ARMCO CULVERT HYDRAULICS

A. MANUAL COMPUTATION

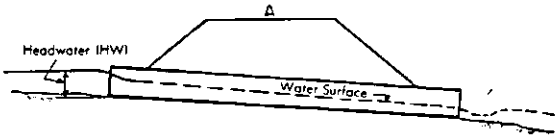
Laboratory tests and field observations show two major types of culvert flow: (1) flow with inlet control and (2) flow with outlet control. For each type of control, different factors and formulas are used to compute the hydraulic capacity of a culvert. Under inlet control, the cross-sectional area of the culvert barrel, the inlet geometry and the amount of headwater or ponding 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.

It is difficult in many instances to predict the type of flow likely to occur for any given discharge and culvert installation. The type of flow or the location of the control is dependent on the quantity of flow, roughness of the culvert barrel, changes in alignment, obstructions, sediment deposits, type of inlet, flow pattern in the approach channel and other factors. In some instances the flow control changes with change in discharge and occasionally the control fluctuates from inlet control to outlet control and vice versa for the same discharge. Thus, to design culverts one should have an understanding of both types of flow so that computations can be made for each type and the design based on the more adverse flow condition. These two types of flow are discussed briefly in subsequent paragraphs.

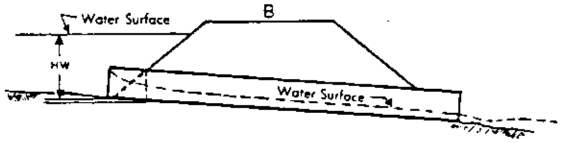
CULVERT FLOWING WITH INLET CONTROL

Inlet control means that the discharge capacity of a culvert is controlled at the culvert entrance by the depth of headwater (HW) and the entrance geometry, including the area, shape and type of inlet edge. Types of inlet controlled flow for an unsubmerged entrance are shown in figure 3-1A. A mitred (bevelled) entrance moves the control downstream to approximately the top of the mitre (see figure 3-1B).

With inlet control the roughness and length of the culvert barrel and outlet conditions (including depth of tailwater) are not factors in determining culvert capacity. The barrel slope has some effect on discharge but any adjustment for slope is considered minor and can be neglected for conventional culverts flowing with inlet control.



A. Square End — Unsubmerged



B. Square End or Mitred Inlet — Submerged

FIG. 3-1

Headwater-discharge relationships for the various types of circular and pipe-arch culverts flowing with inlet control are based on laboratory research of models verified in some instances by prototype tests*.

These research data were analysed, and nomographs for determining culvert capacity for inlet control were developed by the Division of Hydraulic Research, Bureau of Public Roads. Metricated versions of these nomographs, Charts 1 and 2, give headwater-discharge relationships for conventional culverts flowing with inlet control through a range of headwater depths of discharges.

CULVERTS FLOWING WITH OUTLET CONTROL

Culverts flowing with outlet control can flow with the culvert barrel full or part full for part of the barrel length or for all of it, (see fig. 3-2). If the entire cross section of the barrel is filled with water for the total length of the barrel the culvert is said to be in full flow or flowing full, figures 3-2A and 3-2B. The other two common types of outlet-control flow are shown in figures 3-2C and 3-2D. The procedure given in this manual for outlet-control flow does not give an exact solution for a free water surface condition throughout the barrel length shown in figure 3-2D. However, an approximate solution is given for this case (fig. 3-2D) when the headwater (HW) is .75D and above, where D is the height of the culvert barrel.

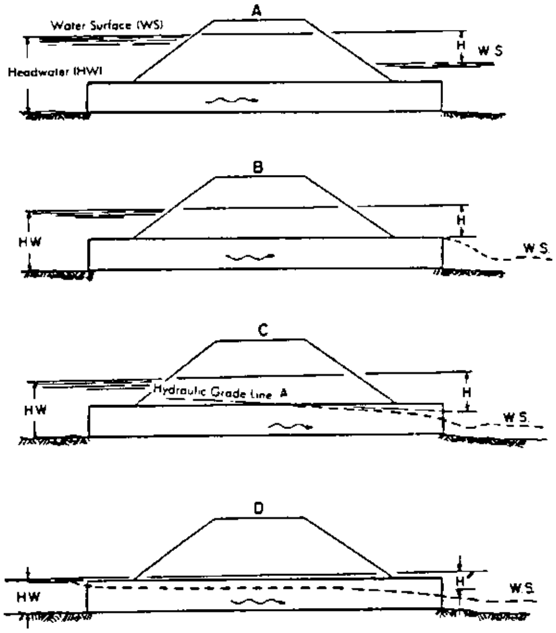


FIG. 3-2

The head H required to pass a given quantity of water through a culvert flowing in outlet control with the barrel flowing full throughout its length is made up of three major parts. These three parts are usually expressed in metres of water and include a velocity head H_v, an entrance loss H_e, and a friction loss H_f. Expressed in equation form:

$$H = H_v + H_e + H_f \quad \ldots\ldots\ldots\ldots \quad 1.$$

The velocity head H_v equals $\frac{V^2}{2g}$, where V is the mean or average velocity in the culvert barrel. The mean velocity is found by dividing the discharge Q by the cross-sectional area A of the flowing water. The velocity head is the kinetic energy of the water in the culvert barrel. This energy is obtained from ponding of water at the entrance. (Energy from the velocity of flow in the approach channel is neglected in the design procedure given in this book. Also all of the velocity head H_v is assumed to be lost or, in other words, the exit loss coefficient equals 1.0).

The entrance loss H_e varies with the type or design of the culvert inlet. This loss is expressed as a coefficient k_e times the barrel velocity head or $k_e \frac{V^2}{2g}$. The coefficients k_e for various types of culvert entrances are as follows:–

Projecting from fill (no headwall)	0.9
Headwall, or headwall and wingwalls Square-edge	0.5
Mitered to conform to fill slope	0.7

The friction head H_f is the energy required to overcome the roughness of the culvert barrel. H_f can be expressed in several ways. Since most engineers are familiar with Manning's 'n' the following expression is used:

*This research is reported in National Bureau of Standards Report No. 4444 entitled "Hydraulic Characteristics of Commonly Used Pipe Entrances" by John L. French and "Hydraulics of Conventional Highway Culverts" by H.G. Bossy. Experimental data for culverts with headwalls and wingwalls were obtained from an unpublished report of the U.S. Geological Survey.

$$H_f = \left[\frac{20n^2 \times L}{R^{1,33}}\right]\frac{V^2}{2g}$$

where

n = Manning's friction factor
L = length of culvert barrel
V = mean velocity of flow in culvert barrel (m/sec)
g = acceleration due to gravity (9,81 m/sec²)
R = hydraulic radius or $\frac{A}{WP}$

where

A = Area of flow for full cross-section – (sq m)
WP = Wetted perimeter (m)

Rewriting equation 1 and simplifying, we get for full flow

$$H = \left(1 + k_e + \left[\frac{20n^2 L}{R^{1,33}}\right]\right)\frac{V^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

Equation 2 can be solved readily by the use of the full-flow nomographs. Refer to chart No. 3. The equations shown on these nomographs are the same as equation 2 expressed in a different form. Each nomograph is drawn for a single value of n as noted on the respective chart. These nomographs can be used for other values of n by modifying the culvert length as directed (see chart 3).

Finding the value of H from nomograph is not the complete solution for outlet control type of flow. Headwater must be determined and other factors such as slope of the culvert barrel and outlet conditions enter into this computation.

The value of H in metres must be measured from some "control" elevation at the outlet. This "control" elevation is dependent on the rate of discharge or the elevation of the water surface of the tailwater. For simplicity a value h_0 is used as the distance in metres from the culvert invert (flow line) at the outlet to the "control" elevation. The following equation is used to compute head water (HW).

$$HW = h_0 + H - LS_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3$$

where S_0 is the slope of the flow line in metres per metre and all terms are in metres. The determination of h_0 is discussed in the following paragraphs for the various flow conditions at the outlet.

If the water surface in the outlet channel (tailwater elevation) is at or above the top of the barrel at the outlet (fig. 3-2A), the solution for HW is simple. The TW depth is equal to h_0 and the relationship of HW to the other terms in equation 3 are illustrated in figure 3-3.

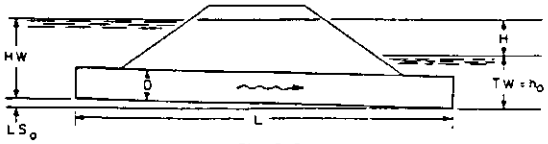


Fig. 3-3.

If the tailwater elevation is below the top or crown of the culvert at the outlet, the determination of h_0 for a given discharge and size of culvert is more difficult. Figures 3-2B, 3-2C and 3-2D are the three common types of flow for outlet control with this low tailwater condition.

In these cases, figures 3-2B, 3-2C and 3-2D, h_0 is found by comparing two values (1) TW depth in the outlet channel and (2) $\frac{d_c + D}{2}$ and setting h_0 equal to the larger of these values. The fraction $\frac{d_c + D}{2}$ is a simplified means of computing h_0 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 " Chart number 4 " and D is the culvert height. The value of d_c should never exceed D, making the upper limit of this fraction equal to D. The sketch in figure 3-4 shows the terms of equation 3 for the cases discussed above.

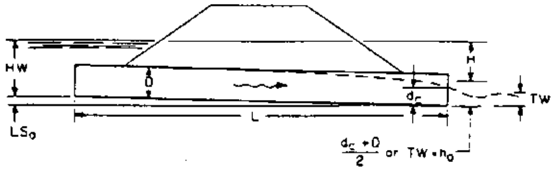


Fig. 3-4.

From more rigorous solutions it has been found that equation 3 gives accurate answers if the culvert flows full for a part of the barrel length as illustrated by figure 3-4. This condition of flow will exist if the headwater (as determined by equation 3) is equal to or greater than the quantity

$$D + (1 + k_e)\frac{V^2}{2g}$$

where V is the mean velocity for the full cross section of the barrel; k_e, the entrance loss coefficient; and D, the culvert height. If the headwater drops below this point the water surface will be free throughout the culvert barrel as shown in figure 3-2D, and equation 3 gives answers with some error as explained in the next paragraph.

In the case 3-2D, equation 3 is used to solve for HW when a free water surface exists through the barrel. Such a computation does not give a true value since the only correct way of finding HW in this case is by a backwater computation starting at the culvert outlet. However, equation 3 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 3-2D to show that the head loss here is an approximation of H. No solution is given for HW less than 0.75D.

Computing Depth of Tailwater

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.

An approximation of the depth of flow in a natural stream (outlet channel) can be made by using Manning's equation if the channel is reasonably uniform in cross section, slope and roughness.

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 relationship of another stream into which the stream in question flows or the securing of data on reservoir elevations if a storage dam is involved.

VELOCITY OF FLOW

A culvert, because of its hydraulic characteristics, increases the velocity of flow over that in the natural channel. High velocities are most critical just downstream from the culvert outlet and the erosion potential from the energy in the water is a feature to be considered in culvert design.

Energy dissipators for channel flow have been investigated in the laboratory and many have been constructed, especially in irrigation channels. All energy dissipators add to the cost of a culvert and engineers should consider using them only when required to prevent a large scour hole or as remedial construction.

The judgement of engineers working in a particular area is required to determine the need for energy dissipators at culvert outlets. As an aid in evaluating this need it is suggested that the outlet velocities be computed. These computed velocities can be compared with outlet velocities of other sizes and types of culverts and with the natural channel velocities. A change in size of culvert does not change outlet velocities appreciably in most cases.

Average outlet velocities for culverts flowing with *inlet control* may be approximated by computing the normal velocity for the culvert cross section using Manning's equation

$$V = \frac{1}{n}R^{2/3}S^{1/2}$$

Since the depth of flow is not known the use of tables or charts is recommended in solving this equation. The outlet velocity for inlet control computed in this manner will be high for culverts having a length-depth ratio less than say 20. For the shorter culverts velocities will be between those computed by Manning's equation and those occuring at critical depth.

In *outlet control*, the average outlet velocity will be discharge divided by the cross-sectional area of flow at the outlet. This flow area will be between that corresponding to critical depth and the full area of the pipe, depending upon the tailwater conditions.

PROCEDURE FOR SELECTION OF CULVERT SIZE

STEP 1.: List given data

a. Design discharge Q in cumecs.
b. Approximate length of culvert, in metres.
c. Allowable headwater depth, in metres, which is the vertical distance from the cuvert (flow line) at the entrance to the water surface elevation permissible in the approach channel upstream from the culvert.
d. Type of culvert, including barrel cross-sectional shape and entrance type.
e. Slope of culvert. (if grade is given in percent, convert to slope m per m)
f. Allowable outlet velocity (if scour is a problem)

Note:— It is suggested that culvert design sheets, similar to figure 3 - 5 be used to record design data.

STEP 2. : Determine a trial size culvert.

a. Refer to the inlet control nomographs for the culvert type selected.
b. Using an $\frac{HW}{D}$ of 1.5 or less 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 colverts is obviously too large in dimension because of limited height of embankment or availability of size, try a diffierent $\frac{HW}{D}$ or multiple culverts by dividing the discharge equally for the number of culverts used. Raising the embankment height or the use of a pipe arch with width greater than height should be considered. Selection should be based on an economic analysis.

STEP 3. : Find headwater HW depth for the trial size culvert.

a. Determine and record headwater HW depth by use of the appropriate inlet control nomograph Chart 1 and 2. Tailwater TW conditions are to be neglected in this determination. HW in this case is found by simply multiplying $\frac{HW}{D}$ obtained from the nomograph by D.
b. Compare and record HW for outlet control as instructed below:
   (1) Approximate the depth of tailwater. TW for the design flood condition in outlet channel. The TW depth may also be due to backwater caused by another stream or some control downstream. An estimate of TW depth can be made by use of channel flow formulas or charts (See general discussion on tailwater).
   (2) For tailwater TW depth equal to or above the depth of the culvert at the outlet, set TW equal to h_o and find HW by the following equation.

$$HW = h_o + H - S_oL$$

where

HW = vertical distance in metres from culvert (flow line) at entrance to pool surface upstream.
H = head loss in metre as determined from the appropriate nomograph (chart 3)
h_o = vertical distance in feet from culvert flow line at outlet to "control" point. (In this case h equals TW).
S_o = slope of barrel in m/m
L = culvert length in m.

   (3) For tailwater TW elevations below the crown of the culvert at the outlet, use the following equation to find headwater HW. (It should be noted that this computation may contain approximations which are disscussed under the heading "Culverts Flowing with Outlet Control").

$$HW = h_o + H - S_oL$$

where

$$h_o = \frac{d_c + D}{2} \text{ or TW, whichever is the greater}$$

d_c = critical depth in m.
D = culvert height (m).

c. Compare the headwaters found in Step 3a and Step 3b (Inlet Control or Outlet Control). The higher headwater governs and indicates the flow control existing under the given conditions.
d. Compare the higher HW above with that allowable at the site. If HW is greater than the allowable, repeat the procedure using a larger culvert. If the HW is less than the allowable, repeat the procedure to investigate the possibility of using a smaller size.

STEP 4.

a. Check outlet velocity for size selected.
If outlet control governs in c above, outlet velocity $= \frac{Q}{A}$ 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 A corresponding to d_c or TW depth, whichever gives the greater area of flow.
b. If inlet control governs in c above, 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 HW by the above procedure.

STEP 6.

Record final selection of culvert with size, type, outlet velocity, required HW and economic justification.

PROJECT: ________________

DESIGNER: ________________

DATE: ________________

HYDROLOGIC AND CHANNEL INFORMATION

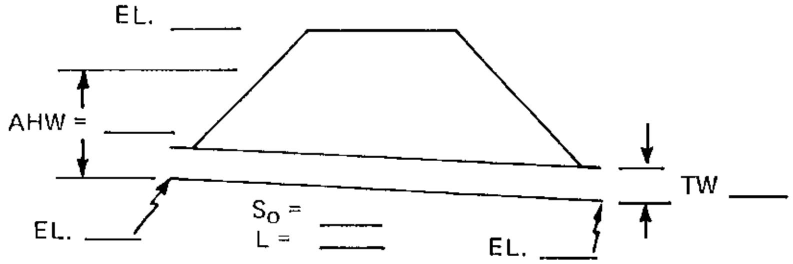
Q_1 = __________ TW_1 = __________

Q_2 = __________ TW_2 = __________

(Q_1 = DESIGN DISCHARGE, SAY Q_{25}
Q_2 = CHECK DISCHARGE, SAY Q_{50} OR Q_{100})

SKETCH

STATION: ________________



MEAN STREAM VELOCITY = ______

MAX. STREAM VELOCITY = ______

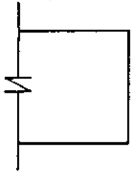
CULVERT DESCRIPTION (Entrance Type)	Q	SIZE	HEADWATER COMPUTATION										Controlling HW	Outlet Velocity	COST	COMMENTS
			INLET CONT.		OUTLET CONTROL HW = H + h_o − LS_o											
			$\frac{HW}{D}$	HW	K_e	H	d_c	$\frac{d_c + D}{2}$	TW	h_o	LS_o	HW				

SUMMARY & RECOMMENDATIONS:

FIG. 3-5

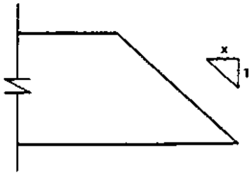
FIGURE 3 - 7 – TYPE OF INLETS AVAILABLE

1.)



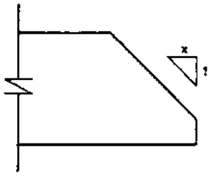
NO BEVEL

2.)



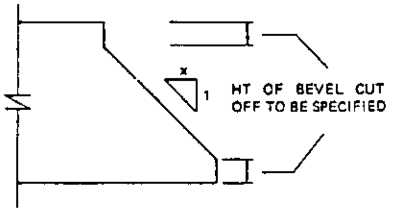
FULL BEVEL

3.)



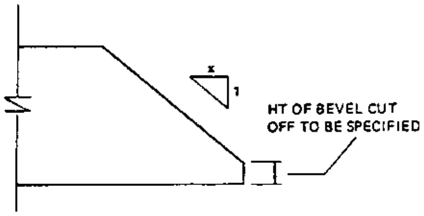
BEVEL ABOVE CORNER PLATES

4.)

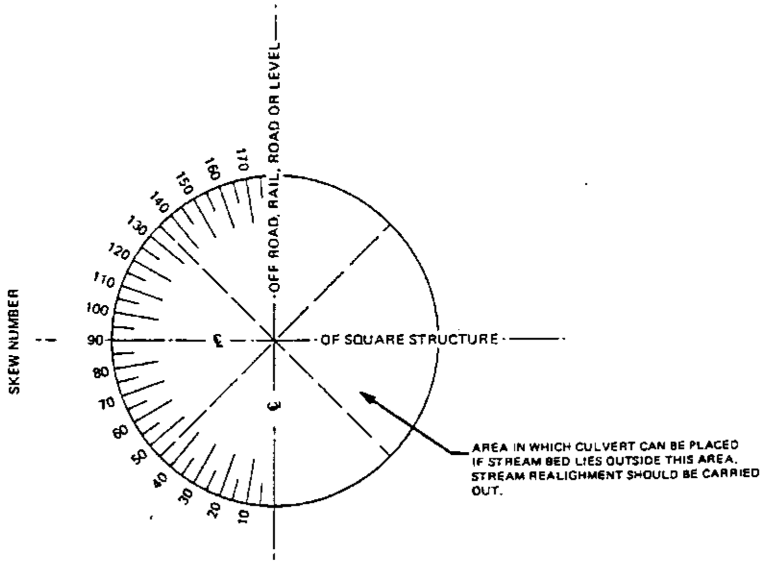


STEP BEVEL

5.)



CUT OFF BEVEL



AREA IN WHICH CULVERT CAN BE PLACED IF STREAM BED LIES OUTSIDE THIS AREA. STREAM REALIGHMENT SHOULD BE CARRIED OUT.

NOTE: IF THE CULVERT IS LOCATED BETWEEN SKEW NOS. 46 ÷ 75 AND 106 ÷ 135, A RING BEAM MUST BE INCORPORATED IN THE STRUCTURE.

B. INSTRUCTIONS FOR USE OF INLET AND OUTLET CONTROL NOMOGRAPHS

CHARTS 1 & 2 INLET CONTROL NOMOGRAPH

1. To determine headwater HW
   - a. Connect with a straightedge the given culvert diameter(D) and the discharge Q. Mark intersection of straightedge on $\frac{HW}{D}$ scale marked (1)
   - b. If $\frac{HW}{D}$ scale marked (1) represents entrance type used, read $\frac{HW}{D}$ on scale (1). If some other entrance type is used extend the point of intersection in (1) horizontally to scale (2) or(3) and read $\frac{HW}{D}$.
   - c. Compute HW by multiplying $\frac{HW}{D}$ by D
2. To determine culvert size
   - a. Given $\frac{HW}{D}$ value, locate $\frac{HW}{D}$ on scale for appropriate entrance type. If scale (2)or(3) is used extend $\frac{HW}{D}$ point horizontally to scale (1).
   - b. Connect point on $\frac{HW}{D}$ scale (1) as found in (a) above to given discharge and read diameter or size of culvert required.
3. To determine discharge (Q)
   - a. Given HW and D, locate $\frac{HW}{D}$ on scale for appropriate entrance type. Continue as in 2a.
   - b. Connect point on HW scale (1) as found in (a) above and the size of culvert on the left scale and read Q on the discharge scale.

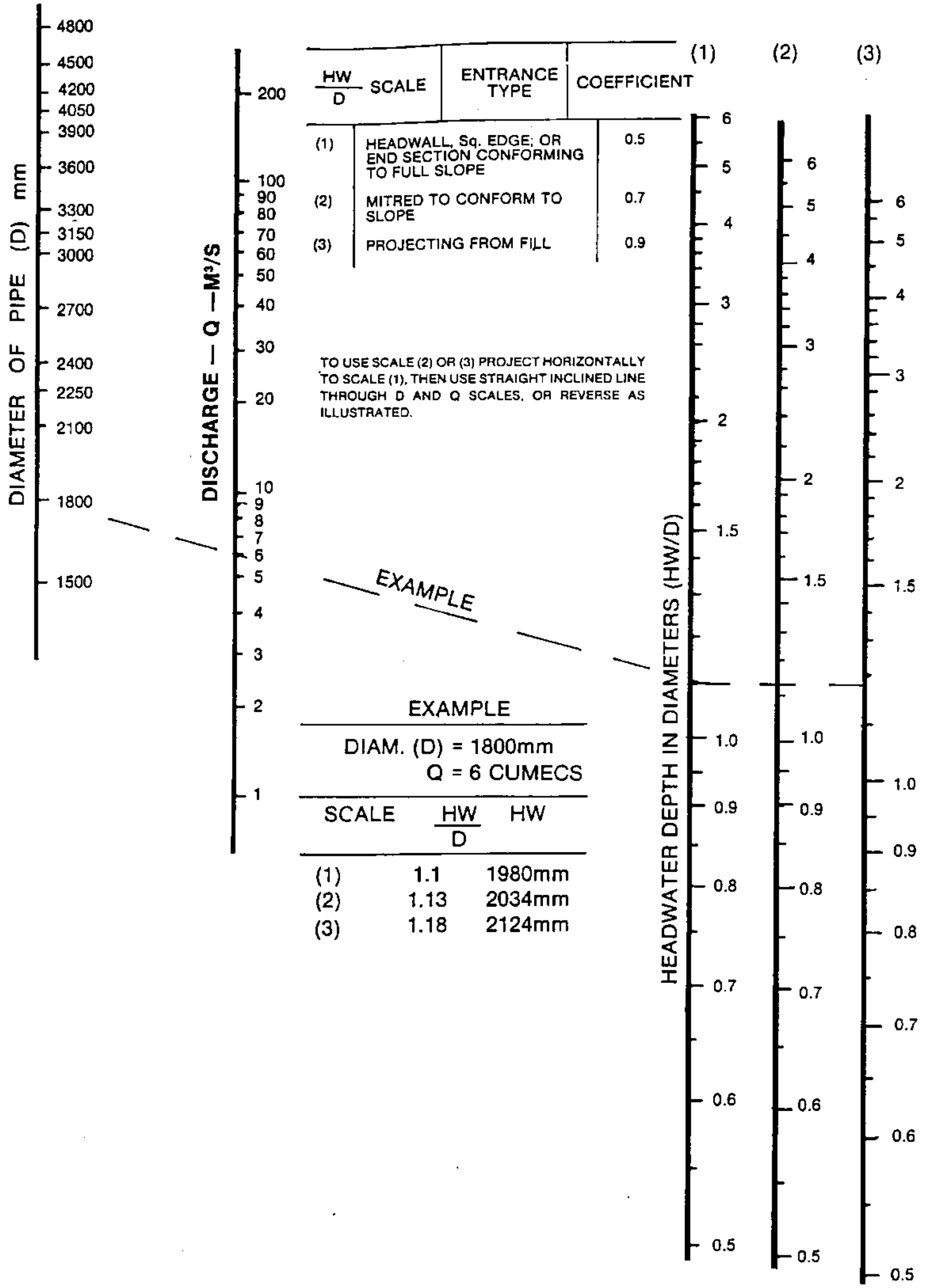
CHART 3 OUTLET CONTROL NOMOGRAPH

Outlet control nomographs are for head H when the culvert barrel flows full for it's entire length. They are also used to determine head H for some part-full flow conditions with outlet control. These nomographs do not give a complete solution for finding headwater HW, since they only give H in the equation $HW = H + h_o - LS_o$

1. To determine head H for a given culvert and discharge Q.
   - a. Locate appropriate nomograph for type of culvert selected. Find k_e for a specific entrance type.
   - b. Begin nomograph solution by locating starting point on length scale. To locate the proper starting point on the length scales follow instuctions below:
     - (1) If the n value of the nomograph corresponds to that of the culvert being used, select the length curve for the proper k_e and locate the starting point at the given culvert length. If the n value for the culvert selected differs from that of the nomograph, adjust length as shown on the charts
     - (2) For the n of the nomograph and a k_e intermediate between the scales given, connect the given length on adjacent scales by a straight line and select a point on this line spaced between the two chart scales in proportion to the k_e values.
   - c. Using a straightedge, connect point on length scale to size of culvert barrel and mark the point of crossing on the "turning line".
   - d. Pivot the straigtedge on this point on the turning line and connect given discharge rate. Read head in meters on the head (H) scale. For values beyond the limit of the chart scales, find H by solving equation (2).

LOSS COEFFICIENT Ke FOR VARIOUS ENTRANCE TYPES

$\frac{HW}{D}$ SCALE	ENTRANCE TYPE	COEFFICIENT
(1)	HEADWALL, Sq. EDGE; OR END SECTION CONFORMING TO FULL SLOPE	0.5
(2)	MITRED TO CONFORM TO SLOPE	0.7
(3)	PROJECTING FROM FILL	0.9



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.

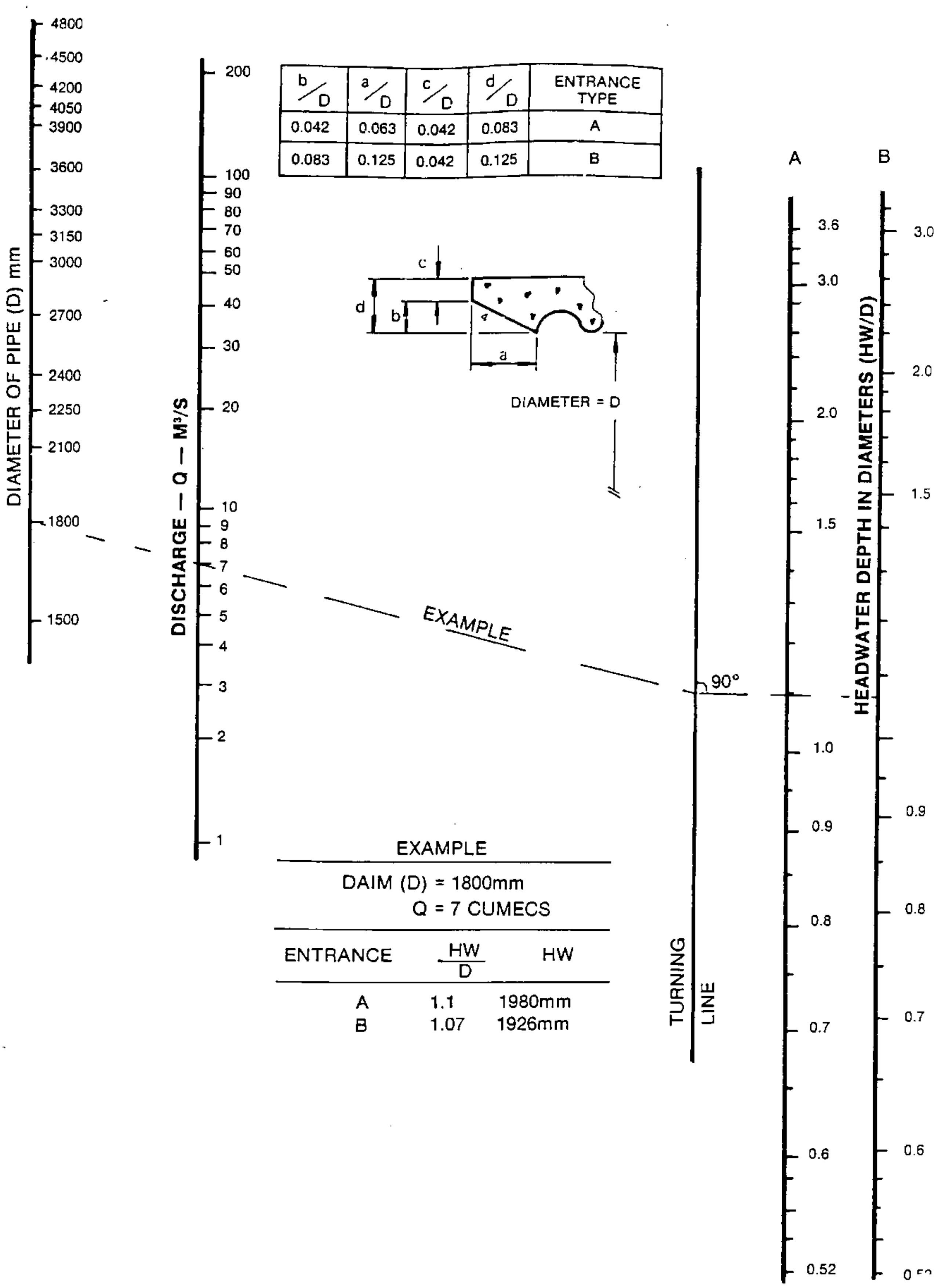
EXAMPLE

DIAM. (D) = 1800mm
Q = 6 CUMECS

SCALE	$\frac{HW}{D}$	HW
(1)	1.1	1980mm
(2)	1.13	2034mm
(3)	1.18	2124mm

HEADWATER DEPTH
CORRUGATED STEEL PIPE CULVERTS
WITH **INLET CONTROL**

CHART 1



b/D	a/D	c/D	d/D	ENTRANCE TYPE
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B

EXAMPLE

DAIM (D) = 1800mm
Q = 7 CUMECS

ENTRANCE	HW/D	HW
A	1.1	1980mm
B	1.07	1926mm

HEADWATER DEPTH FOR
CIRCULAR PIPE CULVERTS
WITH BEVELLED RING
INLET CONTROL

CHART 2

EXAMPLE

SIZE = 4.10 x 2.57 Q = 20 Cumecs

	PROJECT	HEADWALL	
		NO BEV	BEVEL
HW/R	1.21	1.11	1.03
HW m	3.11	2.83	2.65

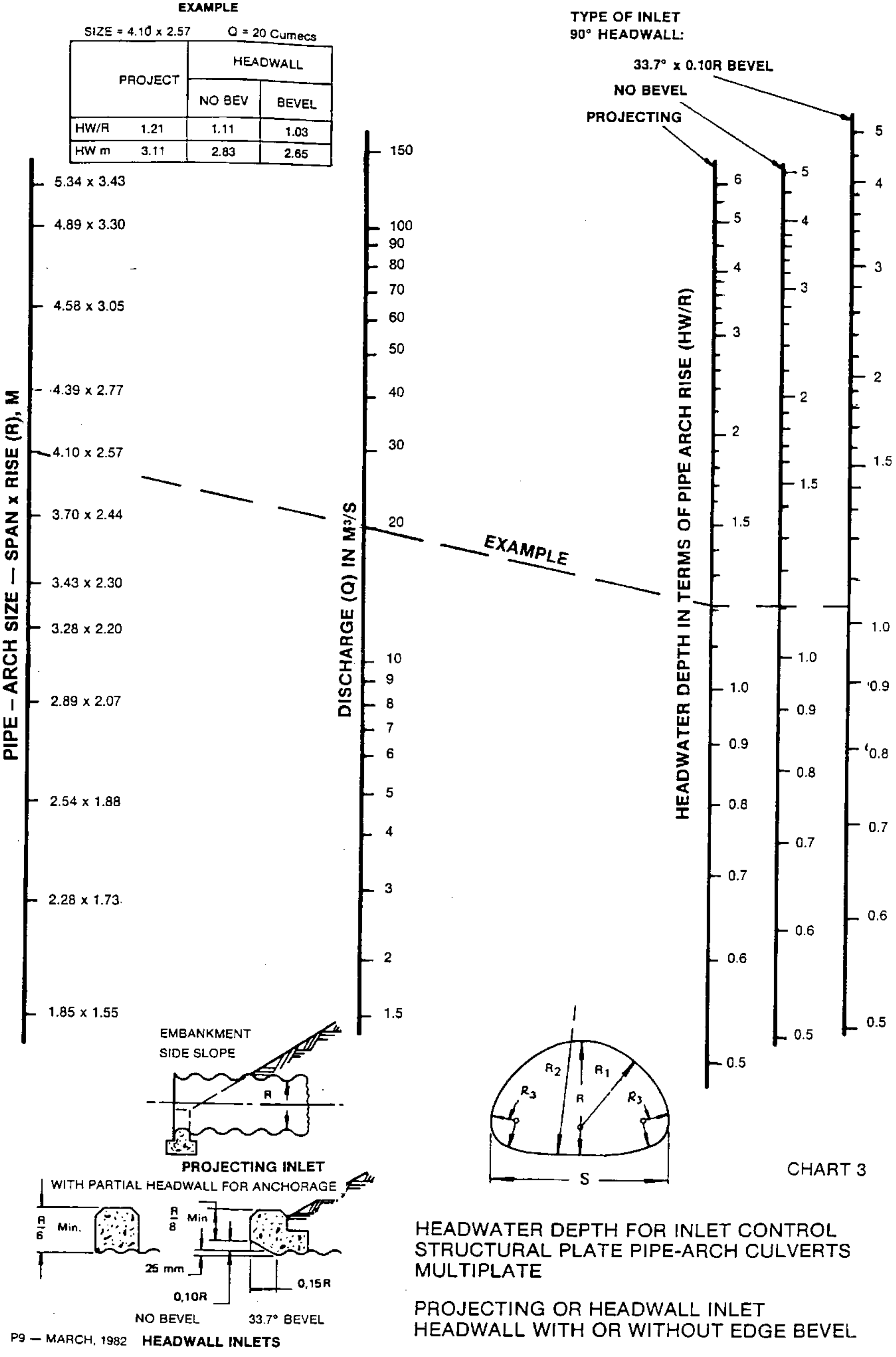
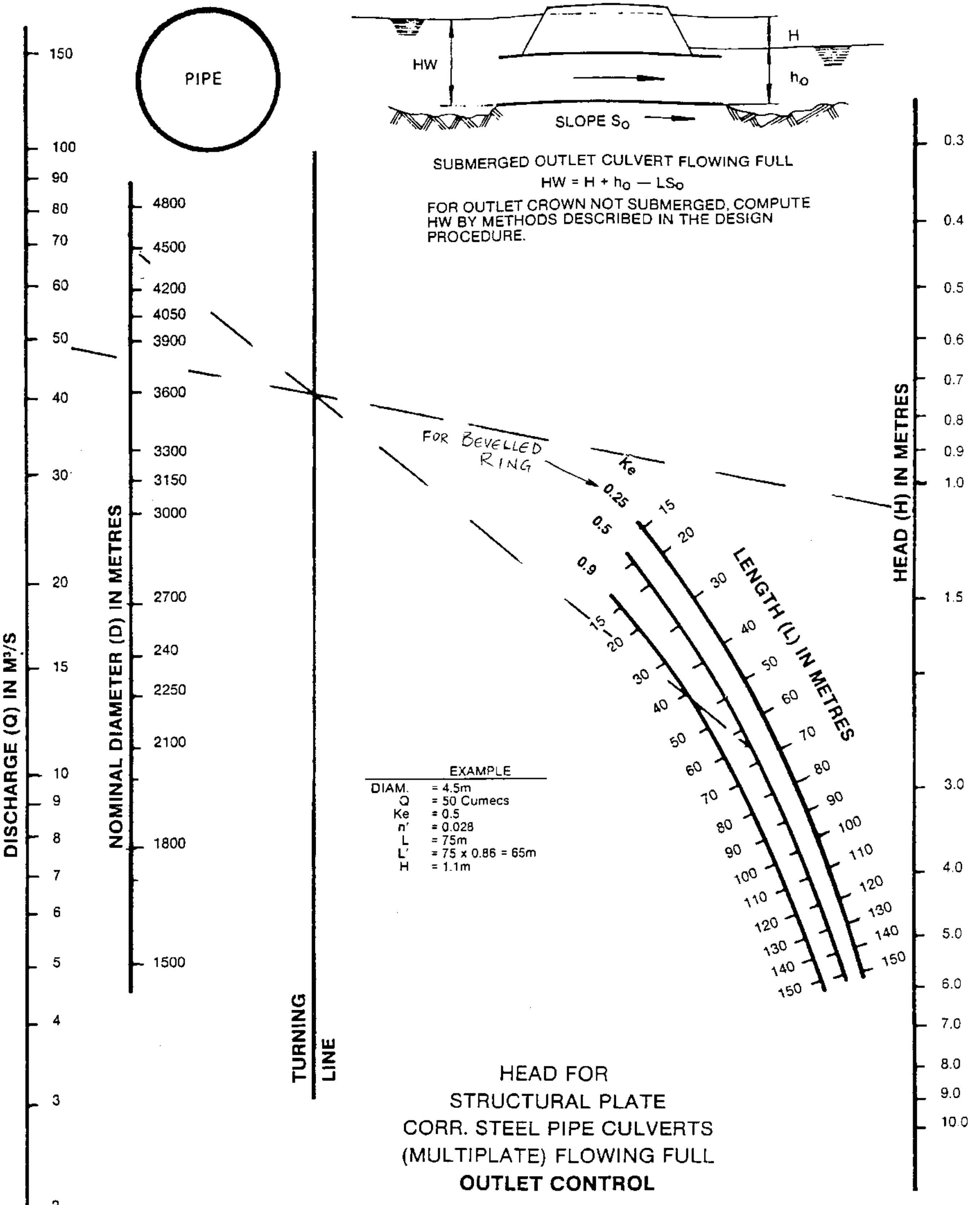


CHART 3

HEADWATER DEPTH FOR INLET CONTROL STRUCTURAL PLATE PIPE-ARCH CULVERTS MULTIPLATE

PROJECTING OR HEADWALL INLET HEADWALL WITH OR WITHOUT EDGE BEVEL



SUBMERGED OUTLET CULVERT FLOWING FULL

$HW = H + h_o - LS_o$

FOR OUTLET CROWN NOT SUBMERGED, COMPUTE HW BY METHODS DESCRIBED IN THE DESIGN PROCEDURE.

EXAMPLE

DIAM. = 4.5m
Q = 50 Cumecs
Ke = 0.5
n' = 0.028
L = 75m
L' = 75 x 0.86 = 65m
H = 1.1m

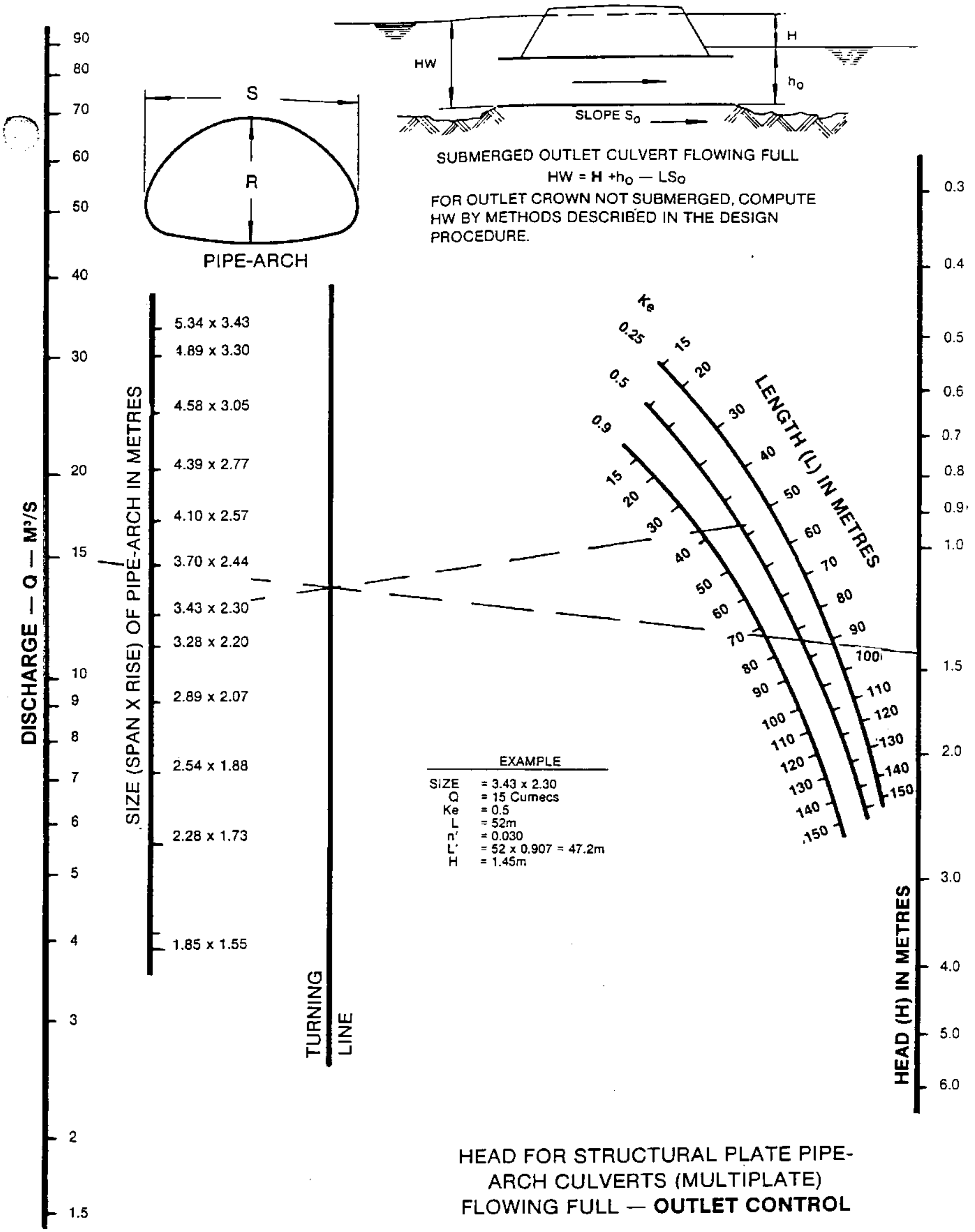
HEAD FOR STRUCTURAL PLATE CORR. STEEL PIPE CULVERTS (MULTIPLATE) FLOWING FULL

OUTLET CONTROL

LENGTH ADJUSTMENT FOR IMPROVED HYDRAULICS

Pipe Diam. in metres.	Roughness Factor		Length Adjustment Factor
	Curves based n =	Actual n' = *	$\left(\frac{n'}{n}\right)^2$
1.50	.0328	.033	1.0
2.10	.0320	.032	1.0
3.00	.0311	.030	0.93
4.50	.0302	.028	0.86

CHART 4



SUBMERGED OUTLET CULVERT FLOWING FULL

$HW = H + h_o - LS_o$

FOR OUTLET CROWN NOT SUBMERGED, COMPUTE HW BY METHODS DESCRIBED IN THE DESIGN PROCEDURE.

EXAMPLE

SIZE = 3.43 x 2.30
Q = 15 Cumecs
Ke = 0.5
L = 52m
n' = 0.030
L' = 52 x 0.907 = 47.2m
H = 1.45m

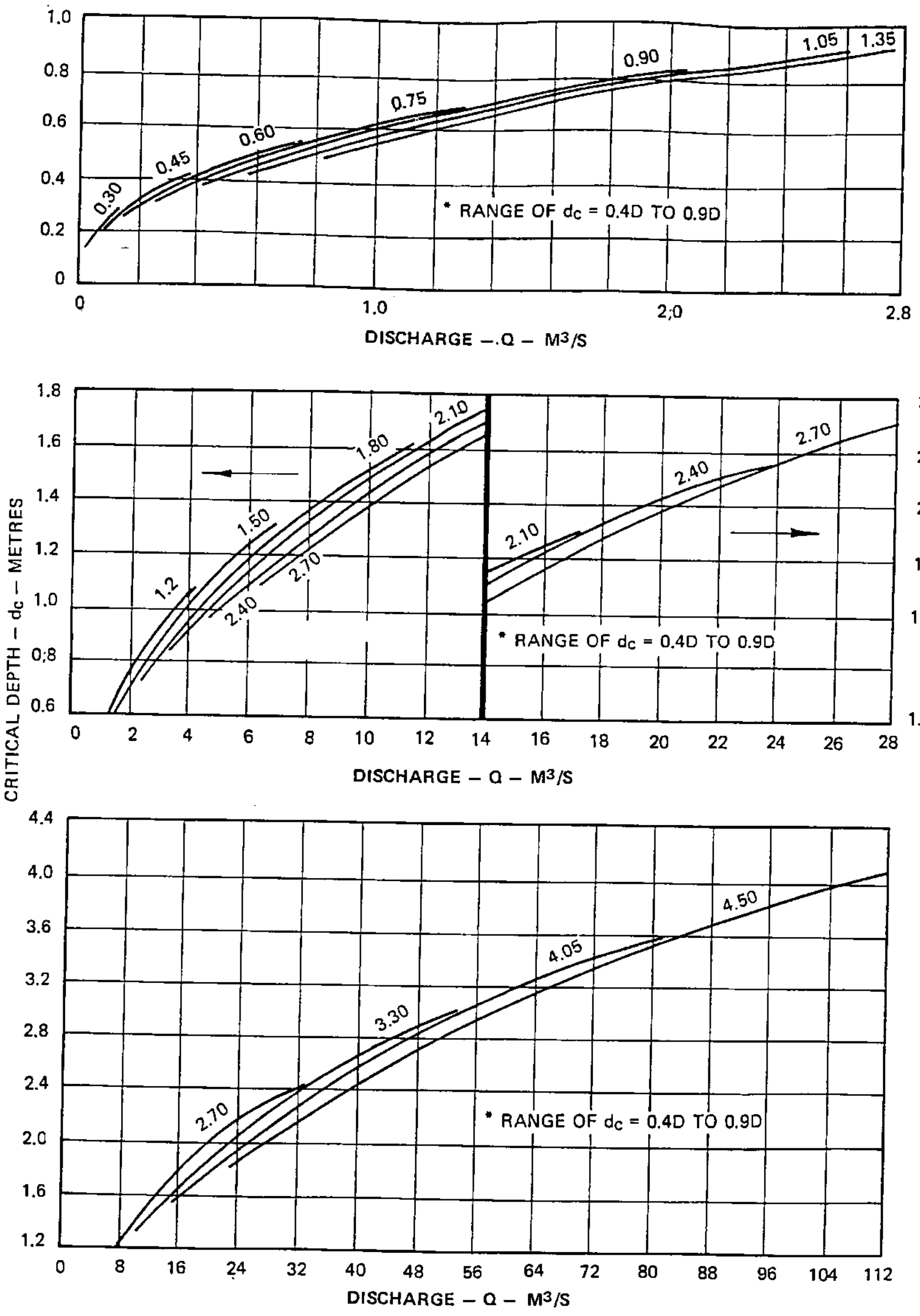
HEAD FOR STRUCTURAL PLATE PIPE-ARCH CULVERTS (MULTIPLATE) FLOWING FULL — **OUTLET CONTROL**

CHART 5

LENGTH ADJUSTMENT FOR IMPROVED HYDRAULICS

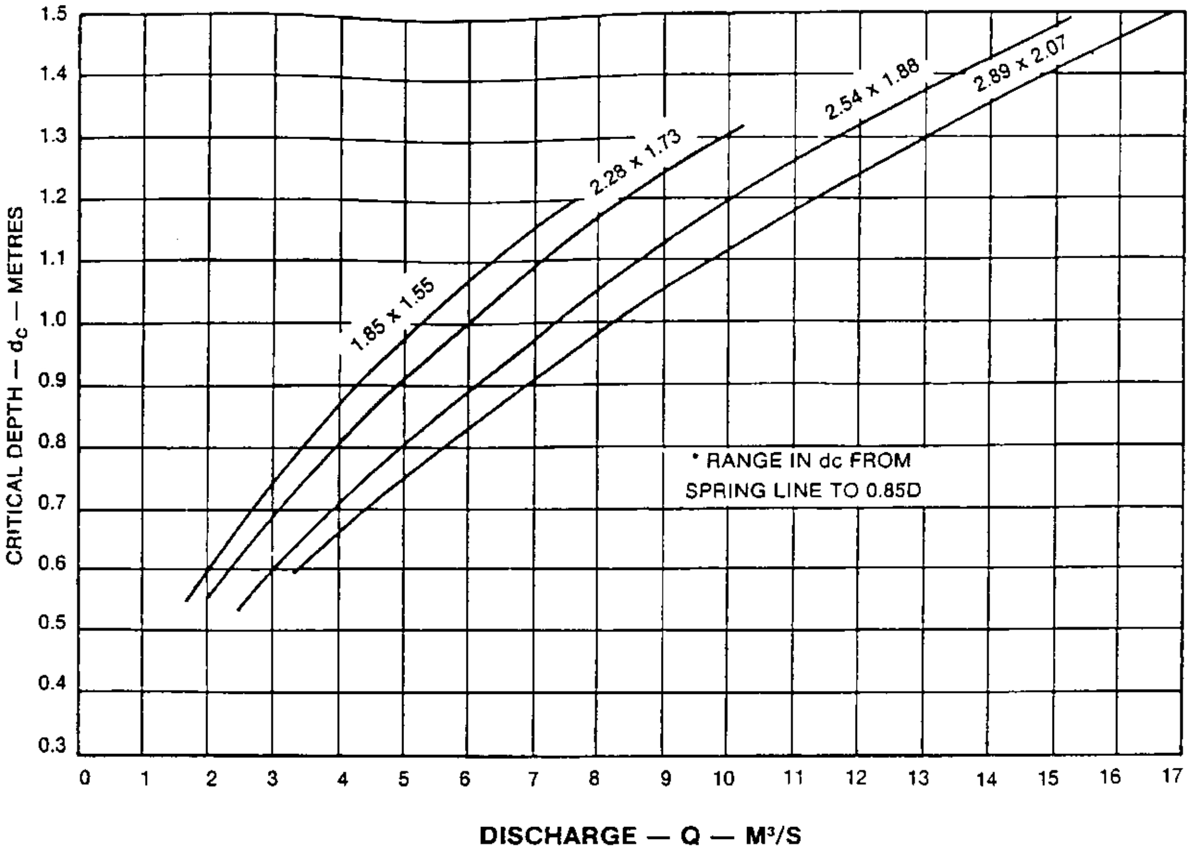
Pipe Arch Size in metres			Length Adjustment Factor $\left(\frac{n'}{n}\right)^2$
	Curves based on *n*	Actual *n'* *	
1.85 x 1.55	.0327	.0327	1.0
2.54 x 1.88	.0321	.032	1.0
3.43 x 2.30	.0315	.030	0.907
4.89 x 3.30	.0306	.028	0.837

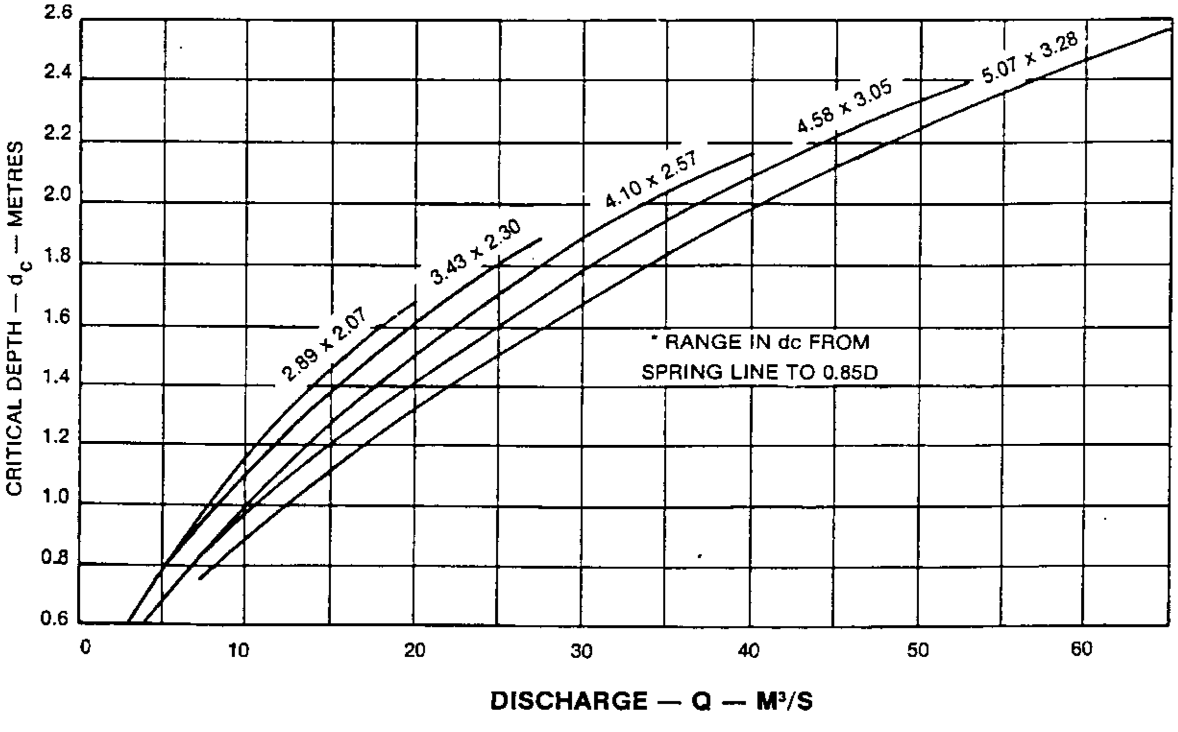
CHART 5



* NOTE: FOR VALUES OF d_c ABOVE CURVE, USE $d_c = D$

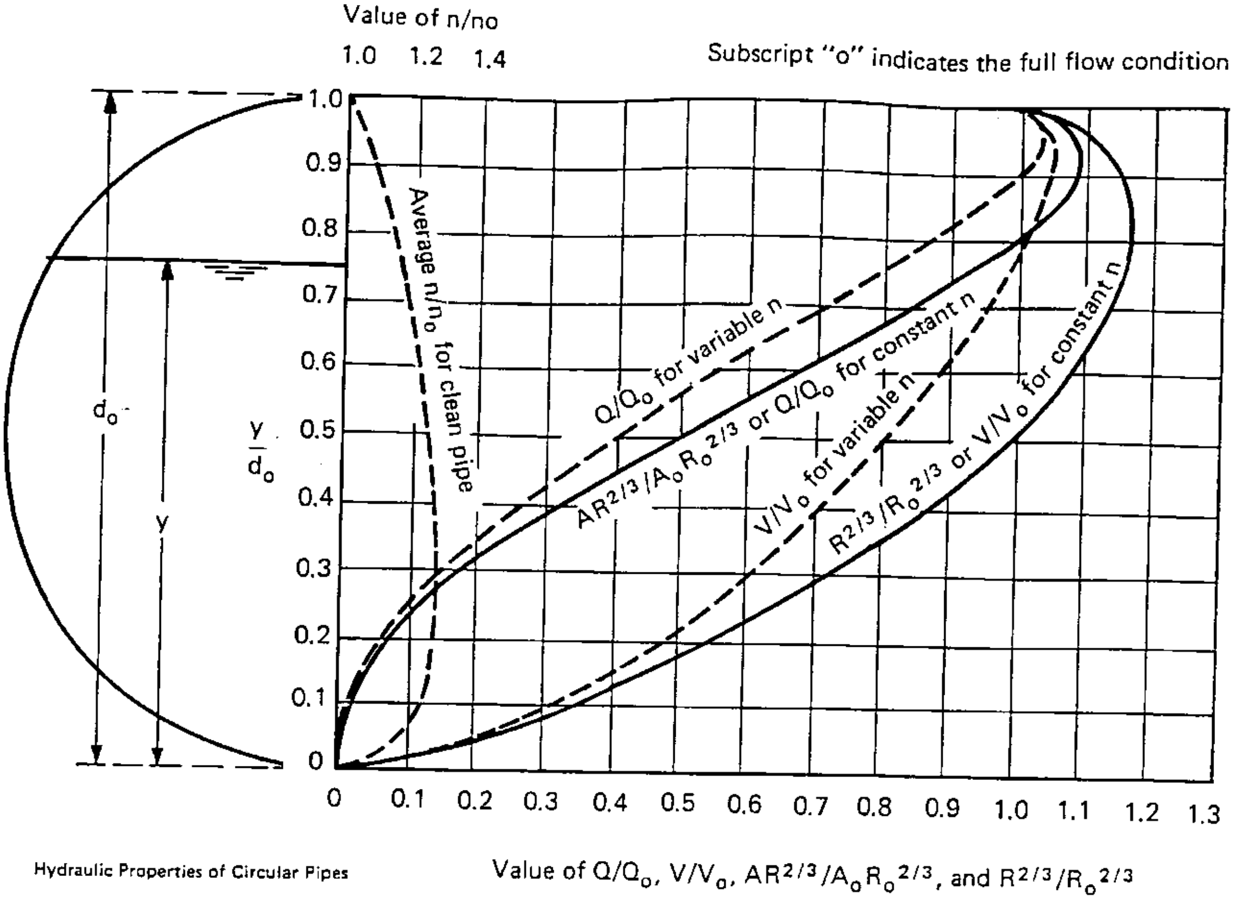
**CIRCULAR PIPE
CRITICAL DEPTH**





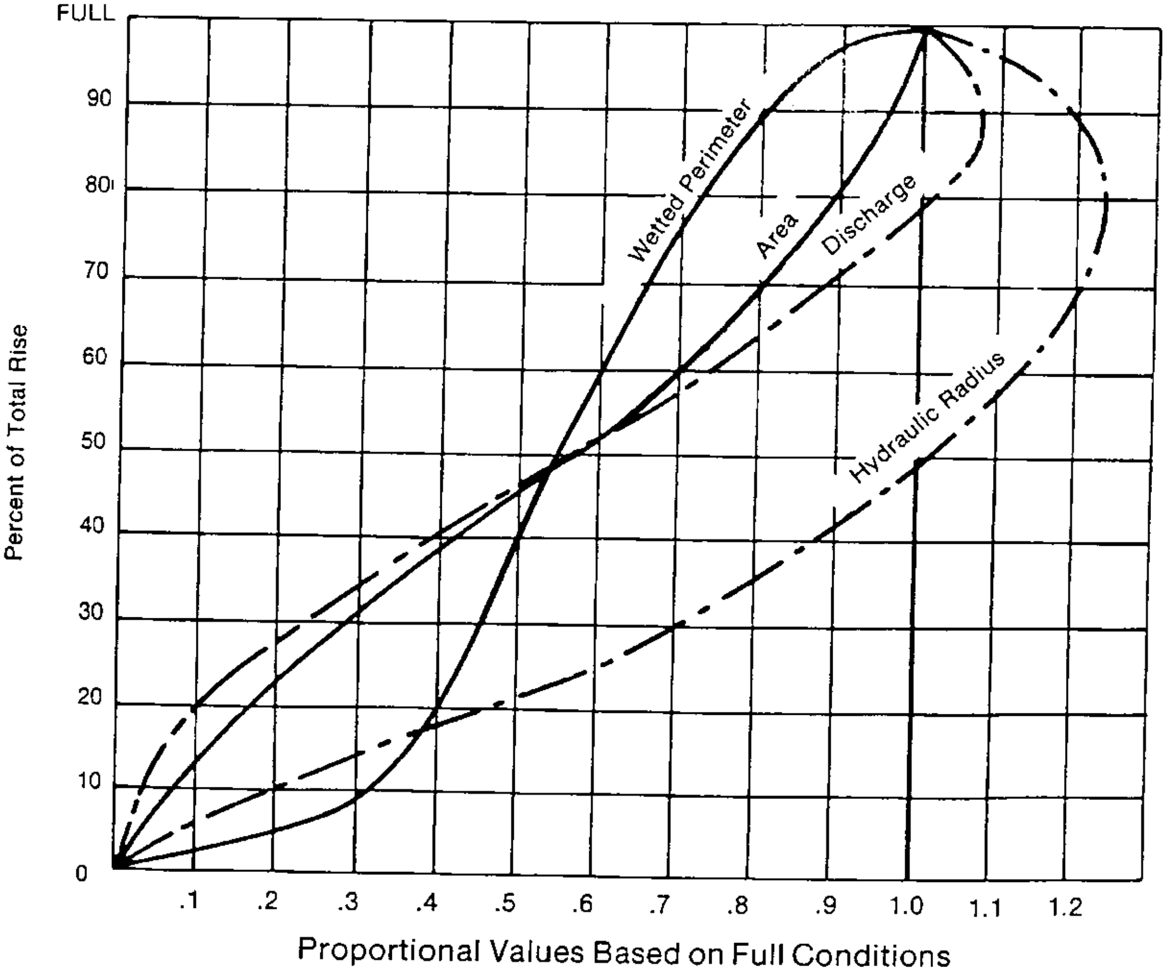
*** NOTE: FOR VALUES OF dc ABOVE CURVE, USE dc = D**

PIPE ARCH
CRITICAL DEPTH



Subscript "o" indicates the full flow condition

Hydraulic Properties of Circular Pipes



Hydraulic properties of corrugated steel and structural plate pipe-arches.