APPENDIX B

HYDRAULIC DESIGN DATA FOR CULVERTS

B-1. General.

a. This appendix presents diagrams, charts, coefficients and related information useful in design of culverts. The information largely has been obtained from the U.S. Department of Transportation, Federal Highway Administration (formerly, Bureau of Public Roads), supplemented or modified as appropriate by information from various other sources and as required for consistency with design practice of the Corps of Engineers.

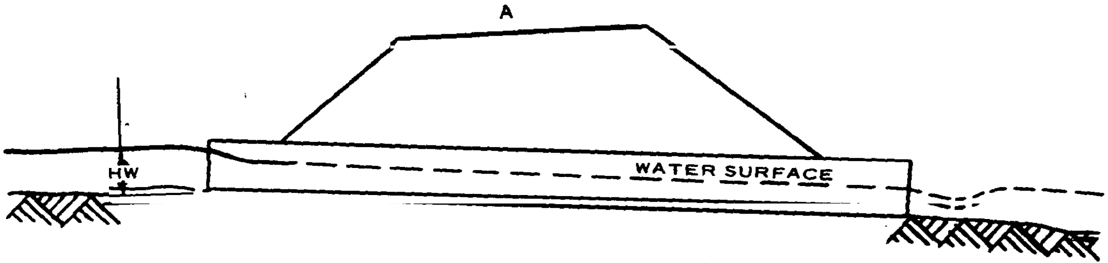
b. Laboratory tests and field observations show two major types of culvert flow: flow with inlet control and flow with outlet control. Under inlet control, the cross-sectional area of the culvert barrel, the inlet geometry and the amount of headwater or pending at the entrance are of primary importance. Outlet control involves the additional consideration of the elevation of the tailwater in the outlet channel and the slope, roughness, and length of the culvert barrel. The type of flow or the location of the control is dependent on the quantity of flow, roughness of the culvert barrel, type of inlet, flow pattern in the approach channel, and other factors. In some instances the flow control changes with varying discharges, and occasionally the control fluctuates from inlet control to outlet control and vice versa for the same discharge. Thus, the design of culverts should consider both types of flow and should be based on the more adverse flow condition anticipated.

B-2. Inlet control. The discharge capacity of a culvert is controlled at the culvert entrance by the depth of headwater (HIV) and the entrance geometry, including the area, slope, and type of inlet edge. Types of inlet-controlled flow for unsubmerged and submerged entrances are shown at A and B in figure B–1. A mitered entrance (fig B–lC) produces little if any improvement in efficiency over that of the straight, sharp-edged, projecting inlet. Both types of inlets tend to inhibit the culvert from flowing full when the inlet is submerged. With inlet control the roughness and length of the culvert barrel and outlet conditions (including depths of tailwater) are not factors in determining culvert capacity. The effect of the barrel slope *on* inlet-control flow in conventional culverts is negligible. Nomography for determining culvert capacity for inlet control were developed by the Division of Hydraulic Research, Bureau of Public Roads. (See *Hydraulics of Bridge Wateways.)* These nomography (figs B–2 through B–9) give headwater-discharge relations for most conventional culverts flowing with inlet control,

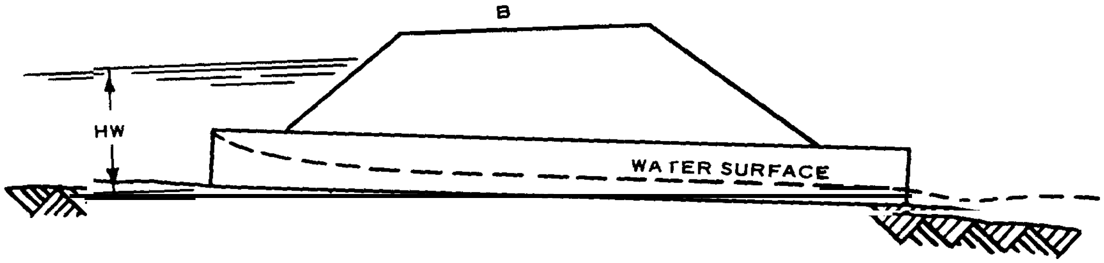
B-3. Outlet control.

a. Culverts flowing with outlet control can flow with the culvert barrel full or partially full for part of the barrel length or for all of it (fig B–10). If the entire barrel is filled (both cross section and length) with water, the culvert is said to be in full flow or flowing full (fig B–1OA and B). The other two common types of outlet-control flow are shown in figure B–1OC and D. The procedure given in this appendix for outlet-control flow does not give an exact solution for a free-water-surface condition throughout the barrel length shown in figure B-1OD. An approximate solution is given for this case when the headwater, HW, is equal to or greater than 0.75D, where D is the height of the culvert barrel. The head, H, required to pass a given quantity of water through a culvert flowing full with control at the outlet is made up of three major parts. These three parts are usually expressed in feet of water and include a velocity head, an **en**trance loss, and a friction loss. The velocity head (the kinetic energy of the water in the culvert barrel) equals $\frac{V^2}{2g}$. The entrance loss varies with the type or design of the culvert inlet and is expressed as a coefficient& times the velocity head or $K_e\frac{V^2}{2g}$. Values of K_e for various types of culvert entrances are given in table B–1. The friction loss, H_f, is the energy required to overcome the roughness of the culvert barrel and is usually expressed in terms of Manning's n and the following expression:

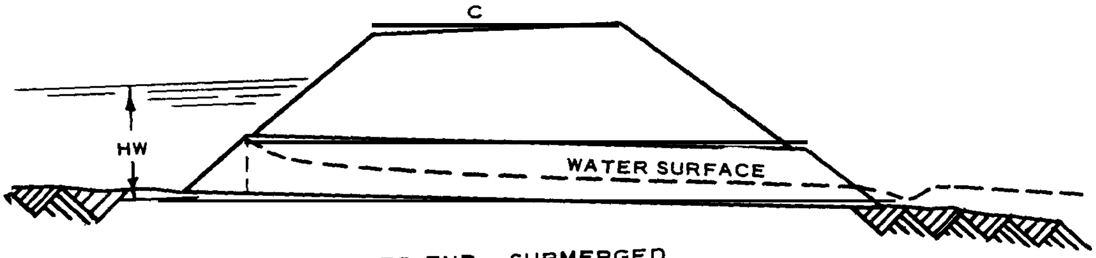
$$H_f = \left(\frac{29n^2L}{R^{1.333}}\right)\left(\frac{V^2}{2g}\right)$$



SQUARE END – UNSUBMERGED



SQUARE END-SUBMERGED



MITERED END – SUBMERGED

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Figure B-1. Inlet control.

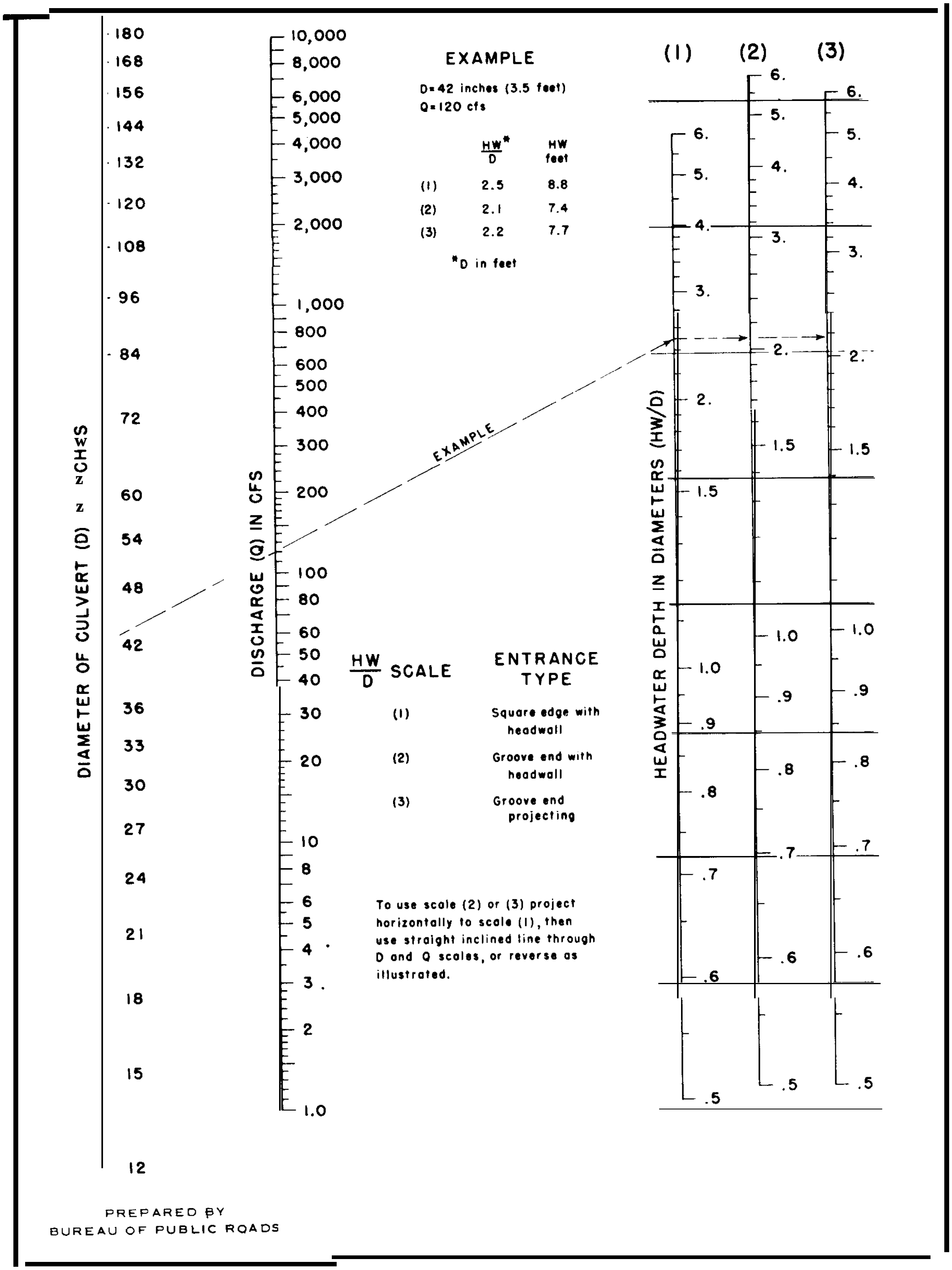
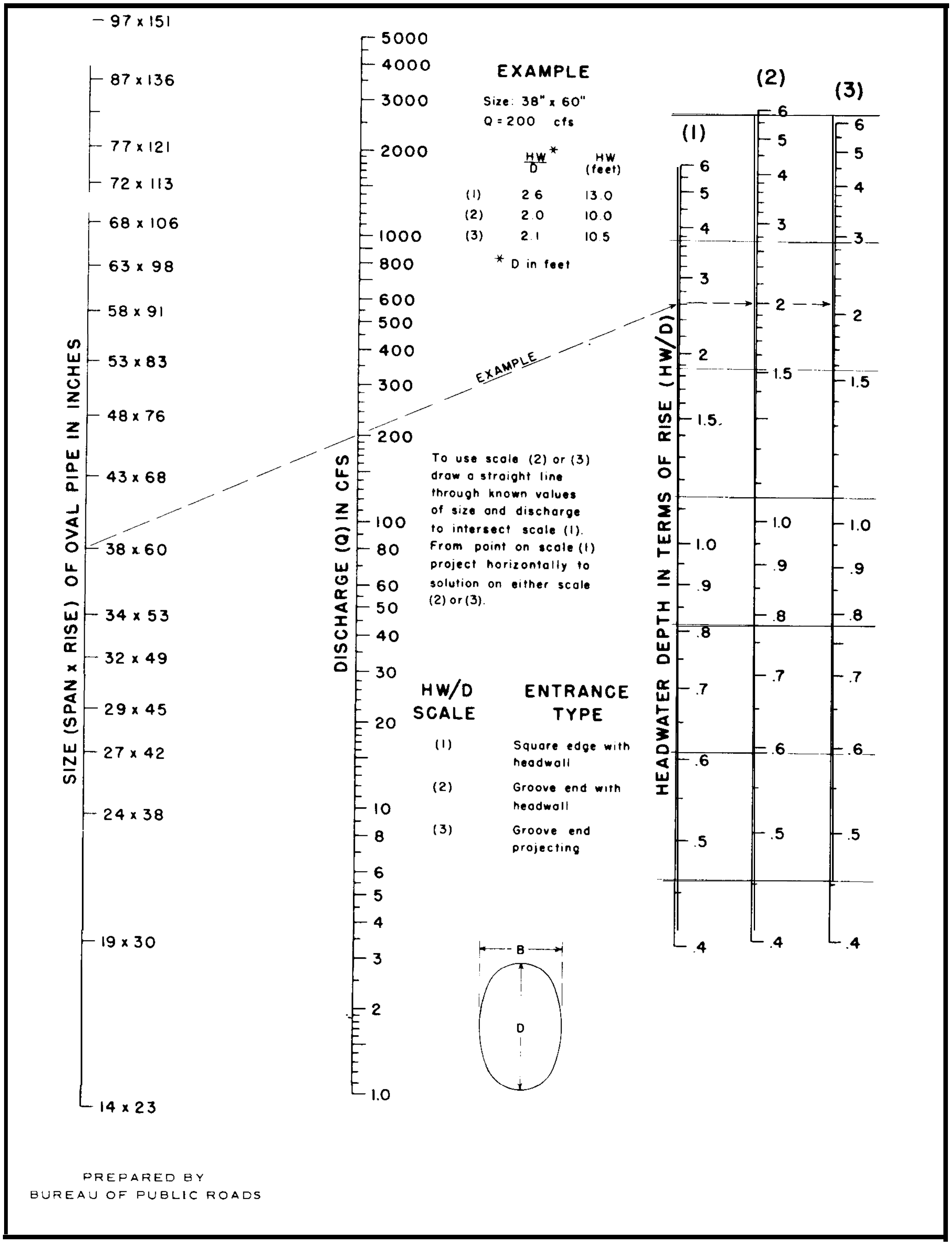


Figure B–2. Headwater depth for concrete pipe culverts with inlet control.



EXAMPLE

Size: 38" x 60"
Q = 200 cfs

	HW/D*	HW (feet)
(1)	2.6	13.0
(2)	2.0	10.0
(3)	2.1	10.5

* D in feet

To use scale (2) or (3) draw a straight line through known values of size and discharge to intersect scale (1). From point on scale (1) project horizontally to solution on either scale (2) or (3).

HW/D SCALE	ENTRANCE TYPE
(1)	Square edge with headwall
(2)	Groove end with headwall
(3)	Groove end projecting

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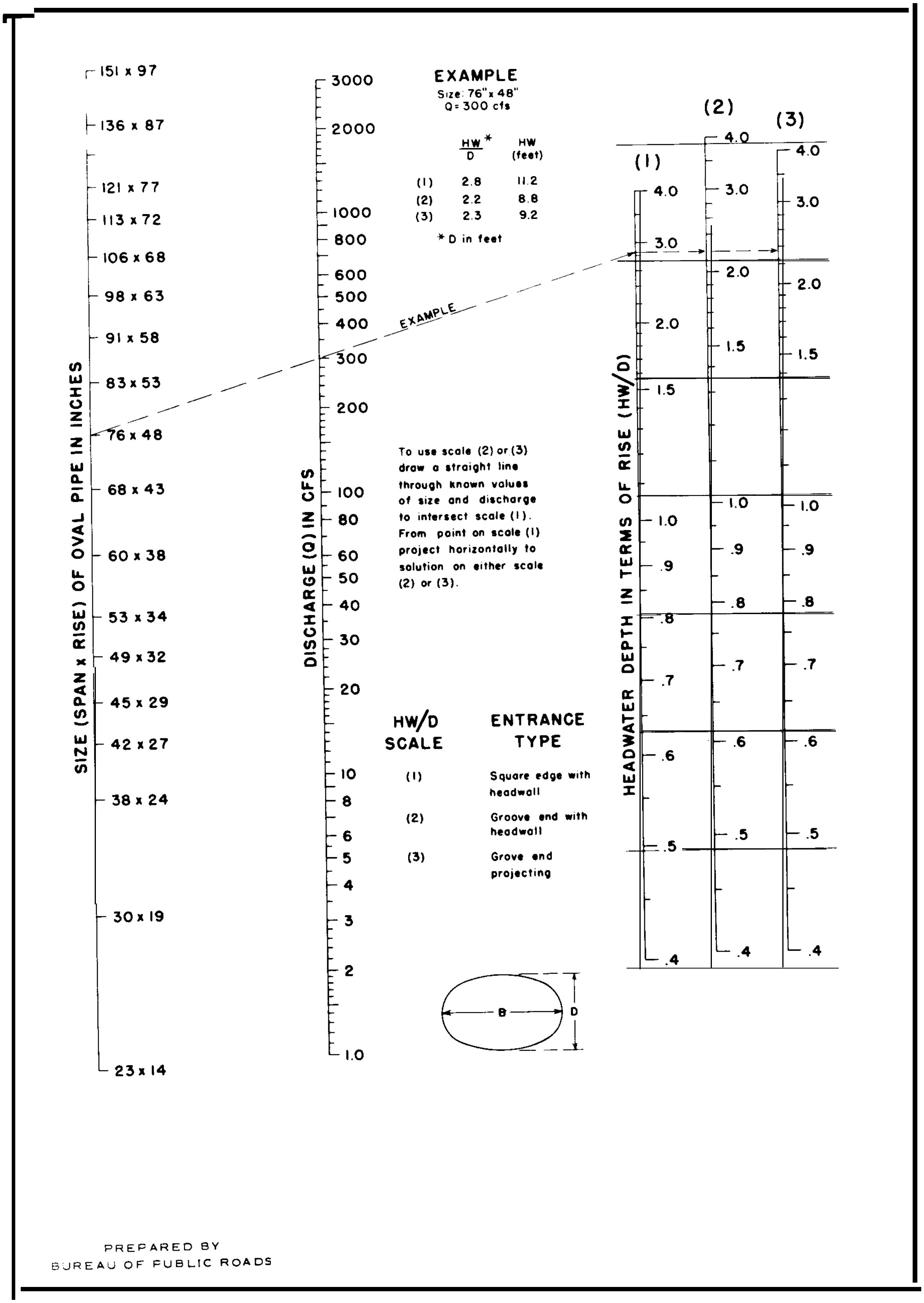
Figure B-3. Headwater depth for oval concrete pipe culverts long axis vertical with inlet control.



EXAMPLE

Size: 76" x 48"
Q = 300 cfs

	$\frac{HW}{D}$*	HW (feet)
(1)	2.8	11.2
(2)	2.2	8.8
(3)	2.3	9.2

*D in feet

To use scale (2) or (3) draw a straight line through known values of size and discharge to intersect scale (1). From point on scale (1) project horizontally to solution on either scale (2) or (3).

HW/D SCALE	ENTRANCE TYPE
(1)	Square edge with headwall
(2)	Groove end with headwall
(3)	Grove end projecting

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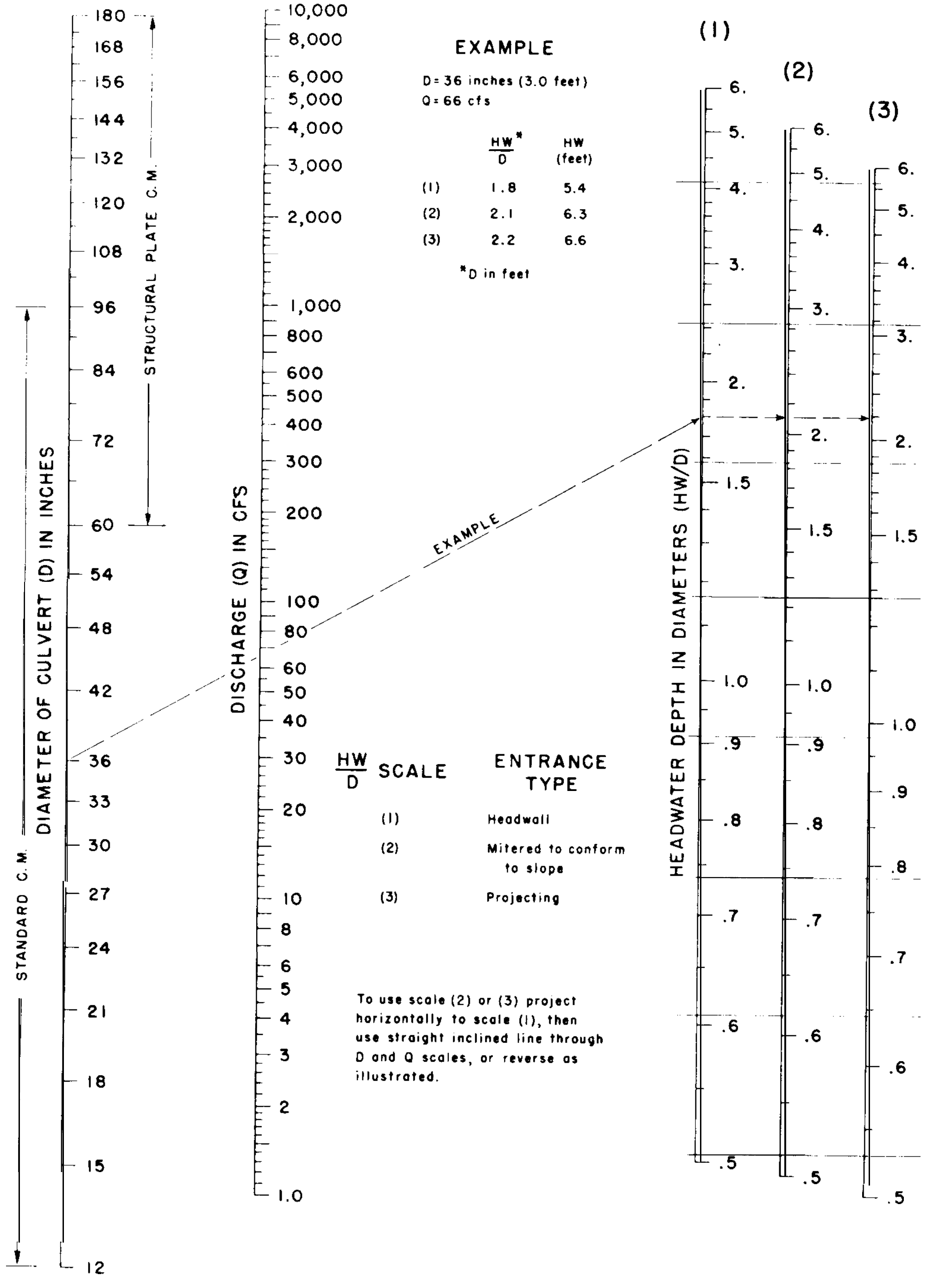
Figure B-4. Headwater depth *for oval* concrete pipe culverts long axis horizontal *with inlet control.*



EXAMPLE

D = 36 inches (3.0 feet)
Q = 66 cfs

	$\frac{HW}{D}$*	HW (feet)
(1)	1.8	5.4
(2)	2.1	6.3
(3)	2.2	6.6

*D in feet

$\frac{HW}{D}$ SCALE	ENTRANCE TYPE
(1)	Headwall
(2)	Mitered to conform to slope
(3)	Projecting

To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scales, or reverse as illustrated.

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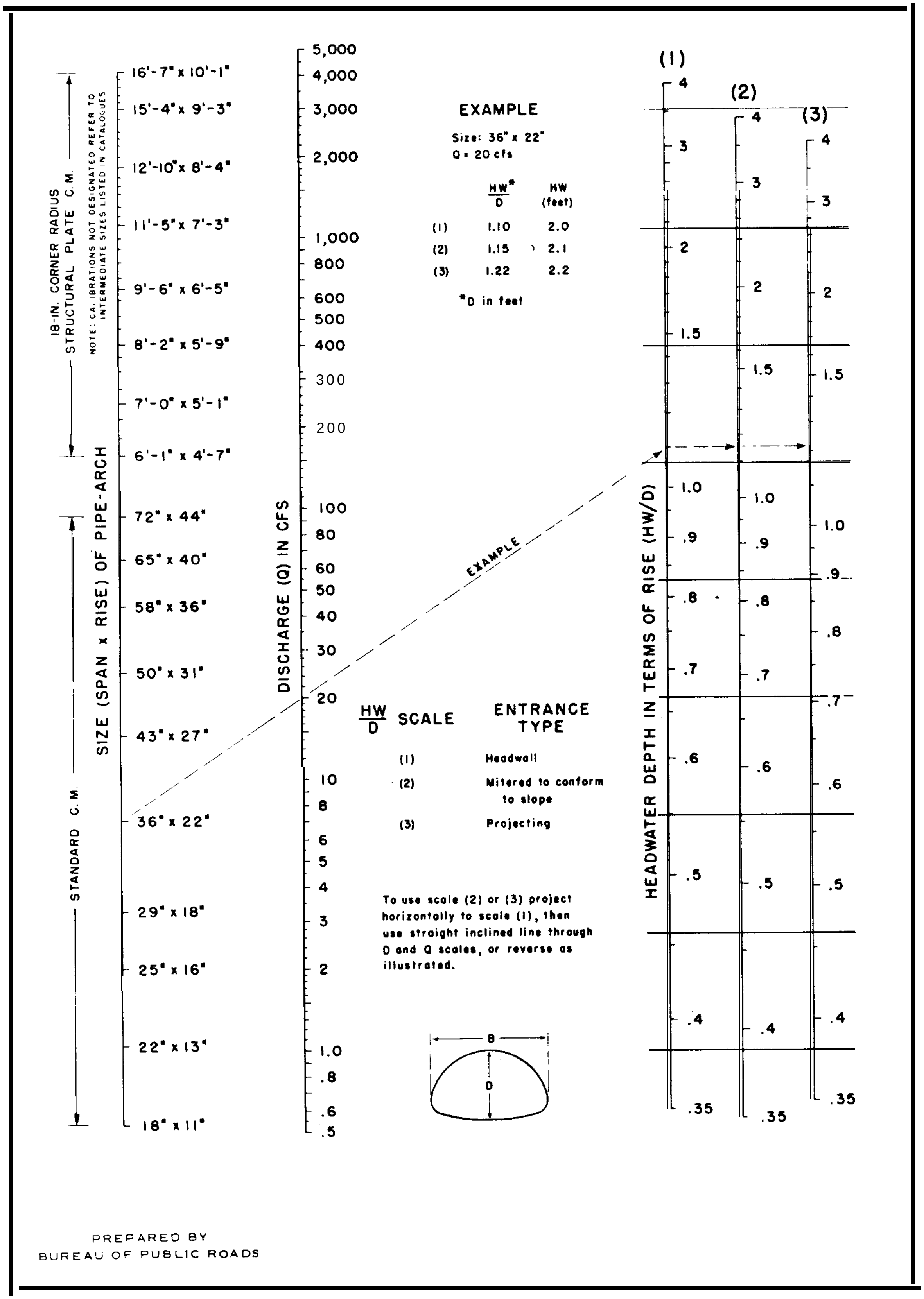
Figure B–5. Headwater depth for corrugated metal pipe culverts with inlet control.



EXAMPLE

Size: 36" x 22"
Q = 20 cfs

	$\frac{HW}{D}$*	HW (feet)
(1)	1.10	2.0
(2)	1.15	2.1
(3)	1.22	2.2

*D in feet

$\frac{HW}{D}$ SCALE	ENTRANCE TYPE
(1)	Headwall
(2)	Mitered to conform to slope
(3)	Projecting

To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scales, or reverse as illustrated.

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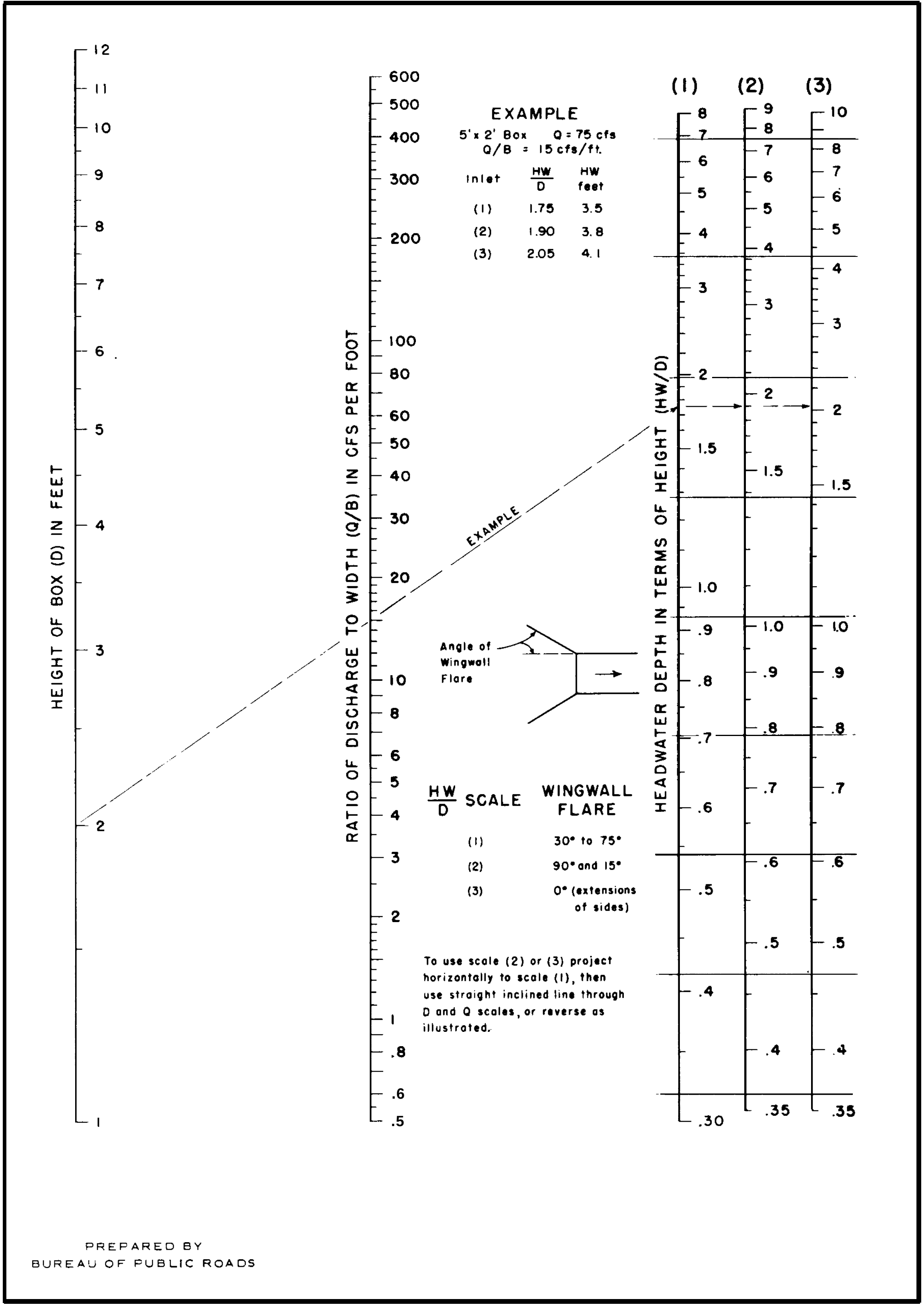
Figure B–6. Headwater depth for structural plate and standard corrugated metal pipe-arch culverts with inlet control.



EXAMPLE

5' x 2' Box   Q = 75 cfs
Q/B = 15 cfs/ft.

Inlet	$\frac{HW}{D}$	HW feet
(1)	1.75	3.5
(2)	1.90	3.8
(3)	2.05	4.1

$\frac{HW}{D}$ SCALE	WINGWALL FLARE
(1)	30° to 75°
(2)	90° and 15°
(3)	0° (extensions of sides)

To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scales, or reverse as illustrated.

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Figure B-7. Headwater depth for box culverts with inlet control.

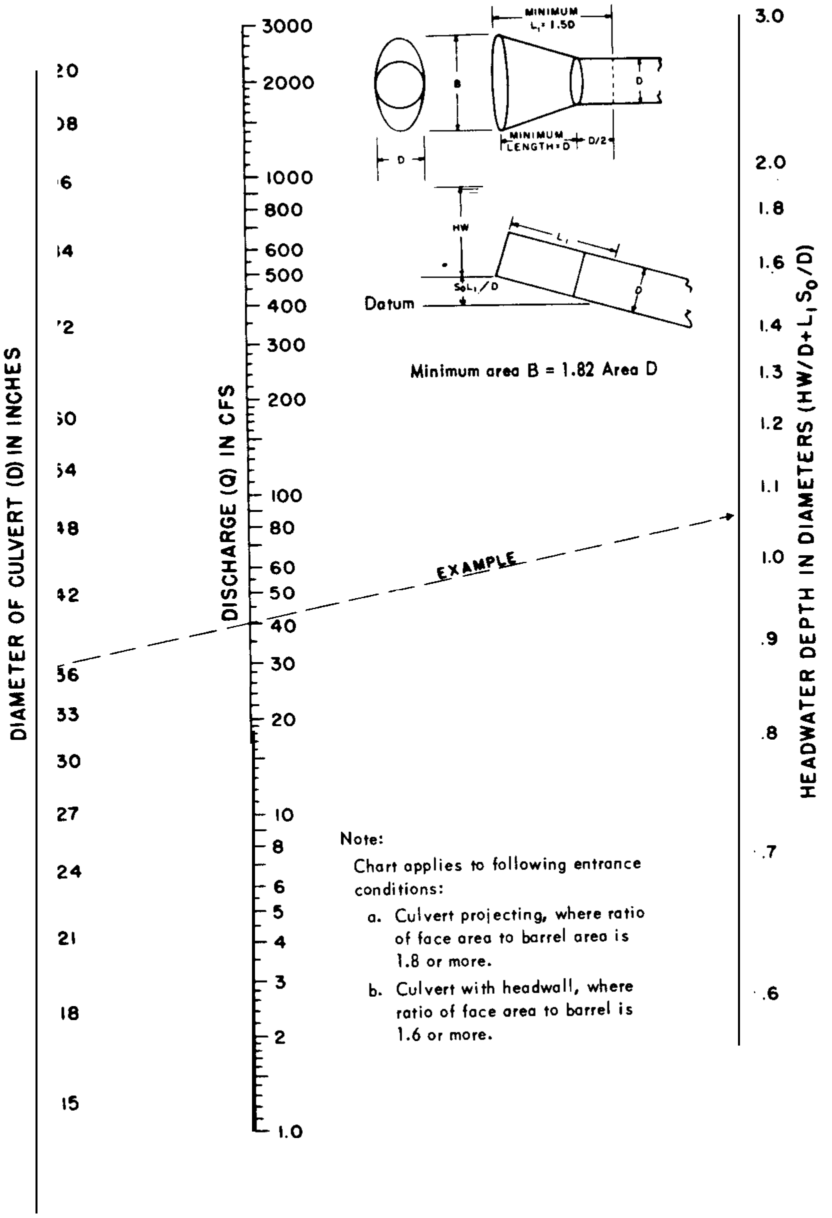

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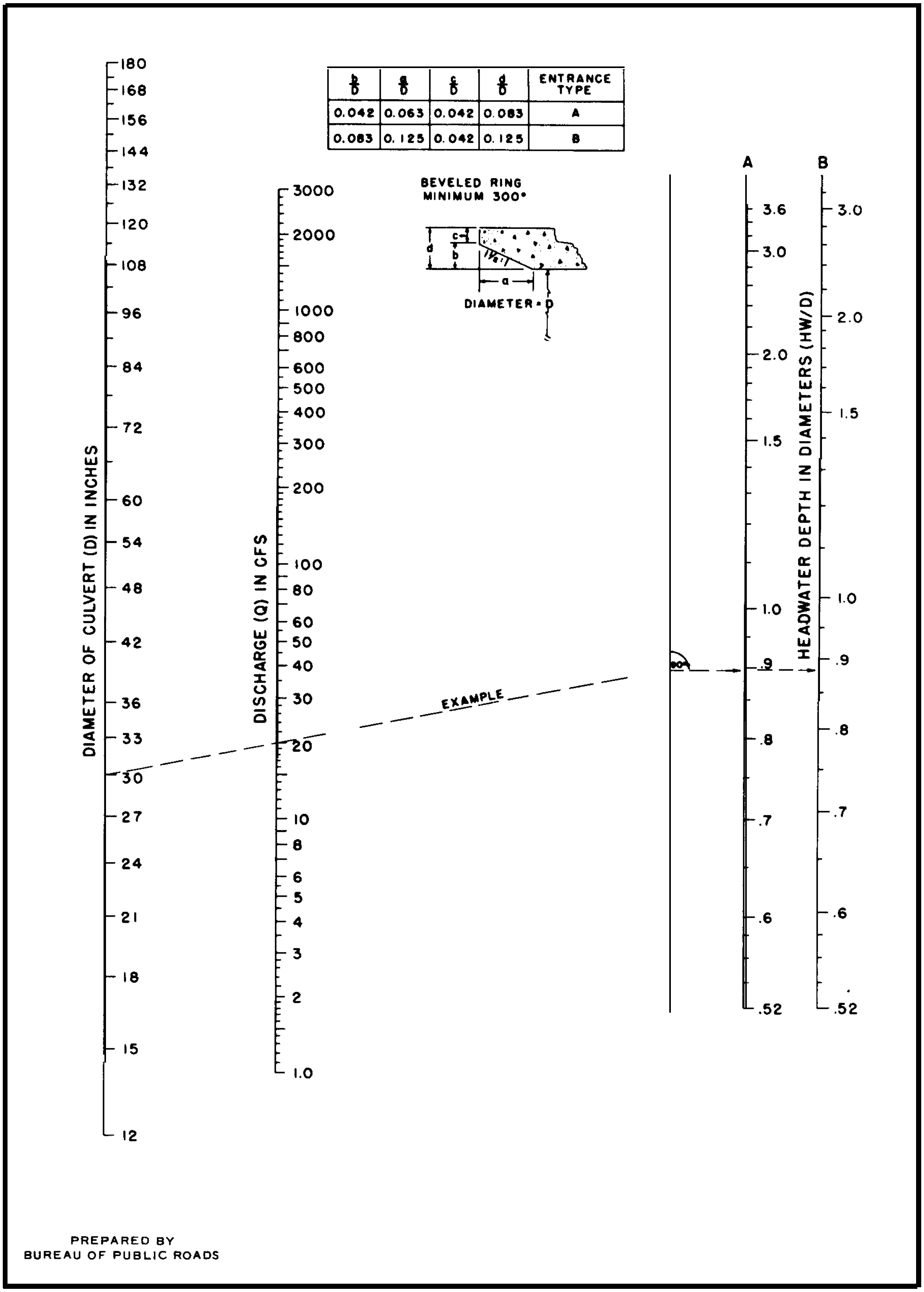
Figure B–8. Headwater depth for corrugated metal pipe culverts with tapered inlet-inlet control.



$\frac{b}{D}$	$\frac{a}{D}$	$\frac{c}{D}$	$\frac{d}{D}$	ENTRANCE TYPE
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B

Figure B–9. Headwater depth for circular pipe culverts with beveled ring inlet control.

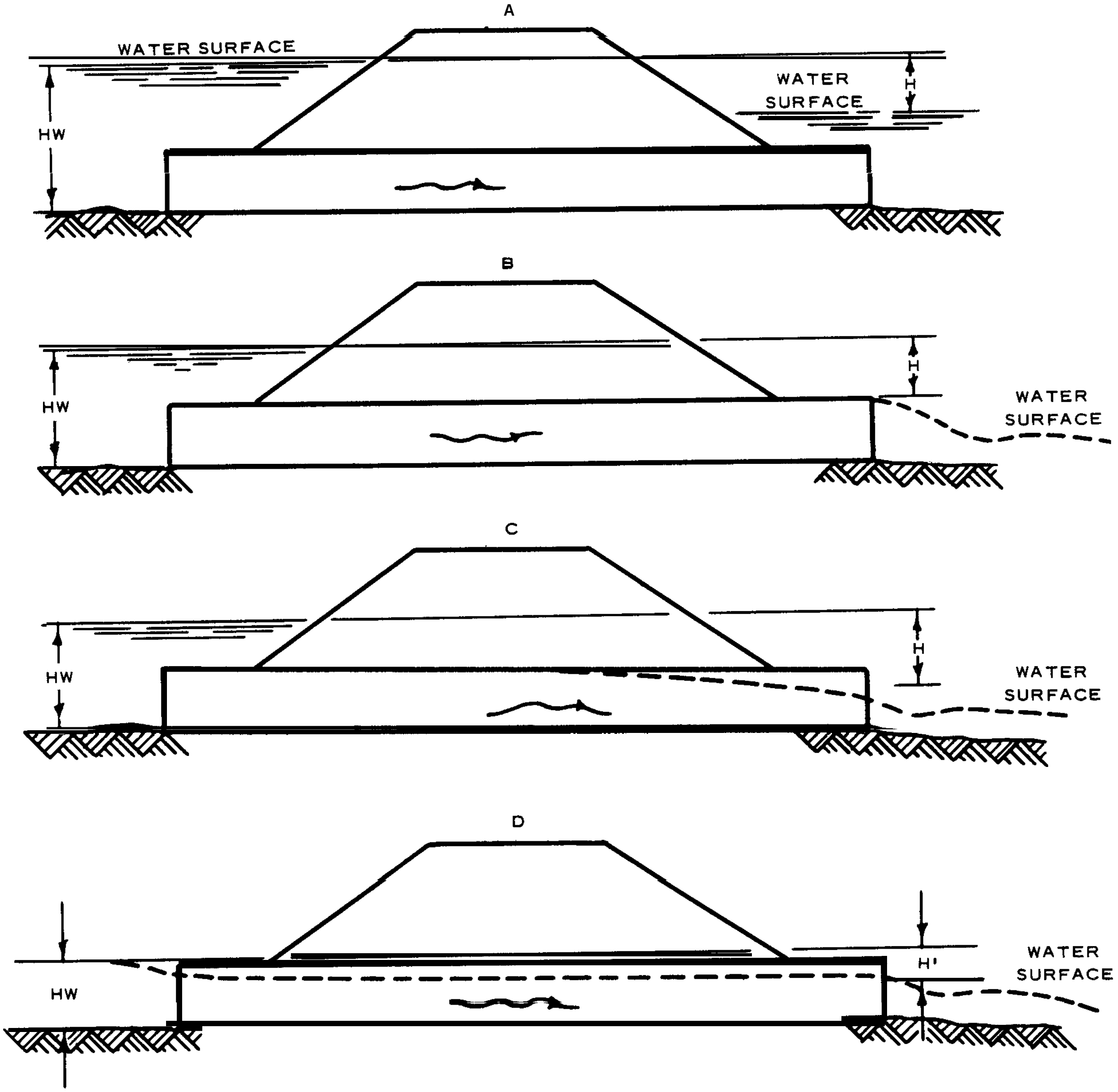


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Figure B–10. Outlet control.

Table B–1. Entrance Loss Coefficients
Outlet Control, Full or Partly Full

Entrance head loss $H_e = K_e \frac{V^2}{2g}$

Type of Structure and Design of Entrance	*Coefficient* K_e
Pipe, Concrete	
Projecting from fill, socket end (groove-end)	0.2
Projecting from fill, square-cut end	0.5
Headwall or headwall and wingwalls	
Socket end of pipe (groove-end)	0.2
Square-edge	0.5
Rounded (radius = 1/12D)	0.2
Mitered to conform to fill slope	0.7
*End Section conforming to fill slope	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side- or slope-tapered inlet	0.2
Pipe, or Pipe-Arch, Corrugated Metal	
Projecting from fill (no headwall)	0.9
Headwall or headwall and wingwalls, square-edge	0.5
Mitered to conform to fill slope, paved or unpaved slope	0.7
*End Section conforming to fill slope	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side- or slope-tapered inlet	0.2
Box, Reinforced Concrete	
Headwall parallel to embankment (no wingwalls)	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius of 1/12 barrel dimension, or beveled edges on 3 sides	0.2
Wingwalls at 30° to 75° to barrel	
Square-edged at crown	0.4
Crown edge rounded to radius of 1/12 barrel dimension, or beveled top edge	0.2
Wingwall at 10° to 25° to barrel	
Square-edged at crown	0.5
Wingwalls parallel (extension of sides)	
Square-edged at crown	0.7
Side- or slope-tapered inlet	0.2

Note:* **"End Section conforming to fill slope," made of either metal or concrete, are the sections commonly available from manufacturers. From limited hydraulic tests they are equivalent in operation to a headwall in both *inlet* **and** *outlet* **control. Some end sections, incorporating a** *closed* **taper in their design, have a superior hydraulic performance. These latter sections can be designed using the information given for the beveled inlet.**

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Variables in the equation are defined in appendix D.

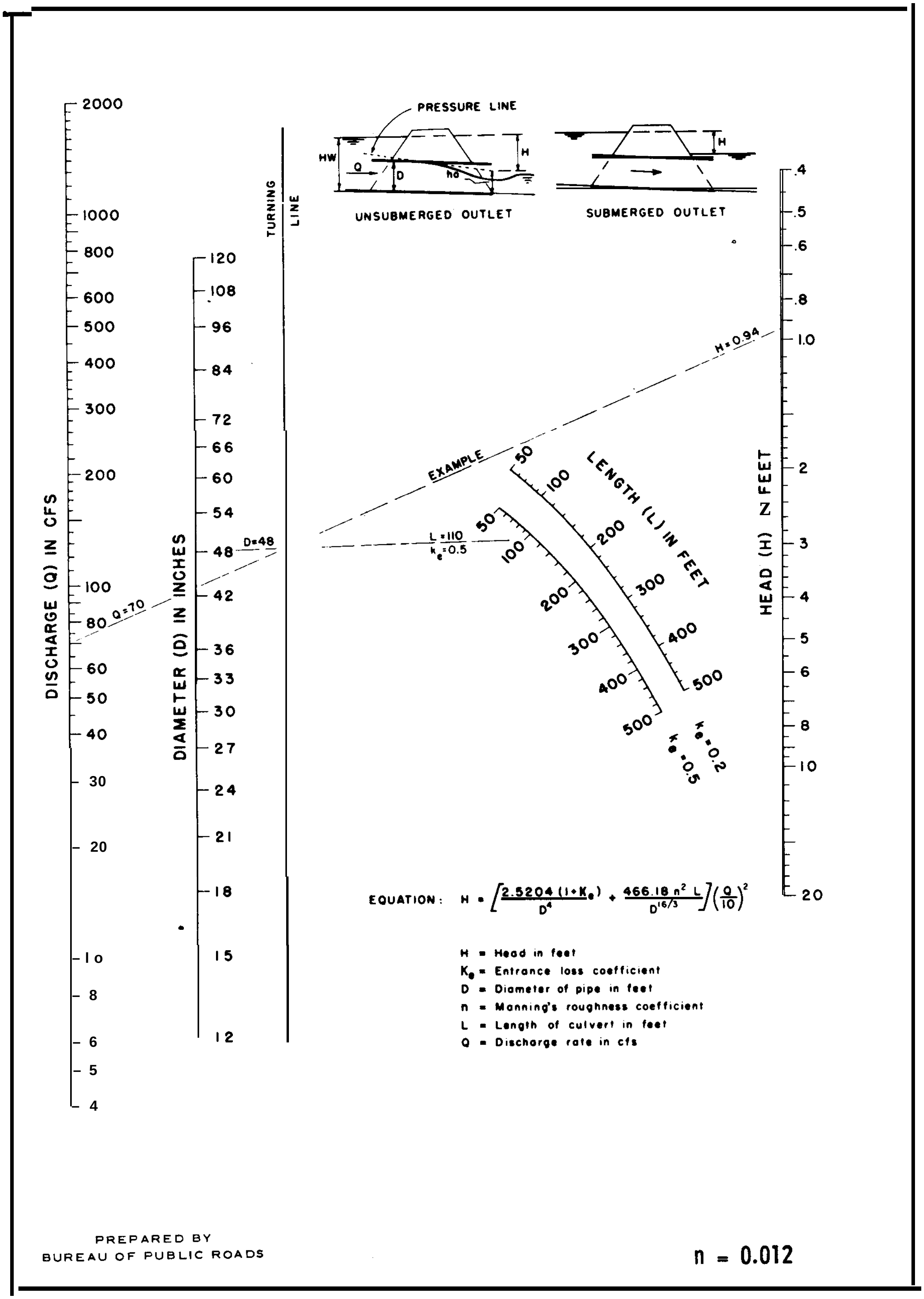
Adding the three terms and simplifying, yields for full pipe, outlet control flow the following expression:

$$H = \left(1 + K_e + \frac{29n^2L}{R^{1.333}}\right)\left(\frac{V^2}{2g}\right) \text{ --------- } (1)$$

This equation can be solved readily by the use of the full-flow nomography, figures B–II through B–17. The equations shown on these nomography are the same as equation 1 expressed in a different form. Each nomograph is drawn for a single value of n as noted in the respective figure. These nomography may be used for other values of n by modifying the culvert length as directed in paragraph B–6, which describes use of the outlet-control nomography. The value of H must be measured from some "control" elevation at the outlet which is dependent on the rate of discharge or the elevation of the water surface of the tailwater. For simplicity, a value h_o is used as the distance in feet from the culvert invert (flow line) at the outlet to the control elevation. The following equation is used to compute headwater in reference to the inlet invert:

$$HW = h_o + H - LS_o \ldots\ldots\ldots\ldots (2)$$

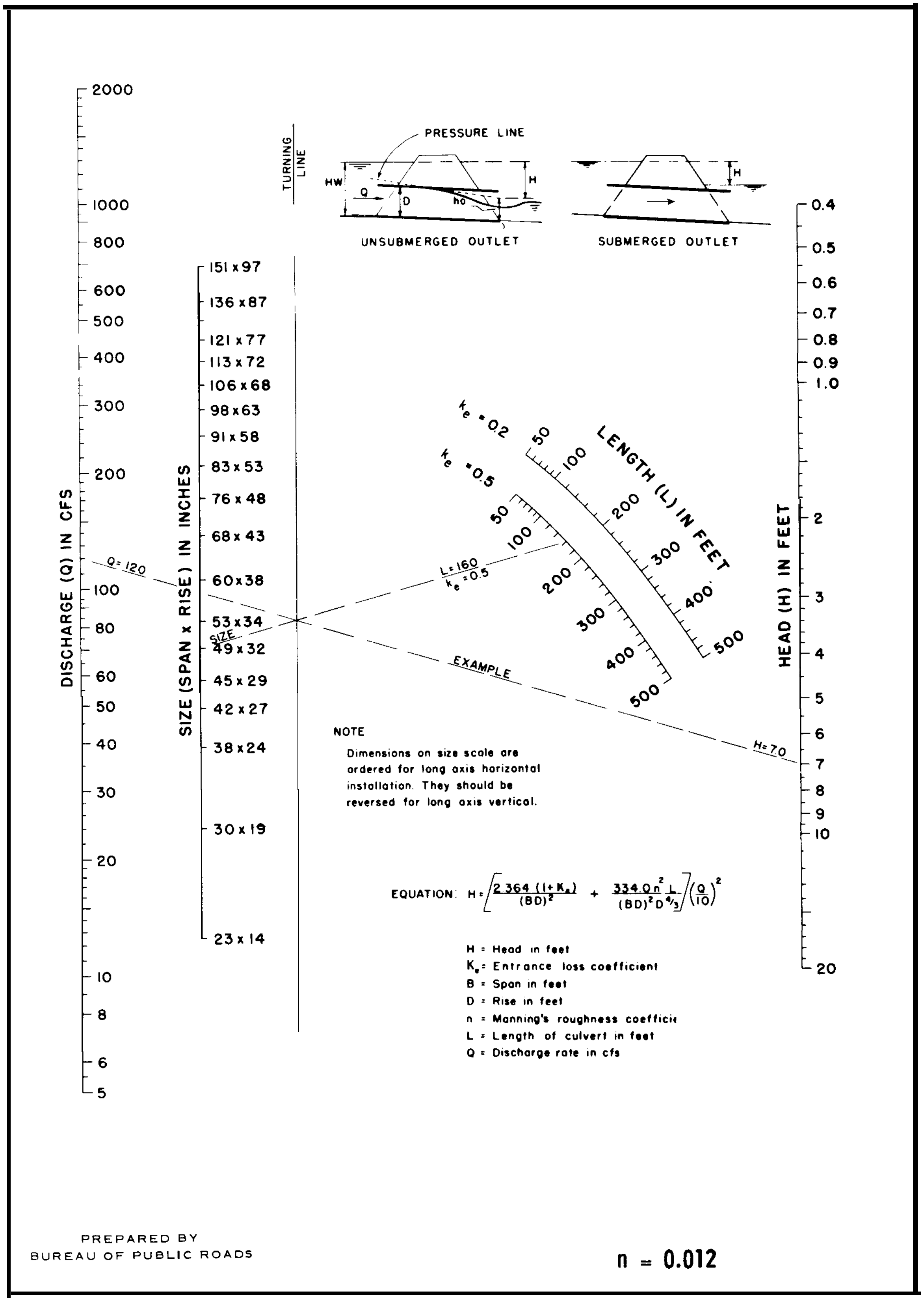
b. Tailwater elevation at or above the top of the culvert barrel outlet (fig B–10A). The tailwater



EQUATION: $H = \left[\frac{2.5204\,(1+K_e)}{D^4} + \frac{466.18\,n^2\,L}{D^{16/3}}\right]\left(\frac{Q}{10}\right)^2$

H = Head in feet
K_e = Entrance loss coefficient
D = Diameter of pipe in feet
n = Manning's roughness coefficient
L = Length of culvert in feet
Q = Discharge rate in cfs

Figure B–11. Head for circular pipe culverts flowing full, n = 0.012.



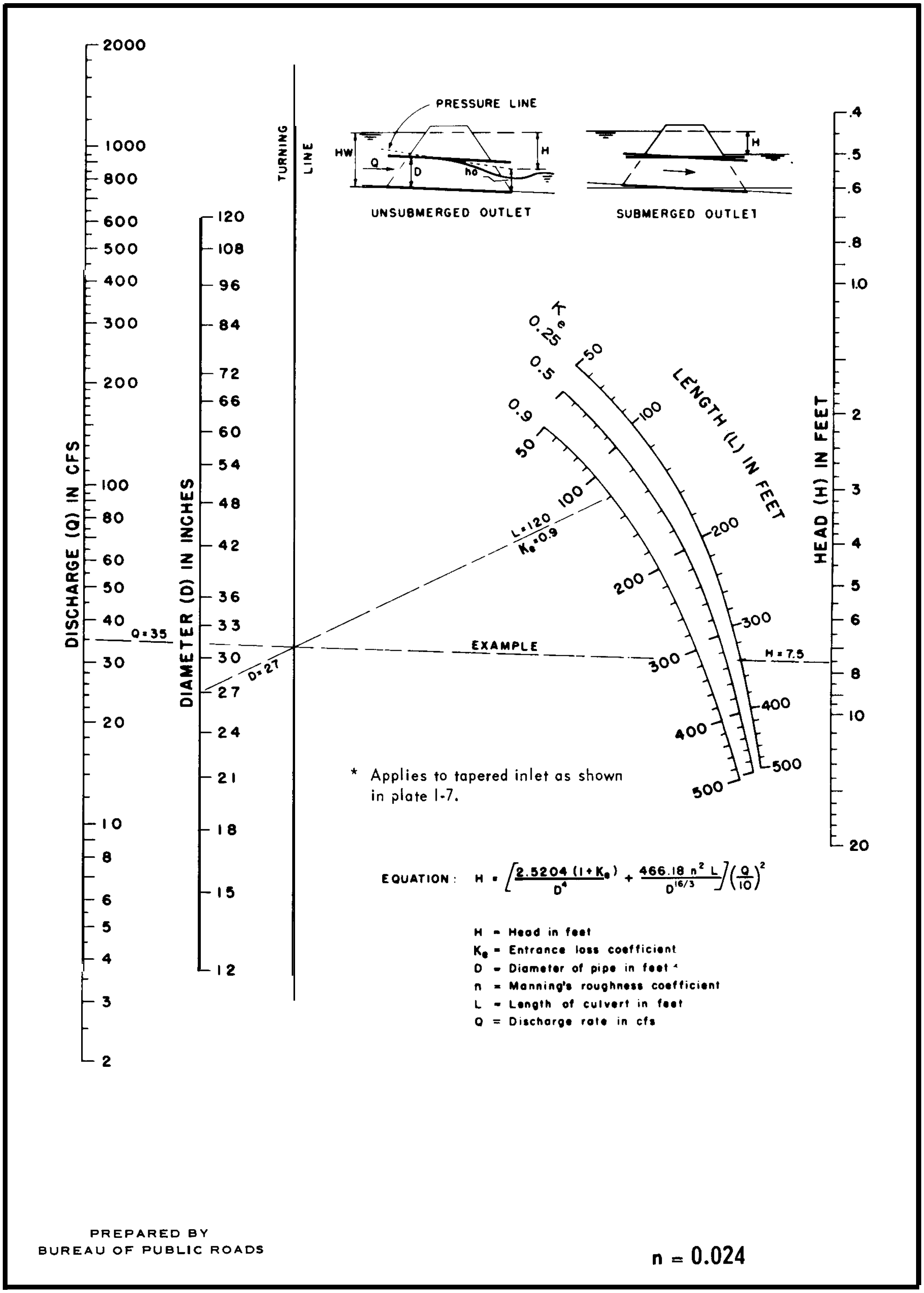
NOTE

Dimensions on size scale are ordered for long axis horizontal installation. They should be reversed for long axis vertical.

EQUATION: $$H = \left[\frac{2.364\,(1+K_e)}{(BD)^2} + \frac{334.0\,n^2 L}{(BD)^2 D^{4/3}}\right]\left(\frac{Q}{10}\right)^2$$

H = Head in feet
K_e = Entrance loss coefficient
B = Span in feet
D = Rise in feet
n = Manning's roughness coefficie
L = Length of culvert in feet
Q = Discharge rate in cfs

Figure B–12. Head for oval circular pipe culverts long axis horizontal or vertical flowing full, n = 0.012.



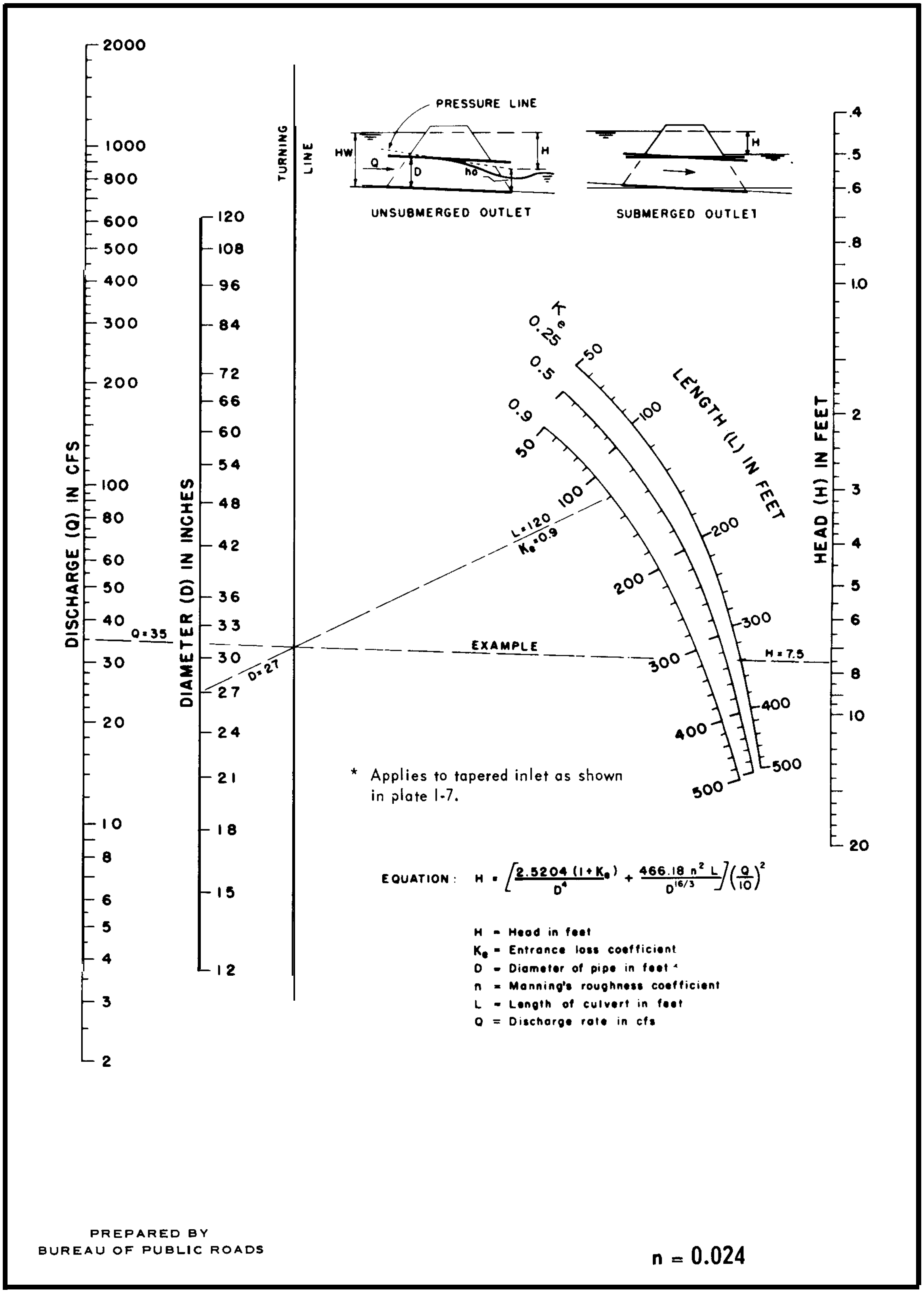
* Applies to tapered inlet as shown in plate 1-7.

EQUATION: $$H = \left[\frac{2.5204\,(1+K_e)}{D^4} + \frac{466.18\,n^2\,L}{D^{16/3}}\right]\left(\frac{Q}{10}\right)^2$$

H = Head in feet
K_e = Entrance loss coefficient
D = Diameter of pipe in feet *
n = Manning's roughness coefficient
L = Length of culvert in feet
Q = Discharge rate in cfs

n = 0.024

Figure B-13. Head for circular pipe culverts flowing full, n = 0.024.

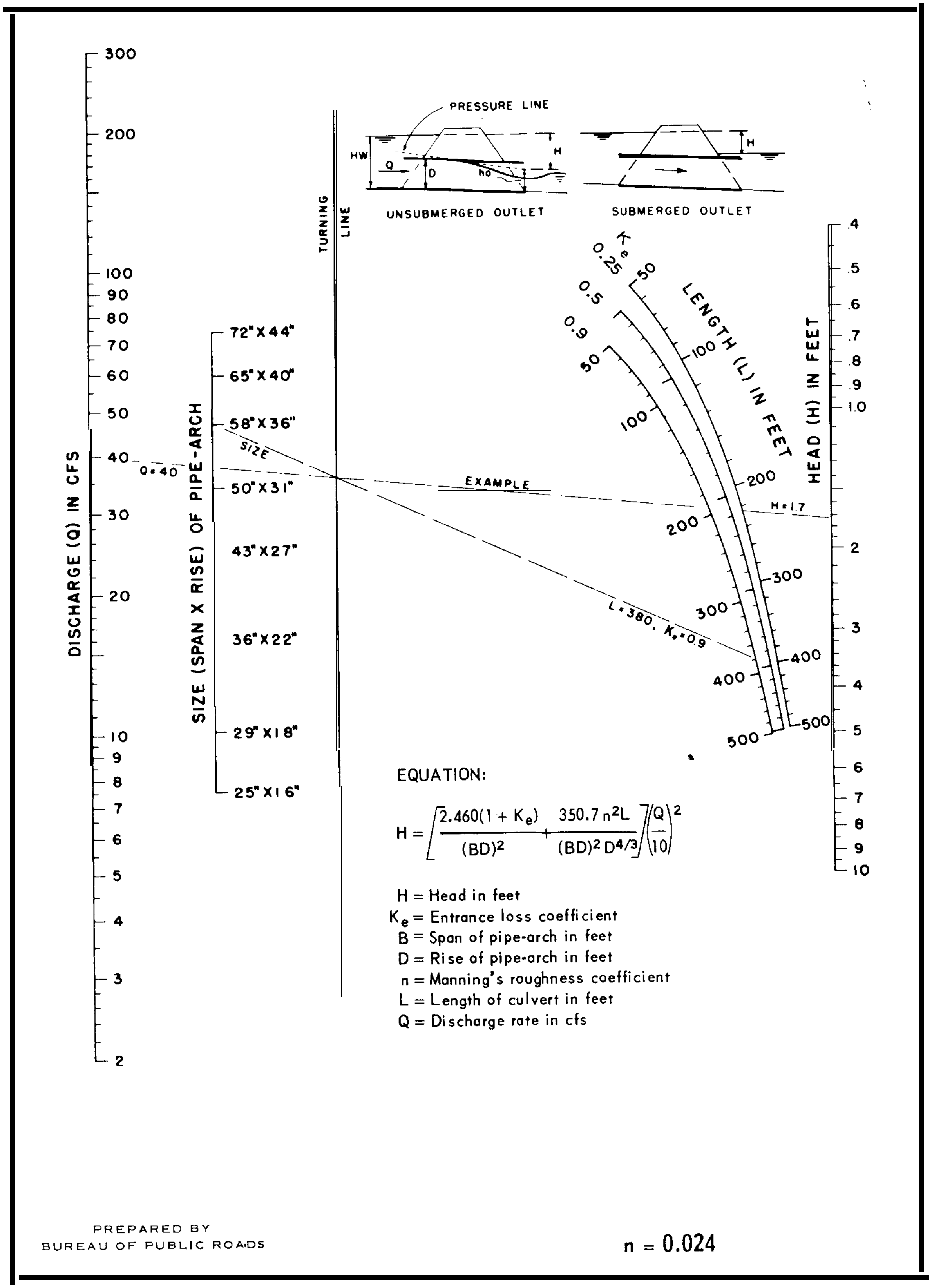


* Applies to tapered inlet as shown in plate 1-7.

EQUATION: $H = \left[\frac{2.5204\,(1+K_e)}{D^4} + \frac{466.18\,n^2\,L}{D^{16/3}}\right]\left(\frac{Q}{10}\right)^2$

H = Head in feet
K_e = Entrance loss coefficient
D = Diameter of pipe in feet *
n = Manning's roughness coefficient
L = Length of culvert in feet
Q = Discharge rate in cfs

Figure B-13. Head for circular pipe culverts flowing full, n = 0.024.



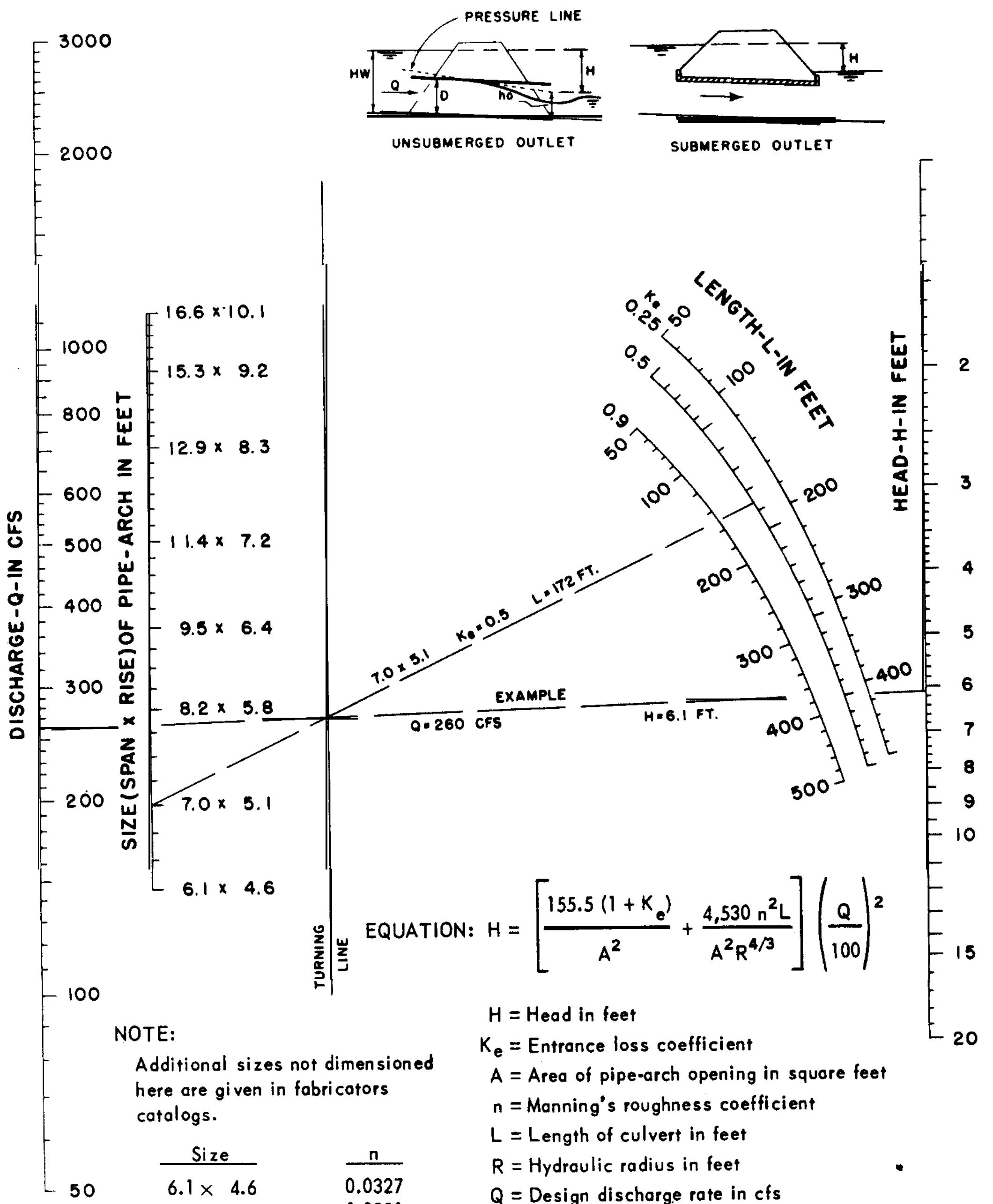
EQUATION:

$$H = \left[\frac{2.460(1+K_e)}{(BD)^2} + \frac{350.7\,n^2 L}{(BD)^2 D^{4/3}}\right]\left(\frac{Q}{10}\right)^2$$

H = Head in feet
K_e = Entrance loss coefficient
B = Span of pipe-arch in feet
D = Rise of pipe-arch in feet
n = Manning's roughness coefficient
L = Length of culvert in feet
Q = Discharge rate in cfs

n = 0.024

Figure B-15. Head for standard corrugated metal pipe-arch culverts flowing full, n = 0.024.



$$\text{EQUATION: } H = \left[\frac{155.5\,(1+K_e)}{A^2} + \frac{4{,}530\, n^2 L}{A^2 R^{4/3}}\right]\left(\frac{Q}{100}\right)^2$$

H = Head in feet
K_e = Entrance loss coefficient
A = Area of pipe-arch opening in square feet
n = Manning's roughness coefficient
L = Length of culvert in feet
R = Hydraulic radius in feet
Q = Design discharge rate in cfs

NOTE:
Additional sizes not dimensioned here are given in fabricators catalogs.

Size	n
6.1 × 4.6	0.0327
8.2 × 5.8	0.0321
11.4 × 7.2	0.0315
16.6 × 10.1	0.0306

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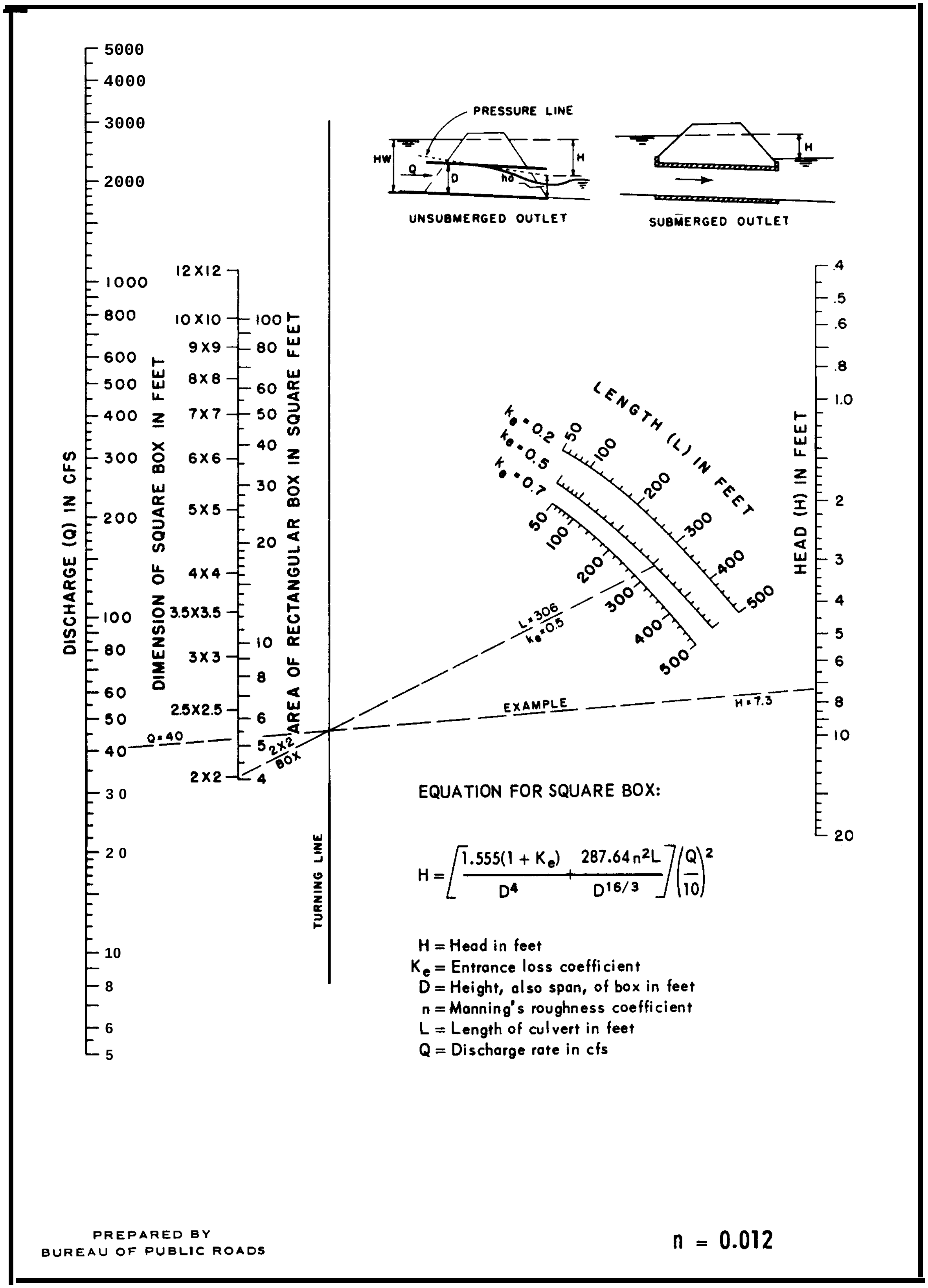
n = 0.0327 TO 0.0306

Figure B–16. Head for field-bolted structural plate pipe-arch culverts 18-in. corner radius flowing full, n = 0.0327 to 0.0306.



EQUATION FOR SQUARE BOX:

$$H = \left[\frac{1.555(1 + K_e)}{D^4} + \frac{287.64 n^2 L}{D^{16/3}}\right]\left(\frac{Q}{10}\right)^2$$

H = Head in feet
K_e = Entrance loss coefficient
D = Height, also span, of box in feet
n = Manning's roughness coefficient
L = Length of culvert in feet
Q = Discharge rate in cfs

Figure B-17. Head for concrete box culverts flowing full, n = 0.012.

(TW) depth is equal to h_o, and the relation of headwater to other terms in equation 2 is illustrated in figure B–18.

c. Tailwater elevation below the top or crown of the culvert barrel outlet. Figure B–1OB, C, and D are three common types of flow for outlet control with this low tailwater condition. In these cases h_o is found by comparing two values, TW depth in the outlet channel and $\frac{d_c + D}{2}$, and setting h_o equal to the larger value. The fraction $\frac{d_c + D}{2}$ is a simplified mean of computing h_o when the tailwater is low and the discharge does not fill the culvert barrel at the outlet. In this fraction, d_c is critical depth as determined from figures B–18 through B–23 and D is the culvert height. The value of DC should never exceed D, making the upper limit of this fraction equal to D. Figure B–19 shows the terms of equation 2 for the cases discussed above. Equation 2 gives accurate answers if the culvert flows full for a part of the barrel length as illustrated by figure B–23. This condition of flow will exist if the headwater, as determined by equation 2, is equal to or greater than the quantity:

$$HW \geqslant D + (1 + K_e)\frac{V^2}{2g}$$

If the headwater drops below this point the water surface will be free throughout the culvert barrel as in figure B–1OD, and equation 2 yields answers with some error since the only correct method of finding headwater in this case is by a backwater computation starting at the culvert outlet. However, equation 2 will give answers of sufficient accuracy for design purposes if the headwater is limited to values greater than 0.75D. H′ is used in figure B–10D to show that the head loss here is an approximation of H. No solution is given for headwater less than 0.75D. The depth of tailwater is important in determining the hydraulic capacity of culverts flowing with outlet control. In many cases the downstream channel is of considerable width and the depth of water in the natural channel is less than the height of water in the outlet end of the culvert barrel, making the tailwater ineffective as a control, so that its depth need not be computed to determine culvert discharge capacity or headwater. There are instances, however, where the downstream water-surface elevation is controlled by a downstream obstruction or backwater from another stream. A field inspection of all major culvert locations should be made to evaluate downstream controls and determine water stages. An approximation of the depth of flow in a natural stream (outlet channel) can be made by using Manning's equation, $V = \frac{1.486}{n} R^{2/3}S^{1/2}$,, if the channel is reasonably uniform in cross section, slope, and roughness. Values of n for natural streams in Manning's formula are given in table B–2. If the water surface in the outlet channel is established by downstream controls other means must be found to determine the tailwater elevation. Sometimes this necessitates a study of the stage-discharge relation of another stream into which the stream in question flows or the securing of data on reservoir elevations if a storage dam is involved.

Table B–2. Manning's n for Natural Stream Channels
(Surface width at flood stage less than 100 feet)

Fairly regular section:	
Some grass and weeds, little or no brush	0.030-0.035
Dense growth of weeds, depth of flow materially greater than weed height	0.035-0.05
Some weeds, light brush on banks	0.035-0.05
Some weeds, heavy brush on banks	0.05-0.07
Some weeds, dense willows on banks	0.06-0.08
For trees within channel, with *branches* submerged at high stage, increase all above values by	0.01-0.02
Irregular sections, with pools, slight channel meander; increase values given above about	0.01-0.02
Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage:	
Bottom of gravel, cobbles, and few boulders	0.04-0.05
Bottom of cobbles, with *large* boulders	0.05-0.07

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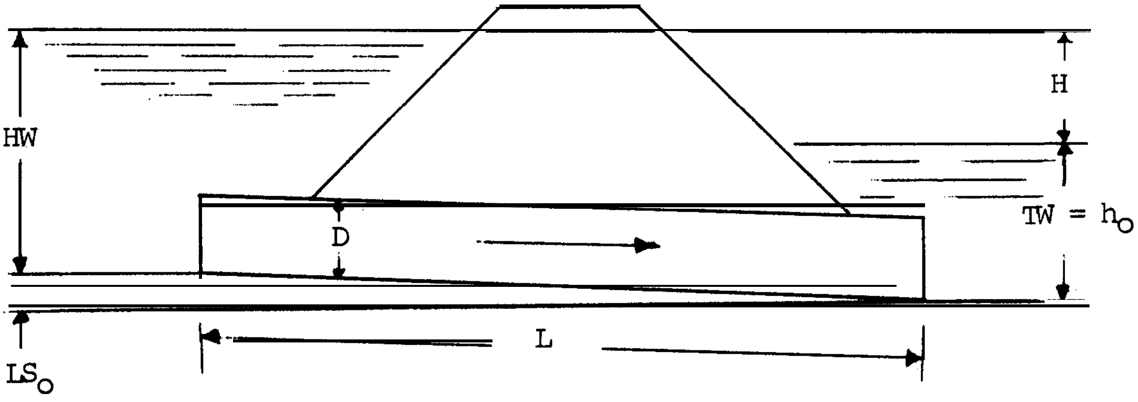

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Figure B-18, Tailgater elevation at or above top of culved.

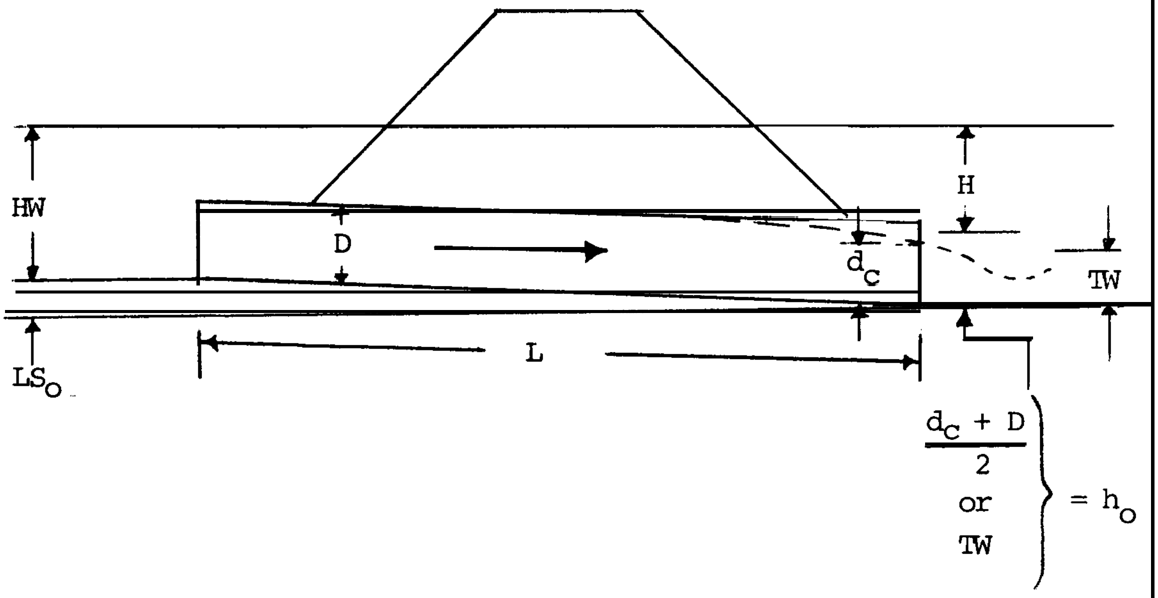

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Figure B-19. Tailwater below the top of the culvert.

B-4. Procedure for selection of culvert size.

Select the culvert size by the following steps:

Step 1: List given data.

a. Design discharge, Q, in cubic feet per second.

b. Approximate length of culvert, in feet.

c. Allowable headwater depth, in feet, which is the vertical distance from the culvert invert (flow line) at entrance to the water-surface elevation permissible in the approach channel upstream from the culvert.

d. Type of culvert, including barrel material, barrel cross-sectional shape, and entrance type.

e. Slope of culvert. (If grade is given in percent, convert to slope in feet per foot.)

f. Allowable outlet velocity (if scour is a problem).

Step 2: Determine a trial-size culvert.

a. Refer to the inlet-control nomograph (figs B–2 through B–9) for the culvert type selected

b. Using an $\frac{HW}{D}$ of approximately 1.5 and the scale for the entrance type to be used, find a trial-size culvert by following the instructions for use of these nomographs. If reasons for lesser or greater relative depth of headwater in a particular case should exist, another value of $\frac{HW}{D}$ may be used for this trial selection.

c. If the trial size for the culverts is obviously too large because of limited height of embankment or availability of size, try a $\frac{HW}{D}$ value or multiple culverts by dividing the discharge equally for the number of culverts used. Raising the embankment height or using pipe arch and box culverts with width greater than height should be considered. Selection should be based on an economic analysis.

Step 3: Find headwater depth for the trial-size culvert.

a. Determine and record headwater depth by use of the appropriate inlet-control nomograph (figs B–2 through B–9). Tailwater conditions are to be neglected in this determination. Headwater in this case is found by simply multiplying $\frac{HW}{D}$ obtained from the nomograph by D.

b. Compute and record headwater for outlet control as instructed below:

(1) Approximate the depth of tailwater for the design flood condition in the outlet channel. The tailwater depth may also be due to backwater caused by another stream or some control downstream.

(2) For tailwater depths equal to or above the depth of the culvert at the outlet, set tailwater equal to h_o and find headwater by the following equation:

$$HW = h_o + H - S_oL$$

(3) For tailwater elevations below the crown of culvert at the outlet, use the following equation to find headwater:

$$HW = h_o + H - S_oL$$

where $h_o = \frac{d_c + D}{2}$ or TW, whichever is greater. When d_c (figs B–20 through B–25) exceeds rectangular section, h_o should be set equal to D.

c. Compare the headwater found in Step 3a and Step 3b (inlet control and outlet control). The higher headwater governs and indicates the flow control existing under the given conditions.

d. Compare the higher headwater above with that allowable at the site. If headwater is greater than allowable, repeat the procedure using a larger culvert. If headwater is less than allowable, repeat the procedure to investigate the possibility of using a smaller size.

Step 4: Check outlet velocities for size selected.

a. If outlet control governs in Step 3c, outlet velocity equals Q/A, where A is the cross-sectional area of flow at the outlet. If d_c or TW is less than the height of the culvert barrel, use cross-sectional area corresponding to d_c or TW depth, whichever gives the greater area of flow.

b. If inlet control governs in Step 3c, outlet velocity can be assumed to equal normal velocity in open-channel flow as computed by Manning's equation for the barrel size, roughness, and slope of culvert selected.

Step 5: Try a culvert of another type or shape and determine size and headwater by the above procedure.

Step 6: Record final selection of culvert with size, type, outlet velocity, required headwater, and economic justification.