PRACTICAL GUIDANCE FOR ESTIMATING AND CONTROLLING EROSION AT CULVERT OUTLETS

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INTRODUCTION

This paper summarizes the results of research conducted at the U. S. Army Engineer Waterways Experiment Station (WES) during the past nine years to develop practical guidance for estimating and controlling erosion downstream of culvert and storm-drain outlets. Initial efforts were concerned with investigation and development of means of estimating the extent of scour to be anticipated downstream of outlets. Subsequent efforts have involved investigation and evaluation of various schemes of protection for controlling erosion such as horizontal blankets of rock riprap, preformed scour holes lined with rock riprap and channel expansions lined with natural and artificial revetments. In addition, efforts have been made to determine the limiting discharges for various energy dissipators including simple flared outlet transitions, stilling wells, U. S. Bureau of Reclamation type VI basins and St. Anthony Falls stilling basins. Empirical equations and charts are presented for estimating the extent of localized scour to be anticipated downstream of culvert and storm-drain outlets, the size and extent of various natural and artificial type revetments and the maximum recommended discharge for each type of energy dissipator investigated. With these results, designers can estimate the extent of scour to be expected and select appropriate and alternative schemes of protection for controlling erosion downstream of culverts and storm-drain outlets.

SCOUR AT OUTLETS

In general, two types of channel instability can develop downstream from a culvert and storm-drain outlet, i.e. either gully scour or localized erosion termed a scour hole. Distinction between the two conditions can be made by comparing the original or existing slope of the channel or drainage basin downstream of the outlet relative to that required for stability. Gully scour initiates at a control point downstream where the channel is stable and will progress upstream if sufficient difference in elevation exists between the outlet and the upstream section of stable channel. Erosion of this type may be of considerable extent depending upon the vertical and horizontal distances existing between the stable channel section and the outlet.

A scour hole is to be expected downstream of an outlet even if the downstream channel is stable. The severity of damage to be anticipated depends upon the conditions existing or created at the outlet and in general will consist of embankment erosion and structural damage of the apron, end wall, and culvert sections if sufficient localized scour is experienced. Noteworthy surveys of conditions at culvert outlets have been accomplished by Keeley[1] in Oklahoma and Scheer[2] in Montana.

The observations and empirical methods developed by Keeley[1,3,4] which provide specific guidance relative to the conditions that produce gully scour or only a localized scour hole as well as those required for stable channels in several Oklahoma soils merit consideration and application in general. An example of a chart developed by Bohan[5] for design of trapezoidal channels with 1 on 2 side slopes in a soil which would deposit and erode with Froude numbers of flow less than 0.15 and greater than 0.35, respectively, is shown in fig. 1. Bohan also reported the results of research conducted at WES to determine the extent of localized scour that may be anticipated downstream of culvert and storm-drain outlets. Empirical equations were developed for estimating the extent of the anticipated scour hole based on knowledge of the design discharge, the culvert diameter, and the duration and Froude number of the design flow at the culvert outlet. However, the relationship between the Froude number of flow at the culvert outlet and a discharge parameter, $Q/D_o^{5/2}$, can be calculated for any shape of outlet and the discharge parameter is just as representative of flow conditions as is the Froude number. The relations between the two parameters for partial and full pipe flow in square culverts are shown in fig. 2. Since the discharge parameter is easier to calculate and is suitable for application purposes, the original data reported by Bohan were reanalyzed to determine the following relations for estimating the extent of localized scour to be anticipated downstream of culvert and storm-drain outlets.

Maximum Depth of Scour:

$$\frac{D_{sm}}{D_o} = 0.80\left(\frac{Q}{D_o^{5/2}}\right)^{0.375} t^{0.10} \qquad \text{Tailwater} < 0.5D_o$$

$$\frac{D_{sm}}{D_o} = 0.74\left(\frac{Q}{D_o^{5/2}}\right)^{0.375} t^{0.10} \qquad \text{Tailwater} \geq 0.5D_o$$

Maximum Width of Scour:

$$\frac{W_{sm}}{D_o} = 1.00\left(\frac{Q}{D_o^{5/2}}\right)^{0.915} t^{0.15} \qquad \text{Tailwater} < 0.5D_o$$

$$\frac{W_{sm}}{D_o} = 0.72\left(\frac{Q}{D_o^{5/2}}\right)^{0.915} t^{0.15} \qquad \text{Tailwater} \geq 0.5D_o$$

Maximum Length of Scour:

$$\frac{L_{sm}}{D_o} = 2.40\left(\frac{Q}{D_o^{5/2}}\right)^{0.71} t^{0.125} \qquad \text{Tailwater} < 0.5D_o$$

$$\frac{L_{sm}}{D_o} = 4.10\left(\frac{Q}{D_o^{5/2}}\right)^{0.71} t^{0.125} \qquad \text{Tailwater} \geq 0.5D_o$$

Volume of Scour:

$$\frac{V_s}{D_o^3} = 0.73 \left(\frac{Q}{D_o^{5/2}}\right)^2 t^{0.375} \qquad \text{Tailwater} < 0.5D_o$$

$$\frac{V_s}{D_o^3} = 0.62 \left(\frac{Q}{D_o^{5/2}}\right)^2 t^{0.375} \qquad \text{Tailwater} \geq 0.5D_o$$

The variables are defined in table 1 and comparisons of predicted and observed values are shown in figs. 3-6. Dimensionless profiles along the center lines of the scour holes to be anticipated with tailwaters less than $0.5D_o$ and equal to or greater than $0.5D_o$ are presented in figs. 7 and 8, respectively. The maximum depth of scour occurred at a distance 0.4 of the maximum length of scour downstream of the culvert outlet for all tailwater conditions. Dimensionless cross sections of the scour hole at this location are also shown in figs. 7 and 8. If the location of the outlet is such that a scour hole is not objectionable, it may be practical to allow localized erosion since the scour hole acts as an excellent energy dissipator; however, a cutoff wall which extends to a depth of at least 0.7 of the maximum depth of scour expected (fig. 7) should be provided to prevent undermining.

SCHEMES OF CONTROLLING EROSION AT OUTLETS

The average size of stone and configuration of a horizontal blanket of riprap at outlet invert elevation required to control or prevent localized scour downstream of an outlet can be estimated based on the results reported by Bohan and subsequent unreported tests. For a given design discharge, culvert diameter or width, and tailwater depth relative to the outlet invert, the minimum average size of stone for a stable horizontal blanket of protection can be estimated by the following relation:

$$\frac{d_{50}}{D_o} = 0.020 \frac{D_o}{TW} \left(\frac{Q}{D_o^{5/2}}\right)^{4/3}$$

The length of stone protection required (fig. 9) can be estimated by the equation,

$$\frac{L_{sp}}{D_o} = 1.7 \left(\frac{Q}{D_o^{5/2}} \right) + 8$$

The variables are defined in table 1 and the recommended configuration of a horizontal blanket of riprap for control of erosion at culvert and storm-drain outlets is presented in fig. 10. Details of a scheme of riprap protection termed "preformed scour hole lined with riprap" are shown in fig. 11. The relative advantage of providing both vertical and lateral expansion downstream of an outlet to permit dissipation of excess kinetic energy in turbulence rather than direct attack of the boundaries is shown in fig. 12 which indicates that the required size of stone may be reduced considerably if a riprap-lined, preformed scour hole is provided in lieu of a horizontal blanket at an elevation essentially the same as the outlet invert.

LINED CHANNEL EXPANSIONS

A research project sponsored by the Louisiana Department of Highways is in progress at WES to investigate the feasibility of lining channel expansions downstream of culvert outlets with either sack revetment, cellular blocks, or rock riprap. After observing flow conditions with various sizes of model culverts and geometries of channel expansions, the channel expansion geometry shown in fig. 13 was selected as a practical configuration. The dimensions of the lined channel expansion are related in terms of that of square box culverts.

Sack revetment with length, width, and thickness of 2 ft, 1.5 ft, and 0.33 ft, respectively, and weighing 120 lb was simulated at a scale of 1:8 as shown in fig. 14. Cellular blocks roughly 0.66 ft by 0.66 ft and 0.33 ft thick which weigh 14 lb were simulated at a scale of 1:4 as shown in fig. 15. Rock of 6 to 8 inch diameter weighing 17 lb was simulated at a scale of 1:4 as shown in fig. 16. The results of tests to determine the conditions of discharge and tailwater required to displace or fail each of the revetments are shown in fig. 17 and indicate that the thickness of geometrically similar revetments can be calculated by means of the following empirical equation:

$$\frac{d_{50}}{D_o} \text{ or } \frac{T_s}{D_o} \text{ or } \frac{T_B}{D_o} = 0.016 \frac{D_o}{TW}\left(\frac{Q}{D_o^{5/2}}\right)^{4/3}$$

The variables are defined in table 1. The relative effectiveness of the lined channel expansion relative tc the other schemes of riprap protection described previously is shown in fig. 12. The relations presented in fig. 12 are recommended for selection of either the size of revetment for a given scheme of protection, discharge, tailwater depth, and culvert dimension or for the selection of the size of culvert with which a given revetment and scheme of protection will remain stable under anticipated conditions of discharge and tailwater depth.

The maximum discharge parameters, $Q/D_o^{5/2}$, of various schemes of protection can be calculated based on the results presented herein and comparisons relative to the cost of each type of protection can be made to determine the most practical design of providing effective drainage and erosion control facilities for a given site. There will be conditions where the design discharge and economical size of culvert or storm-drain will result in a value of $Q/D_o^{5/2}$, the discharge parameter, greater than the maximum value permissible with feasible schemes of protection discussed previously and some form of energy dissipator will be required. In other cases, the value of $Q/D_o^{5/2}$ may be less than that of the aforementioned feasible schemes of protection and a simpler more economical form of protection may be indicated.

FLARED OUTLET TRANSITIONS

Tests were conducted to determine the maximum values of the discharge parameter (table 2) that were considered satisfactory with various conditions of tailwater and 3-, 5-, and 8-D_o-long simple flared outlet transitions whose details are shown in fig. 18. Results of the tests of these simple outlet transitions with the apron at the same elevation as the culvert invert are shown in fig. 19 which indicate that the maximum discharge parameter for a given culvert, length of transition, and tailwater can be calculated by the equation,

$$\frac{Q}{D_o^{5/2}} = 1.60\, \frac{TW}{D_o} \left(\frac{L}{D_o}\right)^{0.4} \left(\frac{D_o}{TW}\right)^{1/3}$$

Similarly, the length of transition for a given situation can be calculated by the equation,

$$\frac{L}{D_o} = 0.30 \left(\frac{D_o}{TW}\right)^2 \left(\frac{Q}{D_o^{5/2}}\right)^{2.5} \left(\frac{TW}{D_o}\right)^{1/3}$$

Variables are defined in table 1 and from fig. 19 it can be seen that this type of protection is satisfactory only for low values of $Q/D_o^{5/2}$. The arbitrary extent of scour depth equal to or less than $0.5D_o$ was used to classify satisfactory conditions.

Attempts were made to investigate the effectiveness of recessing the apron of these flared outlet transitions and providing an end sill at the downstream end; however, fig. 20 indicates that this modification did not significantly improve energy dissipation or increase the applicable maximum value of the discharge parameter, $Q/D_o^{5/2}$.

COMMONLY USED ENERGY DISSIPATORS

Grace and Pickering[6] have reported the results of model tests to evaluate the maximum values of the discharge parameter, $Q/D_o^{5/2}$, applicable to various sizes of three commonly used energy dissipators; stilling wells, U. S. Bureau of Reclamation Type VI Basins and St. Anthony Falls stilling basins.

The stilling well consists of a vertical section of circular pipe affixed to the outlet end of a storm drain as shown in fig. 21. The recommended depth of the well below the invert of the incoming pipe is dependent on the slope and diameter of the incoming pipe and can be determined from the plot shown in fig. 21. The recommended height of stilling well above the invert of the incoming pipe is two times the diameter of the incoming pipe. The top of the well should be located at the elevation of the invert of a stable channel or drainage basin.

The area adjacent to the well may be protected by riprap or paving; however, if there is no adjacent erodible embankment within two well diameters of the periphery of the stilling well, there is no need for protection. Energy dissipation is accomplished without the necessity of maintaining a specified tailwater depth in the vicinity of the outlet.

Details of the U. S. Bureau of Reclamation Type VI basin and the St. Anthony Falls stilling basin are presented in figs. 22 and 23. Maximum values of the discharge parameter, $Q/D_o^{5/2}$, considered satisfactory for various sizes of each of the energy dissipators are presented in table 3. These data are satisfied by the following equations which may be used to compute the diameter or width of each type of energy dissipator relative to that of the incoming pipe:

$$\frac{D_W}{D_o} = 0.53 \left(\frac{Q}{D_o^{5/2}}\right)^{1.0} \qquad \text{stilling well}$$

$$\frac{W_{SAF}}{D_o} = 0.30 \left(\frac{Q}{D_o^{5/2}}\right)^{1.0} \qquad \text{St. Anthony Falls stilling basin}$$

$$\frac{W_{VI}}{D_o} = 1.30 \left(\frac{Q}{D_o^{5/2}}\right)^{0.55} \qquad \text{U. S. Bureau of Reclamation Type VI basin}$$

It is recommended that the size of stone protection to be provided downstream of these energy dissipators be estimated by the following relations:

$$\frac{d_{50}}{W_{ED}} = 0.020 \frac{W_{ED}}{TW} \left(\frac{Q}{W_{ED}^{5/2}}\right)^{4/3}$$

or

$$\frac{d_{50}}{D} = 1.0 \left(\frac{V}{\sqrt{gd}}\right)^{3}$$

Guidance other than engineering judgment for estimating the length of stone protection required downstream of an energy dissipator are not available due to the lack of systematic investigations of this aspect of the problem.

ACKNOWLEDGMENTS

The results reported herein are based on research conducted at the U. S. Army Engineer Waterways Experiment Station and sponsored by the Directorate of Military Construction, Office, Chief of Engineers and the U. S. Department of Transportation, Federal Highway Administration and the Louisiana Department of Highways. Permission for the authors to present this paper does not signify that the contents necessarily reflect the views and policy of either the U. S. Army Corps of Engineers, the U. S. Department of Transportation, Federal Highway Administration or the Louisiana Department of Highways, nor does mention of trade names or commercial products constitute indorsement or recommendations for use.

TABLE 1

DEFINITION OF VARIABLES

A	Cross-sectional area of flow, ft^2
B	Base width of channel, ft
D	Depth of flow in channel, ft
D_o	Diameter or width of culvert, ft
D_S	Depth of scour, ft
D_{SM}	Maximum depth of scour, ft
D_W	Diameter of stilling well, ft
d	Depth of uniform flow in culvert, ft
d_{50}	Diameter of average size stone, ft
F	Froude number of flow at culvert outlet, $F = Q/A \sqrt{gd}$
F_{ch}	Froude number of flow in channel, $F_{ch} = Q/\sqrt{gA^3/T}$
g	Acceleration due to gravity, ft/sec^2
H	Depth of recessed apron and height of end sill, ft
L	Length of flared outlet transition, ft
L_S	Length of scour, ft
L_{SM}	Maximum length of scour, ft
L_{sp}	Length of stone protection, ft
n	Manning's roughness coefficient
Q	Discharge, cfs
S	Slope of channel bottom and energy gradient
T	Top width of flow in channel, ft
T_B	Thickness of cellular block, ft
T_S	Thickness of sack revetment, ft

(Continued)

TABLE 1 (Continued)

TW	Tailwater depth above invert of culvert, ft
t	Duration of flow, minutes
V	Average velocity of flow in channel, ft/sec
V_S	Volume of scour, ft^3
W_{ED}	Width of energy dissipator, ft
W_{SAF}	Width of St. Anthony Falls stilling basin, ft
W_{VI}	Width of U. S. Bureau of Reclamation type VI basin, ft
W_S	One-half total width of scour, ft
W_{SM}	One-half maximum width of scour, ft

TABLE 2

MAXIMUM DISCHARGE RECOMMENDED FOR VARIOUS FLARED OUTLET TRANSITIONS

Limiting Values of $Q/D_o^{5/2}$			
L/D_o	h/D_o	TW/D_o	$Q/D_o^{5/2}$
3	0	0	0.88
3	0	0.50	1.78
3	0	1.00	2.56
3	0.25	0.25	1.28
3	0.25	0.50	1.78
3	0.25	1.00	2.56
3	0.50	0.25	1.58
3	0.50	0.50	2.00
3	0.50	1.00	2.56
5	0	0.25	1.20
5	0	0.50	2.40
5	0	1.00	3.20
5	0.25	0.25	1.58
5	0.25	0.50	2.78
5	0.25	1.00	3.47
5	0.50	0.25	1.47
5	0.50	0.50	2.77
5	0.50	1.00	3.46
8	0	0.25	1.68
8	0	0.50	2.40
8	0	1.00	3.75
8	0.25	0.25	2.17
8	0.25	0.50	3.36
8	0.25	1.00	4.44
8	0.50	0.25	2.46
8	0.50	0.50	3.65
8	0.50	1.00	4.55

TABLE 3

MAXIMUM DISCHARGE RECOMMENDED FOR VARIOUS TYPES AND SIZES OF ENERGY DISSIPATORS

Relative Width and Type of Energy Dissipator	Maximum $Q/D_o^{5/2}$
Stilling Well	
1 D_o Diameter	2.0
2 D_o Diameter	3.5
3 D_o Diameter	5.0
5 D_o Diameter	10.0
USBR Type VI Basin	
1 D_o Wide	0.6
2 D_o Wide	2.2
3 D_o Wide	4.5
4 D_o Wide	7.6
5 D_o Wide	11.5
7 D_o Wide	21.0
SAF Stilling Basin	
1 D_o Wide	3.5
2 D_o Wide	7.0
3 D_o Wide	9.5

TABLE 4

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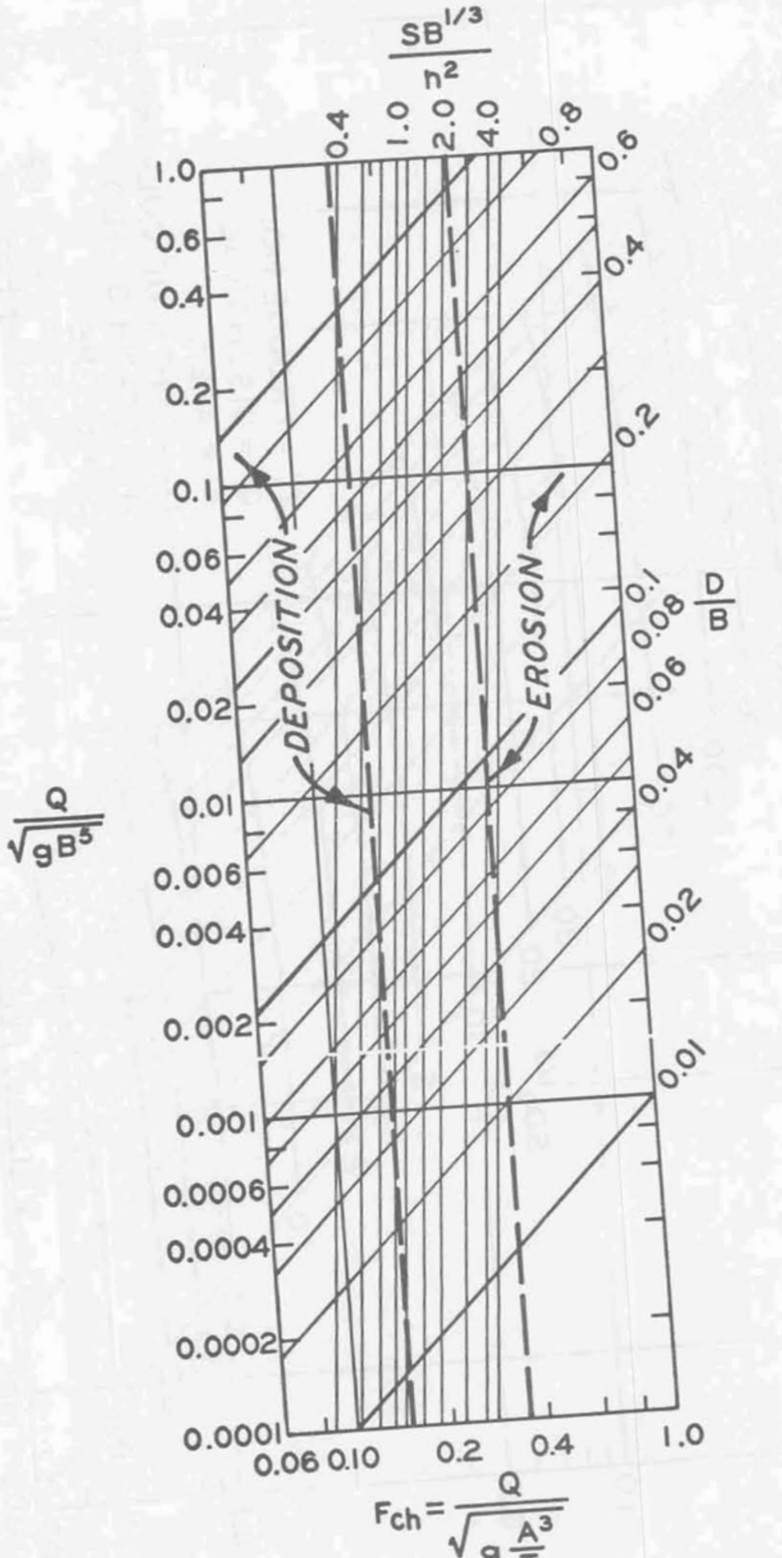


Fig. 1. Characteristics of a trapezoidal channel with 1-on-2 side slopes as a function of Froude number

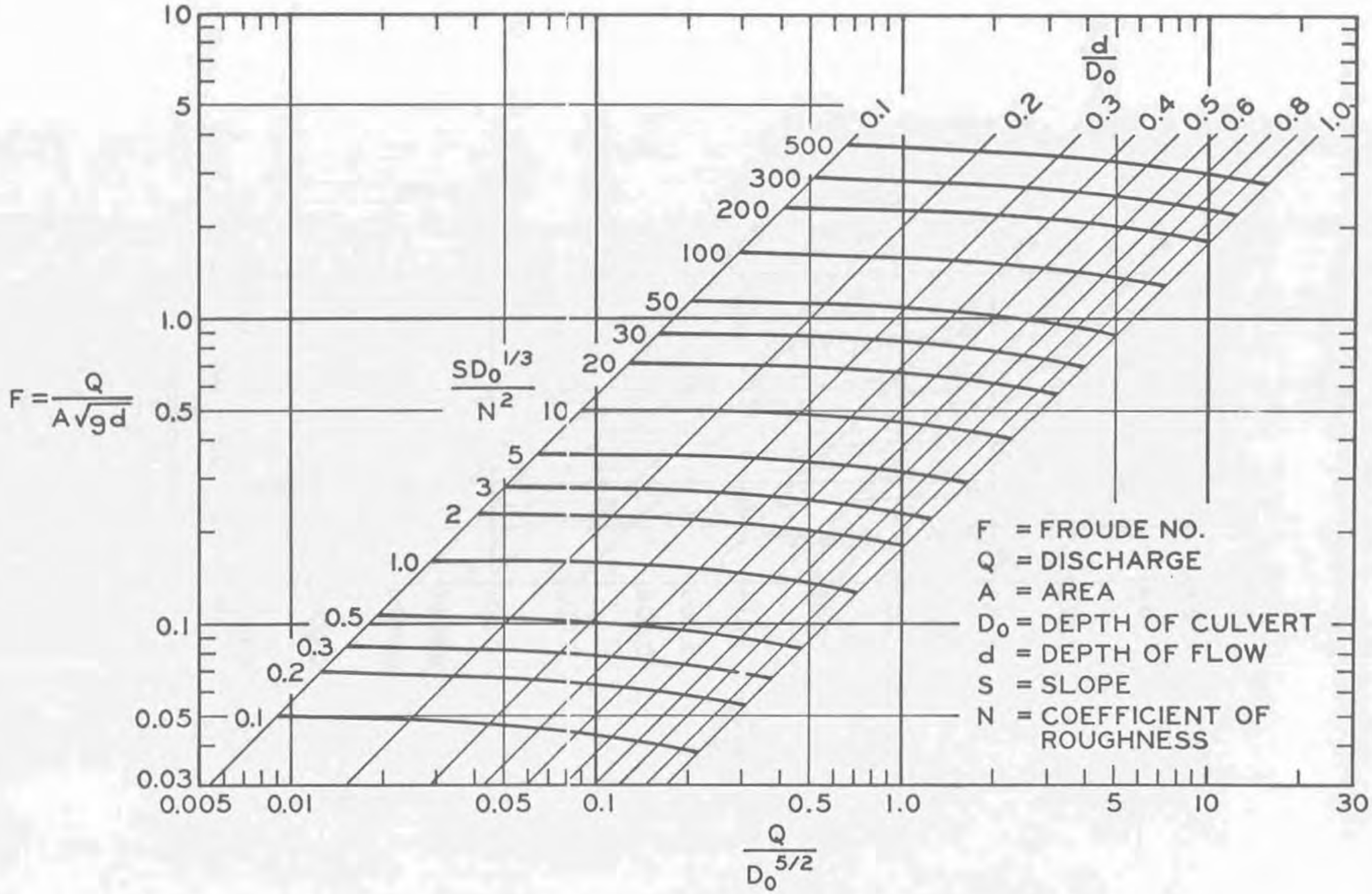


Fig. 2. Square culvert - Froude number versus discharge

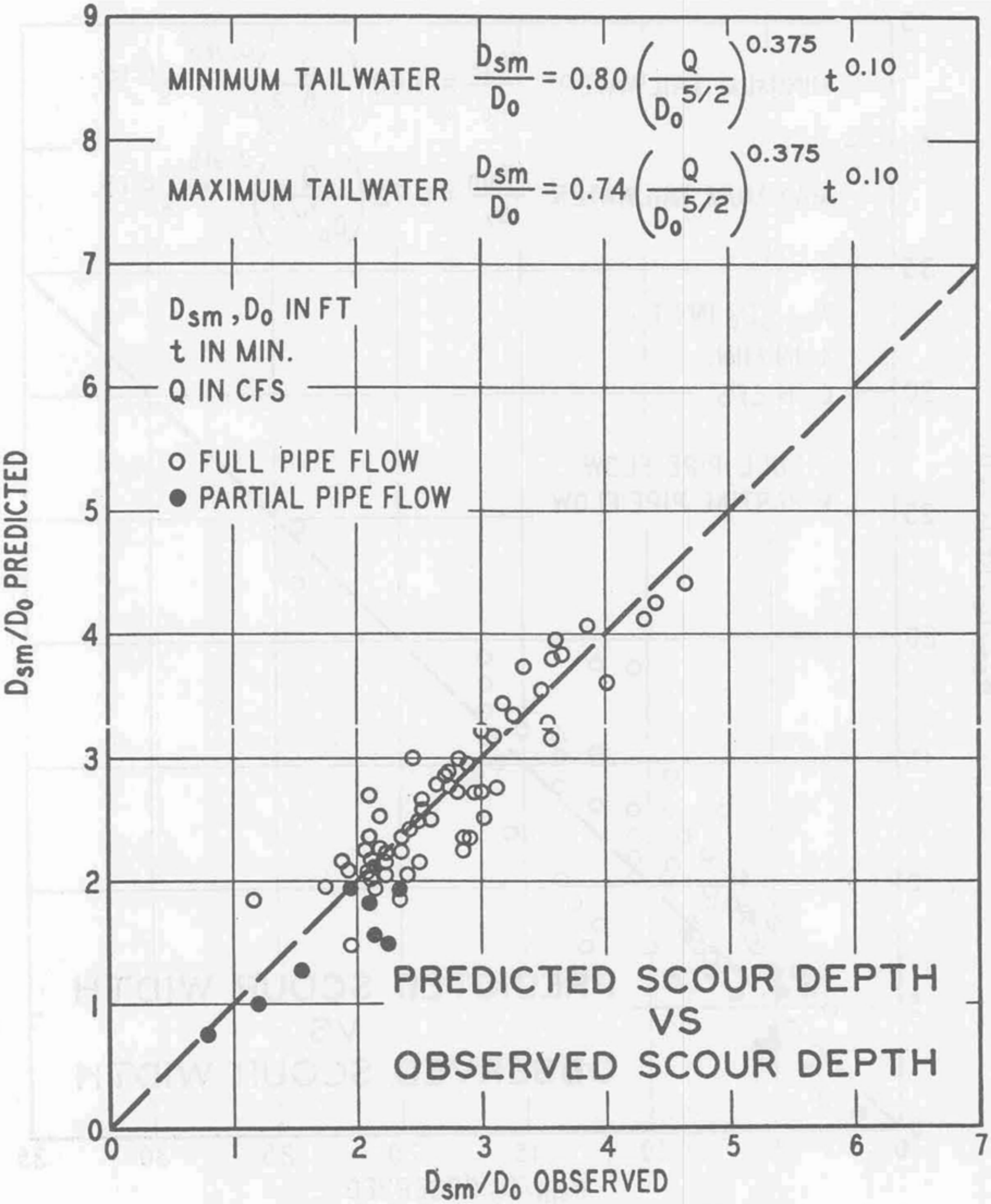


Fig. 3. Predicted scour depth versus observed scour depth

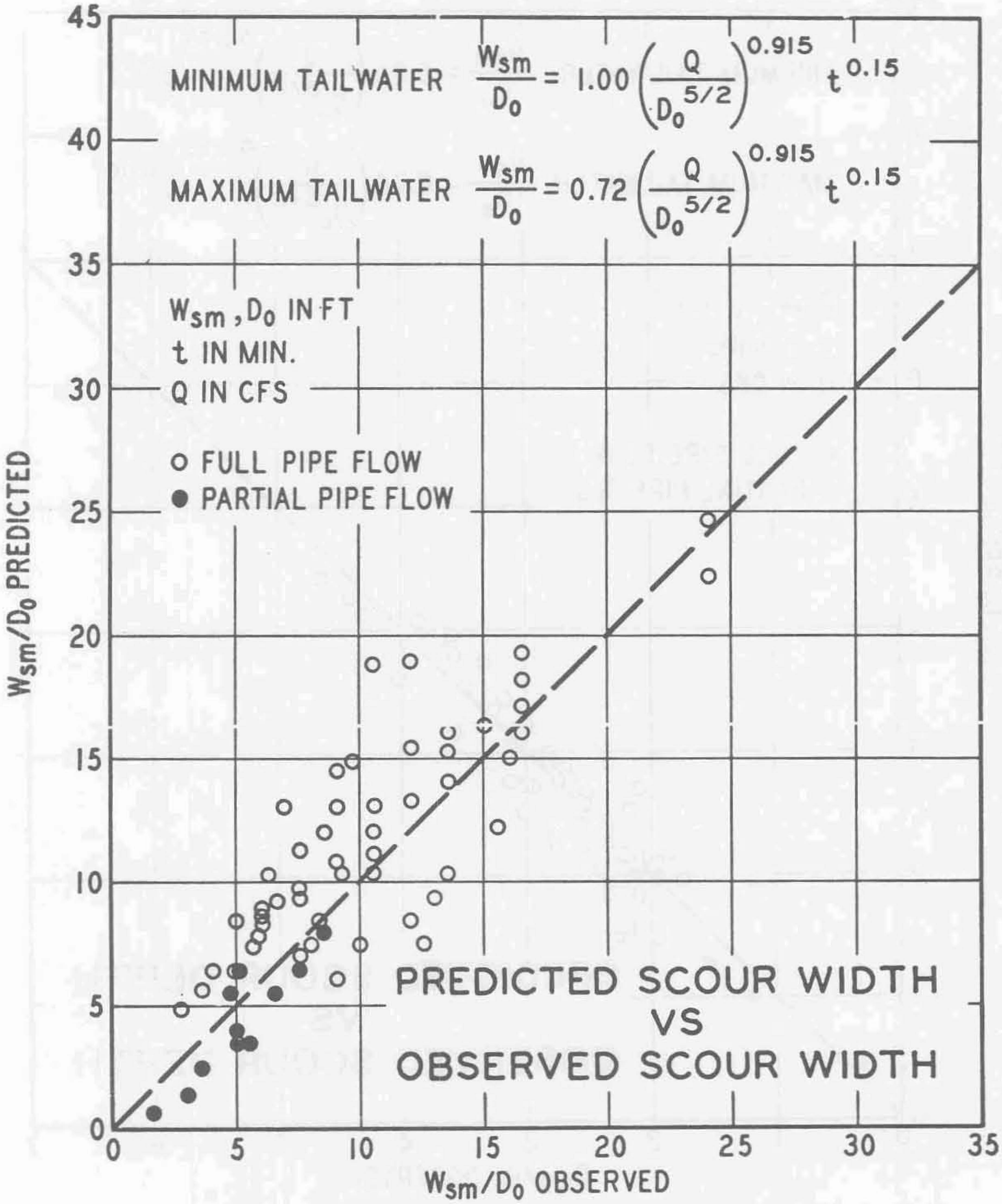


Fig. 4. Preducted scour width versus observed scour width

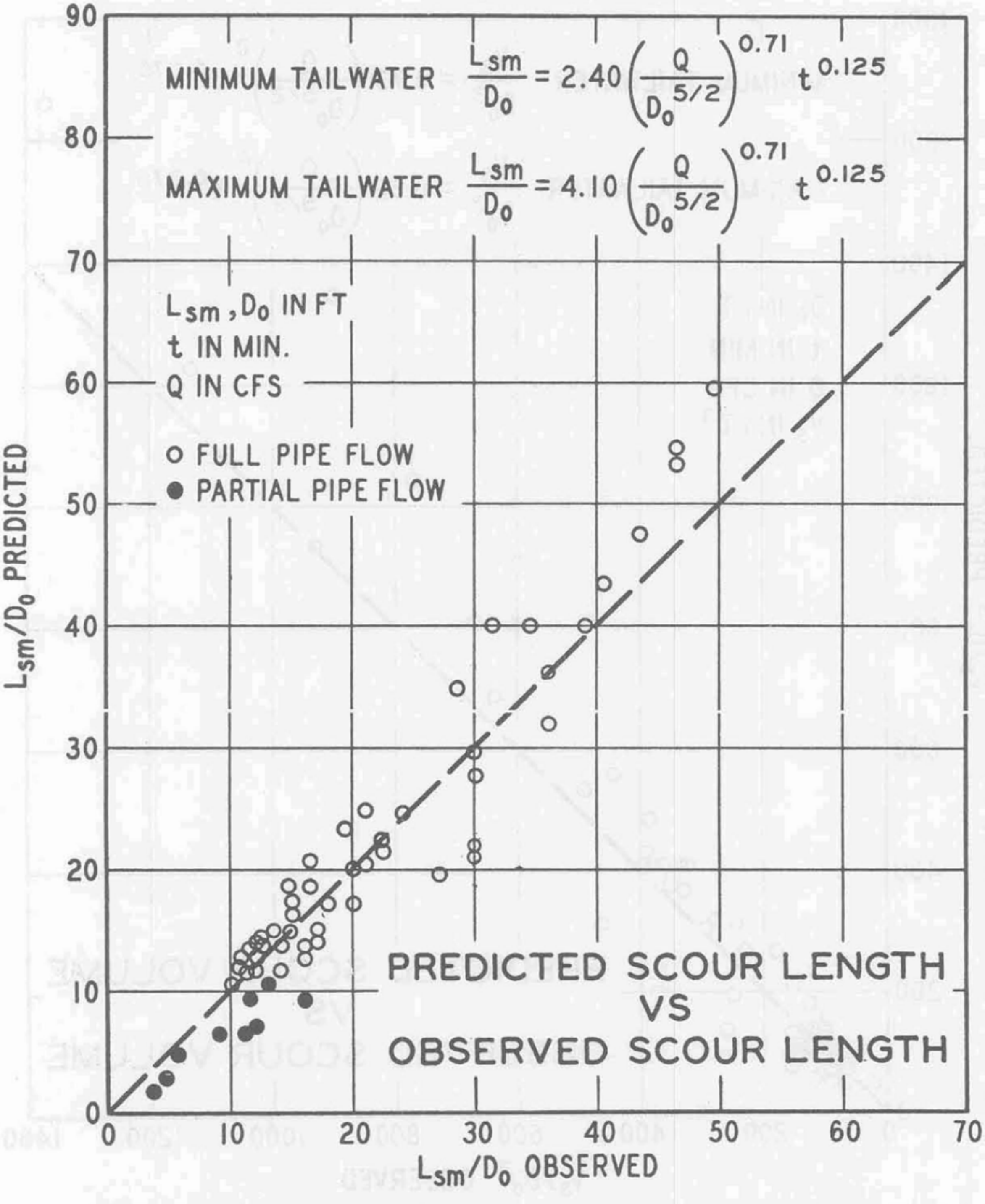


Fig. 5. Predicted scour length versus observed scour length

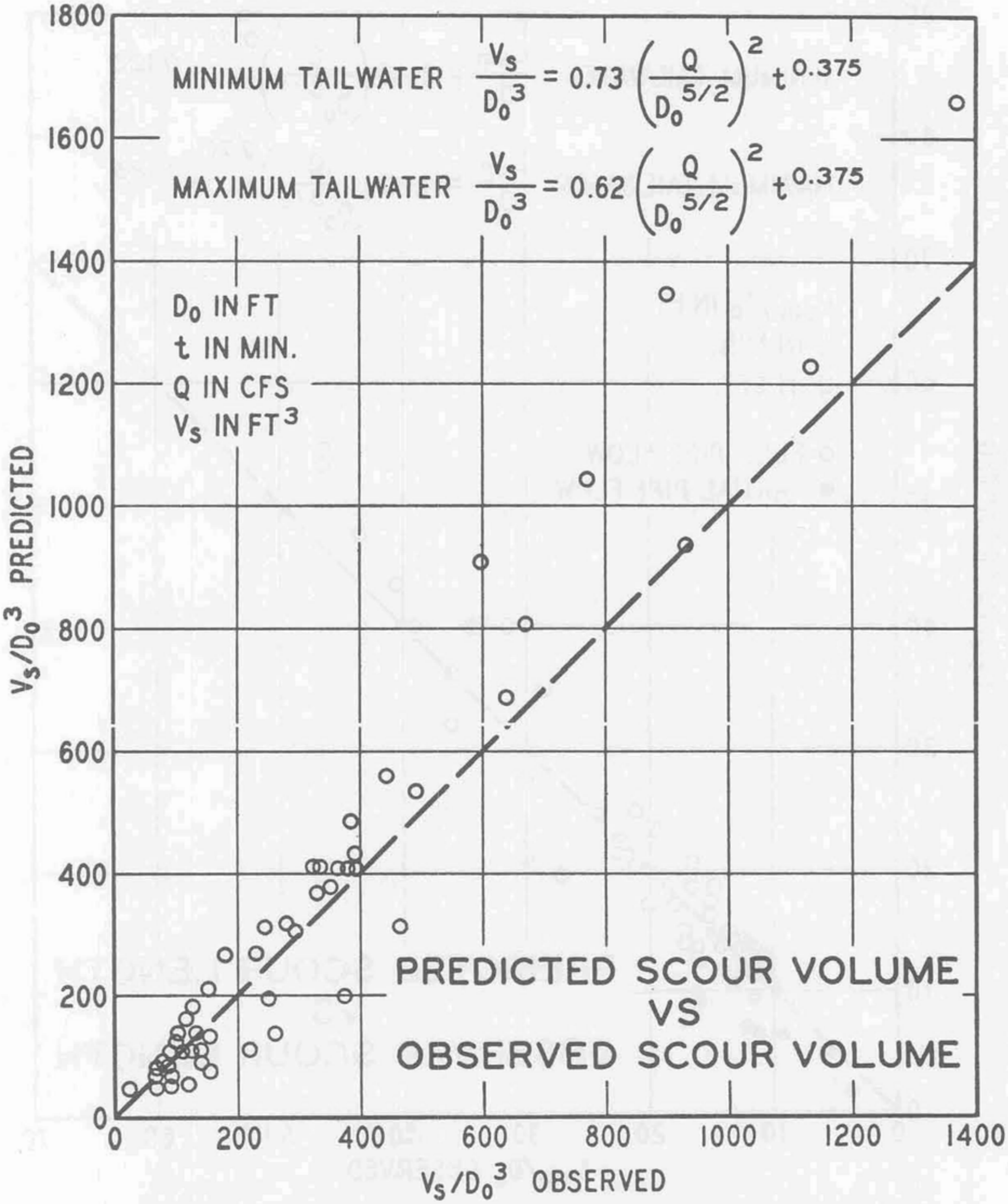


Fig. 6. Predicted scour volume versus observed scour volume

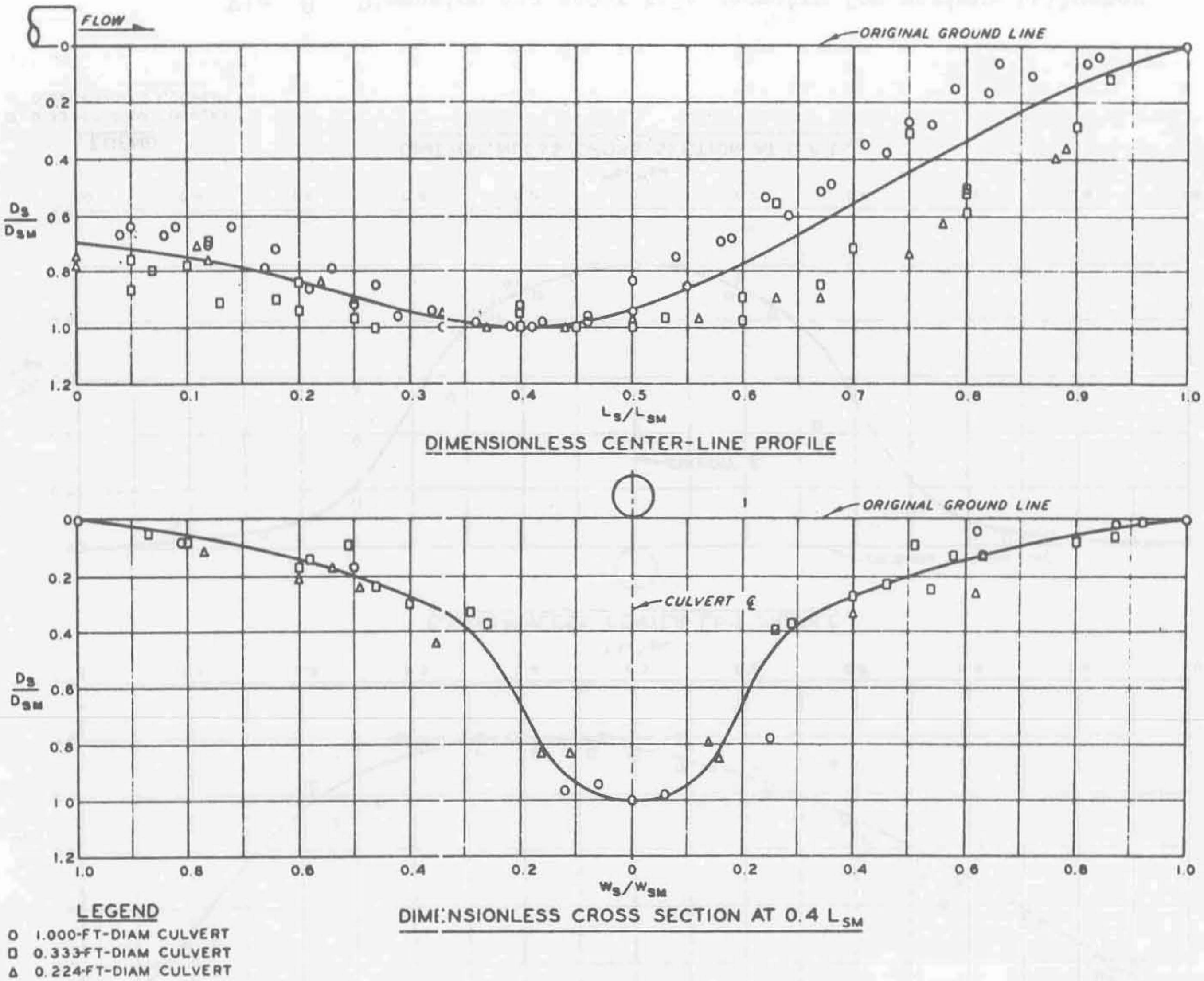


Fig. 7. Dimensionless scour hole geometry for minimum tailwater

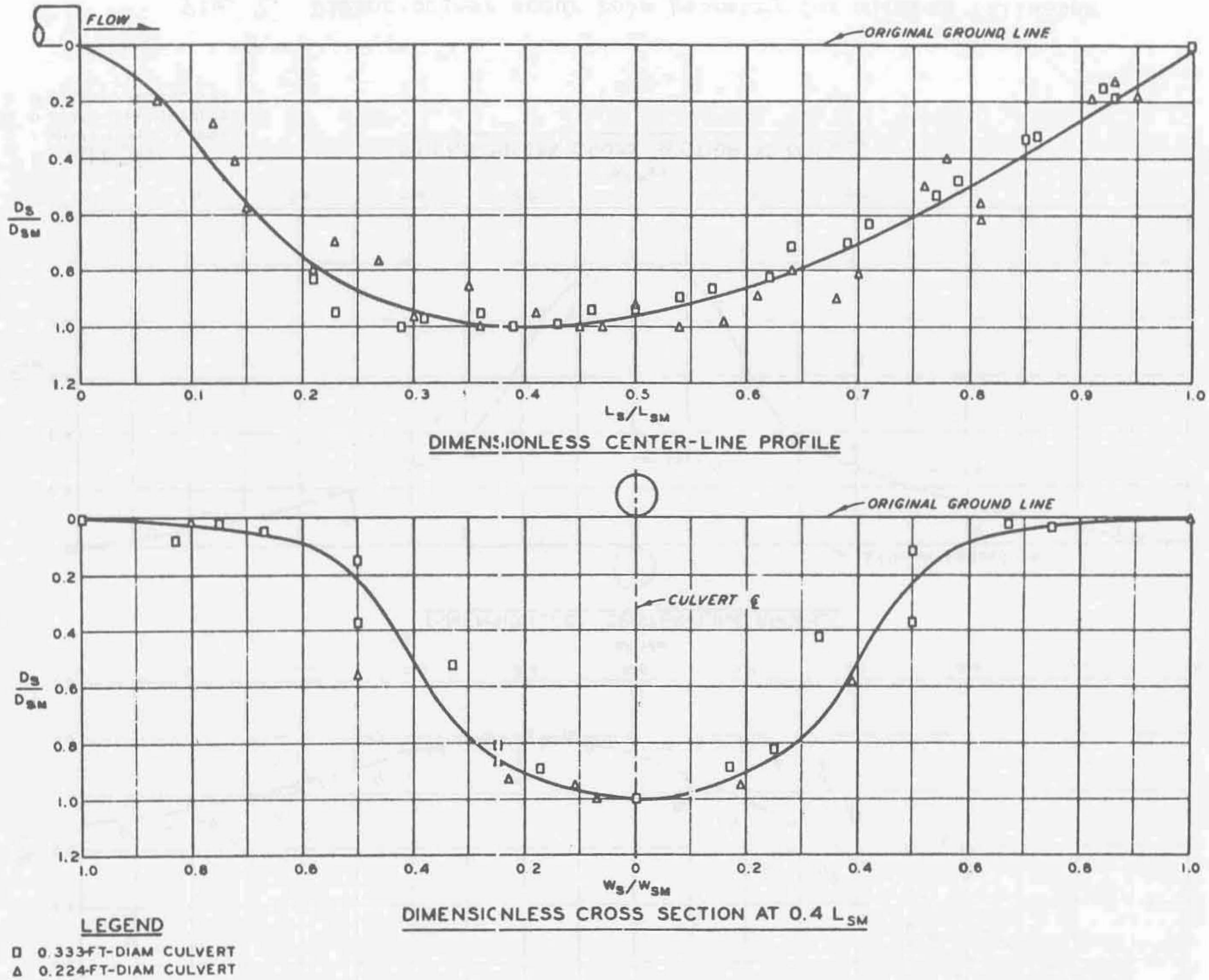


Fig. 8. Dimensionless scour hole geometry for maximum tailwater

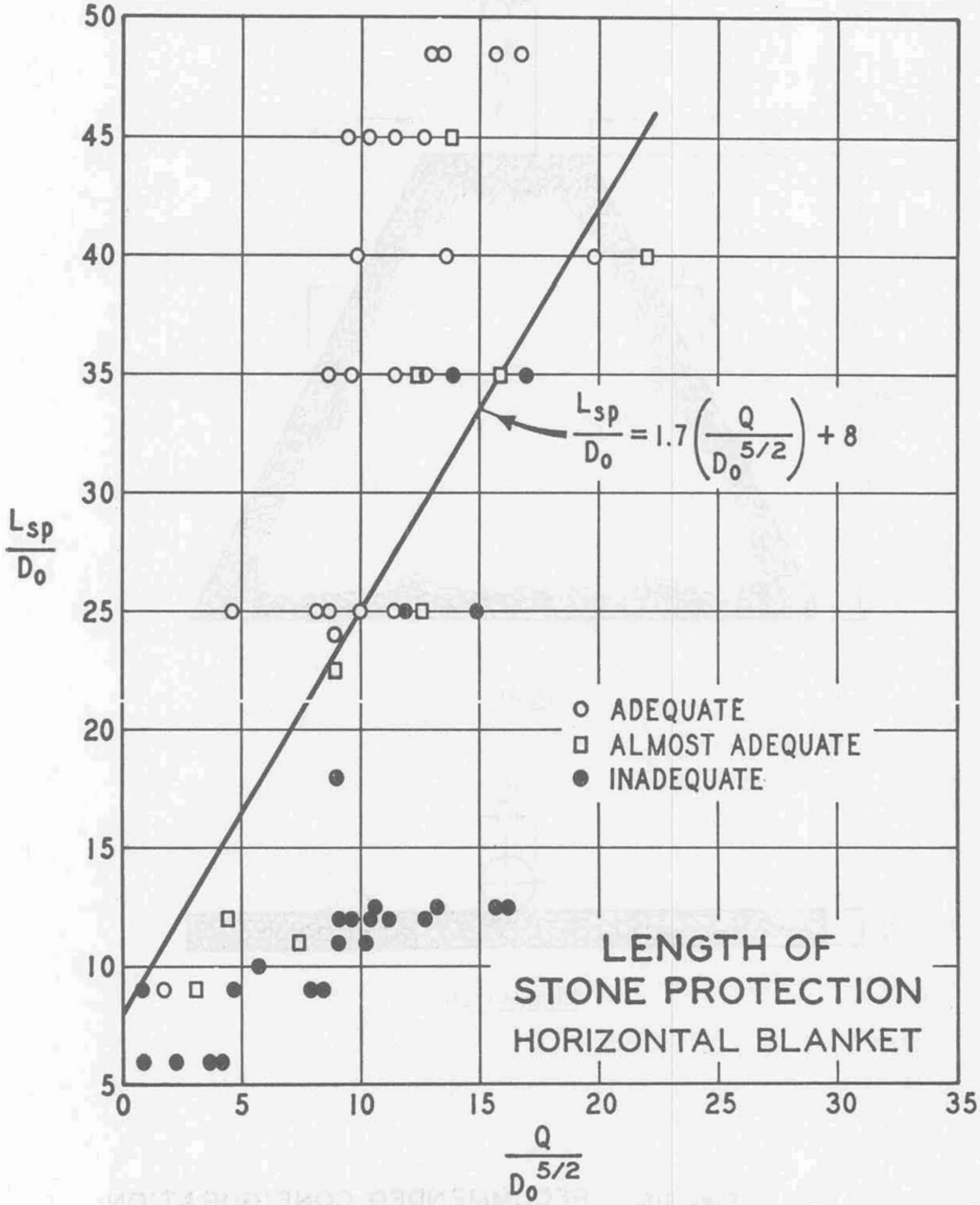


Fig. 9. Length of stone protection, horizontal blanket

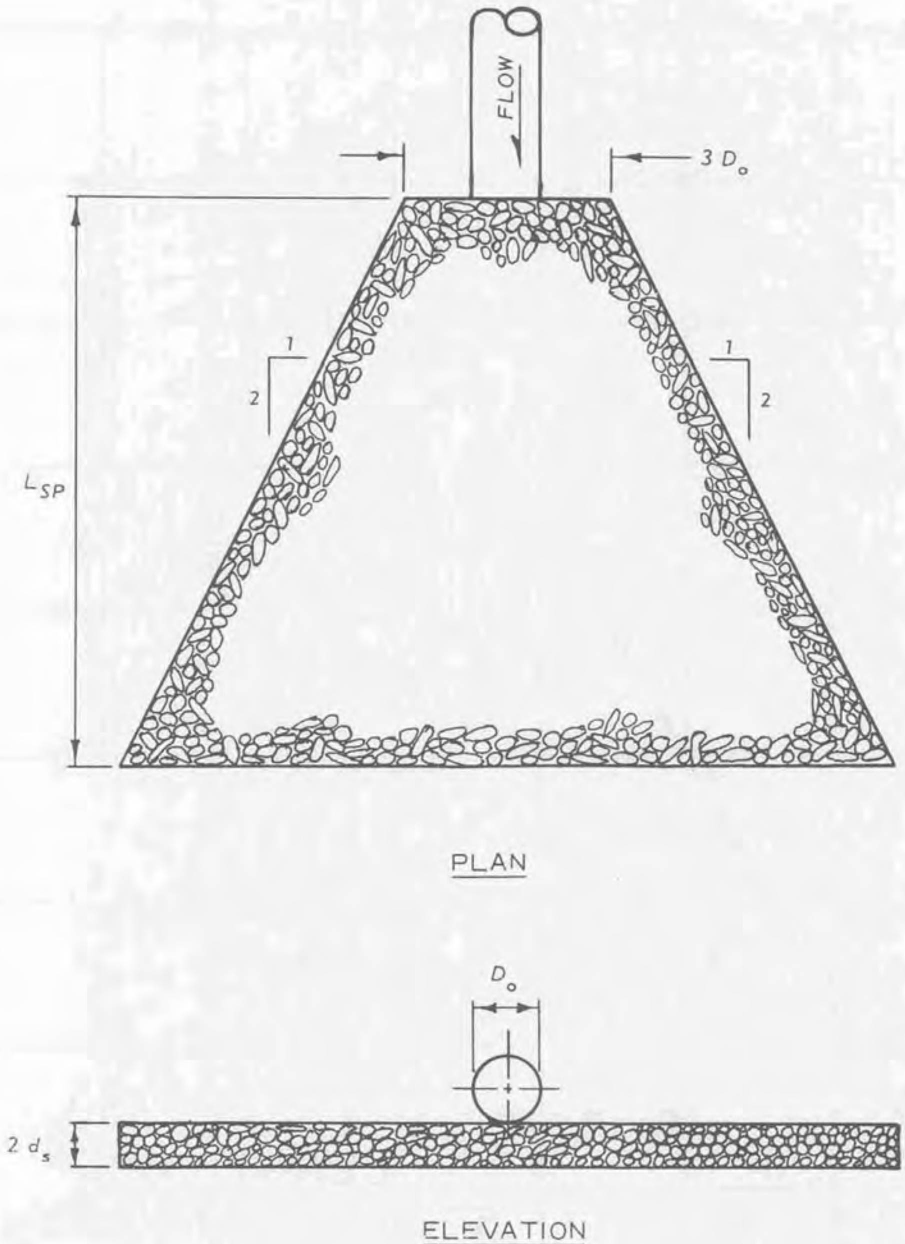


Fig. 10. RECOMMENDED CONFIGURATION OF RIPRAP BLANKET

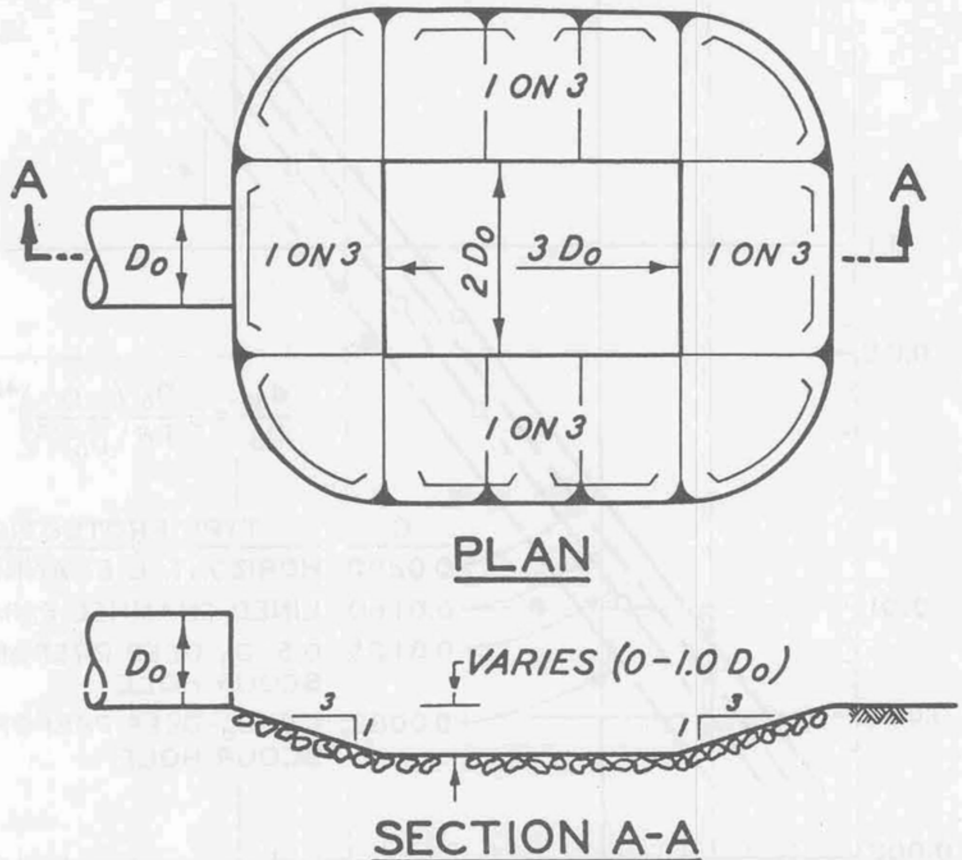


Fig. 11. Preformed scour hole

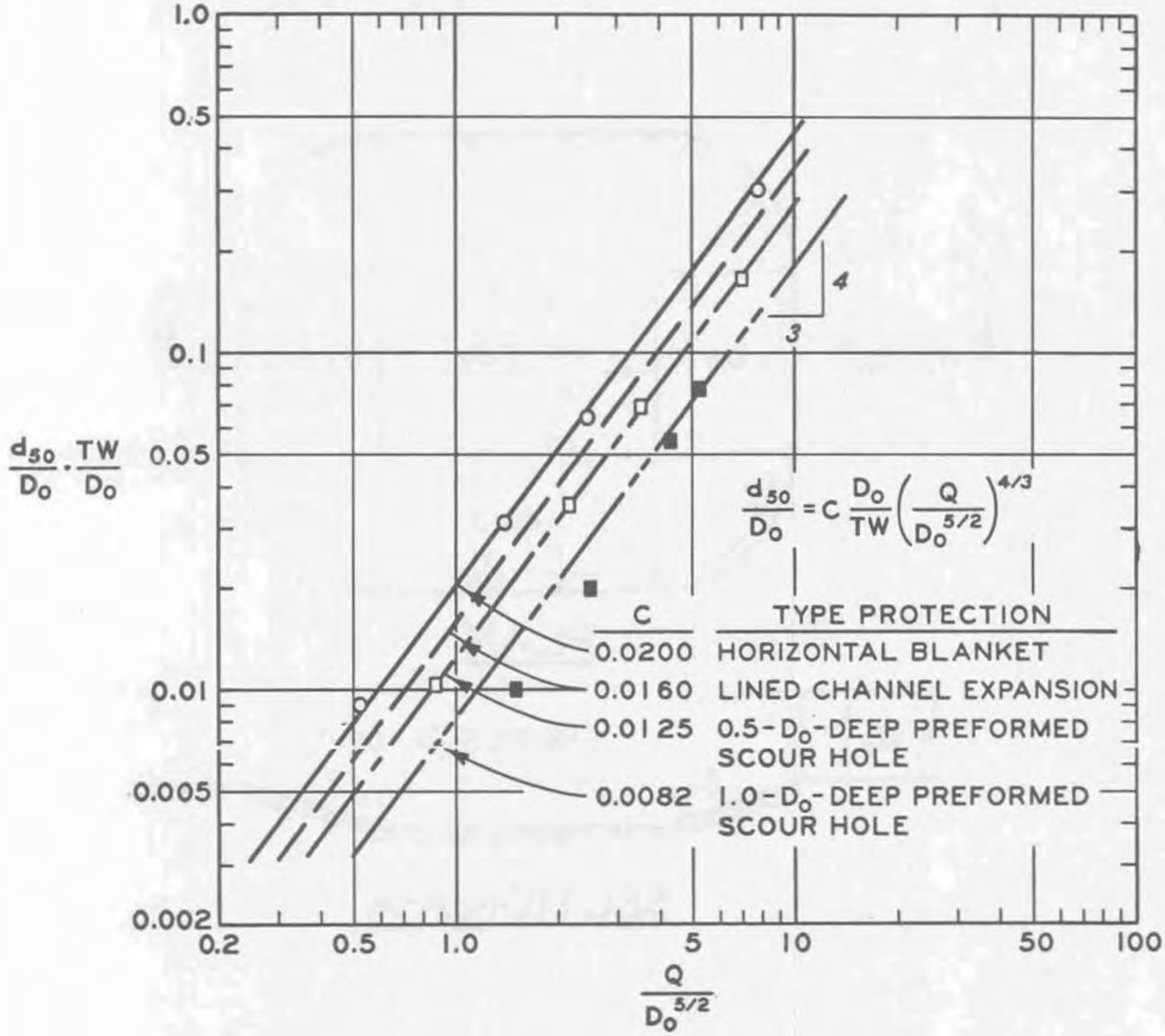


Fig. 12. Recommended size of protective stone

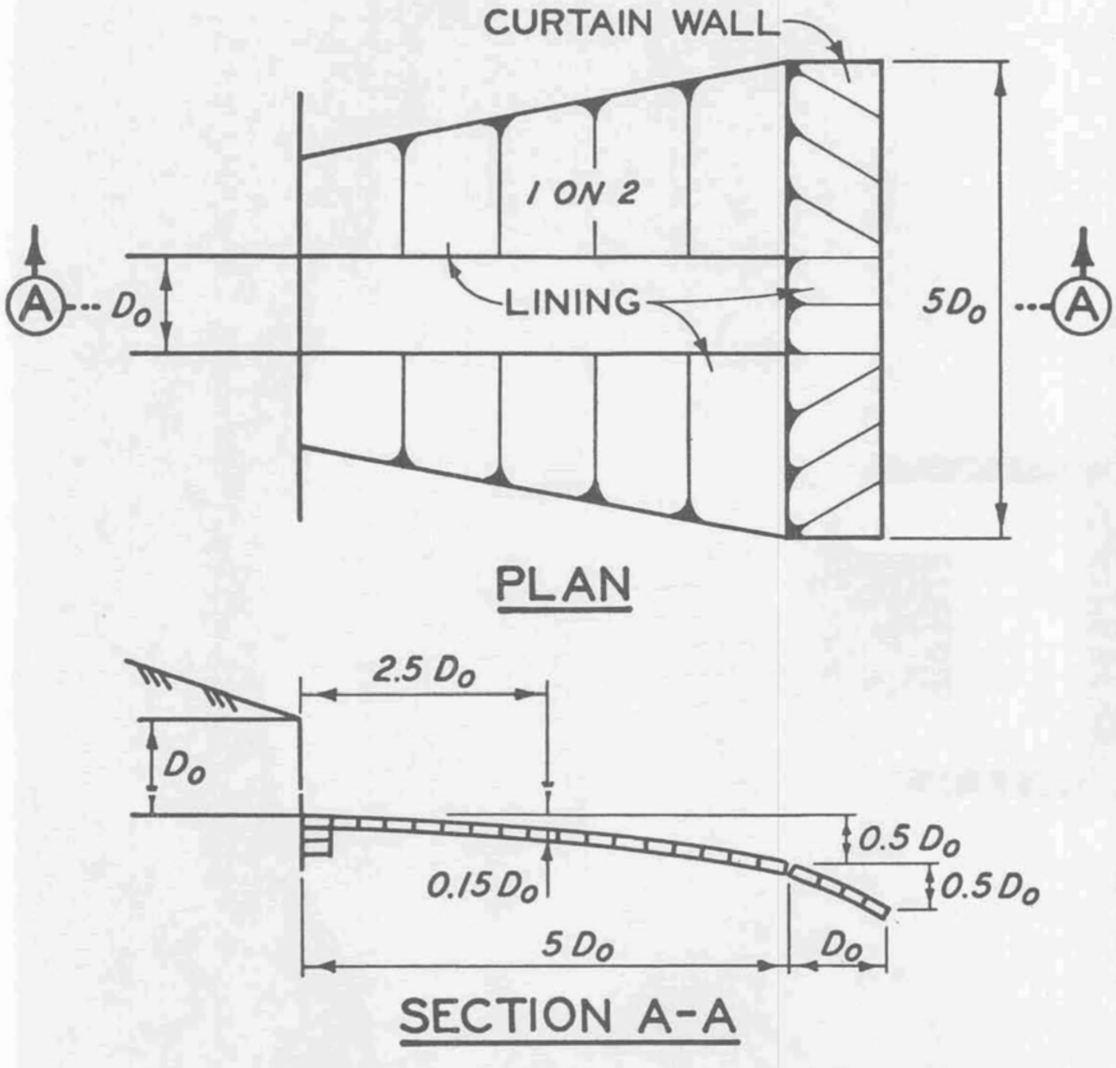


Fig. 13. Culvert outlet erosion protection, lined channel expansions

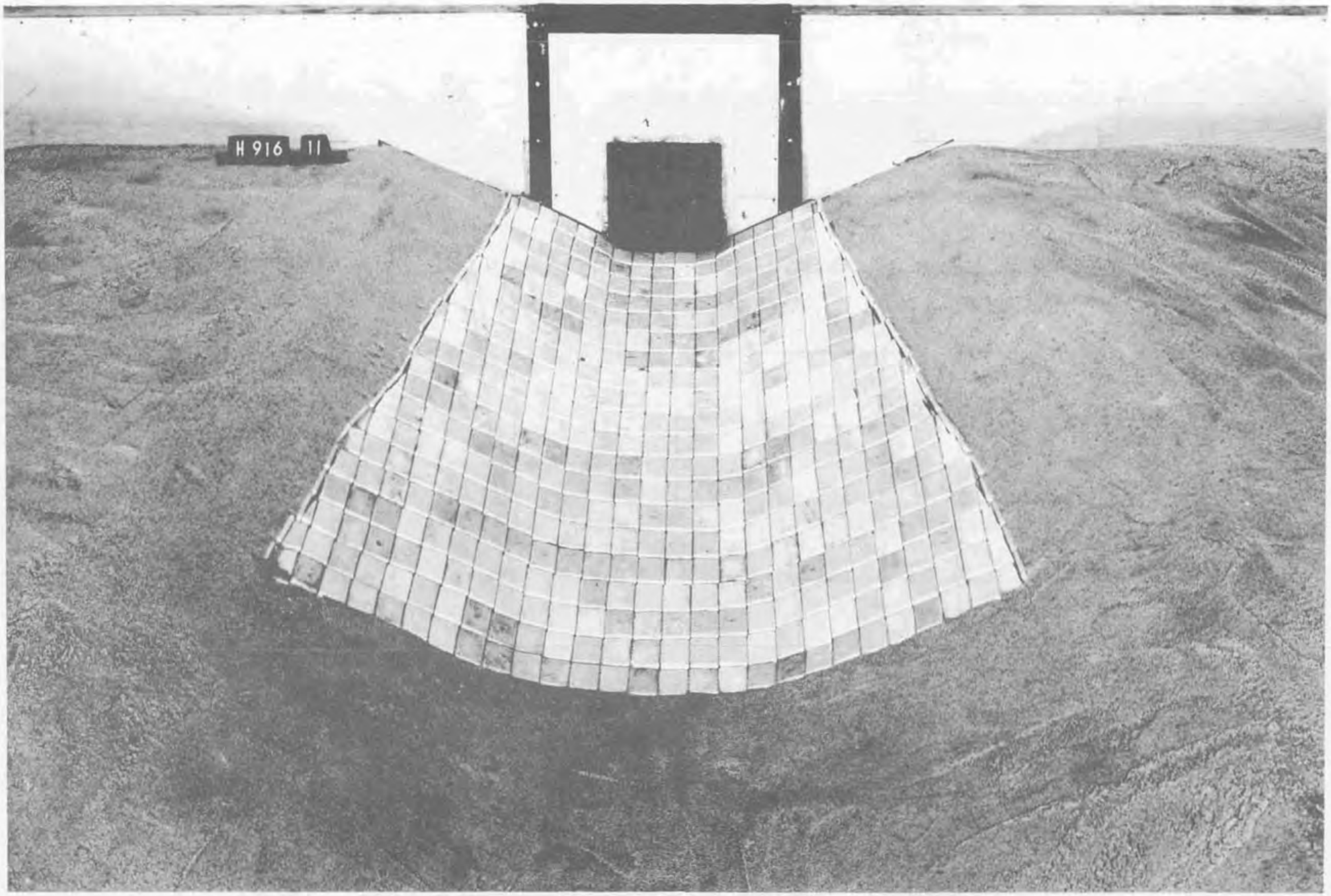


Fig. 14. Channel expansions lined with sack revetment

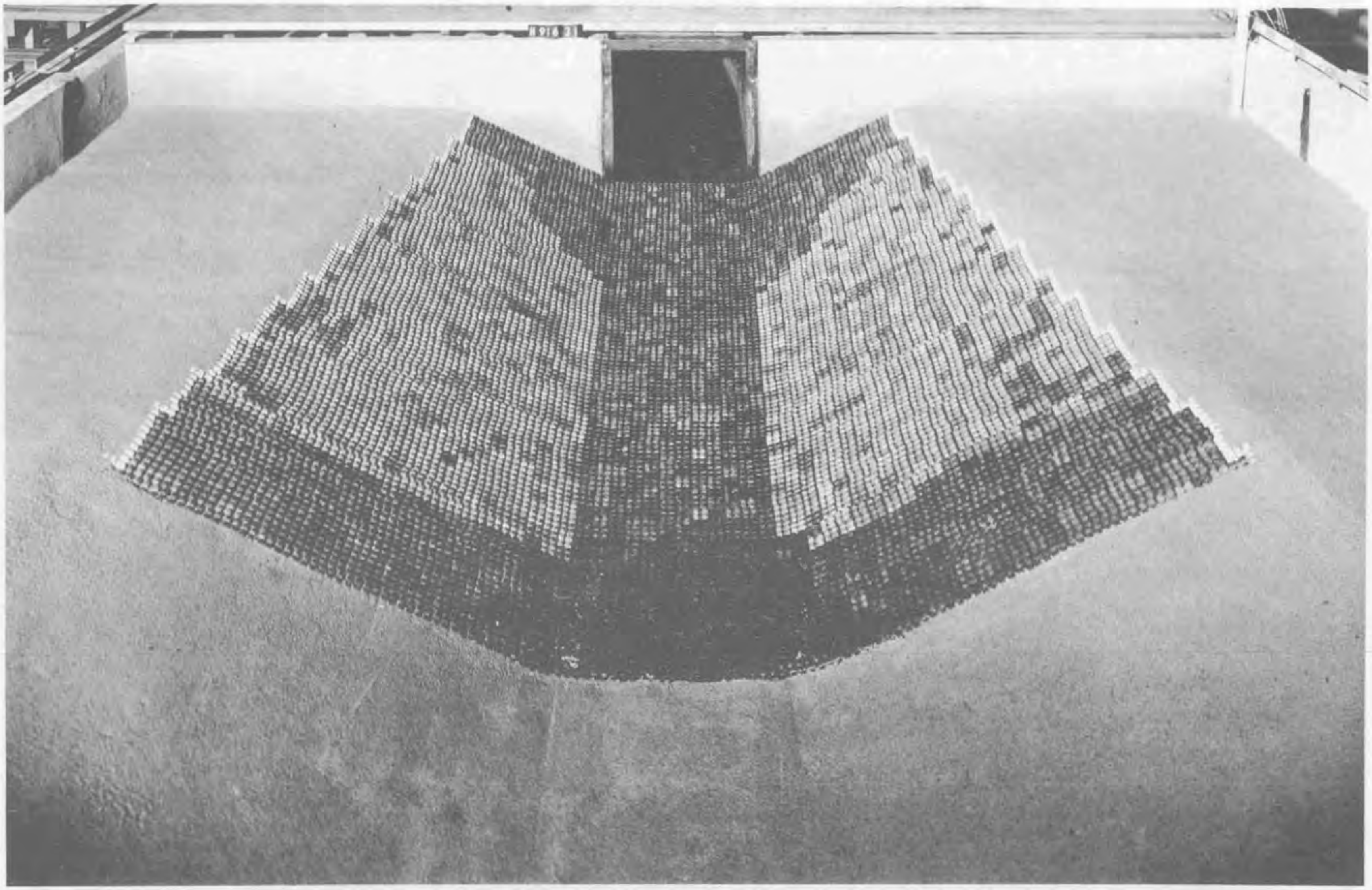


Fig. 15. Channel expansion lined with cellular blocks

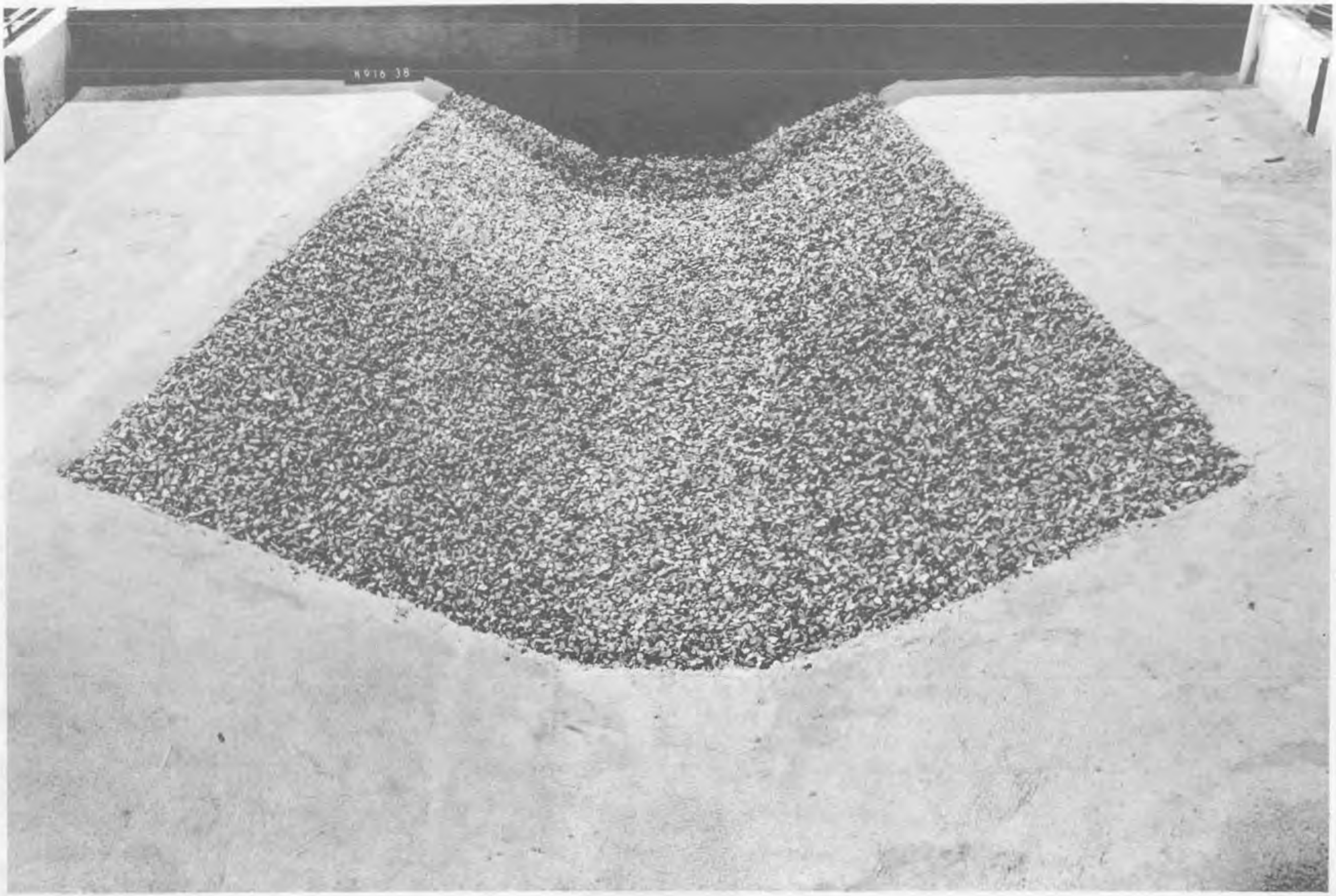


Fig. 16. Channel expansion lined with riprap

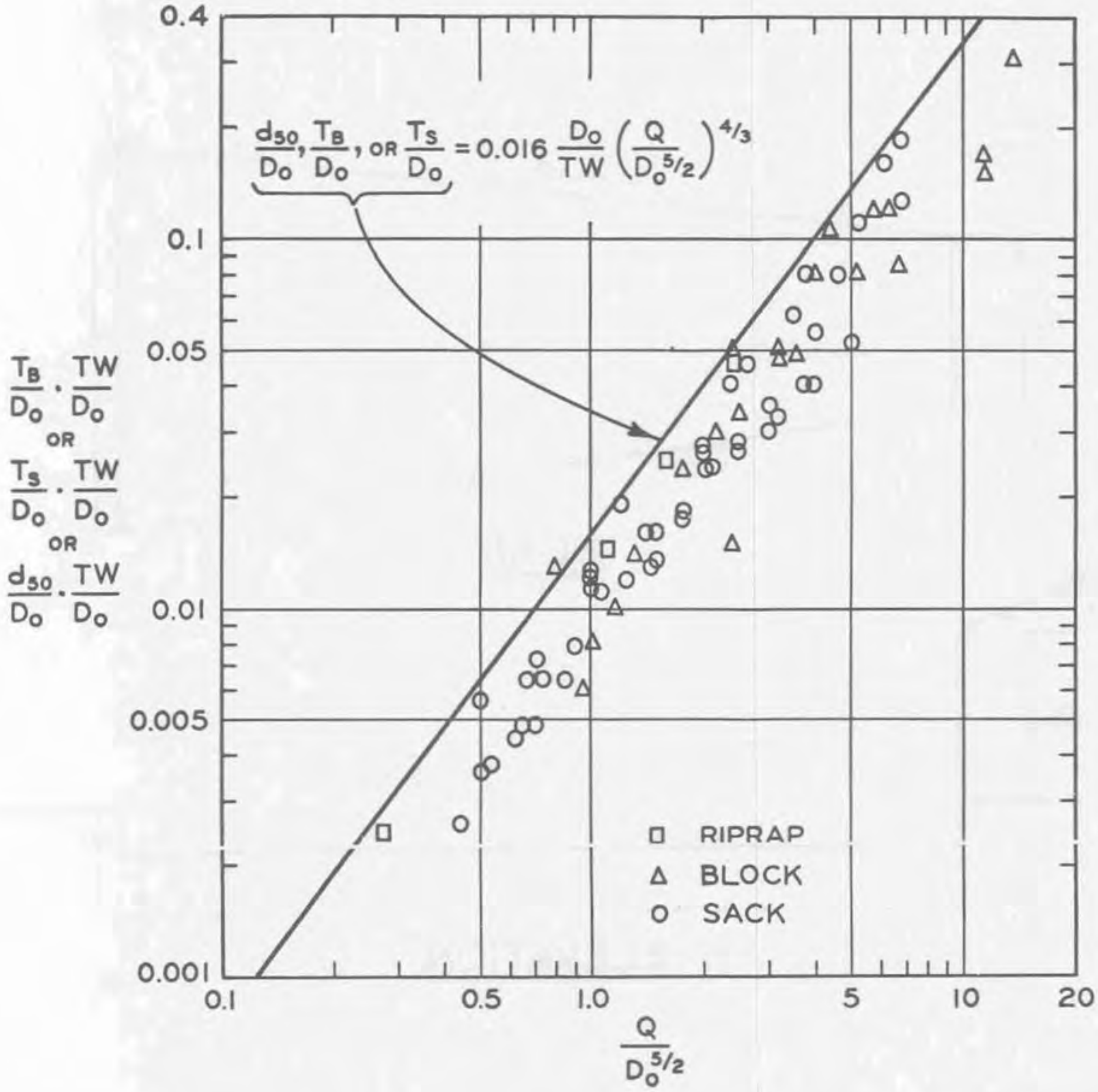


Fig. 17. Maximum permissible discharge for lined channel expansions

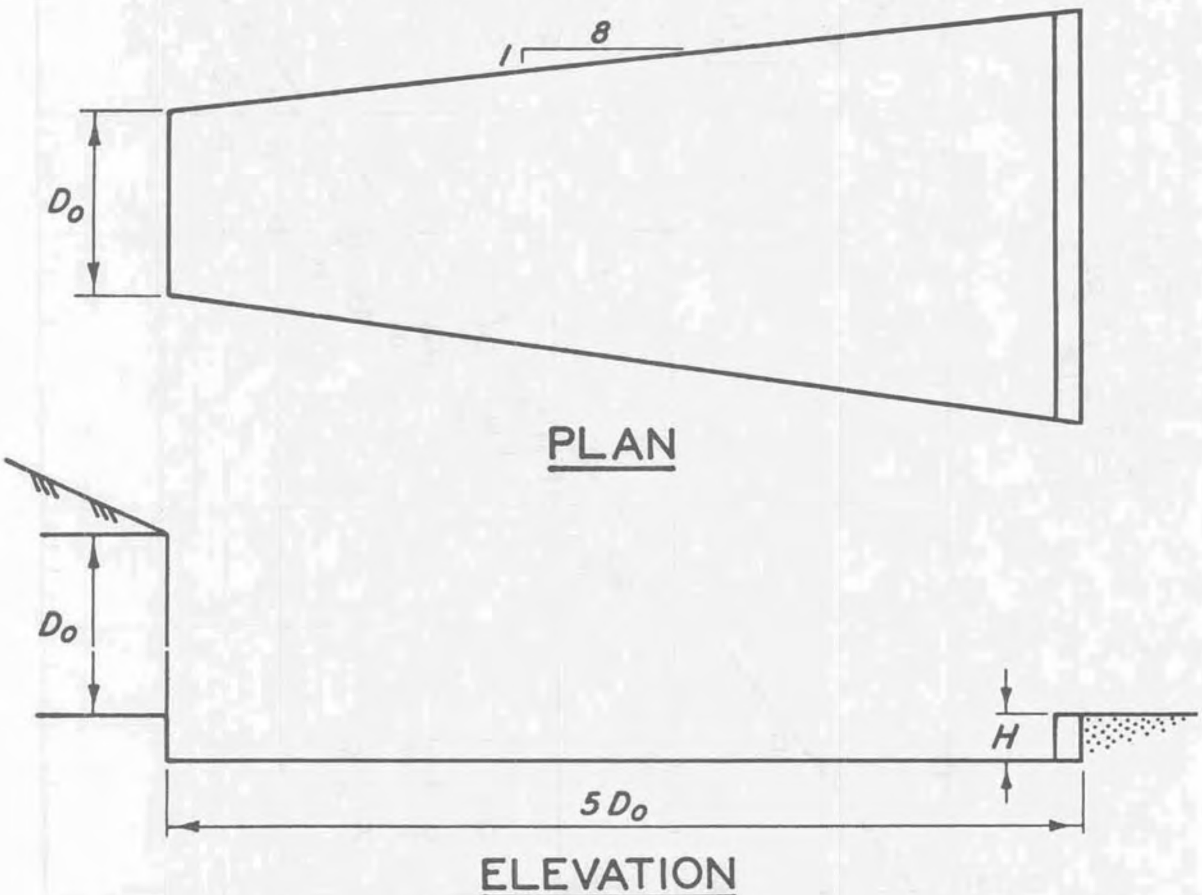


Fig. 18. Flared outlet transition

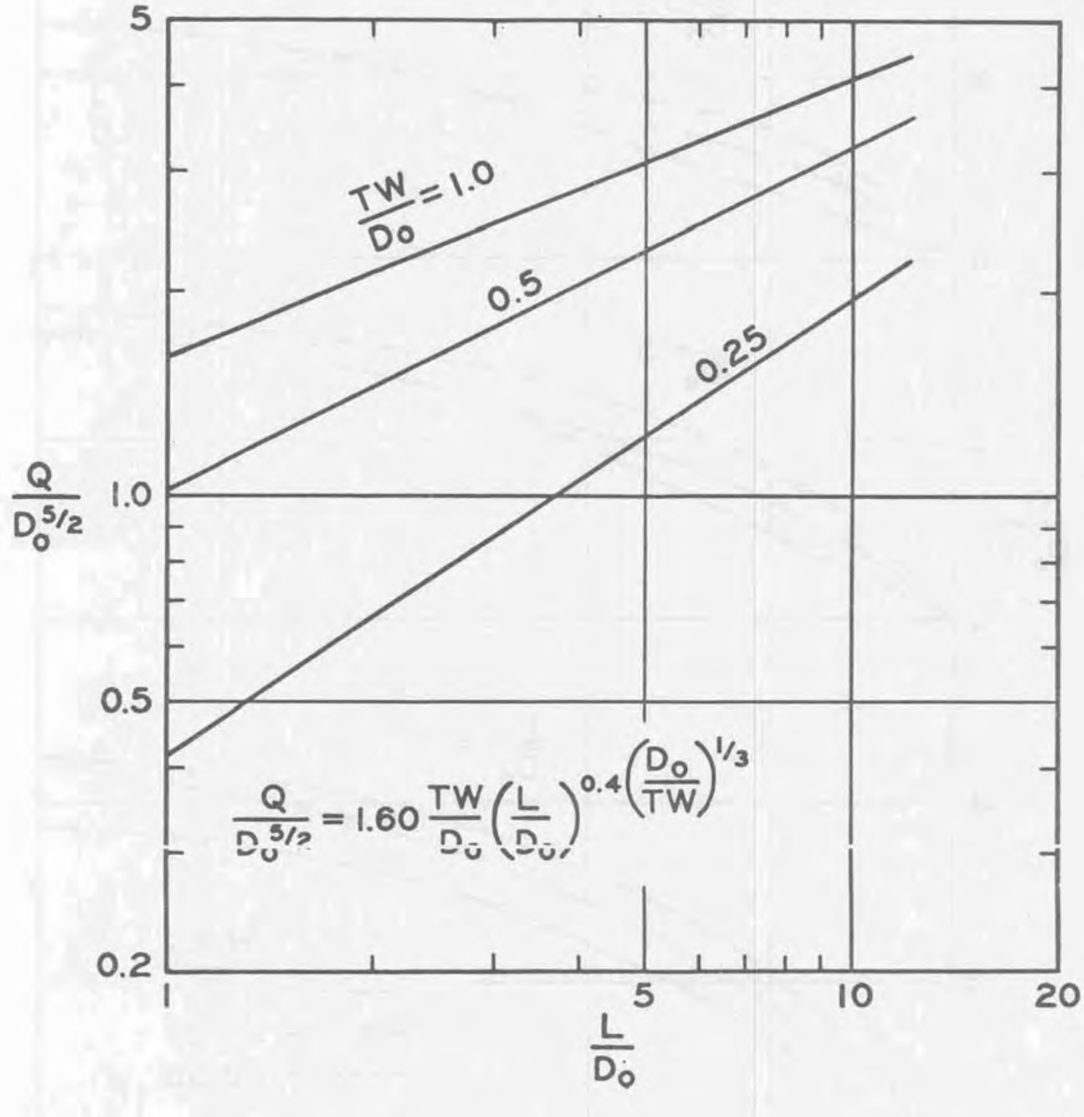


Fig. 19. Maximum permissible discharge for various lengths of flared outlet transition and tailwaters

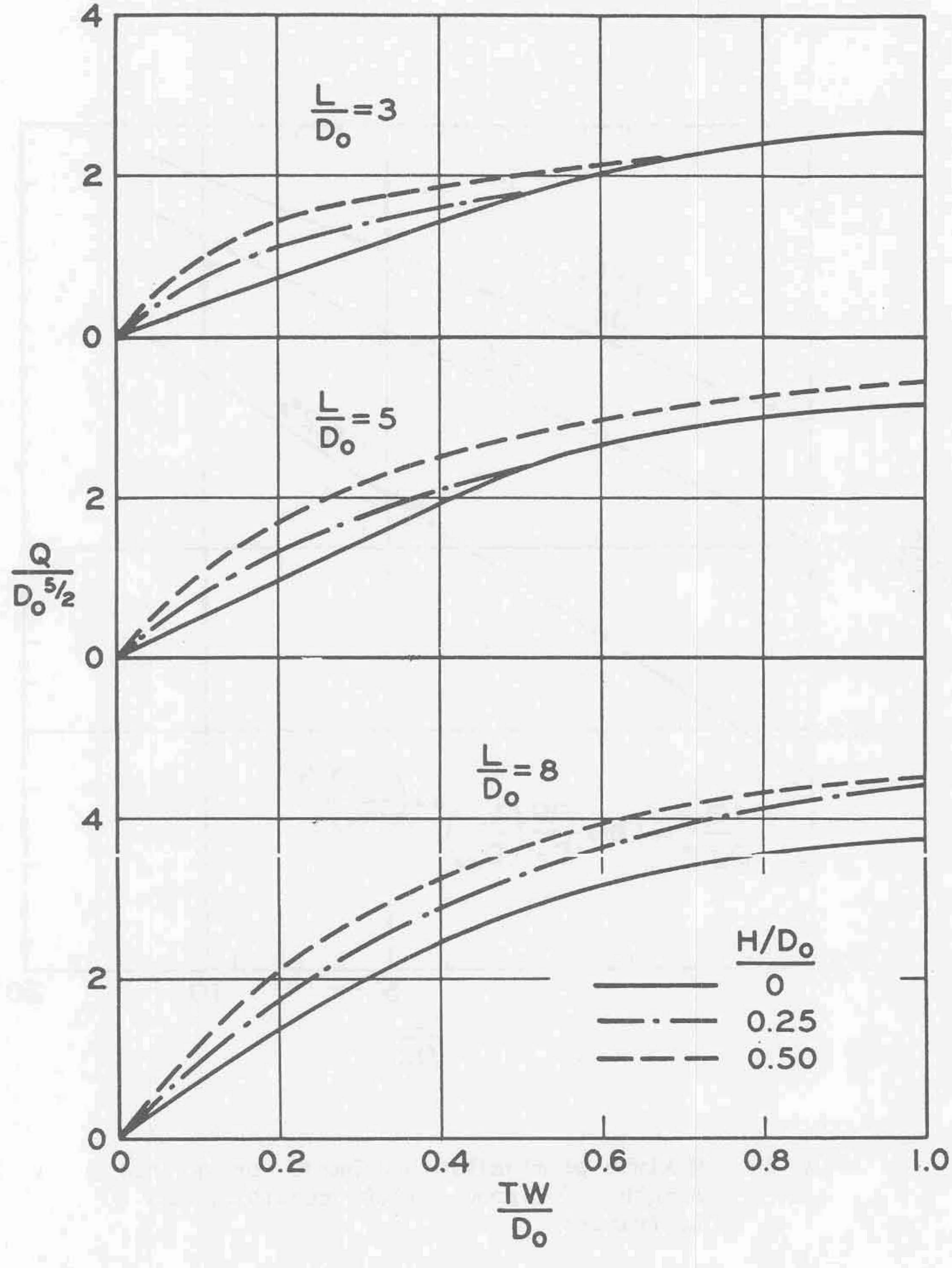


Fig. 20. Relative effects of recessed apron and end sill on permissible discharge

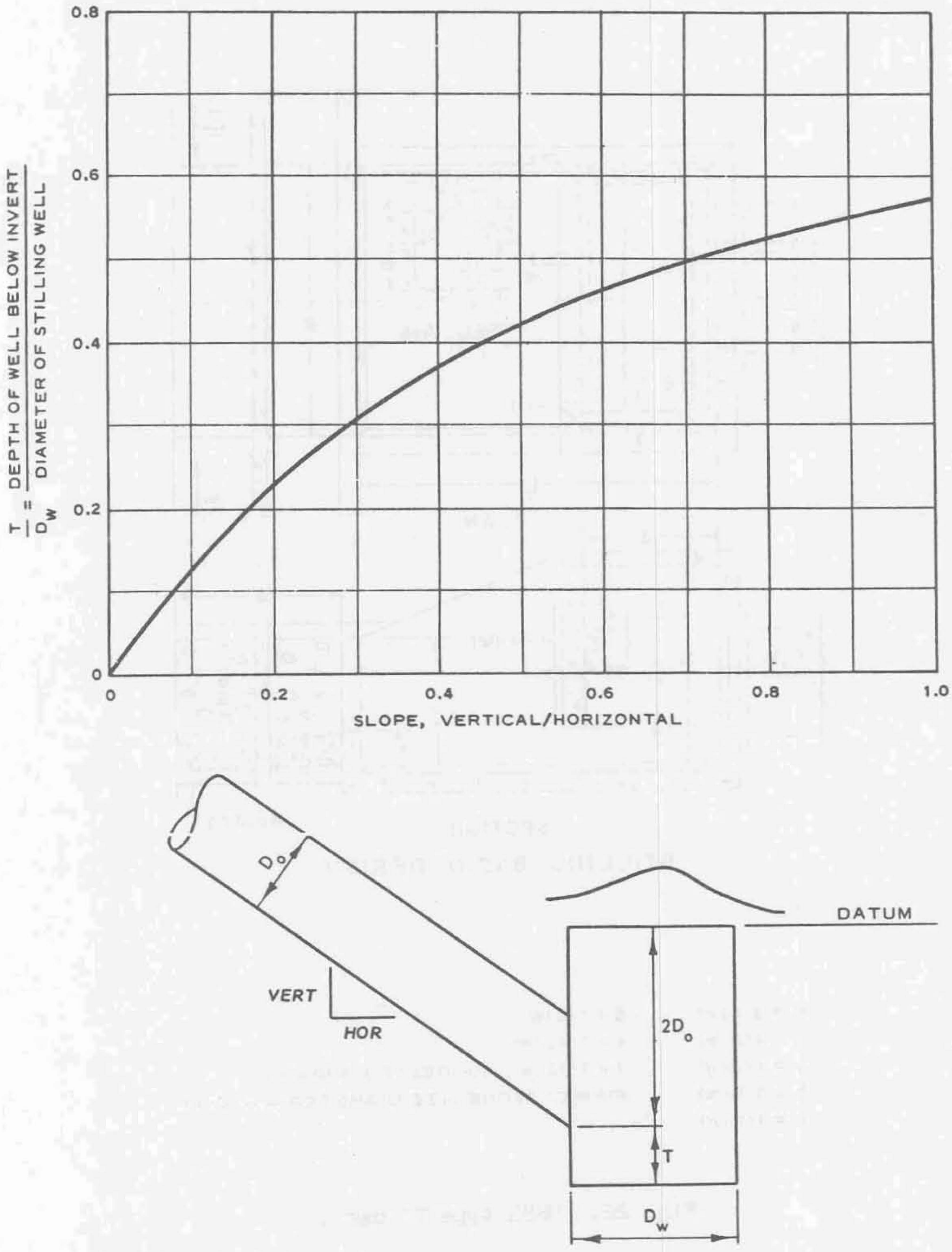
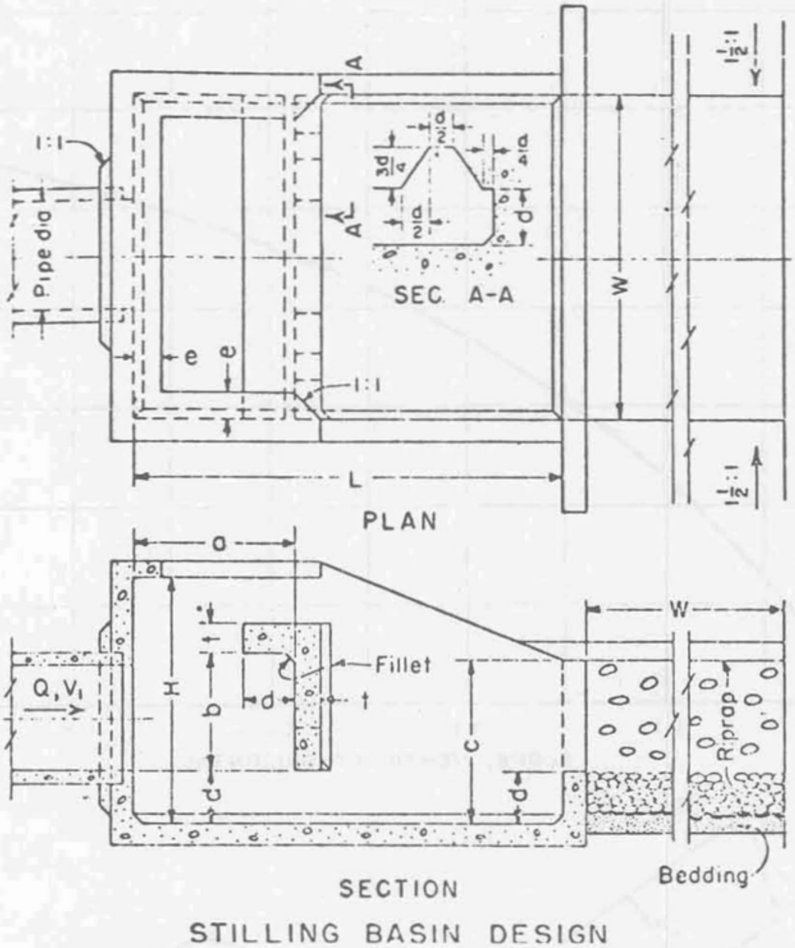
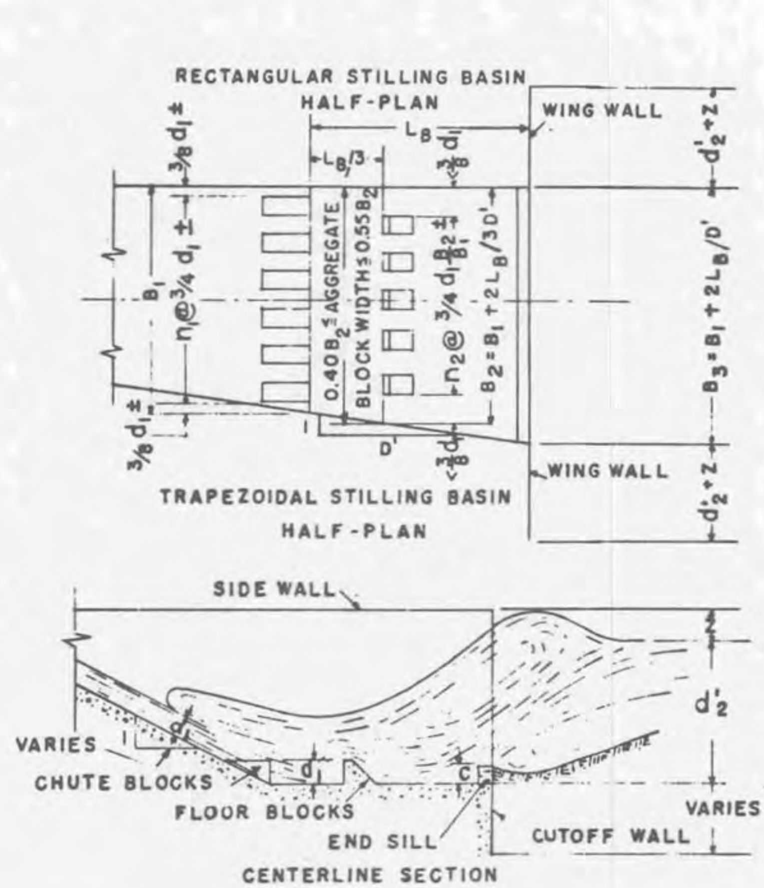


Fig. 21. Stilling well



H = 3/4 (W)
L = 4/3 (W)
a = 1/2 (W)
b = 3/8 (W)
c = 1/2 (W)
d = 1/6 (W)
e = 1/12 (W)
t = 1/12 (W), SUGGESTED MINIMUM
RIPRAP STONE SIZE DIAMETER = 1/20 (W)

Fig. 22. USBR type VI basin



DESIGN EQUATIONS

(1) $F = \frac{V_1^2}{gd_1}$ (2) $d_2 = \frac{d_1}{2}(-1 + \sqrt{8F+1})$

(3a) $F = 3$ TO 30 $d'_2 = (1.10 - F/120)\, d_2$

(3b) $F = 30$ TO 120 $d'_2 = 0.85\, d_2$

(3c) $F = 120$ TO 300 $d'_2 = (1.00 - F/800)\, d_2$

(4) $L_B = \frac{4.5 d_2}{F^{0.38}}$ (5) $Z = \frac{d_2}{3}$ (6) $c = 0.07 d_2$

Fig. 23. Proportions of SAF stilling basin