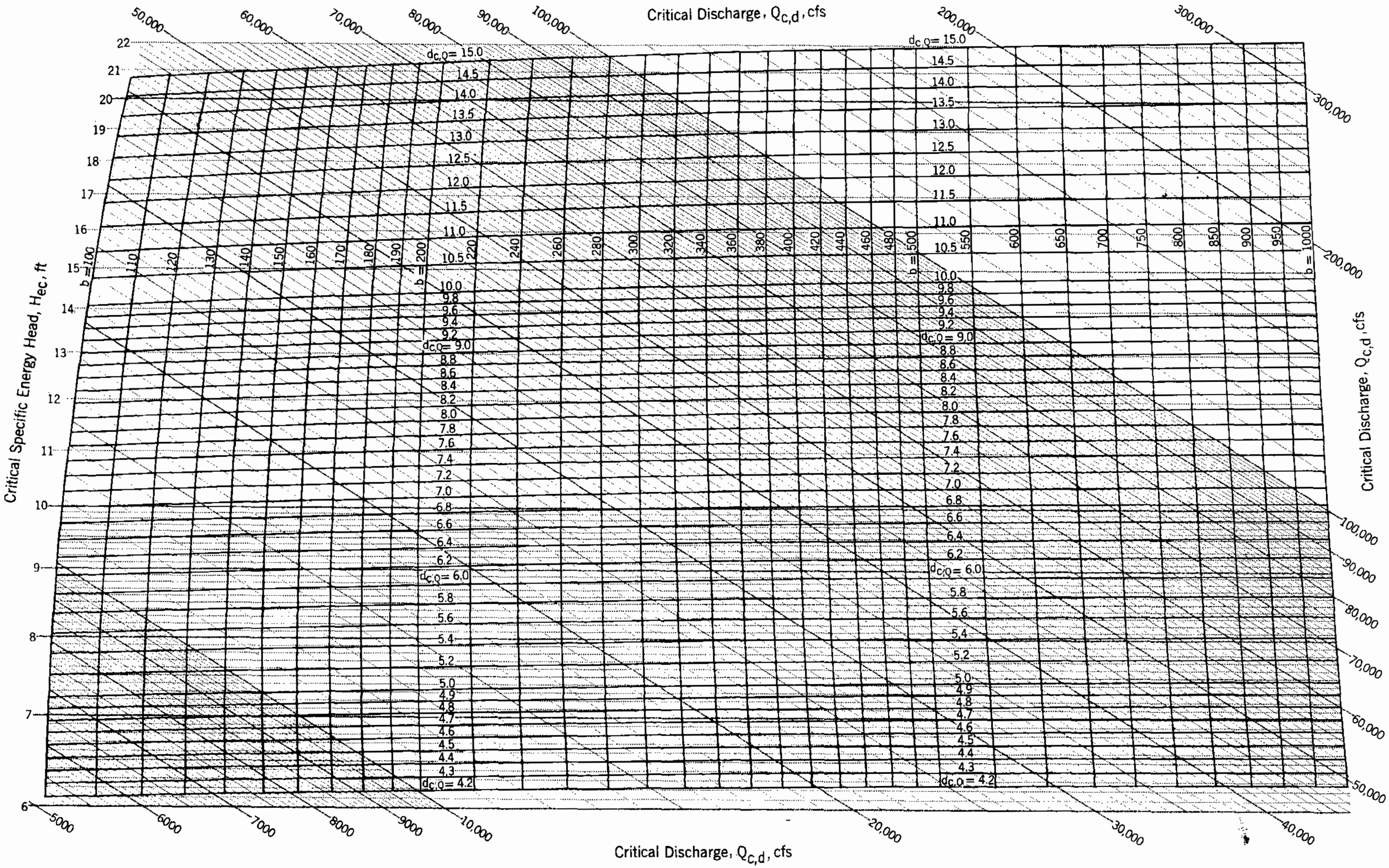
HYDRAULICS: H_{ec} vs $Q_{c,d}$ for Various Bottom Widths, b

Z = 3
100 ft ≤ b ≤ 1000 ft
4.2 ft ≤ $d_{c,Q}$ ≤ 15.0 ft



REFERENCE

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STANDARD DWG. NO.
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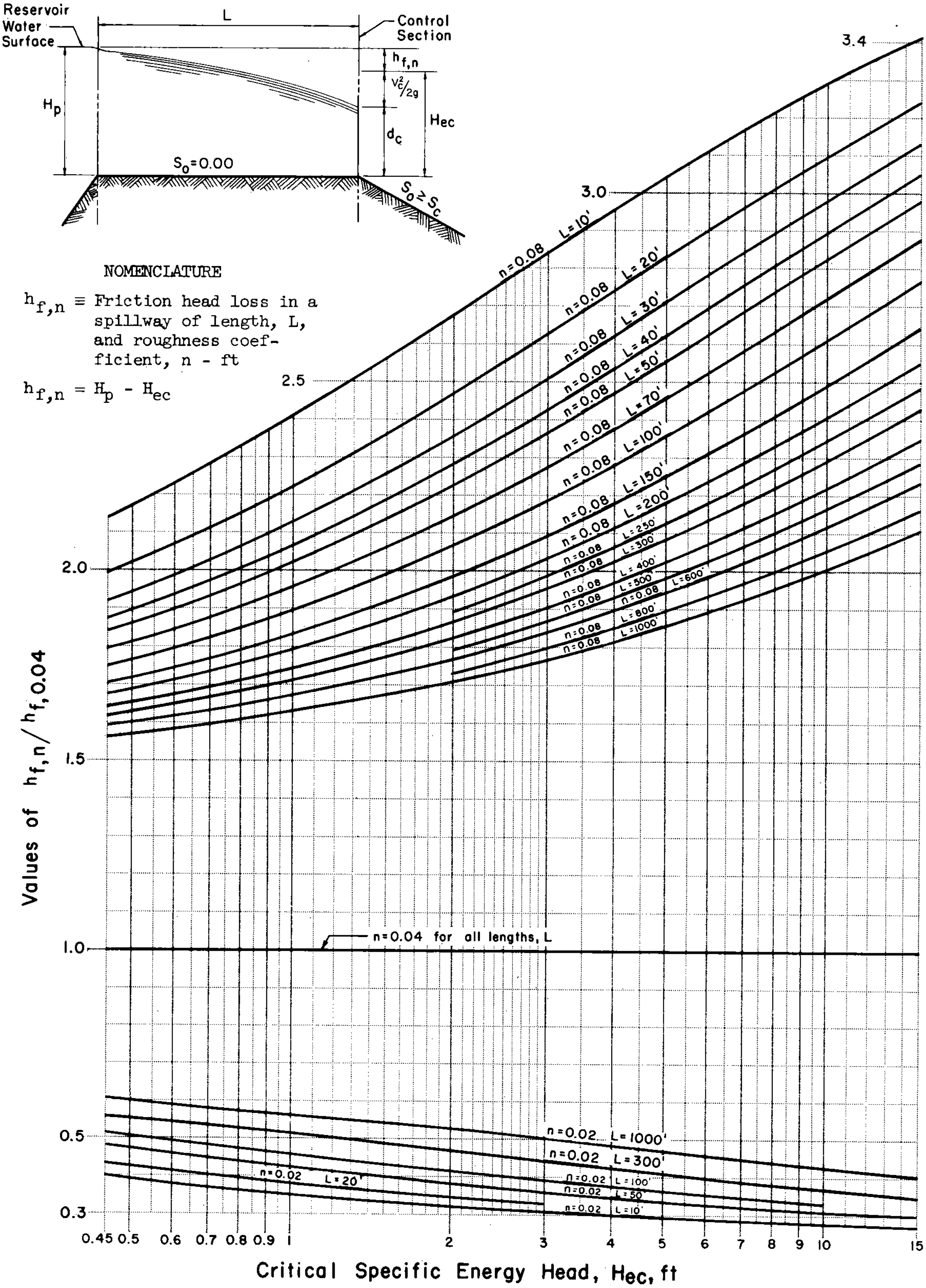
SPILLWAYS: Effect of n on Friction Head Loss

Case I
b=100 ft
z = 2



NOMENCLATURE

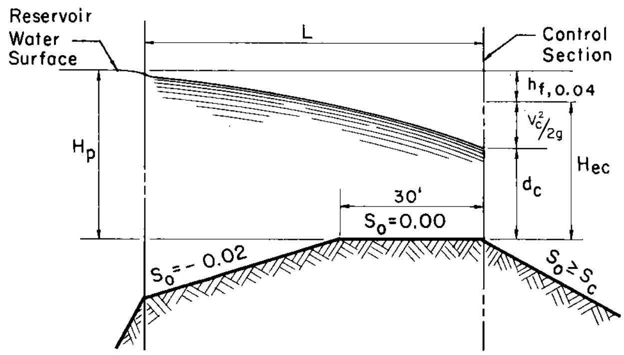
$h_{f,n}$ ≡ Friction head loss in a spillway of length, L, and roughness coefficient, n - ft

$h_{f,n} = H_p - H_{ec}$

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 176 SHEET 1 OF 13 DATE 2-67

SPILLWAYS: Effect of n on Friction Head Loss for n = 0.04

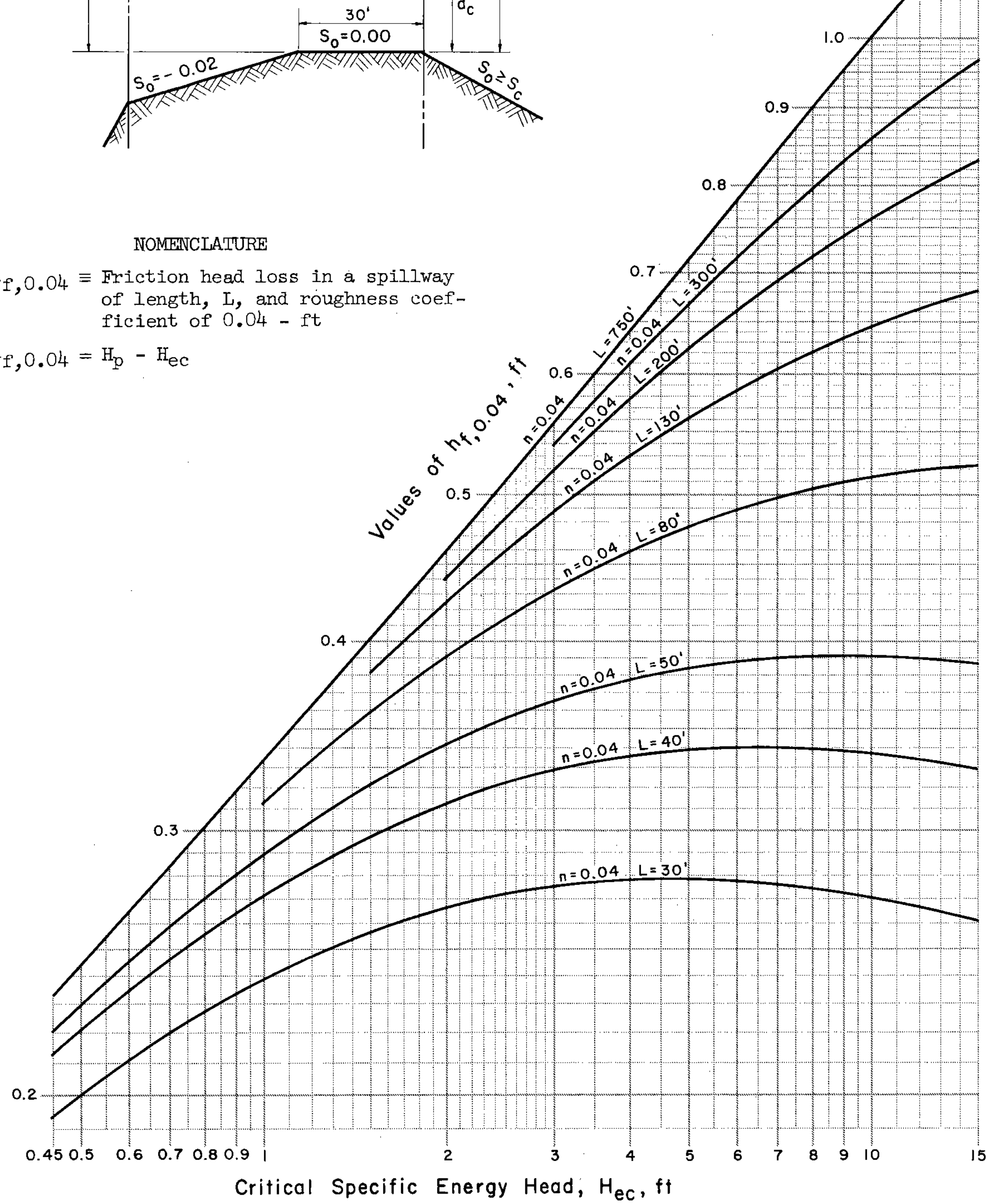
Case 2
b = 100 ft
z = 2



NOMENCLATURE

$h_{f,0.04}$ ≡ Friction head loss in a spillway of length, L, and roughness coefficient of 0.04 - ft

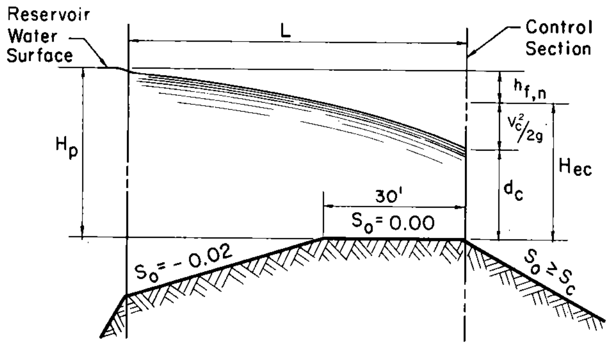
$h_{f,0.04} = H_p - H_{ec}$



REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 176 SHEET 2 OF 13 DATE 2-67

SPILLWAYS: Effect of n on Friction Head Loss for n = 0.02 and 0.08

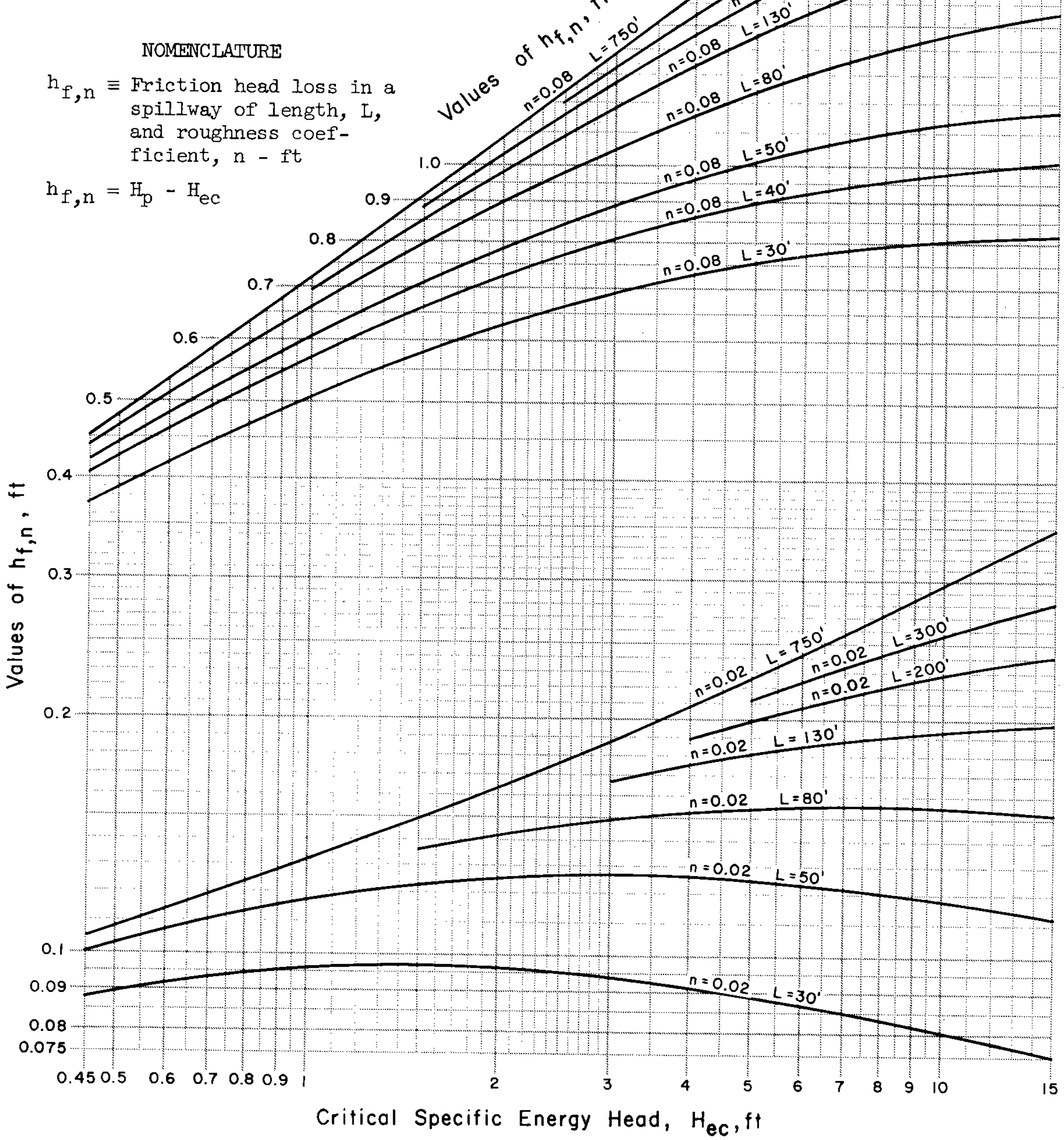
Case 2
b = 100 ft
z = 2



NOMENCLATURE

$h_{f,n}$ ≡ Friction head loss in a spillway of length, L, and roughness coefficient, n - ft

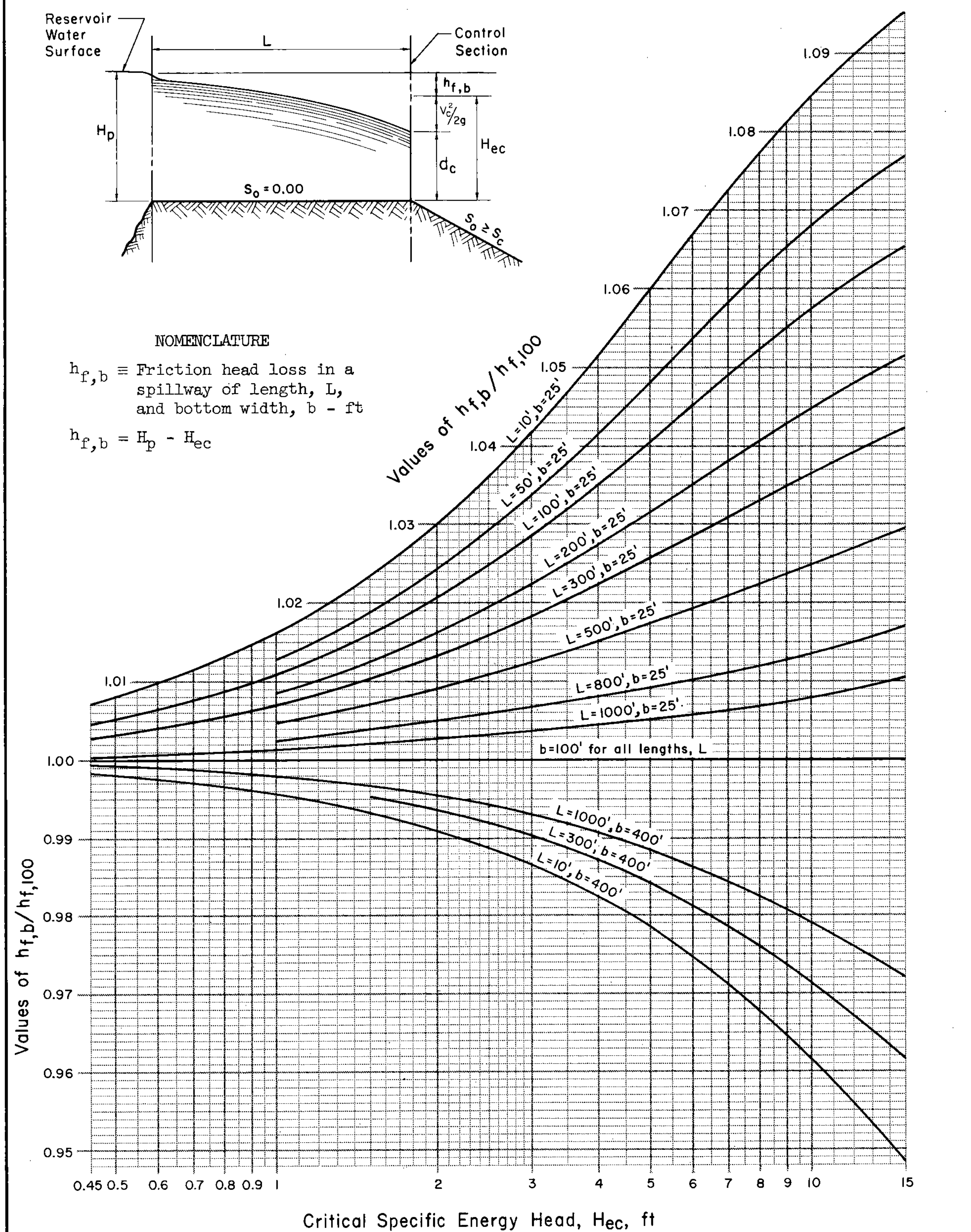
$h_{f,n} = H_p - H_{ec}$



REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 176 SHEET 3 OF 13 DATE 2-67

SPILLWAYS: Effect of b on Friction Head Loss

Case I
n = 0.04
z = 2



REFERENCE

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ES- 176
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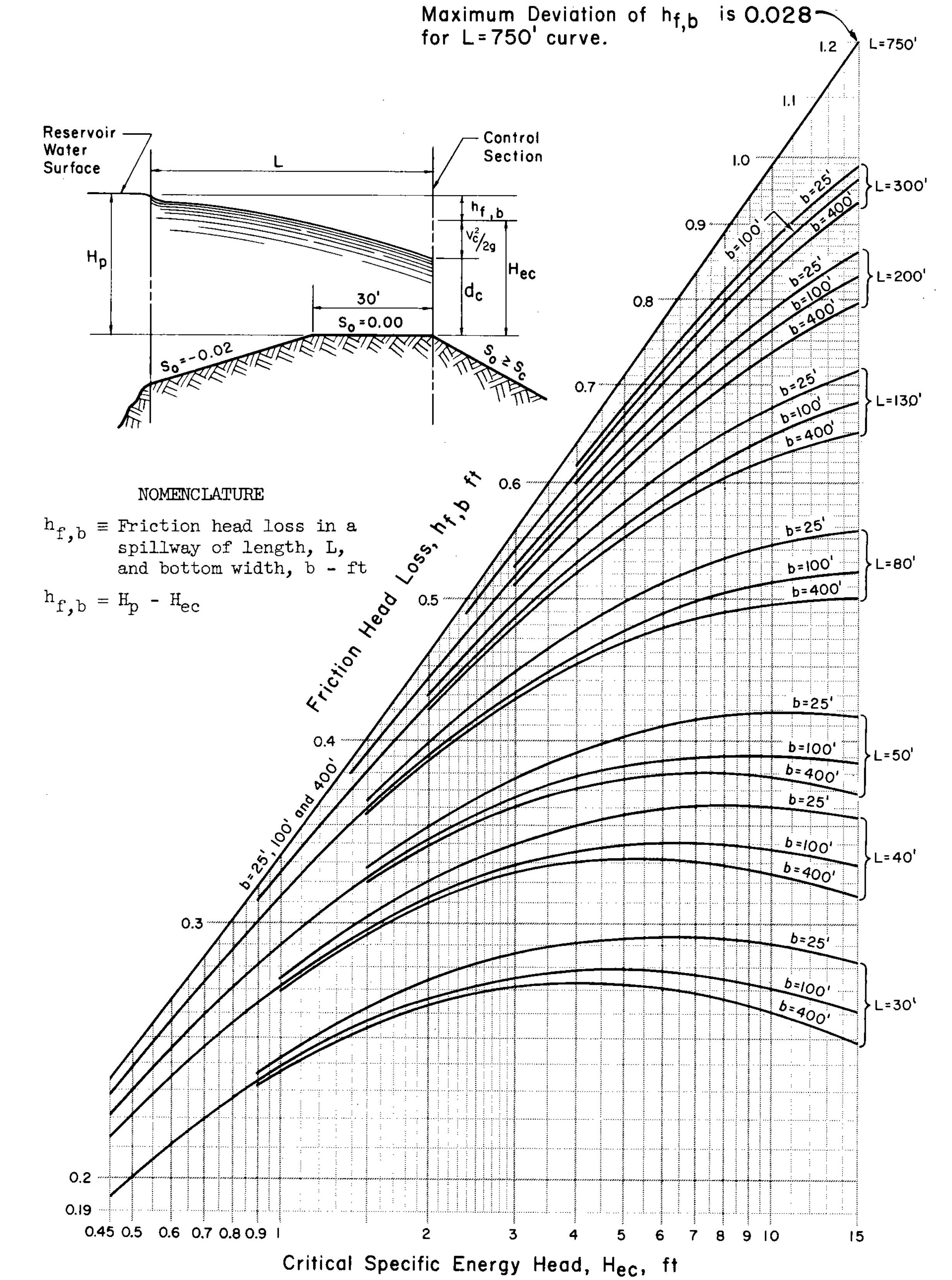
DATE 2-67

SPILLWAYS: Effect of b on Friction Head Loss

Case 2
n = 0.04
z = 2



NOMENCLATURE

$h_{f,b}$ ≡ Friction head loss in a spillway of length, L, and bottom width, b - ft

$h_{f,b} = H_p - H_{ec}$

REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
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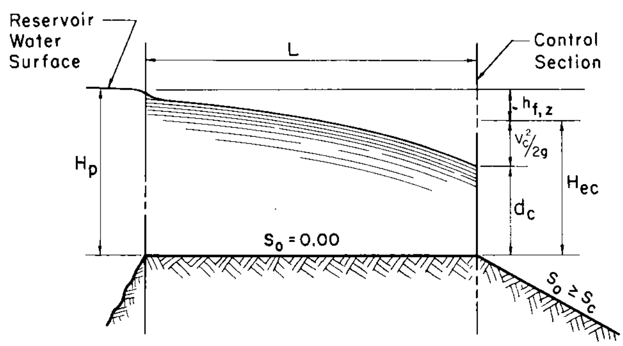
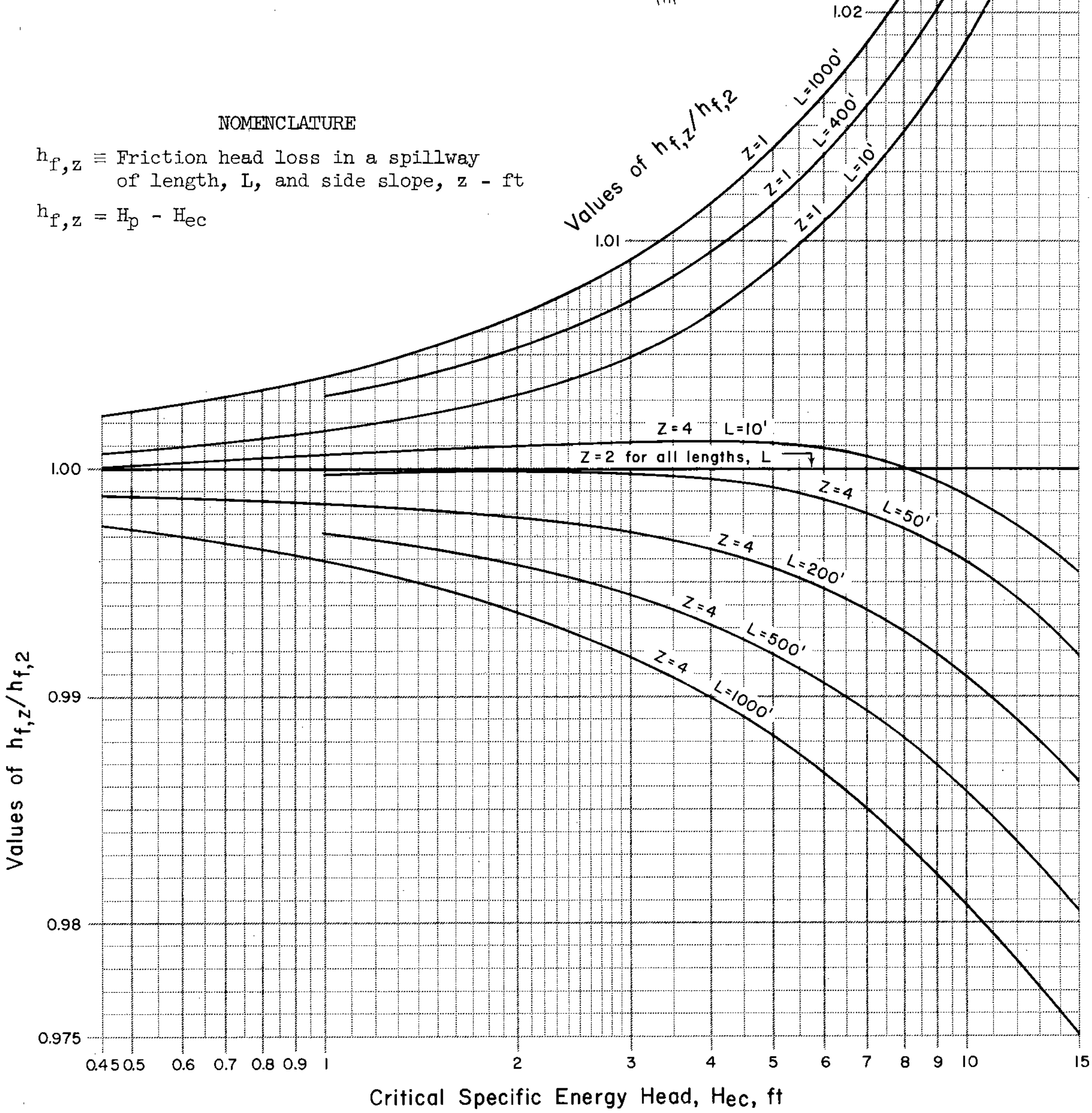
SPILLWAYS: Effect of z on Friction Head Loss	Case I b = 100 ft n = 0.04



NOMENCLATURE

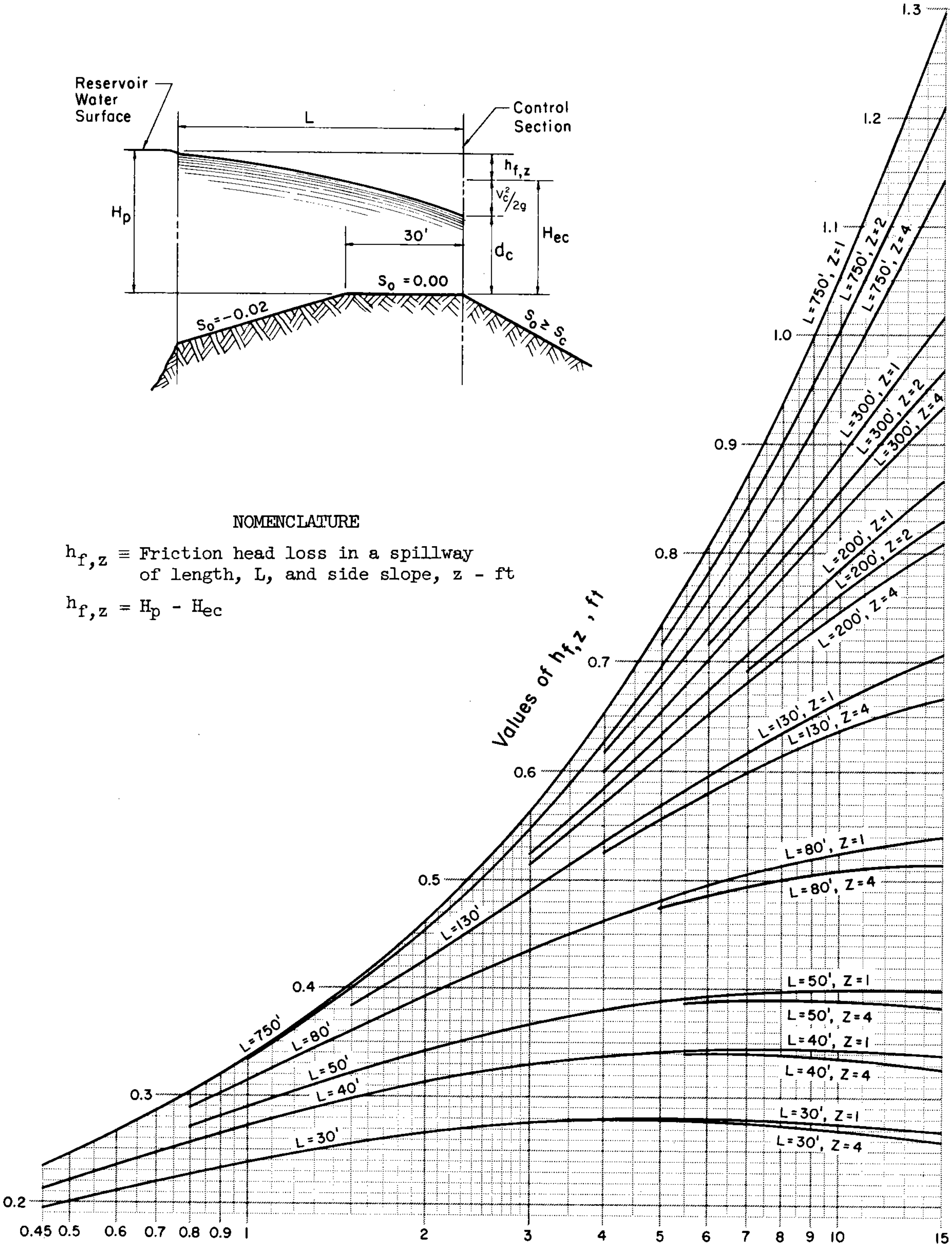
$h_{f,z} \equiv$ Friction head loss in a spillway of length, L, and side slope, z - ft

$h_{f,z} = H_p - H_{ec}$



REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES- 176 SHEET 6 OF 13 DATE 2-67

SPILLWAYS: Effect of z on Friction Head Loss



NOMENCLATURE

$h_{f,z}$ ≡ Friction head loss in a spillway of length, L, and side slope, z - ft

$h_{f,z} = H_p - H_{ec}$

EXAMPLE 1

Given:

Emergency spillway bottom profile as shown in figure

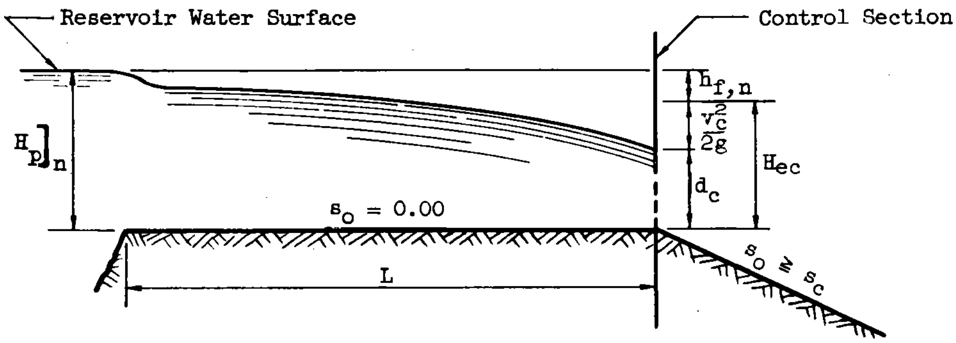
H_{ec} = 4.50 ft

z = 2

b = 100 ft

L = 200 ft

$H_p]_{n=0.04}$ = 5.51 ft (obtained from ES-171, sheet 1)



Determine:

$H_p]_{n=0.08}$

Solution:

1. $h_{f,0.04} = H_p]_{n=0.04} - H_{ec} = 5.51 - 4.50 = 1.01$ ft
2. Use ES-176, sheet 1.

   For H_{ec} = 4.50 ft, n = 0.08, and L = 200 ft, read $\frac{h_{f,0.08}}{h_{f,0.04}} = 2.15$.

   Then $h_{f,0.08} = 2.15\,(h_{f,0.04}) = 2.15(1.01) = 2.17$ ft

   $H_p]_{n=0.08} = H_{ec} + h_{f,0.08} = 4.50 + 2.17 = 6.67$ ft

EXAMPLE 2

Given:

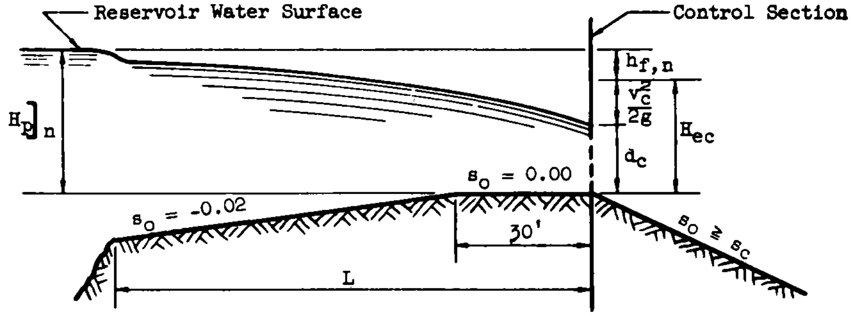
Emergency spillway bottom profile as shown in figure

$H_{ec} = 4.50$ ft

$z = 2$

$b = 100$ ft

$L = 200$ ft



Determine:

$H_p]_n$ where n = 0.02, 0.04, 0.08, and 0.05.

Solution:

1. Determine $H_p]_{n=0.02}$

   Use ES-176, sheet 3.

   For $H_{ec} = 4.50$ ft, n = 0.02, and L = 200 ft, read $h_{f,0.02} = 0.20$ ft.

   Then $H_p]_{n=0.02} = H_{ec} + h_{f,0.02} = 4.50 + 0.20 = 4.70$ ft

2. Determine $H_p]_{n=0.04}$

   Use ES-176, sheet 2.

   For $H_{ec} = 4.50$ ft, n = 0.04, and L = 200 ft, read $h_{f,0.04} = 0.60$ ft.

   For n = 0.04, $H_p]_{n=0.04} = H_{ec} + h_{f,0.04} = 4.50 + 0.60 = 5.10$ ft.

3. Determine $H_p]_{n=0.08}$

   Use ES-176, sheet 3.

   For $H_{ec} = 4.50$ ft, n = 0.08, and L = 200 ft, read $h_{f,0.08} = 1.54$ ft.

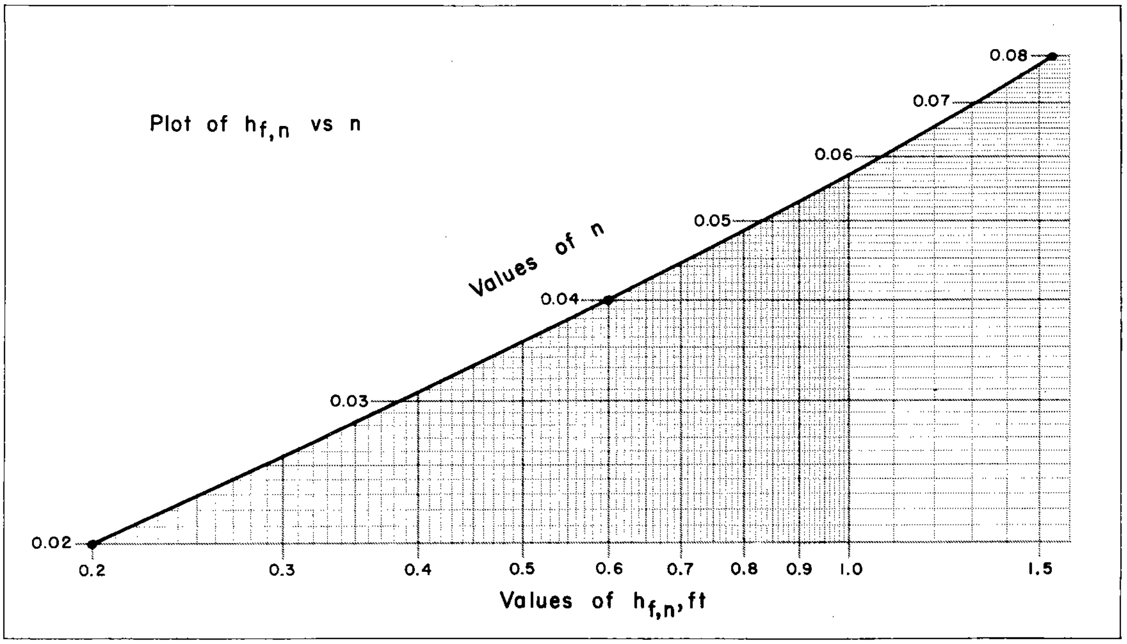
   Then $H_p]_{n=0.08} = H_{ec} + h_{f,0.08} = 4.50 + 1.54 = 6.04$ ft.

4. Determine $H_p]_{n=0.05}$

   Prepare plot of $h_{f,n}$ vs n.

   From plot read $h_{f,0.05} = 0.83$ ft.

   Then $H_p]_{n=0.05} = H_{ec} + h_{f,0.05} = 4.50 + 0.83 = 5.33$ ft.



EXAMPLE 3

Given:

Emergency spillway bottom profile as shown in figure

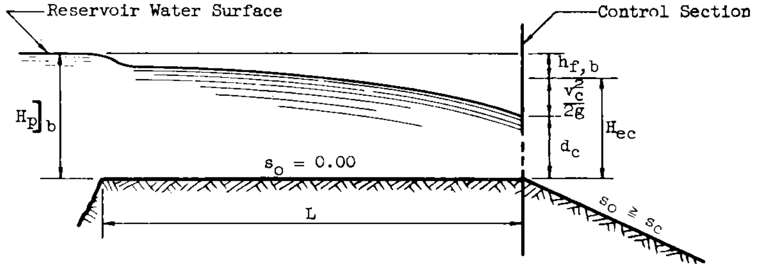
H_{ec} = 4.50 ft

z = 2

L = 200 ft

n = 0.04

$H_p]_{b=100}$ = 5.51 ft (obtained from ES-171, sheet 1)



Determine:

$H_p]_{b=400}$

Solution:

1. $h_{f,100} = H_p]_{b=100} - H_{ec} = 5.51 - 4.50 = 1.01$ ft
2. Use ES-176, sheet 4.

   For H_{ec} = 4.50 ft, b = 400 ft, and L = 200 ft, read $\frac{h_{f,400}}{h_{f,100}} = 0.985$.

   Then $h_{f,400} = 0.985(h_{f,100}) = 0.985(1.01) = 0.99$ ft.

   $H_p]_{b=400} = H_{ec} + h_{f,400} = 4.50 + 0.99 = 5.49$ ft

EXAMPLE 4

Given:

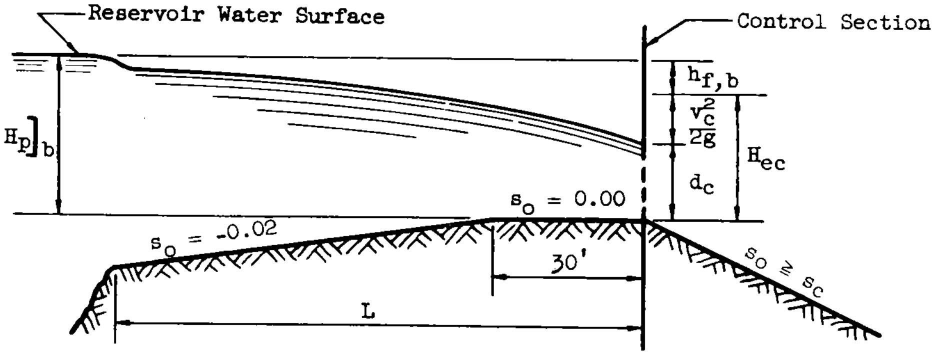
Emergency spillway bottom profile as shown in figure

H_{ec} = 6.00 ft

z = 2

L = 300 ft

n = 0.04



Determine:

$H_p]_b$ where b = 25, 100, and 400 ft

Solution:

1. Use ES-176, sheet 5.
   For L = 300 ft and
   - b = 25 ft, read $h_{f,25}$ = 0.73 ft;
   - b = 100 ft, read $h_{f,100}$ = 0.72 ft;
   - b = 400 ft, read $h_{f,400}$ = 0.70 ft.
2. Then where
   - b = 25 ft, $H_p]_{b=25} = H_{ec} + h_{f,25} = 6.00 + 0.73 = 6.73$ ft;
   - b = 100 ft, $H_p]_{b=100} = H_{ec} + h_{f,100} = 6.00 + 0.72 = 6.72$ ft;
   - b = 400 ft, $H_p]_{b=400} = H_{ec} + h_{f,400} = 6.00 + 0.70 = 6.70$ ft.

EXAMPLE 5

Given:

Emergency spillway bottom profile as shown in figure

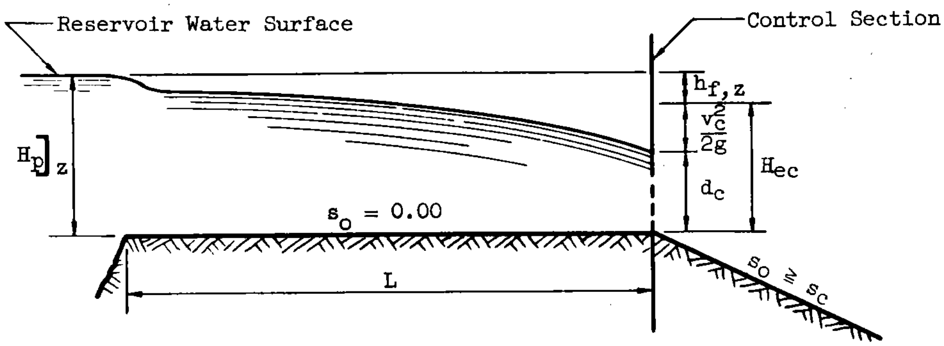
H_{ec} = 4.50 ft

b = 100 ft

L = 200 ft

n = 0.04

$H_p\big]_{z=2}$ = 5.51 ft (obtained from ES-171, sheet 1)



Determine:

$H_p\big]_{z=4}$

Solution:

1. $h_{f,2} = H_p\big]_{z=2} - H_{ec} = 5.51 - 4.50 = 1.01$ ft
2. Use ES-176, sheet 6.

   For H_{ec} = 4.50 ft, z = 4, and L = 200 ft, read $\frac{h_{f,4}}{h_{f,2}} = 0.996$.

   Then $h_{f,4} = 0.996(h_{f,2}) = 0.996(1.01) = 1.01$ ft.

   $H_p\big]_{z=4} = H_{ec} + h_{f,4} = 4.50 + 1.01 = 5.51$ ft

EXAMPLE 6

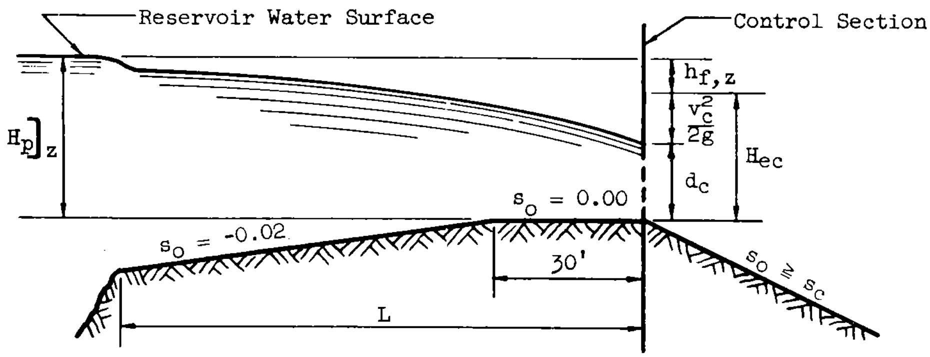
Given:

Emergency spillway bottom profile as shown in figure

H_{ec} = 7.50 ft

b = 100 ft

L = 300 ft



Determine:

$H_p]_z$ where z = 1, 2, and 4

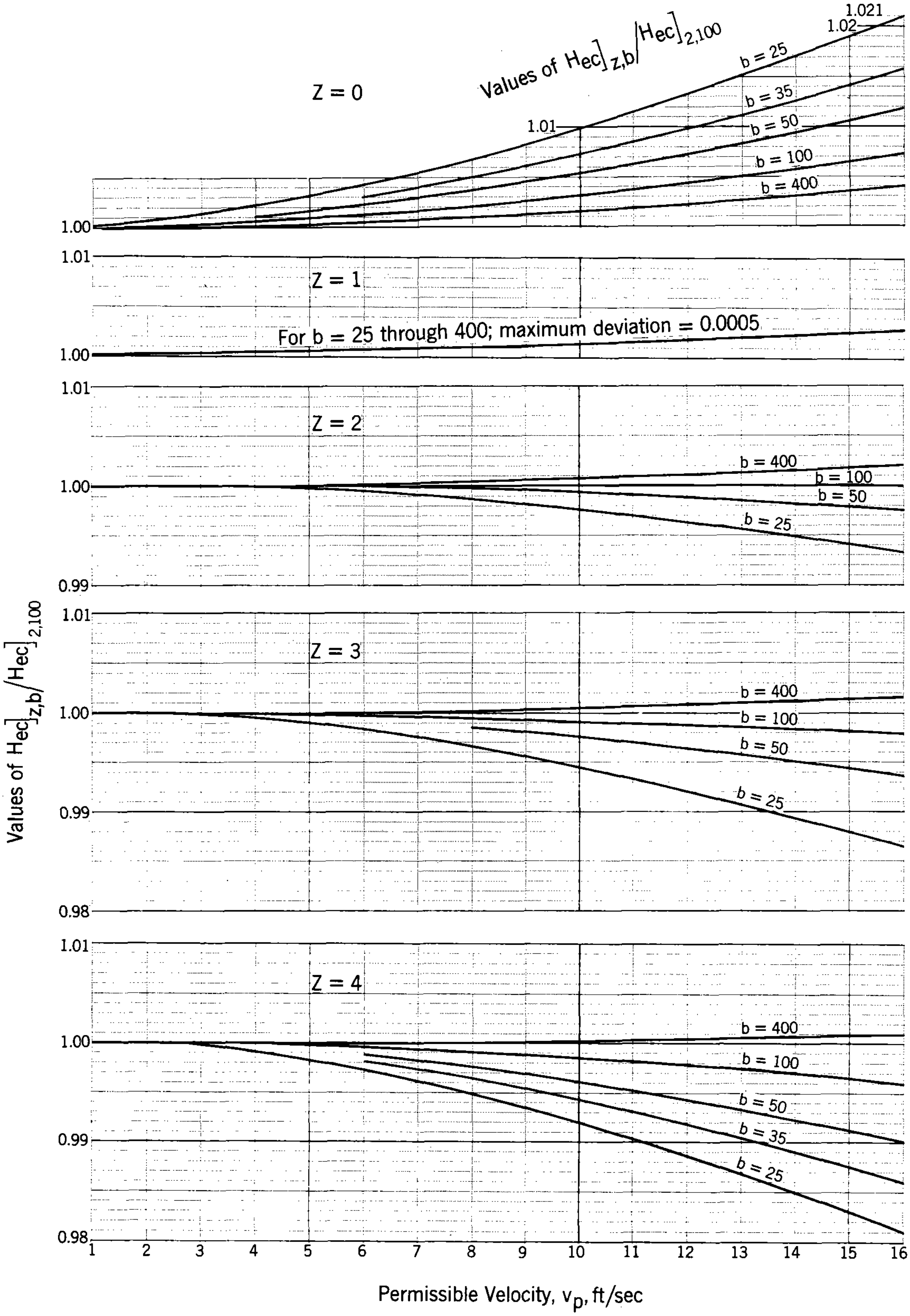
Solution:

1. Use ES-176, sheet 7.
   For L = 300 ft and
   z = 1, read $h_{f,1}$ = 0.80 ft;
   z = 2, read $h_{f,2}$ = 0.78 ft;
   z = 4, read $h_{f,4}$ = 0.76 ft.
2. Then where
   z = 1, $H_p]_{z=1} = H_{ec} + h_{f,1} = 7.50 + 0.80 = 8.30$ ft;
   z = 2, $H_p]_{z=2} = H_{ec} + h_{f,2} = 7.50 + 0.78 = 8.28$ ft;
   z = 4, $H_p]_{z=4} = H_{ec} + h_{f,4} = 7.50 + 0.76 = 8.26$ ft.

SPILLWAYS: Effect of b and z on Permissible H_{ec}

$\frac{n^2}{s_o} = 0.002$

Z = 1, 2, 3, and 4



REFERENCE

U. S. DEPARTMENT OF AGRICULTURE
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STANDARD DWG. NO.
ES-177
SHEET 1 OF 8
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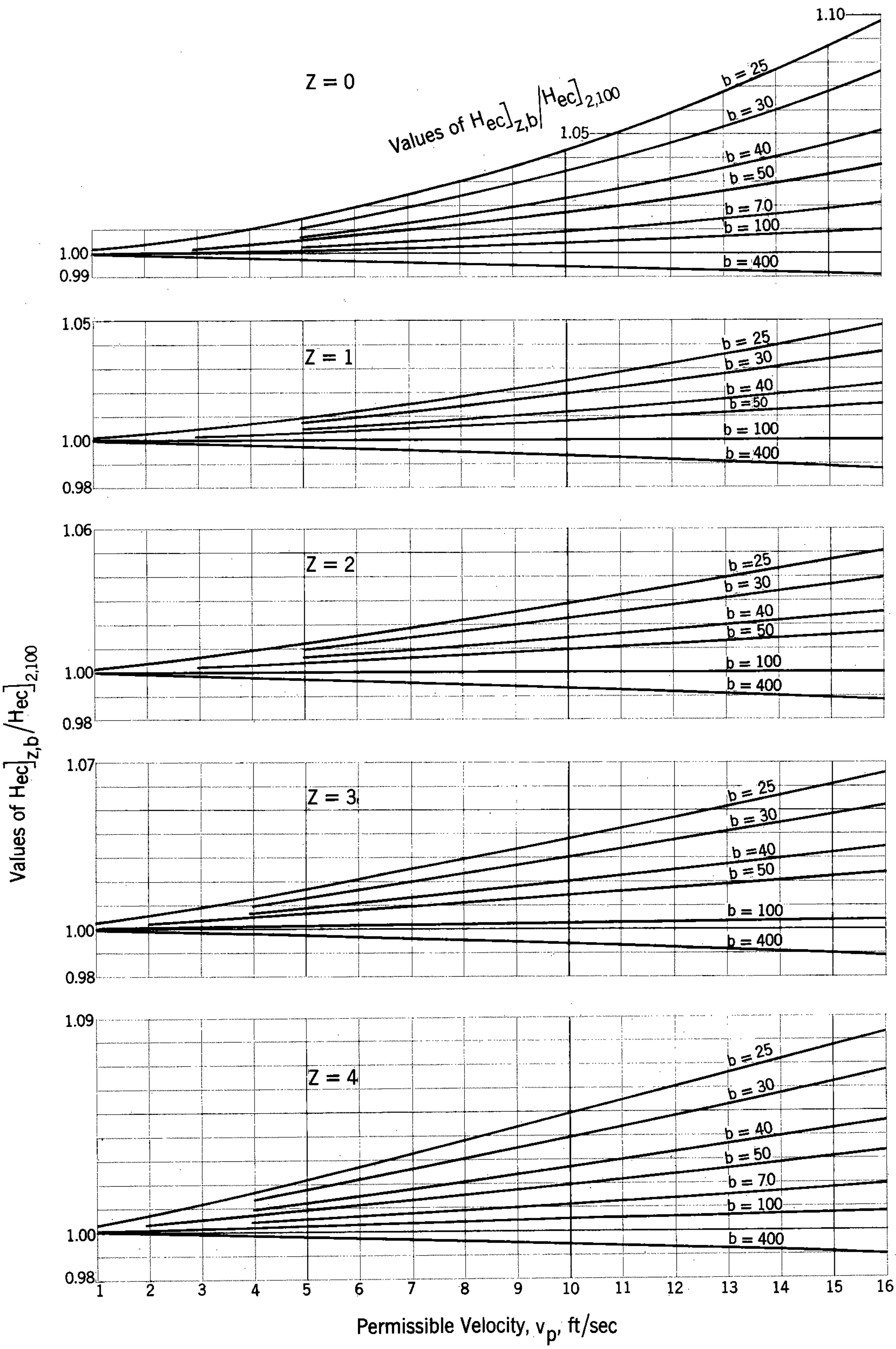
SPILLWAYS: Effect of b and z on Permissible H_{ec}

$\frac{n^2}{s_o} = 0.02$

Z = 0, 1, 2, 3, and 4



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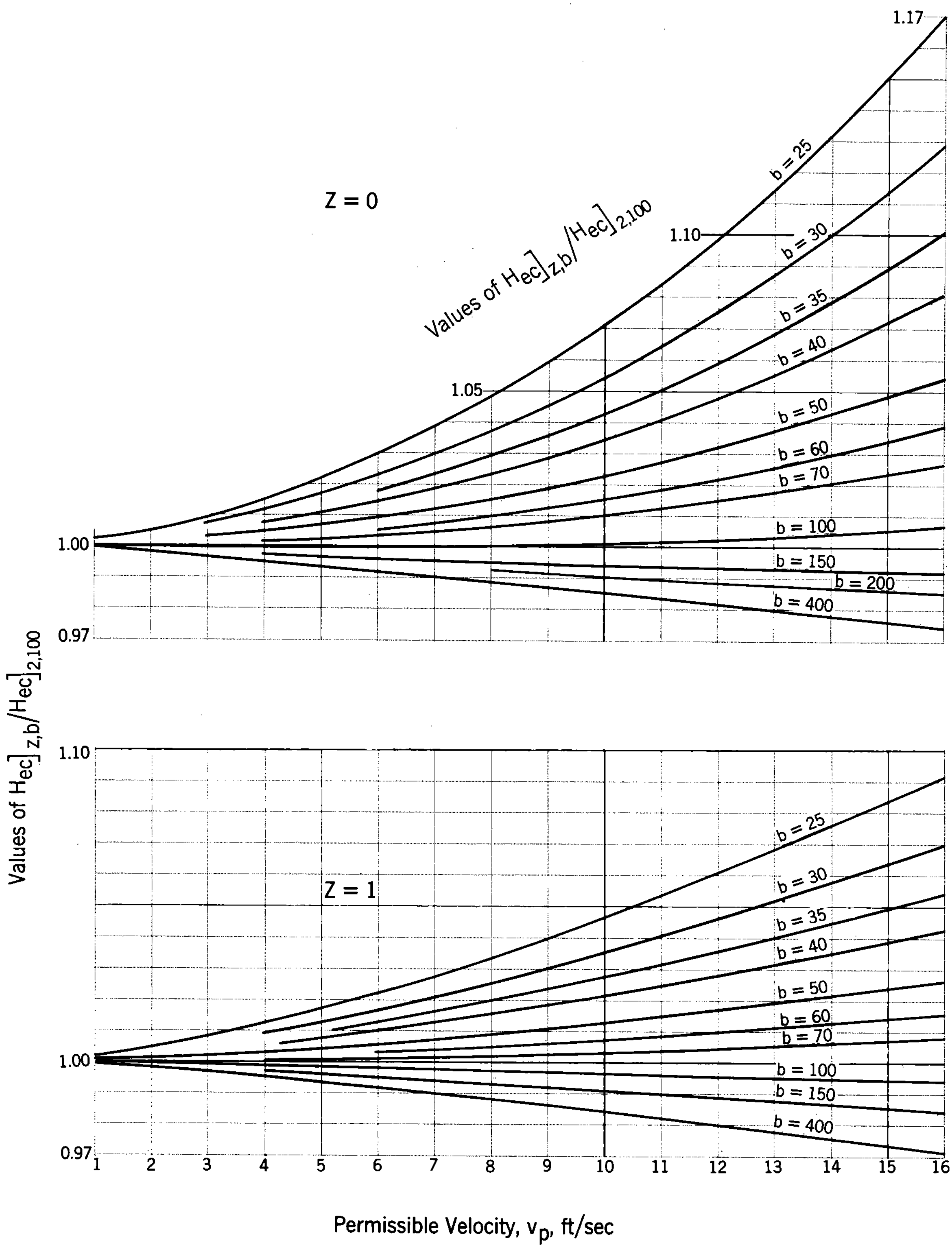
STANDARD DWG. NO.
ES-177
SHEET 2 OF 8
DATE 1-68

SPILLWAYS: Effect of b and z on Permissible H_{ec}

$\frac{n^2}{s_o} = 0.04$
Z = 0 and 1



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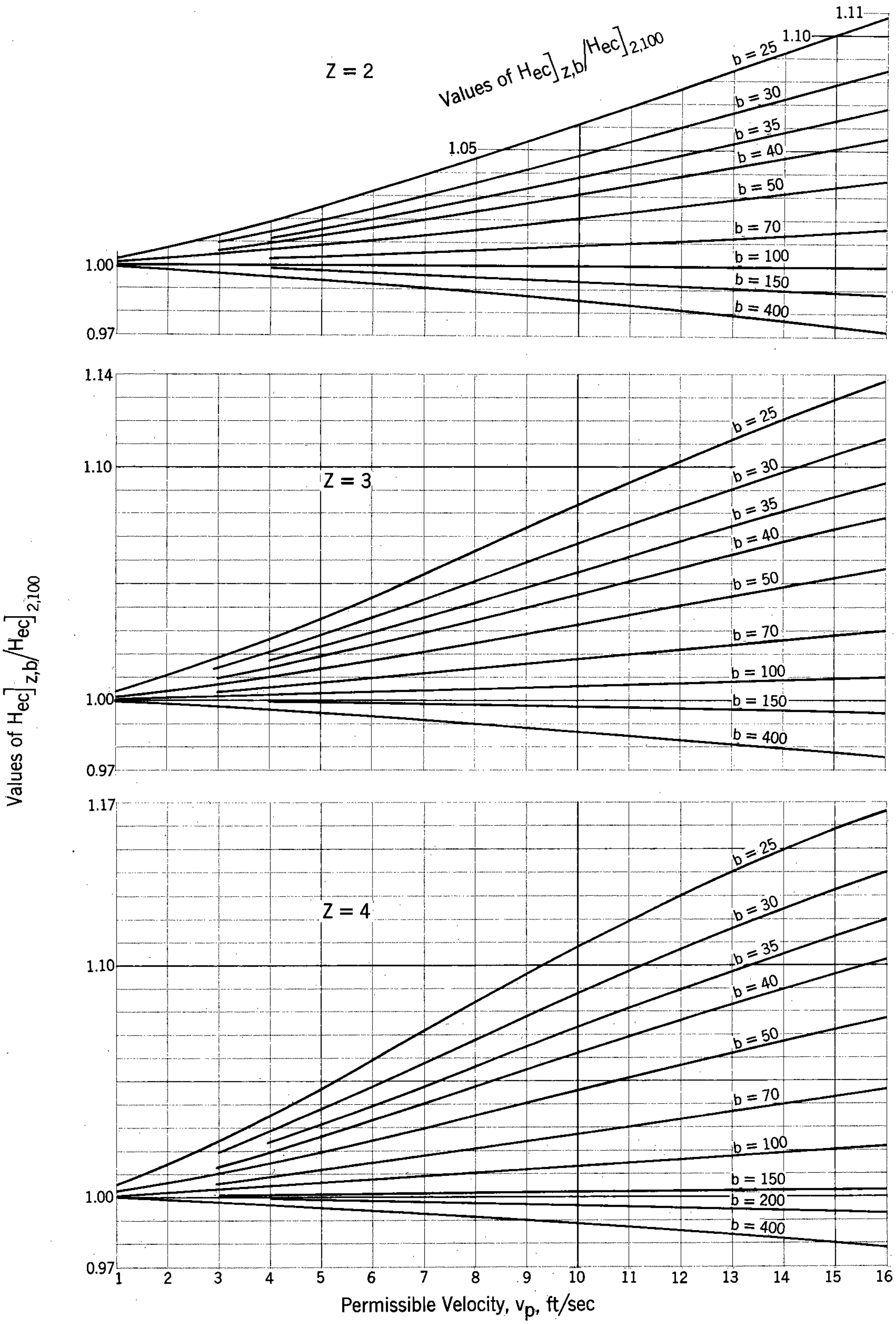
ES-177
SHEET 3 OF 8
DATE 1-68

SPILLWAYS: Effect of b and z on Permissible H_{ec}

$\frac{n^2}{s_o} = 0.04$

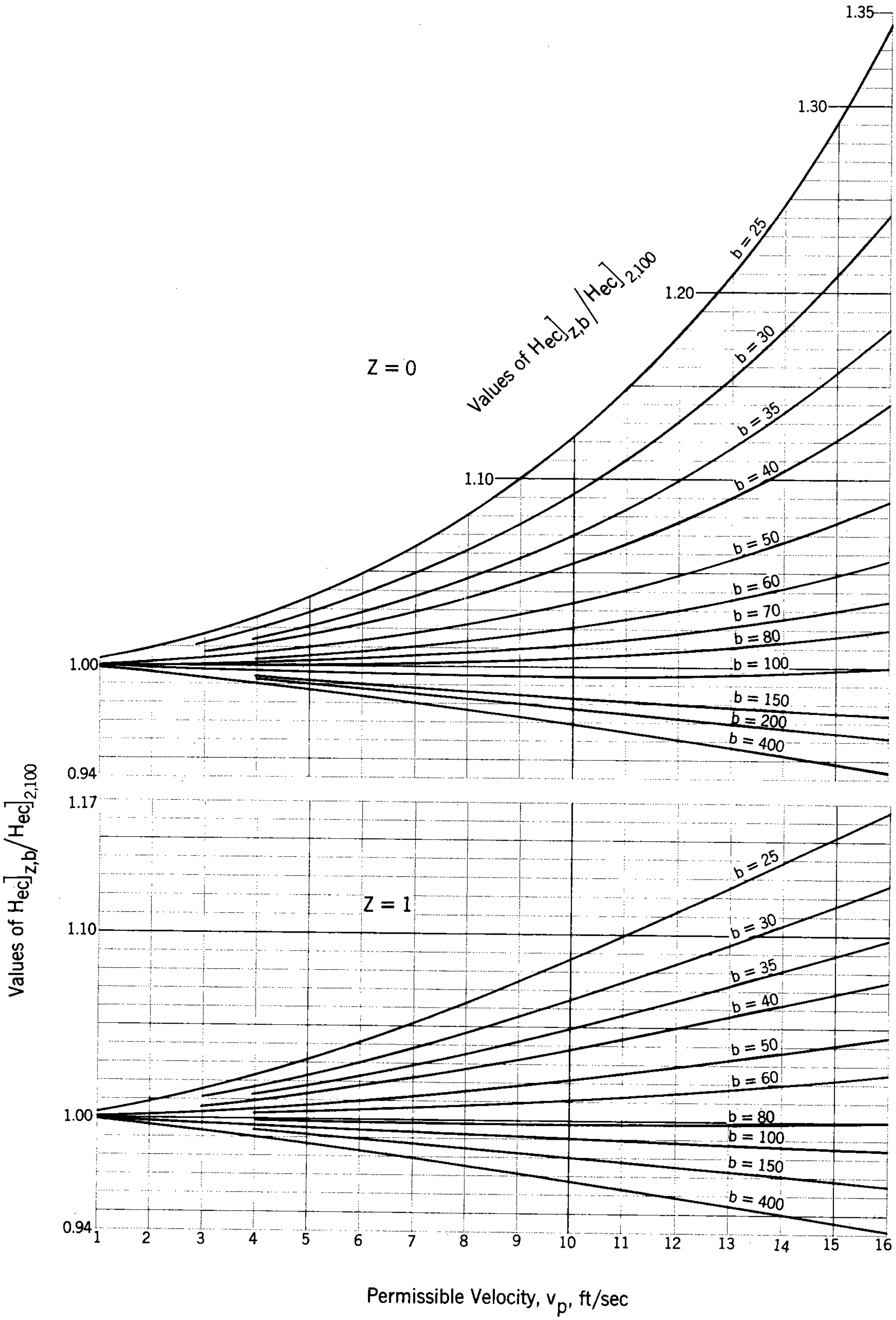
Z = 2, 3, and 4



REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION · DESIGN UNIT	STANDARD DWG. NO. ES-177 SHEET 4 OF 8 DATE 1-68

SPILLWAYS: Effect of b and z on Permissible H_{ec}

$\frac{n^2}{s_o} = 0.08$
Z = 0 and 1



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STANDARD DWG. NO.
ES-177
SHEET 5 OF 8
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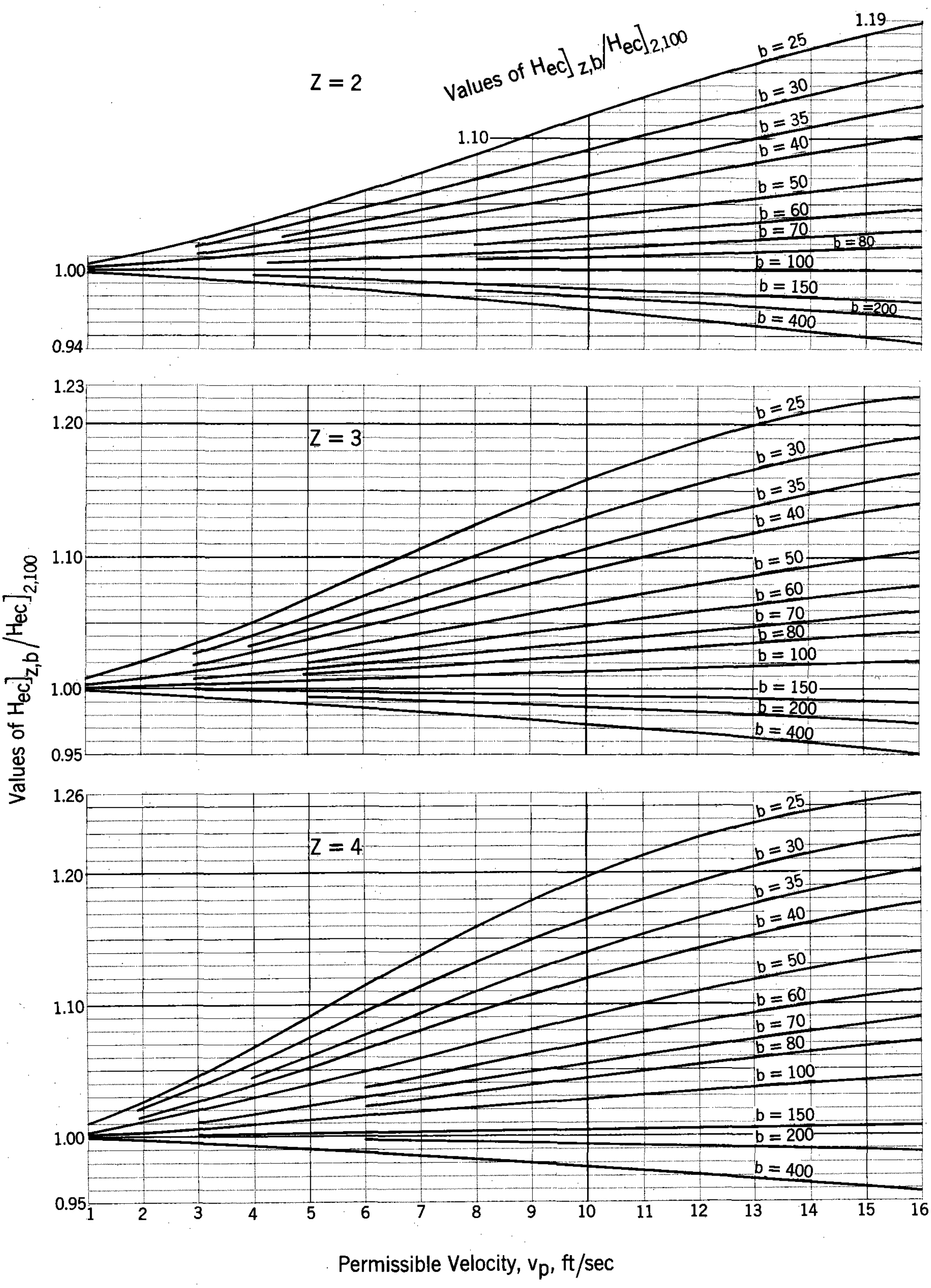
SPILLWAYS: Effect of b and z on Permissible H_{ec}

$\frac{n^2}{s_o} = 0.08$
Z = 2, 3, and 4



REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES-177 SHEET 6 OF 8 DATE 1-68

SPILLWAYS: Examples–Effect of b and z on Permissible H_{ec}

NOMENCLATURE

$H_{ec}]_{2,100}$ ≡ the permissible critical specific energy head for a spillway with $z = 2$ and $b = 100$ ft – ft

$H_{ec}]_{z,b}$ ≡ the permissible critical specific energy head for a spillway with side slopes, z, and bottom width, b – ft

s_o ≡ the exit channel bottom slope – ft/ft

EXAMPLE 1

<u>Given</u>:

Emergency spillway bottom profile as shown in figure

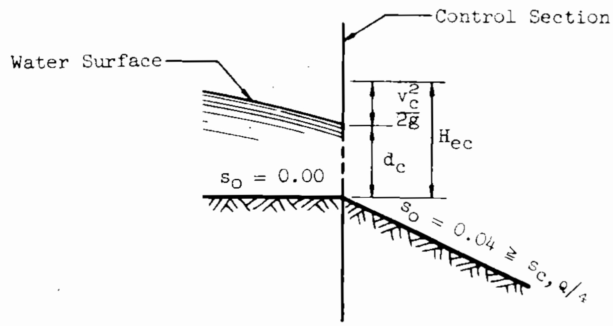
$z = 3$

$b = 50$ ft

$n = 0.04$

$v_p = 8$ ft/sec

$H_{ec}]_{2,100} = 2.06$ ft (obtained from ES-170, sheet 1)



<u>Determine</u>:

Permissible $H_{ec}]_{3,50}$

<u>Solution</u>:

1. Compute $\frac{n^2}{s_o}$

$$\frac{n^2}{s_o} = \frac{(0.04)^2}{0.04} = 0.04$$

2. Use ES-177, sheet 4.
For $z = 3$, $b = 50$ ft, and $v_p = 8$ ft/sec, read

$$H_{ec}]_{z,b} \Big/ H_{ec}]_{2,100} = 1.025.$$

Then $H_{ec}]_{3,50} = 1.025\ H_{ec}]_{2,100} = 1.025(2.06) = 2.11$ ft

EXAMPLE 2

Given:

Emergency spillway bottom profile as shown in figure for Example 1 except that the exit channel bottom slope, s_o, is equal to 0.052.

$z = 4$
$b = 70$ ft
$n = 0.04$
$v_p = 6.0$ ft/sec
$H_{ec}]_{2,100} = 1.12$ ft (obtained from ES-170, sheet 1)

Determine:

Permissible $H_{ec}]_{4,70}$

Solution:

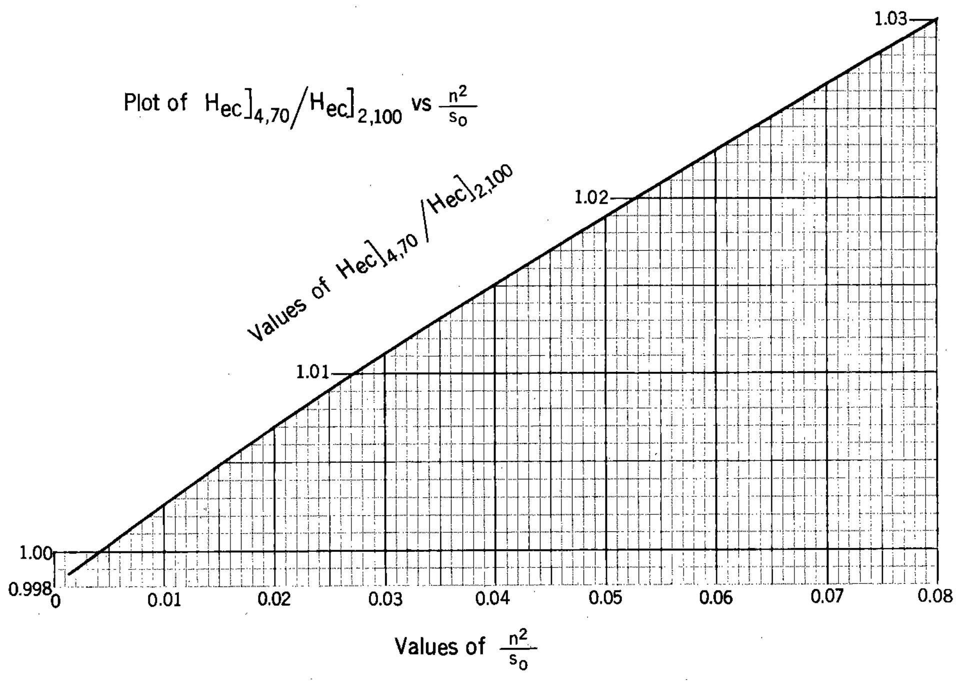
1. Compute $\frac{n^2}{s_o}$

$$\frac{n^2}{s_o} = \frac{(0.04)^2}{0.052} = 0.0308$$

2. Use ES-177.
For $z = 4$, $b = 70$ ft, and $v_p = 6$ ft/sec, read values of $H_{ec}]_{z,b} / H_{ec}]_{2,100}$ for $\frac{n^2}{s_o}$ values of 0.002, 0.02, 0.04, and 0.08.

3. Plot $H_{ec}]_{4,70} / H_{ec}]_{2,100}$ vs $\frac{n^2}{s_o}$

4. For $\frac{n^2}{s_o} = 0.0308$, read from the plot $H_{ec}]_{4,70} / H_{ec}]_{2,100} = 1.011$.
Then $H_{ec}]_{4,70} = 1.011\ H_{ec}]_{2,100} = 1.011(1.12) = 1.13$ ft



SPILLWAYS: Effect of b on Critical Slope

Z = 0
n = 0.04

NOMENCLATURE

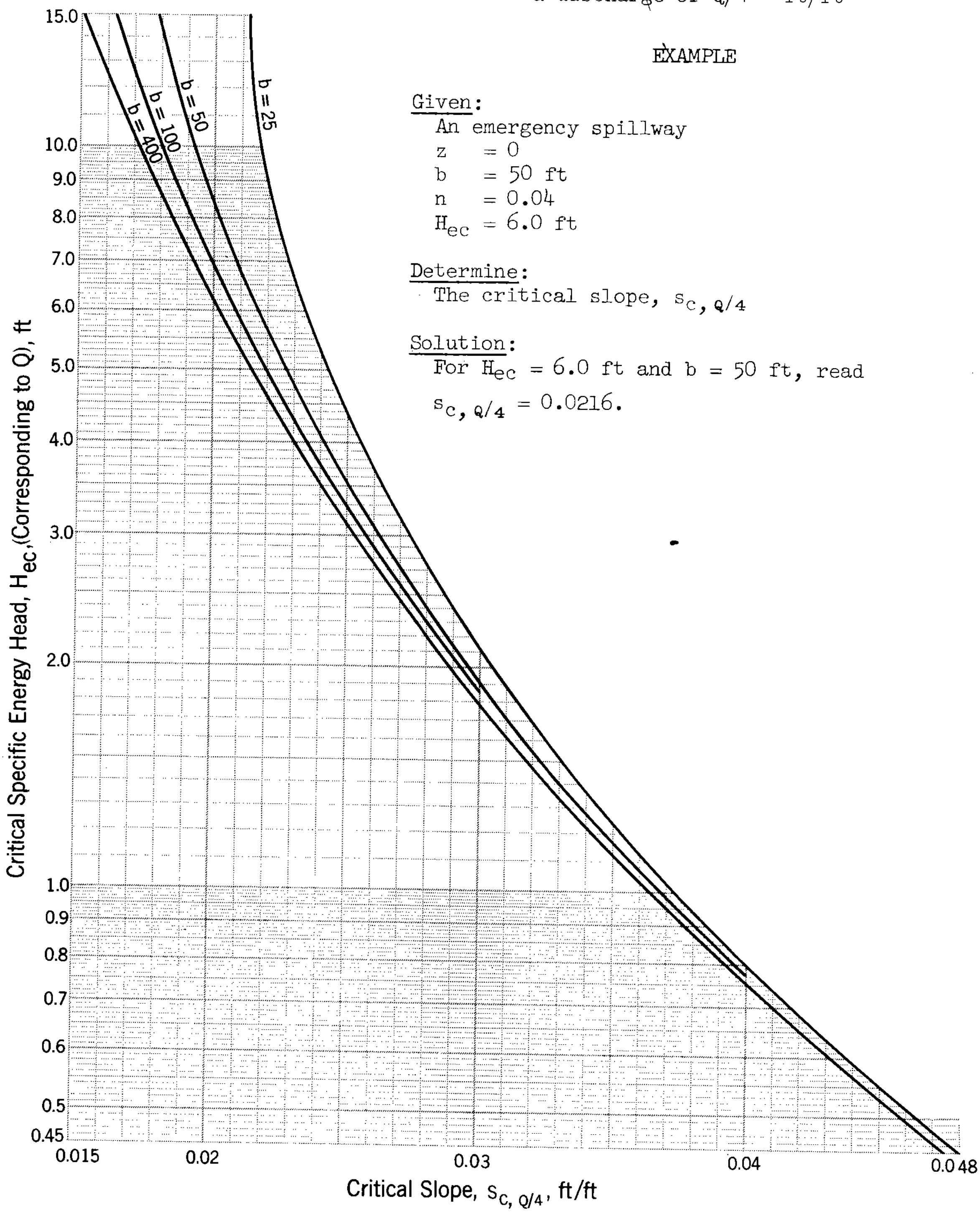
$s_{c,\,Q/4}$ ≡ the critical slope corresponding to a discharge of Q/4 - ft/ft

EXAMPLE

Given:
An emergency spillway
z = 0
b = 50 ft
n = 0.04
H_{ec} = 6.0 ft

Determine:
The critical slope, $s_{c,\,Q/4}$

Solution:
For H_{ec} = 6.0 ft and b = 50 ft, read
$s_{c,\,Q/4}$ = 0.0216.



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SPILLWAYS: Effect of b and z on Critical Slope

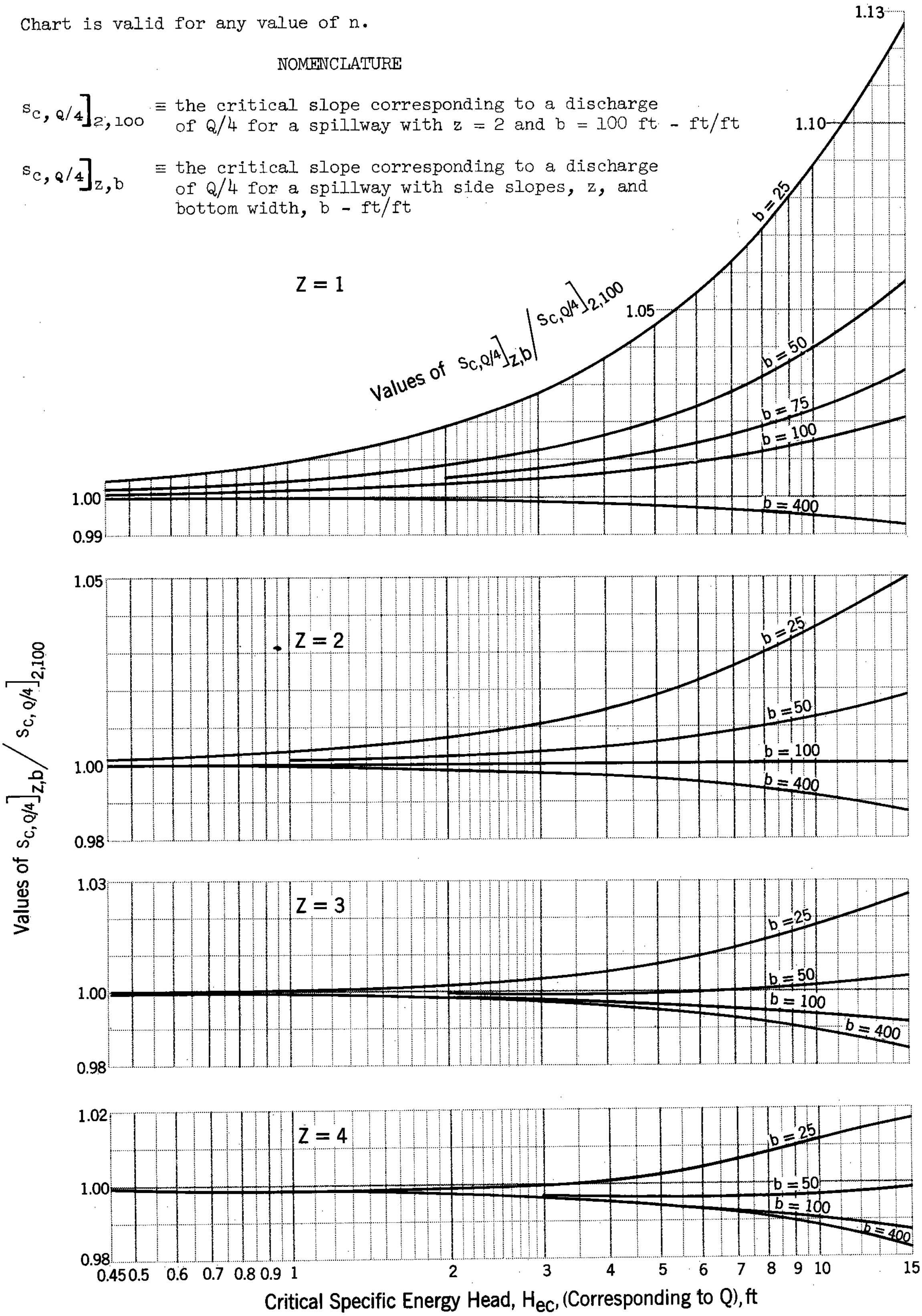
Z = 1, 2, 3, and 4

Chart is valid for any value of n.

NOMENCLATURE

$s_{c,Q/4}\big]_{2,100}$ ≡ the critical slope corresponding to a discharge of Q/4 for a spillway with z = 2 and b = 100 ft - ft/ft

$s_{c,Q/4}\big]_{z,b}$ ≡ the critical slope corresponding to a discharge of Q/4 for a spillway with side slopes, z, and bottom width, b - ft/ft



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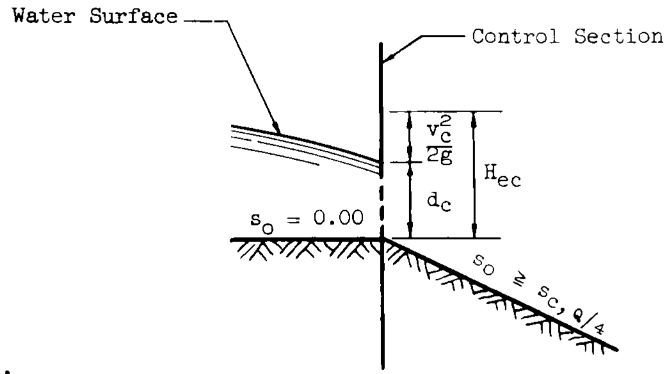
ENGINEERING DIVISION - DESIGN UNIT

STANDARD DWG. NO.
ES - 178
SHEET 2 OF 3
DATE 1-68

EXAMPLE

Given:

$H_{ec} = 4.5$ ft
$z = 1$
$b = 75$ ft
$n = 0.04$
$\left.s_{c,Q/4}\right]_{2,100} = 0.0221$ (obtained from ES-172)



Determine:

$\left.s_{c,Q/4}\right]_{1,75}$

Solution:

Use ES-178, sheet 2.
For $z = 1$, $b = 75$ ft, and $H_{ec} = 4.5$ ft, read
$\left.s_{c,Q/4}\right]_{z,b} \Big/ \left.s_{c,Q/4}\right]_{2,100} = 1.011$
Then $\left.s_{c,Q/4}\right]_{1,75} = 1.011\left(\left.s_{c,Q/4}\right]_{2,100}\right) = (1.011)(0.0221) = 0.0223$

EXAMPLE 1

Given:

Emergency spillway bottom profile as shown in figure

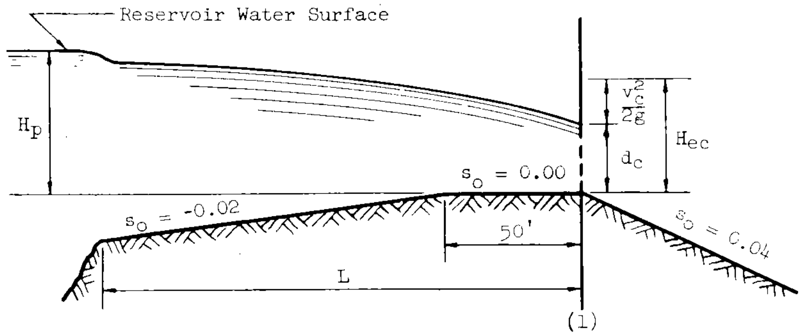
$z = 2$

$b = 100$ ft

$n = 0.04$

$L = 300$ ft

$v_p = 6$ ft/sec



Determine:

I. Permissible H_{ec}

II. The discharge, Q, corresponding to the permissible H_{ec}

III. Critical slope for Q/4, $s_{c,\,Q/4}$

IV. The energy head, H_p, above the crest at the distance, L, upstream from section (1)

Solution:

I. Determine permissible H_{ec}
Use ES-170, sheet 1.
For $s_o = 0.04$ and $v_p = 6$ ft/sec, read permissible $H_{ec} = 1.28$ ft.

II. Determine Q
Use ES-174, sheet 2.
For $H_{ec} = 1.28$ ft and $b = 100$ ft, read $Q = 457$ cfs.

III. Determine $s_{c,\,Q/4}$
Use ES-170, sheet 1 or ES-172, sheet 1.
For $H_{ec} = 1.28$ ft, read $s_{c,\,Q/4} = 0.0334$.

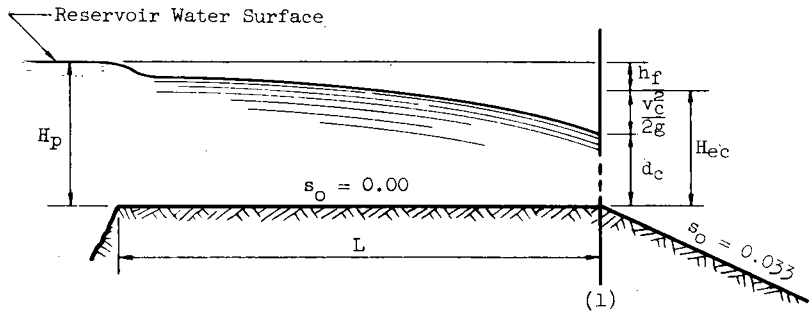
Since the exit channel bottom slope, s_o, is greater than $s_{c,\,Q/4}$, a control section exists at section (1) for discharges in the interval Q/4 to Q.

IV. Determine H_p
Use ES-171, sheet 4.
For $H_{ec} = 1.28$ ft and $L = 300$ ft, read $H_p = 1.72$ ft.

EXAMPLE 2

Given:

Emergency spillway bottom profile as shown in figure
$z = 3$
$n = 0.035$
$L = 200$ ft
$v_p = 7$ ft/sec



Determine:

I. For $b = 100$ ft, $z = 2$, and $n = 0.035$
   A. Permissible H_{ec}
   B. The energy head, H_p, corresponding to the permissible H_{ec}

II. The required spillway bottom width, b, assuming that the routing of the emergency spillway hydrograph yields a maximum discharge, Q, of 450 cfs corresponding to the permissible H_p.

III. For the b determined in II, $z = 3$, and $n = 0.035$
   A. Permissible H_{ec}
   B. s_c, Q/4
   C. H_p corresponding to the permissible H_{ec}

Solution:

I. For $b = 100$ ft, $z = 2$, and $n = 0.035$
   A. Determine permissible H_{ec}
   Use ES-170, sheet 1.
   Since the value of n is not 0.04, the abscissa of sheet 1 will be redesignated as $\left[\frac{0.04}{n}\right]^2 s_o$.

   For $\left[\frac{0.04}{n}\right]^2 s_o = \left[\frac{0.04}{0.035}\right]^2 \left[0.033\right] = 0.0431$ and $v_p = 7$ ft/sec,

   read permissible $H_{ec} = 1.58$ ft.

   B. Determine H_p

   1. Use ES-171, sheet 1.
   For $H_{ec} = 1.58$ ft, $L = 200$ ft, and $n = 0.04$, read $H_p = 2.35$ ft.

   Then the head loss, $h_{f,0.04}$, assuming $n = 0.04$ is

   $h_{f,0.04} = H_p - H_{ec} = 2.35 - 1.58 = 0.77$ ft

2. Use ES-176, sheet 1 and a graphical procedure similar to that used in Example 2 of ES-176.
   For H_{ec} = 1.58 ft, L = 200 ft, and n = 0.035, obtain
   $h_{f,0.035}/h_{f,0.04} = 0.87$.
   $h_{f,0.035} = 0.87(h_{f,0.04}) = 0.87(0.77) = 0.67$ ft
   The value of H_p adjusted for the n value is given by
   $H_p = H_{ec} + h_{f,0.035} = 1.58 + 0.67 = 2.25$ ft

II. Determine b with z = 3
Use ES-175, sheet 5.
For H_{ec} = 1.58 ft and Q = 450 cfs, read b = 70 ft.

III. For b = 70 ft, z = 3, and n = 0.035
A. Determine permissible H_{ec}
Use ES-177 and the procedure used in Example 2 of ES-177.
$\frac{n^2}{s_o} = \frac{(0.035)^2}{0.033} = 0.0371$
For z = 3, b = 70 ft, and v_p = 7 ft/sec, obtain
$H_{ec}\big]_{3,70} \big/ H_{ec}\big]_{2,100} = 1.01$.
$H_{ec}\big]_{3,70} = 1.01\ H_{ec}\big]_{2,100} = 1.01(1.58) = 1.60$ ft

B. Determine $s_{c,\,Q/4}$
1. Use ES-172, sheet 1.
   Since the value of n is not 0.04, the abscissa of ES-172, sheet 1 will be redesignated $\left[\frac{0.04}{n}\right]^2 s_{c,\,Q/4}\Big]_n$.
   For z = 2, b = 100 ft, H_{ec} = 1.60 ft, and n = 0.04, read $s_{c,\,Q/4} = 0.0311$.
   For z = 2, b = 100 ft, H_{ec} = 1.60 ft, and n = 0.035,
   compute $s_{c,\,Q/4}\Big]_{0.035} = \left[\frac{0.035}{0.04}\right]^2 s_{c,\,Q/4}$
   $= (0.766)(0.0311) = 0.0238$
2. Use ES-178, sheet 2.
   For z = 3, b = 70 ft, and H_{ec} = 1.60 ft, read
   $s_{c,\,Q/4}\Big]_{z,b} \Big/ s_{c,\,Q/4}\Big]_{2,100} = 0.999$.
   Then $s_{c,\,Q/4}\Big]_{3,70} = 0.999\ s_{c,\,Q/4}\Big]_{2,100}$
   $= 0.999(0.0238) = 0.0238$
   This is the $s_{c,\,Q/4}$ for z = 3, b = 70 ft, H_{ec} = 1.60 ft, and n = 0.035. The exit channel bottom slope, s_o, is greater than $s_{c,\,Q/4}$; therefore, a control section exists at section (1) for discharges in the interval Q/4 to Q.

C. Determine H_p

1. Use ES-171, sheet 1.
For $b = 100$ ft, $z = 2$, $n = 0.04$, $L = 200$ ft, and $H_{ec} = 1.60$ ft, read $H_p = 2.37$ ft.
Then the head loss, $h_f]_{Ref}$, assuming the Reference Section is

$h_f]_{Ref} = H_p - H_{ec} = 2.37 - 1.60 = 0.77$ ft

2. Use ES-176, sheet 1 and a graphical procedure similar to that in Example 2 of ES-176.
For $H_{ec} = 1.60$ ft, $L = 200$ ft, and $n = 0.035$, obtain

$h_{f,0.035}/h_{f,0.04} = 0.87$.

$h_{f,0.035} = 0.87(h_{f,0.04}) = 0.87(0.77) = 0.67$ ft

Then $\Delta h_{f,n} = h_{f,0.035} - h_{f,0.04} = 0.67 - 0.77 = -0.10$ ft

3. Use ES-176, sheet 4.
For $H_{ec} = 1.60$ ft, $L = 200$ ft, and $b = 70$ ft, read

$h_{f,b}/h_{f,100} = 1.002$. (This was obtained from a plot of b vs $h_{f,b}/h_{f,100}$.)

$h_{f,70} = 1.002(h_{f,100}) = 1.002(0.77) = 0.77$ ft

Then $\Delta h_{f,b} = h_{f,70} - h_{f,100} = 0.77 - 0.77 = 0$ ft

4. Use ES-176, sheet 6.
For $H_{ec} = 1.60$ ft, $L = 200$ ft, and $z = 3$, read

$h_{f,z}/h_{f,2} = 0.999$. (This was obtained from a plot of z vs $h_{f,z}/h_{f,2}$.)

$h_{f,3} = 0.999(h_{f,2}) = 0.999(0.77) = 0.77$ ft

Then $\Delta h_{f,z} = h_{f,3} - h_{f,2} = 0.77 - 0.77 = 0$ ft

5. The total change in friction head loss, Δh_f, is given by

$\Delta h_f = \Delta h_{f,n} + \Delta h_{f,b} + \Delta h_{f,z} = -0.10 + 0 + 0 = -0.10$ ft

Then $h_f = h_f]_{Ref} + \Delta h_f = 0.77 - 0.10 = 0.67$ ft

$H_p = H_{ec} + h_f = 1.60 + 0.67 = 2.27$ ft