TECHNICAL REPORT H-74-9

PRACTICAL GUIDANCE FOR DESIGN OF LINED CHANNEL EXPANSIONS AT CULVERT OUTLETS

Hydraulic Model Investigation

by

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This report presents the detailed results of research conducted to develop practical guidance for design of lined channel expansions at culvert outlets. Appendix A summarizes the results of related research efforts of the U. S. Army Engineer Waterways Experiment Station during the past decade to develop practical guidance for estimating and controlling erosion downstream of culvert and storm-drain outlets. Empirical equations and charts are presented
(Continued)

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SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)* for estimating the extent of localized scour to be anticipated downstream of culvert and storm-drain outlets and the size and extent of various natural and artificial type revetments and energy dissipators that may be used to control localized scour. 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 culvert and storm-drain outlets.

R & D IMPLEMENTATION DATA SHEET

PART A

REPORTING STATE LOUISIANA

NOTE - The receiving office will code card Col. 3 thru 7, and 17 thru 25.

1 2 State	3 Yr	4 6 Id. Num.	7 UD	8 Cd	9 16 State Project Number	17 23 FCP Code	24 AP	25 Fnd	26 31 Proj. Start Date (Mo. Day Yr.)	32 37 Proj. Compl. Date (Mo. Day Yr.)	38 43 Date This Report (Mo. Day Yr.)
1 6				A	76-Ø1-54		4	6	Ø4Ø671		

44 47 STUDY COST To Date ($1000's)
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PART B

48 IS	49 IO	50 IP	51 IA	52 TA	53 RU	54 NI
2	1	1		4	1	

IMPLEMENTATION STATUS = (IS) in Col. 48
1 Implemented (ing) - Code Col. 49 & 52
② Implementable - Code Col. 49, 50, & 51
3 No implementation planned - Code Col. 53 or 54.

IMPLEMENTABLE BY OTHERS = (IO) in Col. 49
① By most other states
2 Some other states
3 No other states
4 Other (Explain)

IMPLEMENTATION PLANS = (IP) in Col. 50
1 Will be implemented or underway in next 12 months
2 Will be implemented or underway in next 24 months
3 Implementation is planned, subject to action noted, in Col. 51

IMPLEMENTATION ACTION NEEDED = (IA) in Col. 51
1 Equipment changes or modifications needed
2 Administrative decision required
3 Need new or revised procedures, guidelines, manual, &/or standards or specifications
4 Training aids need to be prepared
5 Other (Explain)

NOT IMPLEMENTABLE = (NI) in Col. 54
1 Negative findings
2 Confirms present practice
3 Additional evaluation or study needed
4 Findings too complex
5 " impractical
6 " inconclusive
7 " unreliable
8 Other (Explain)

RESULTS POTENTIALLY USEFUL = (RU) in Col. 53
① A phase, or one of a group of studies
2 Points up need for further research
3 Findings are theoretical in nature
4 Exploratory
5 Findings valuable in decision making
6 Other (Explain

TRAINING AIDS USED, PLANNED OR NEEDED = (TA) in Col. 52
1 Workshops
2 Movies
3 Slides
④ Other
5 None used, but some are needed (Explain)

PART C

55 56 Rep. State	57 62 Benefit End Date (Mo. Day Yr.)	63 64 Num. Mo.	65 SB	66 67 Accid. Prev.	68 69 Lives Saved	70 73 Cash $ Saved	74 77 User $ Saved	78 79 Ben/C	80 Yes No
1 6									1

State Reporting Implement.

TIME PERIOD OF SAVINGS & BENEFITS
Period ending date - Col's. 57 - 62
Total period in months-- Col's. 63 & 64

TYPE OF SAVINGS OR BENEFITS = (SB) in Col. 65
1 Cash savings to agency
2 Highway user savings (monetary)
3 Savings probable but difficult to assess
4 Improved safety or convenience
5 Improved aesthetics, environmental aspects
*For combination benefits, see manual for codes.

ESTIMATED No. of ACCIDENTS PREVENTED & No. of LIVES SAVED
No. of Accidents in Col's 66 & 67
No. of Lives saved in Col's 68 & 69

BEST EST. OF $ SAVINGS THRU IMPLEMENTATION
Enter agency savings ($1000) in Col's 70-73
Enter user savings ($1000) in Col's 74 - 77

BENEFIT/COST RATIO (For reporting period)
Enter in Col's. 78 & 79, to nearest unit $, the benefits per research dollar invested

DID RESEARCH PAY OFF - Col. 80
If no estimate is possible, do you feel that benefits substantially exceeded the cost? Enter code, Yes = 1, No = 2

8 Card	9 R & D Study Title 80
B	PRACTICAL GUIDANCE FOR DESIGN OF EXPANSIONS AT CULVERT OUTLETS
C	
D	

NOTE - Type no more than 72 characters (Elite) per line including all spaces and punctuation. Use ALL CAPS

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8 Card	9 Study Objectives 80
G	TO DEVELOP A CHANNEL EXPANSION GEOMETRY THAT WOULD PROVIDE SATISFAC-
H	TORY FLOW CONDITIONS IN THE EXIT AREA: DETERMINE THE HYDRAULIC CONDI-
I	TIONS UNDER WHICH LININGS COMPOSED OF SACK REVETMENT, CELLULAR BLOCKS,
J	OR ROCK RIPRAP WERE STABLE; AND DEVELOP APPROPRIATE DESIGN GUIDANCE.

8 Card	9 Study Findings 80
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N	MATERIALS IN LIEU OF RIGID CONCRETE CHANNEL EXPANSIONS TO PROVIDE
O	EFFECTIVE AND MORE ECONOMICAL PLANS OF PROTECTION AT CULVERT OUTLETS.
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V	TESTS WERE CONDUCTED OF VARIOUS LINED CHANNEL EXPANSIONS DOWNSTREAM OF
W	3 MODEL BOX CULVERTS WITH DIMENSIONS OF 0.5 × 0.5, 1.0 × 1.0, AND 2.0
X	× 2.0 FT. THE THREE TYPES OF LINING INVESTIGATED CONSISTED OF SACK
Y	REVETMENT, CELLULAR BLOCKS, AND ROCK RIPRAP. THE LININGS WERE
Z	SUBJECTED TO VARIOUS PARTIAL AND FULL CULVERT DISCHARGES AND TAIL-
Ø	WATERS UNTIL DISPLACEMENT OR FAILURE WAS OBSERVED AND RECORDED.
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J. L. GRACE, JR.	B. P. FLETCHER
Name	Name

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16. Abstract

This report presents the detailed results of research conducted to develop practical guidance for design of lined channel expansions at culvert outlets and summarizes the results of related research efforts of the U. S. Army Engineer Waterways Experiment Station during the past decade to develop practical guidance for estimating and controlling erosion downstream of culvert and storm-drain outlets. Empirical equations and charts are presented for estimating the extent of localized scour to be anticipated downstream of culvert and storm-drain outlets and the size and extent of various natural and artificial type revetments and energy dissipators that may be used to control localized scour. 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 culvert and storm-drain outlets.

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SUMMARY

This report presents the results of specific research to develop practical guidance for design of channel expansions lined with either sack revetment, cellular blocks, or rock riprap to prevent localized scour at culvert outlets. Appendix A summarizes the results of related research efforts of the U. S. Army Engineer Waterways Experiment Station during the past decade to develop practical guidance for estimating and controlling erosion downstream of culvert and storm-drain outlets.

The results derived from this study provide guidance that was previously not available and will permit the use of either of the three lining materials in lieu of rigid concrete channel expansions to provide effective and more economical plans of protection at culvert outlets. Potentially unstable channels that do not warrant the conventional type of rigid concrete structures due to the cost of such protection may be reconsidered in light of the guidance and alternatives developed from this research.

The results presented in Appendix A permit designers to estimate the extent of localized scour to be expected and select appropriate and alternative schemes of protection for controlling erosion downstream of culvert and storm-drain outlets.

PREFACE

The model study of Lined Channel Expansions at Culvert Outlets was authorized by the Office, Chief of Engineers, on 6 April 1971, at the request of the Louisiana Department of Highways and the Federal Highway Administration.

The study was conducted during the period April 1971 to April 1973 in the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under the direction of Messrs. E. P. Fortson, Jr. (retired), and H. B. Simmons, Chiefs of the Hydraulics Laboratory, and T. E. Murphy (retired), Chief of the Structures Division. The tests were conducted by Messrs. B. P. Fletcher, W. A. Walker, and B. P. Perkins under the direct supervision of Mr. J. L. Grace, Jr., Chief of the Structures Division and former Chief of the Spillways and Channels Branch. This report was prepared by Messrs. Fletcher and Grace.

During the course of the study Messrs. T. B. Lawson, A. L. Cox, S. M. Law, H. B. Rushing, J. E. Ross, and W. Marcum of the Louisiana Department of Highways; C. J. Gaudin of the Louisiana Department of Public Works, and B. Burch, B. Prochaska, D. Richards, M. Cory, B. Baumgardner, M. Cook, M. Smith, J. Lazenby, and R. Driskell of the Federal Highway Administration visited WES to discuss the program of model tests, observe the model in operation, and correlate test results with concurrent design work.

Directors of WES during the conduct of the study and the preparation and publication of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	0.0254	meters
feet	0.3048	meters
square feet	0.092903	square meters
cubic feet	0.02831685	cubic meters
pounds (mass)	0.45359237	kilograms
feet per second	0.3048	meters per second
cubic feet per second	0.02831685	cubic meters per second
feet per second per second	0.3048	meters per second per second

PRACTICAL GUIDANCE FOR DESIGN OF LINED CHANNEL EXPANSIONS AT CULVERT OUTLETS

Hydraulic Model Investigation

PART I: INTRODUCTION

Background

1. One of the most prevalent problems experienced with storm-drainage facilities is that of erosion at culvert and storm-drain outlets. Due to the relatively flat terrain of a large portion of Louisiana, culvert and storm-drain outlets are subjected to considerable submergence or depths of tailwater relative to the outlet invert. Contrary to the usual assumption, excessive depths of tailwater at such outlets concentrate rather than diffuse the efflux, and as a result severe localized erosion is experienced for a considerable distance downstream. Rigid concrete-lined channel expansions have been used as one means of protection for preventing excessive localized scour in exit channels downstream of culvert outlets. In the interest of developing practical guidance for design of lined channel expansions downstream of box culvert outlets, the Louisiana Department of Highways and the Federal Highway Administration sponsored the program of research reported herein.

Purpose of Study

2. The subject hydraulic model investigation was conducted to develop a channel expansion geometry that would provide satisfactory flow conditions in the exit area; determine the hydraulic conditions under which linings composed of sack revetment, cellular blocks, and rock riprap were stable and unstable; and develop appropriate guidance for design of stable lined channel expansions downstream of culvert outlets.

PART II: MODELS AND TEST PROCEDURES

Test Facilities

3. The experimental facilities shown in Figure 1 were used for tests of various lined channel expansions downstream of three model box culverts with dimensions of 0.5 x 0.5 ft,* 1.0 x 1.0 ft, and 2.0 x 2.0 ft. The three types of linings investigated consisted of sack revetment, cellular blocks, and rock riprap. Sack revetment weighing 120 lb with overall dimensions of 2.0 x 1.5 x 0.33 ft was simulated at a scale of 1:8. The cellular blocks which weighed 14 lb (Figure 2) were simulated at a scale of 1:4. Rock riprap linings composed of

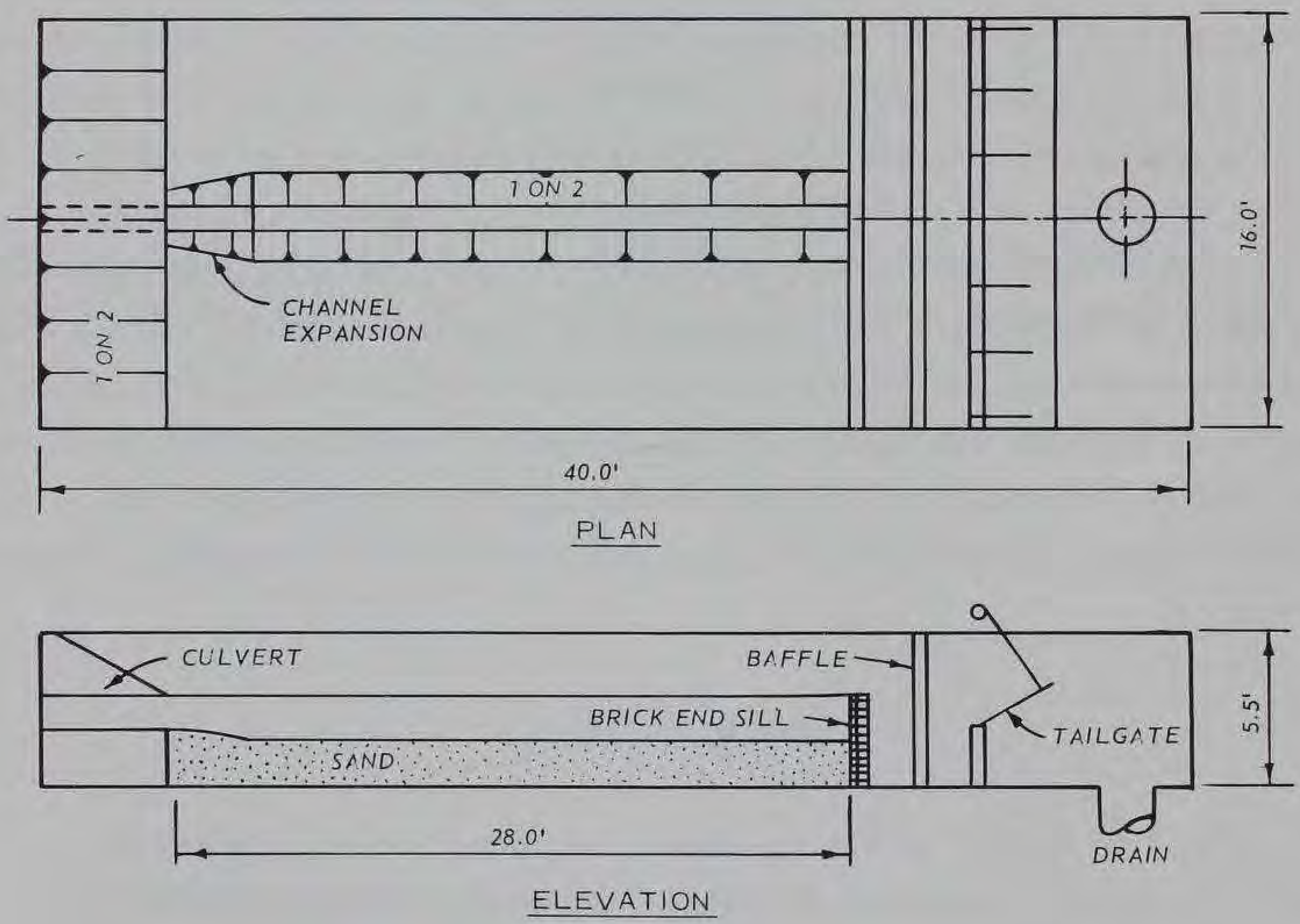

Figure 1. Experimental facilities

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

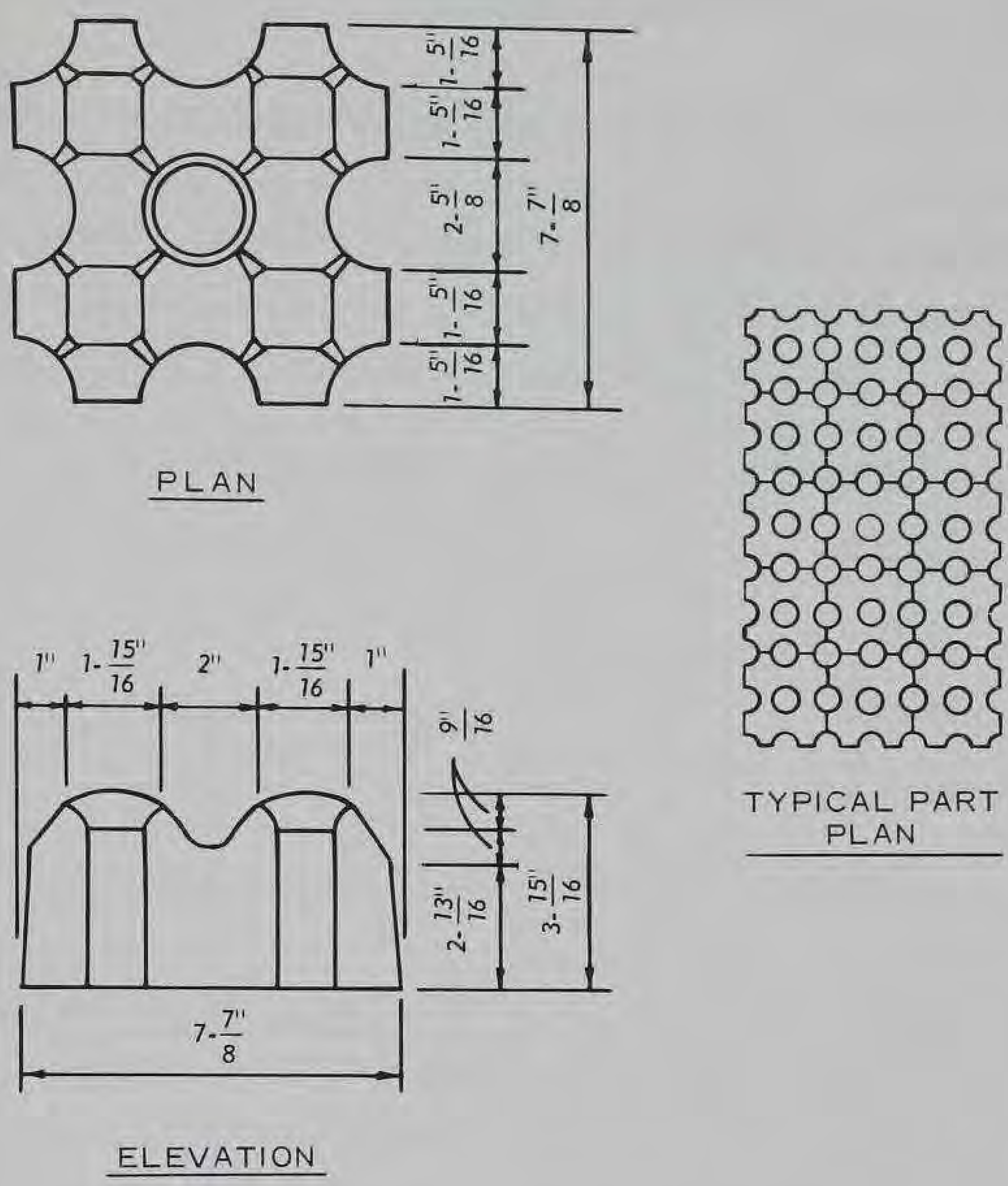

Figure 2. Cellular block details

stones with an average diameter (d_{50})* of 2.5 and 7 in. were reproduced at a scale of 1:4.

4. Water used in the operation of the models was supplied by pumps, and discharges were measured by means of calibrated venturi meters. Steel rails set to grade along the sides of the flume provided a reference plane and support for measuring devices. Water-surface elevations were measured by means of point gages and current patterns were determined by means of dye injected into the water and confetti sprinkled on the water surface. Tailwater elevations were regulated by a gate at the downstream end of the flume.

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* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix B).

Scale Relations

5. The accepted equations of hydraulic similitude, based upon the Froudian criteria, were used to express the mathematical relations between the dimensions and hydraulic quantities of the models and prototypes. The general relations expressed in terms of model scale or length ratio, L_r , are presented in the following tabulation:

Dimension	Ratio	Scale Relations	
Length	L_r	1:4	1:8
Area	$A_r = L_r^2$	1:16	1:64
Weight	$W_r = L_r^3$	1:64	1:512
Velocity	$V_v = L_r^{1/2}$	1:2	1:2.83
Discharge	$Q_r = L_r^{5/2}$	1:32	1:181

6. Quantitative measurements of discharge, water-surface elevation, and velocity in the model were converted to prototype dimensions by means of the above scale relations. Experimental data also indicate that the prototype-to-model scale ratio is valid for scaling riprap and revetment in the sizes used in this investigation, since the ratio of flow depth to revetment thickness and Froude number of flow in the model were the same as those in the prototype.

Test Procedures

7. Prior to each series of tests to determine the limits of stability for each of the three types of lining for channel expansions, the trapezoidal channel downstream of the expansion was molded in sand and slowly flooded to prevent erosion and provide a maximum desired tailwater elevation. A predetermined discharge was released through the culvert and the tailwater was lowered in small increments until displacement of the lining was observed and recorded.

PART III: TESTS AND RESULTS

Channel Expansion Geometry

8. Geometric details of the channel expansion initially investigated are shown in Figure 3. Reasonable performance was indicated with the original geometry of channel expansion. However, flow tended to concentrate along either side of this geometry, indicating that the expansion provided by the geometry was greater than that required and desired for relatively uniform distribution of flow in the exit area.

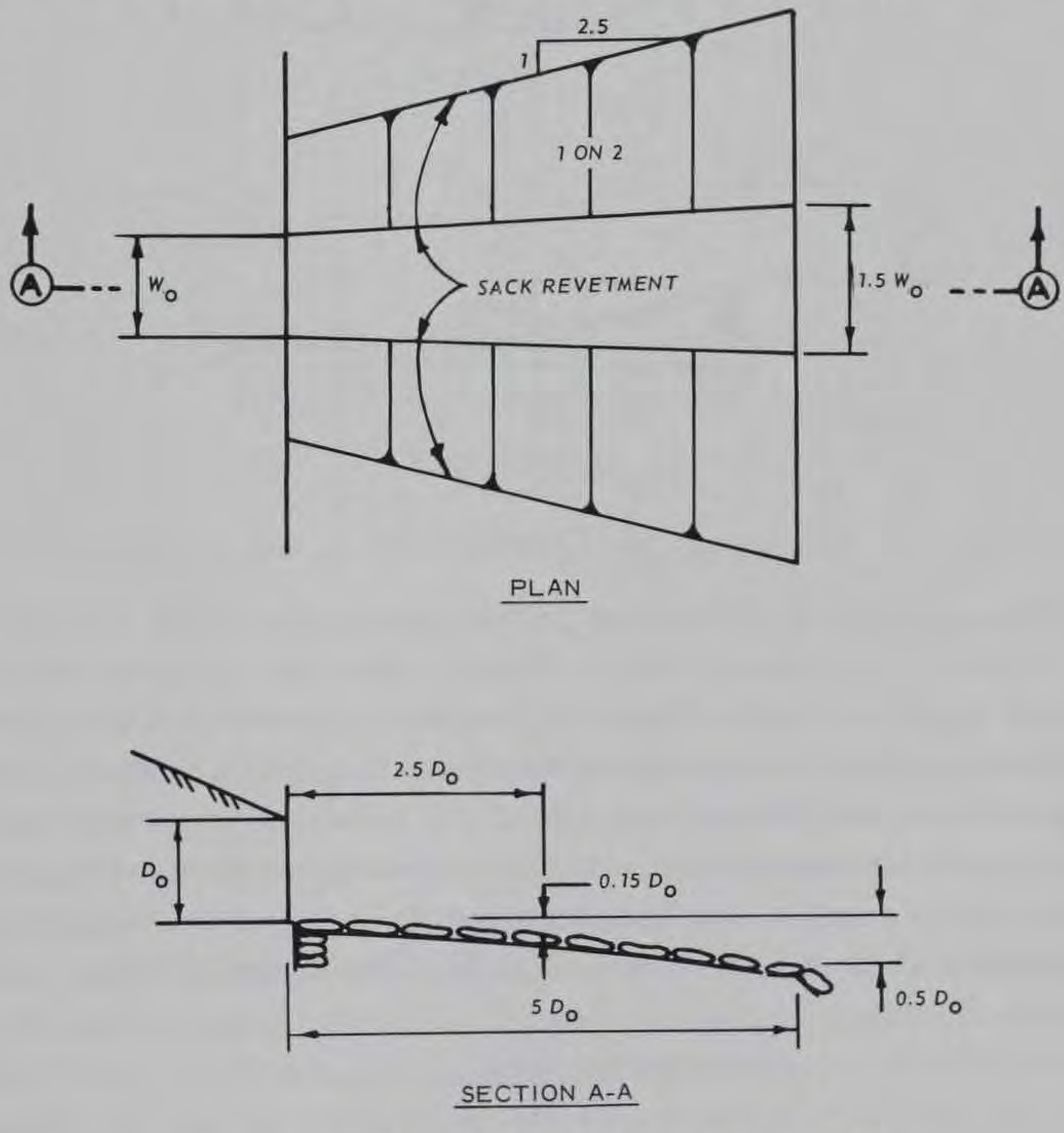

Figure 3. Original channel expansion geometry

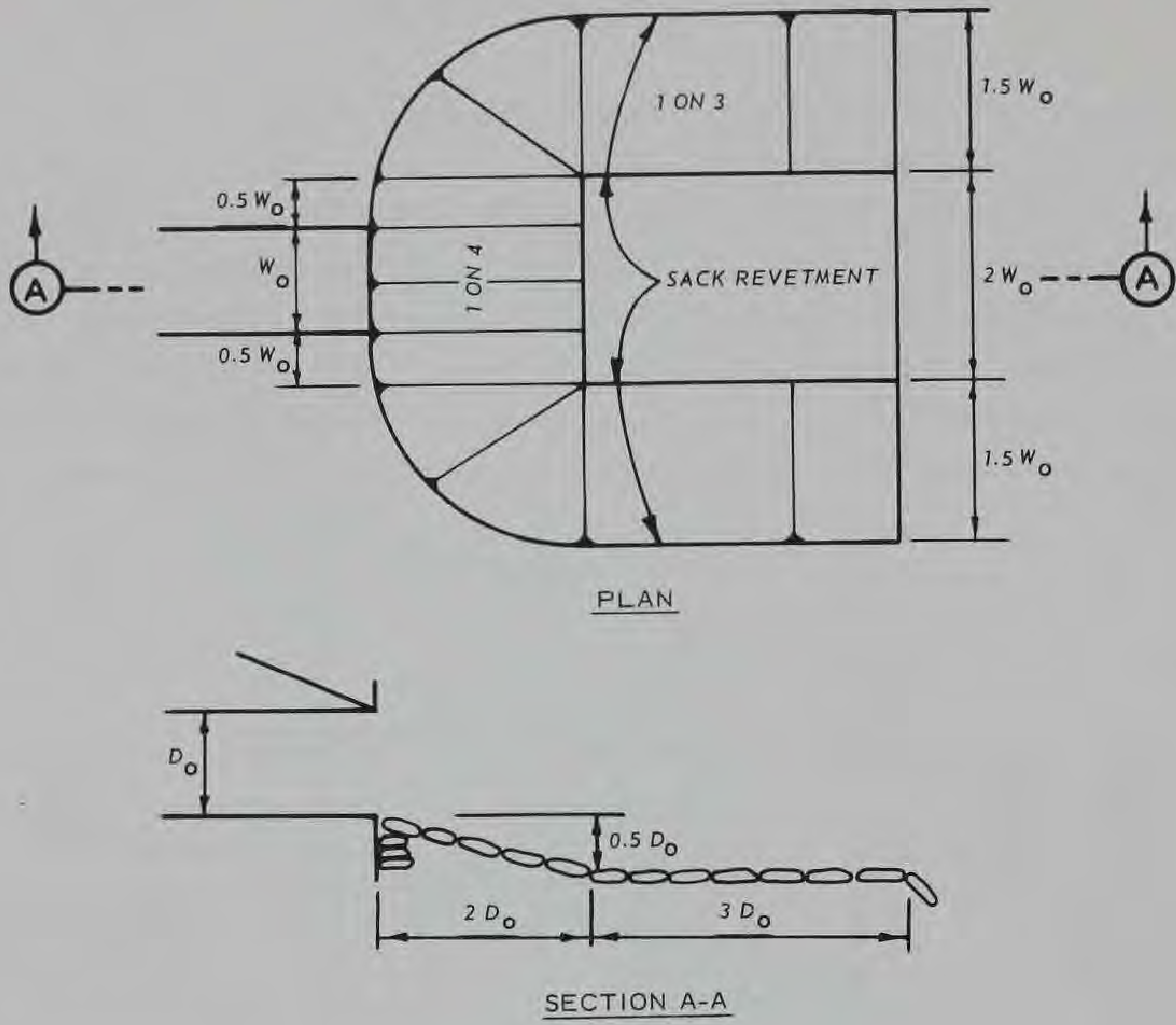

Figure 4. Geometry of lined channel with sudden expansion

Therefore, additional configurations were molded and tested to develop a more stable and economical plan of channel expansion. A geometry that provided sudden expansion (Figure 4) permitted flow to concentrate severely along either side of the expansion sufficient to produce a strong and undesirable eddy on the opposite side. Favorable performance was obtained with the recommended geometry of channel expansion shown in Figure 5 which provided satisfactory expansion of flow and required a smaller base width for the invert as well as fewer armor units.

Sack Revetment

9. The recommended geometry of channel expansion was molded and

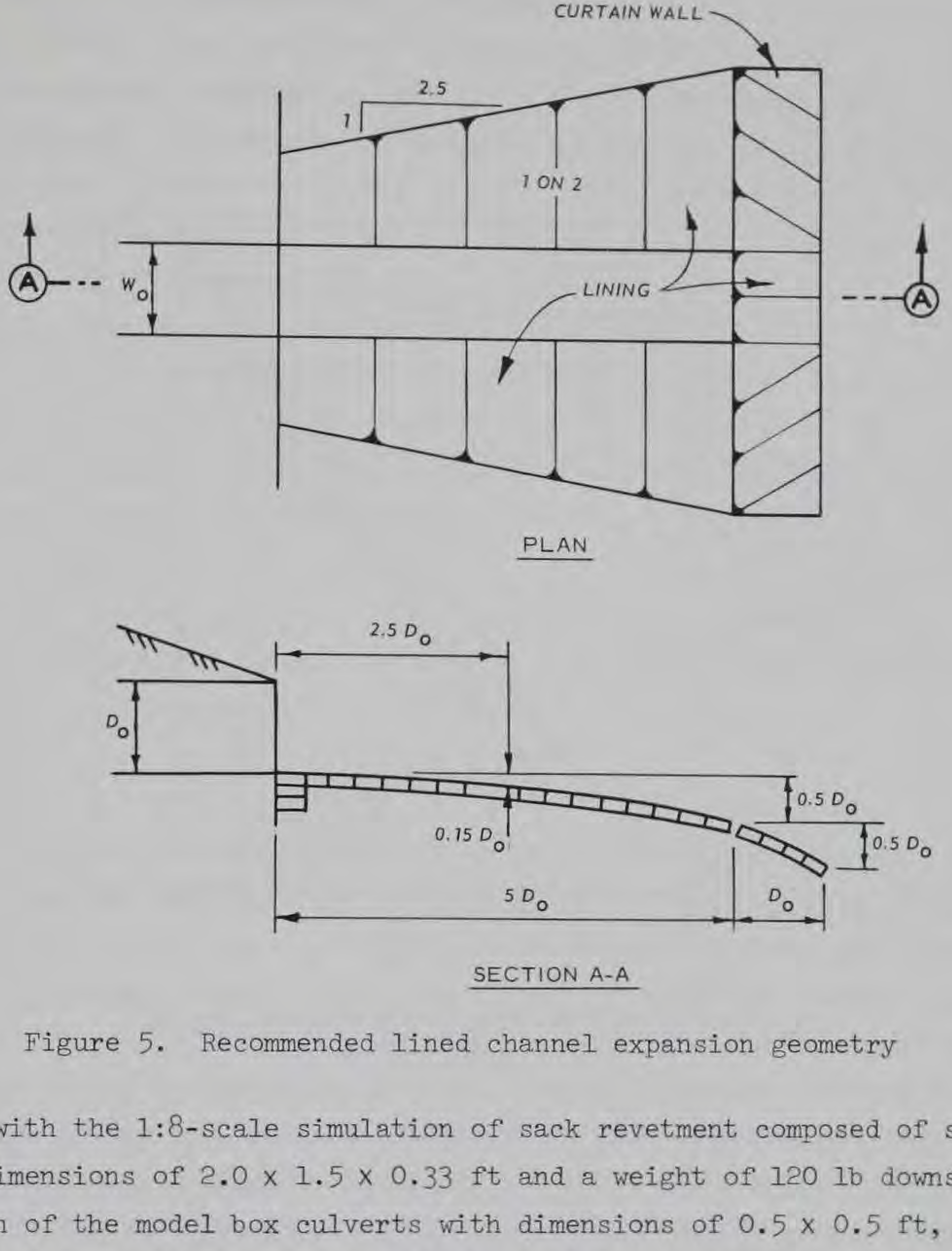

Figure 5. Recommended lined channel expansion geometry

lined with the 1:8-scale simulation of sack revetment composed of sacks with dimensions of 2.0 x 1.5 x 0.33 ft and a weight of 120 lb downstream of each of the model box culverts with dimensions of 0.5 x 0.5 ft, 1.0 x 1.0 ft, and 2.0 x 2.0 ft, which simulated prototype culverts of 4 x 4 ft, 8 x 8 ft, and 16 x 16 ft, respectively (Photo 1). The extent of each sack-revetted channel expansion was preserved in accordance with the recommended geometry (Figure 5) and the respective culvert dimension. Each of the three channel expansions and corresponding culverts were subjected to various discharges, tailwaters, and both partial and full pipe flow conditions until displacement or failure of the sack revetment was experienced. Flow conditions and displacement and/or failure are shown in Photos 2-4. Basic data obtained from the tests of sack revetment are presented in Table 1 and plotted in Figure 6. The description and units of all variables are presented in Appendix B: Notation.

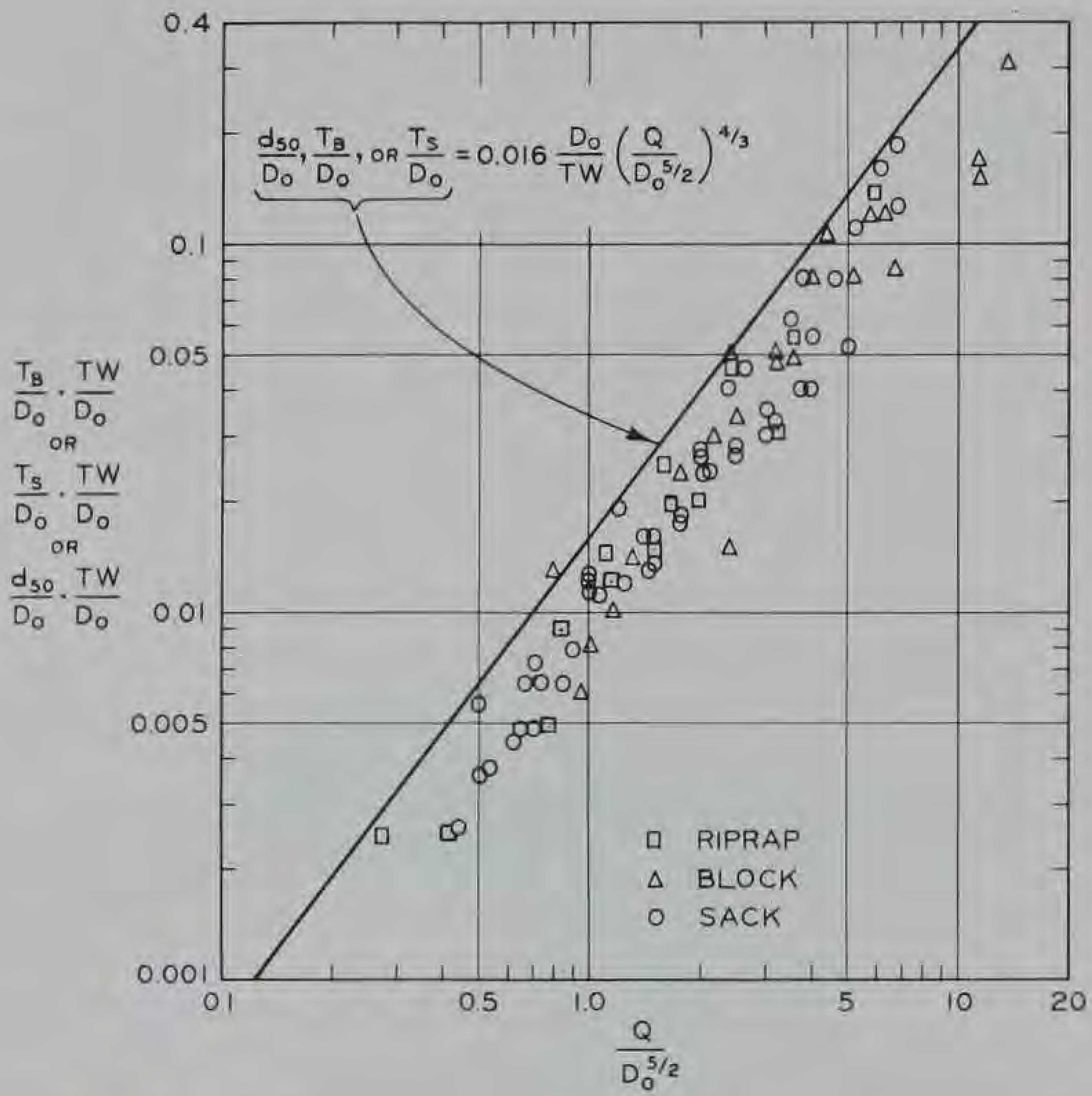

Figure 6. Maximum permissible discharge for lined channel expansions

10. In general, the initial displacement of one or two sacks resulted in immediate and extensive failure of the lining. Failure along the side slopes of the channel expansion was observed most often with excessive tailwaters and Froude numbers of flow at the outlet less than unity. With lesser tailwaters and Froude numbers of outlet flow greater than unity, failure was generally most severe along the invert of the expansion at a distance approximately one culvert height downstream of the outlet or directly beneath the toe of the hydraulic jump.

Cellular Blocks

11. The recommended and appropriately dimensioned channel expansion lined with the 1:4-scale simulation of cellular block revetment constructed of blocks weighing 14 lb and with dimensions shown in Figure 2 was investigated downstream of each of the three model box culverts that simulated prototype culverts with dimensions of 2 x 2 ft, 4 x 4 ft, and 8 x 8 ft. Typical conditions before, during, and after tests in which the cellular-block lined channel expansions were subjected to various discharges, tailwaters, and both partial and full pipe flow conditions are shown in Photos 5, 6, and 7, respectively. Basic data obtained from the tests of cellular block revetment are presented in Table 2 and Figure 6. The failure triggered by the displacement of one or two cellular blocks was considered to be more severe and extensive than that observed with either sack revetment or rock riprap.

Rock Riprap

12. The recommended and appropriately dimensioned channel expansion lined with a 1:4-scale simulation of rock riprap with an average diameter of 2.5 in. was investigated downstream of each of the three model box culverts that simulated prototype culverts with dimensions of 2 x 2 ft, 4 x 4 ft, and 8 x 8 ft. The largest box culvert was also investigated with an appropriately sized channel expansion lined with model stone that simulated rock riprap with an average diameter of 7 in. Typical conditions before, during, and after tests of the simulated 2- x 2-ft box culvert and corresponding channel expansion lined with stone of 2.5-in. average diameter are shown in Photo 8. Basic data obtained from the tests of rock riprap revetment are presented in Table 3 and Figure 6. Failures observed on either of the side slopes and along the invert of the channel expansion lined with rock riprap were not as extensive as those observed with either the sack revetment or cellular blocks.

Data Analyses

13. The basic variables investigated included the size of the culvert, the geometry of individual pieces of the three types of revetment, the discharge or rate of flow, and the depth of tailwater relative to the invert of the culvert outlet. The size or dimension of the square culvert (D_o) was arbitrarily selected as the fundamental or primary dimension that should be common to each dimensionless parameter used in analysis of the data.

14. The data obtained from tests of each revetment and culvert were used to calculate the quasi-dimensionless parameter $Q/D_o^{5/2}$ which is a useful, descriptive parameter for classifying the relative discharge capacity of circular and square shaped closed conduits including culverts. This parameter is also related to the Froude number of flow at the outlet, commonly used to classify subcritical or supercritical flow conditions and in design of open channel facilities. Ratios of tailwater depth above the invert of the outlet to the height of the culvert TW/D_o were calculated also.

15. Plots of the parameters $Q/D_o^{5/2}$ versus TW/D_o on log-log paper for each size of square culvert and the corresponding lined channel expansion indicated that an equation of the form $Q/D_o^{5/2} = C(TW/D_o)^{3/4}$ could be used to describe the limiting hydraulic conditions required for stability of each plan of protection. Since the size of individual pieces of each lining was constant relative to a given culvert dimension, but variable relative to various sizes of culverts, it was considered that the relative size of the revetment to the culvert height would be an important parameter. This was confirmed by log-log plots made to correlate the magnitude of the coefficient C indicated from the plots of $Q/D_o^{5/2}$ versus TW/D_o relative to the ratio of revetment thickness to culvert height T_B/D_o. These latter plots indicated that an equation of the form $C = K(T_B/D_o)^{3/4}$ would satisfy the data.

16. Combining these two relations indicated that an expression of the following form would satisfy the data of all tests of each type

of revetment used to line the appropriate channel expansion downstream of various sized square culverts:

$$\frac{Q}{D_o^{5/2}} = C \left(\frac{TW}{D_o}\right)^{3/4} \tag{1}$$

where

$$C = K \left(\frac{T_B}{D_o}\right)^{3/4} \tag{2}$$

Combining Equations 1 and 2 yields

$$\frac{Q}{D_o^{5/2}} = K \left(\frac{T_B}{D_o}\right)^{3/4} \left(\frac{TW}{D_o}\right)^{3/4} \tag{3}$$

or

$$\left(\frac{T_B}{D_o}\right)\left(\frac{TW}{D_o}\right) = K_2 \left(\frac{Q}{D_o^{5/2}}\right)^{4/3} \tag{4}$$

Therefore, the basic data were plotted as shown in Figure 6, and a reasonable trend is indicated. The recommended equation for square culverts indicated by a conservative fit of the data is:

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

where

d_{50} = diameter of average size stone, ft
T_S = thickness of geometrically similar sack revetment, ft
T_B = thickness of geometrically similar cellular block, ft
D_o = height of culvert, ft

TW = tailwater depth above invert of culvert outlet, ft

Q = discharge, cfs

It is considered that Equation 5, developed for square outlets, can be applied directly to circular outlets. It is also considered that the results presented herein can be applied to other outlet shapes, provided geometric similarity is preserved in application of the recommended guidance. For outlets with aspect ratios, W_o/D_o, other than unity, it is considered that the parameters or ratios involving revetment thickness and tailwater depth above the outlet invert to the height of the outlet are appropriate; however, the discharge parameter should be revised to adequately describe the unit discharge per foot of outlet width, q. Therefore, the following equation is recommended for rectangular culverts with an aspect ratio other than unity:

$$\frac{d_{50}}{D_o} \text{ or } \frac{T_S}{D_o} \text{ or } \frac{T_B}{D_o} = 0.016 \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3} \qquad (6)$$

Equations 5 and 6 are recommended for selection of either the size of revetment for a given lined channel expansion, discharge, tailwater depth, and culvert dimension or for the selection of a size of culvert with which a given revetment lined channel expansion will remain stable under anticipated conditions of discharge and tailwater depth.

17. In an attempt to provide a convenient method for describing the condition of flow to be anticipated at the outlet of various shaped culverts, calculations were made to relate the Froude number of flow at the outlet to the quasi-dimensionless parameter $Q/D_o^{5/2}$ for various partial and full pipe flow conditions. These calculations involved equating a given value (say 1.0 and 0.1) to the Froude number of flow at the outlet of any given shape of conduit (see Appendix B: Notation) to determine the corresponding value of the $Q/D_o^{5/2}$ ratio required to satisfy both the hydraulic and geometric properties involved. The following procedure was developed and used to compute desired relations for square and rectangular conduits: For $F = Q/A\sqrt{gd}$ = any value, let

$W_o/D_o = A_c$, the conduit aspect ratio; $d/D_o = A_d$, the ratio of actual uniform flow depth to conduit height; and $A_c A_d = A_r$, the ratio of area of flow to the square of the conduit height. Then, the area of flow A equals the product of $A_r D_o^2$. Therefore,

$$F = \frac{Q}{A_r} D_o^2 \sqrt{g} \sqrt{A_d D_o} = \frac{Q}{D_o^{5/2}} A_r \sqrt{A_d} \sqrt{g}$$

or

$$\frac{Q}{D_o^{5/2}} = A_r \sqrt{A_d} \sqrt{g}\, F \qquad (7)$$

A similar procedure was followed to determine the relations for circular conduits. The following relation exists for partial and full conduit flow conditions in circular pipes:

$$F = \frac{Q}{A\sqrt{gd}} = \text{any given value}$$

$$F = \frac{Q}{CD_o^2 \sqrt{g}\sqrt{A_d D_o}}$$

where C is a function of d/D_o ,* and

$$\frac{Q}{D_o^{5/2}} = C \sqrt{g}\sqrt{A_d}\, F \qquad (8)$$

For full pipe flow with $A = \pi D_o^2/4$ and $d = D_o$,

---

* H. W. King, Handbook of Hydraulics, 4th ed., McGraw-Hill, New York, 1954, Table 84.

$$F = \frac{4Q}{\pi D_o^2 \sqrt{gD_o}}$$

or

$$\frac{Q}{D_o^{5/2}} = \left(\frac{\pi \sqrt{g}}{4}\right) F = 4.46F$$

Similar relations for full conduit flow in rectangular conduits with conduit aspect ratios ranging from 1 to 4 are presented for comparison as follows:

$$\frac{Q}{D_o^{5/2}} = 5.67F \quad \text{when} \quad \frac{W_o}{D_o} = 1$$

$$\frac{Q}{D_o^{5/2}} = 11.35F \quad \text{when} \quad \frac{W_o}{D_o} = 2$$

$$\frac{Q}{D_o^{5/2}} = 17.02F \quad \text{when} \quad \frac{W_o}{D_o} = 3$$

$$\frac{Q}{D_o^{5/2}} = 22.7F \quad \text{when} \quad \frac{W_o}{D_o} = 4$$

18. However, the hydraulic capacity of a given culvert is dependent upon the slope, length, and flow or hydraulic resistance of the barrel. For uniform partial pipe flow, the slope of the barrel and the energy gradient are the same. In the case of full pipe flow, the slope of the energy gradient and the barrel may differ and the slope of the energy gradient dictates the hydraulic capacity of the culvert.

19. Obviously, only one combination of conditions will satisfy the relations calculated as described in paragraph 17. Other relations for full pipe flow conditions with various combinations of the slope of the energy gradient, the hydraulic resistance of the barrel, culvert

size and shape, and discharge were calculated on the basis of the Manning formula. It was also used to calculate relations for uniform partial pipe flows with various combinations of the slope of the culvert barrel, hydraulic resistance of the barrel, shape and size of the culvert, depth of uniform flow, and discharge. The calculations were made following the school of thought that the numerator (1.486) of the Manning formula contains $\sqrt{g}$, and that for physical and practical reasons "n" has the dimensions of length to the one-sixth power. This permits the results to be presented in terms of dimensionless parameters as shown in Figures 7-11. Thus, for selected or given hydraulic and geometrical conditions, the type of flow to be anticipated at geometrically similar culvert outlets can be determined from Figures 7-11. However, it is not mandatory that the Froude number of flow at the outlet portal be known for design of lined channel expansions. The size of revetment or the size of culvert and channel expansion required for a given size of revetment to remain stable under anticipated conditions of discharge and tailwater depth can be determined by means of the recommended Equations 5 and/or 6.

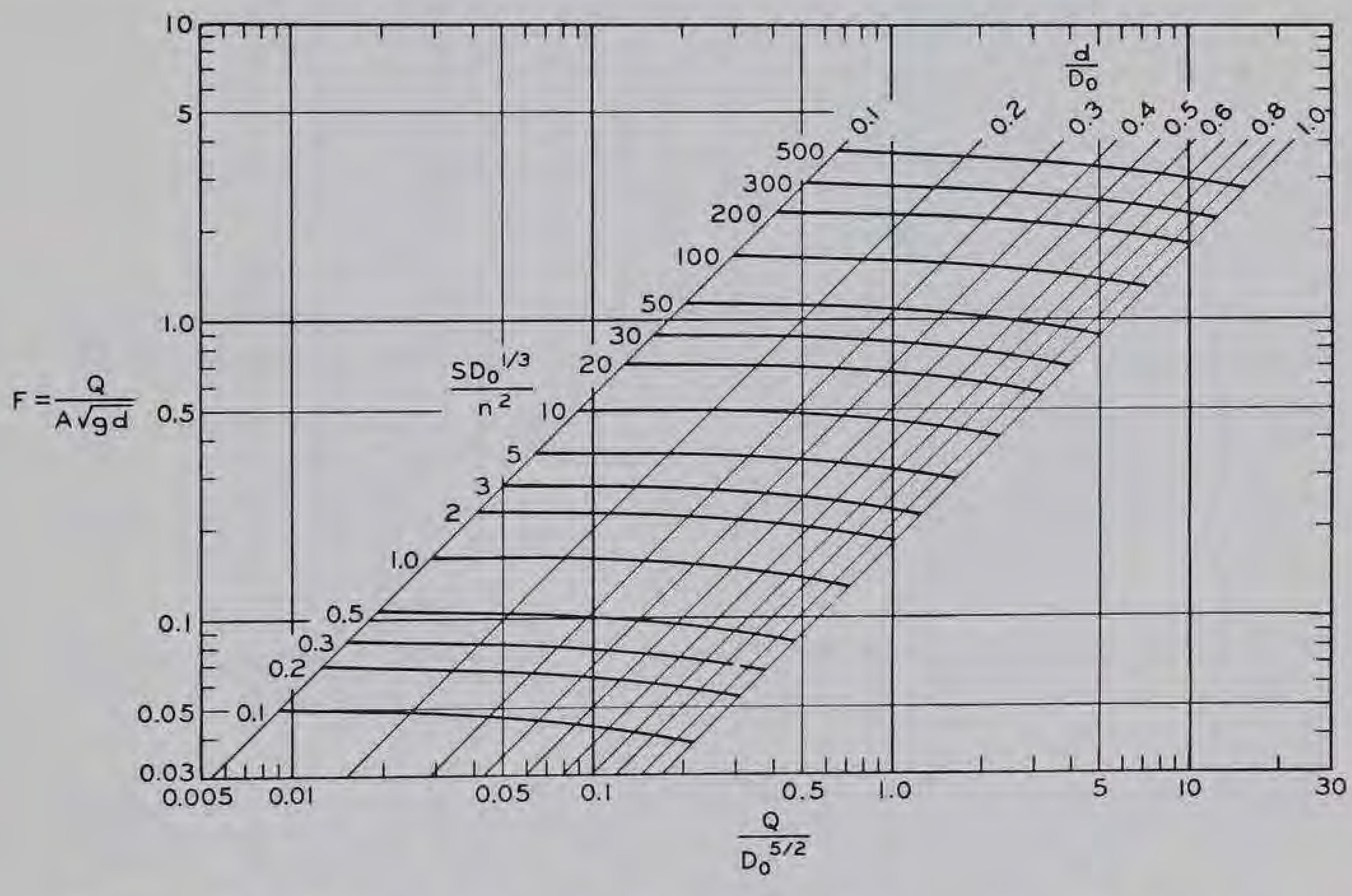

Figure 7. Square culvert; Froude number versus discharge

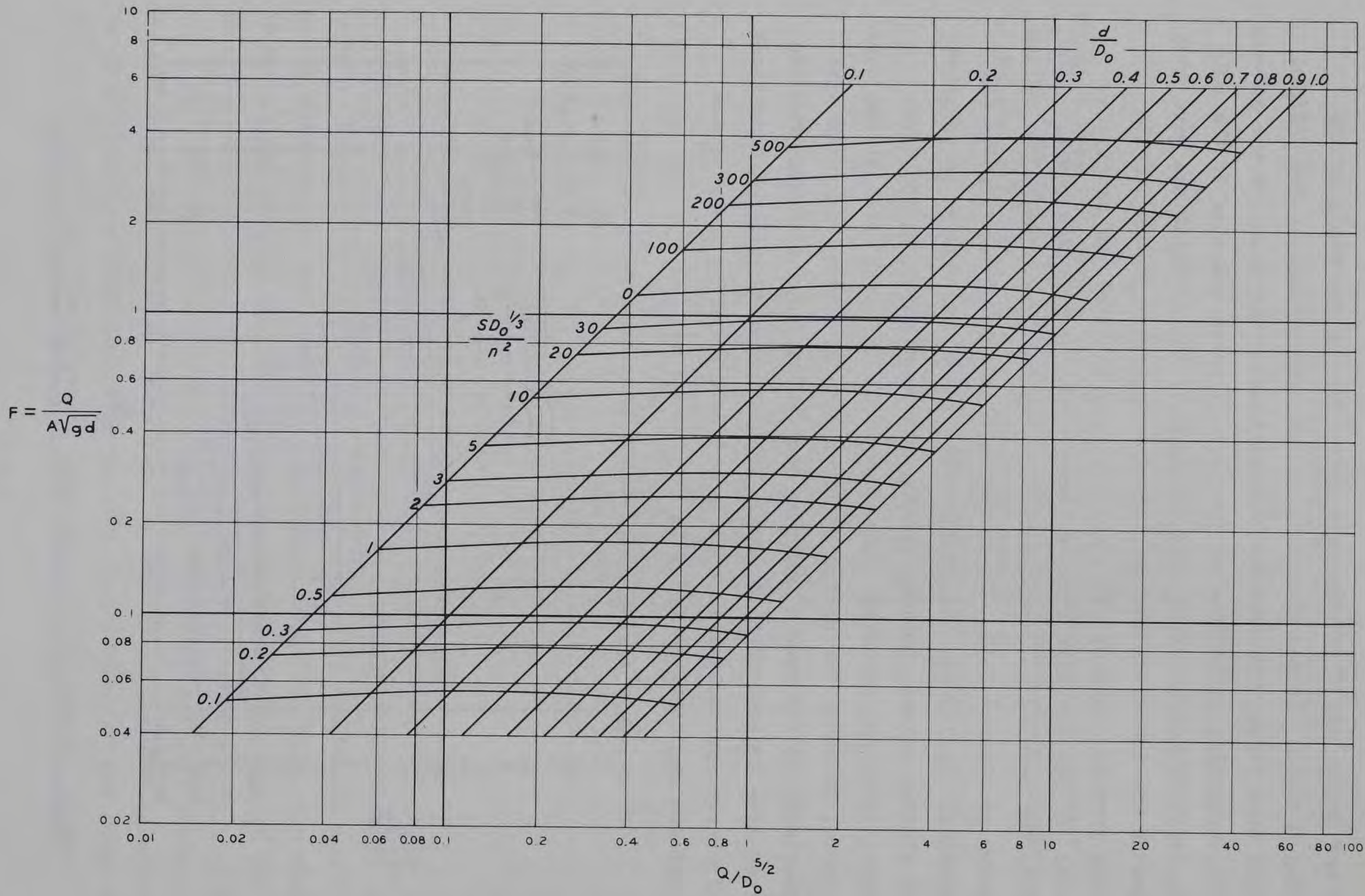

Figure 8. Rectangular culvert ($W_o = 2D_o$); Froude number versus discharge

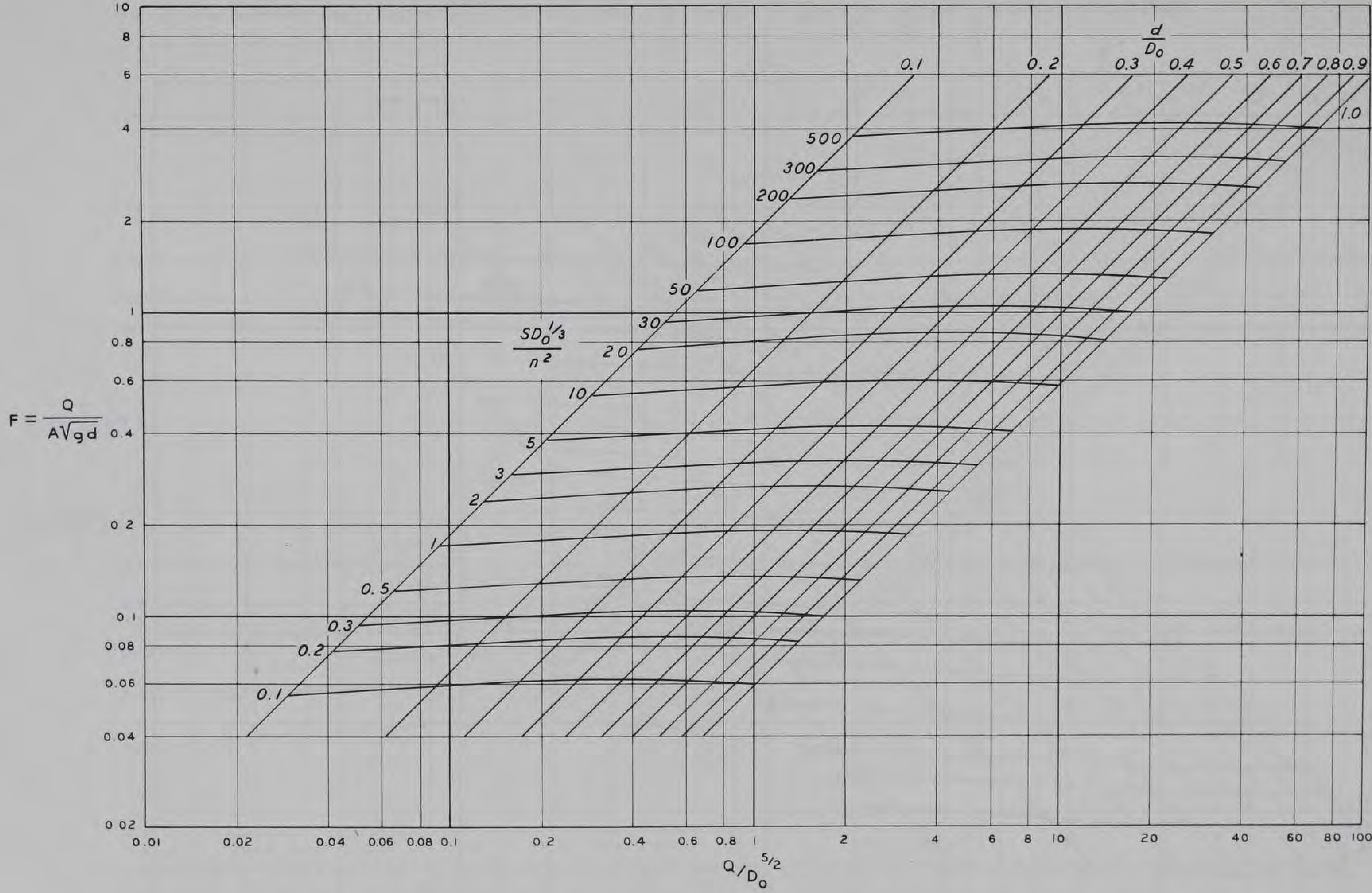

Figure 9. Rectangular culvert ($W_o = 3D_o$); Froude number versus discharge

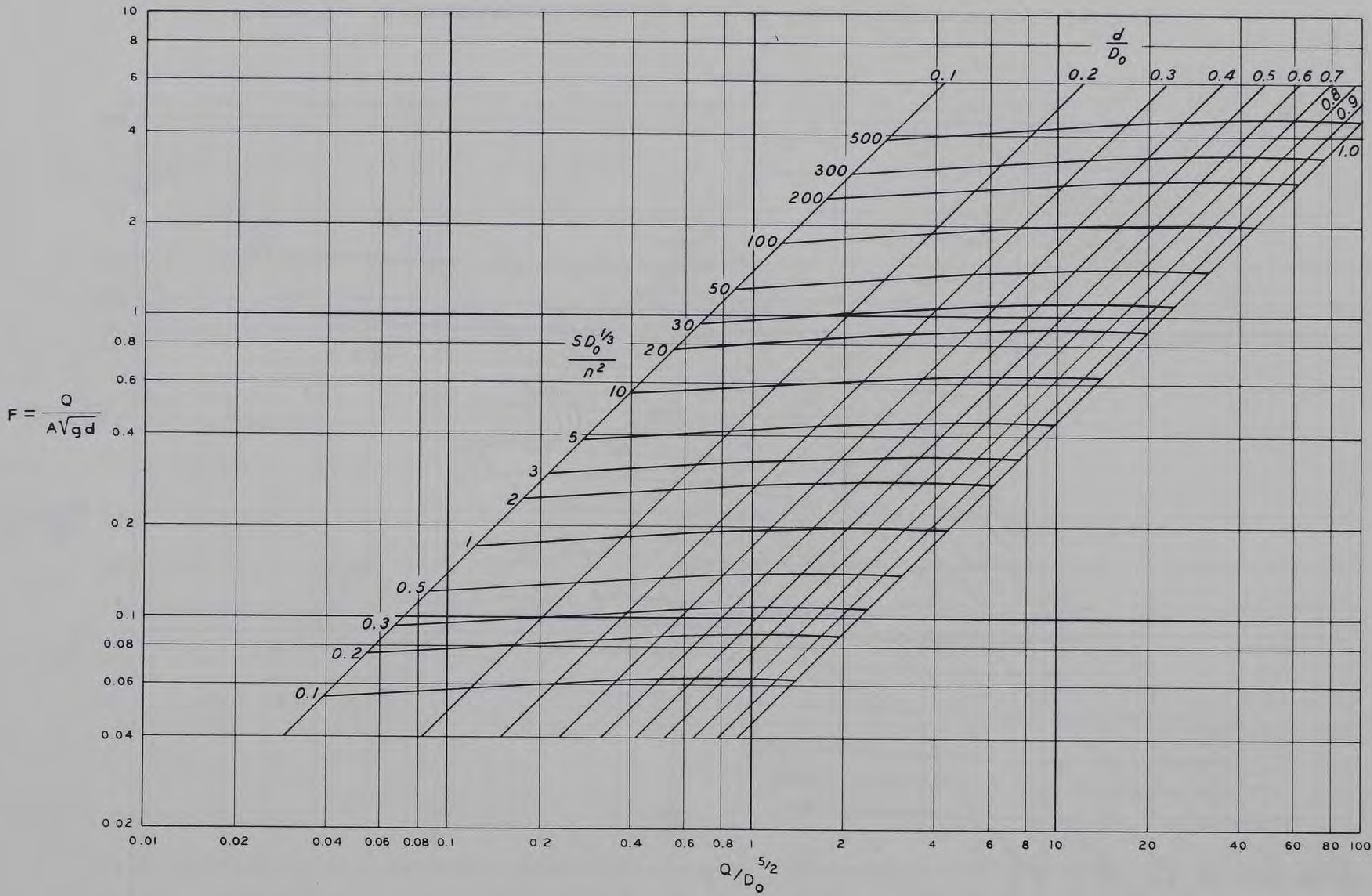

Figure 10. Rectangular culvert ($W_o = 4D_o$); Froude number versus discharge

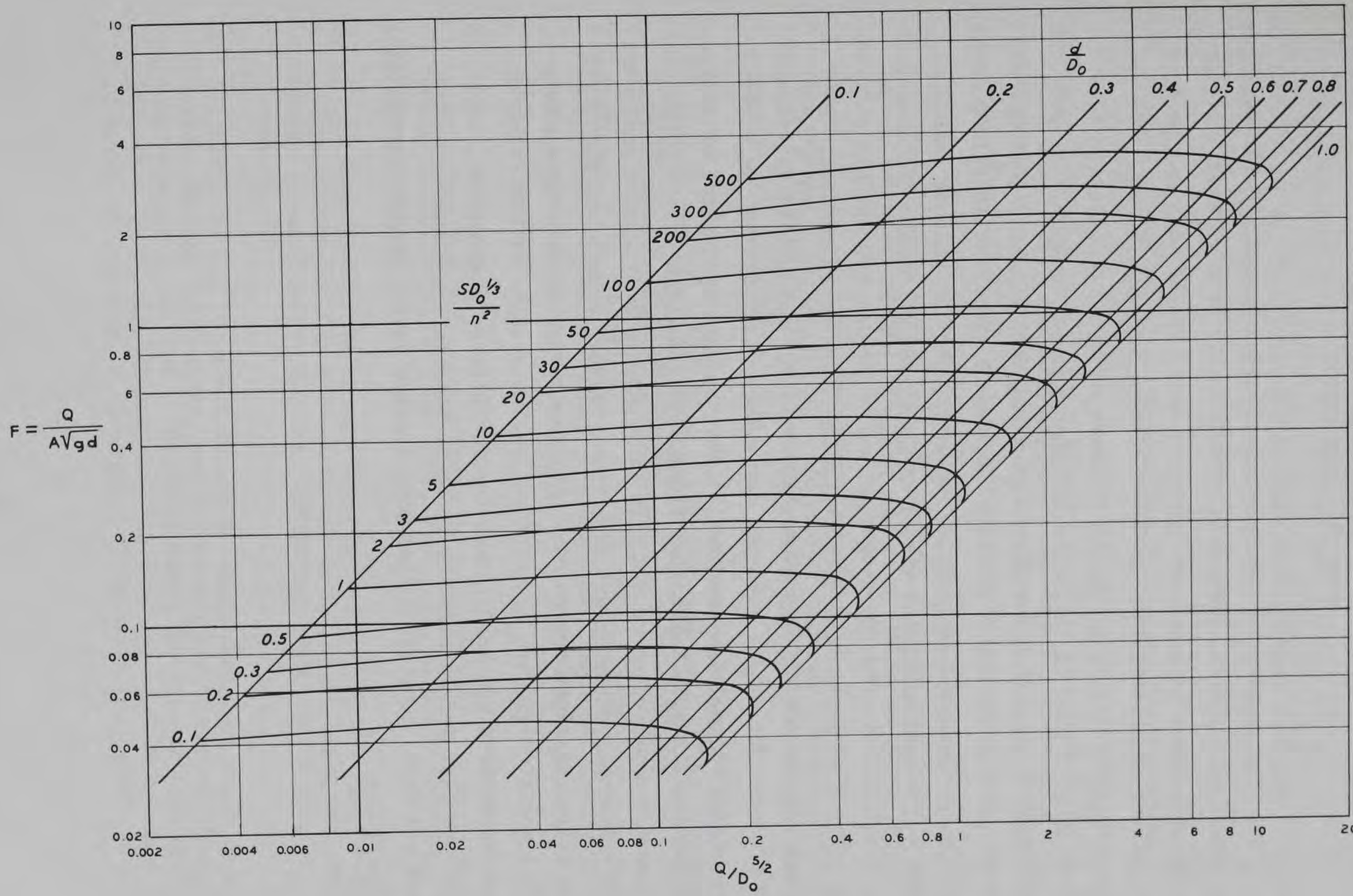

Figure 11. Circular culvert; Froude number versus discharge

PART IV: DISCUSSION

20. The results of the research reported herein provide guidance for design of a channel expansion geometrically proportioned in terms of the dimensions of a culvert or storm-drain outlet that may be lined with either sack revetment, cellular blocks, or rock riprap. The results are particularly pertinent to these outlets subjected to relatively large depths of tailwater or submergence. However, the use of a lined channel expansion downstream of a culvert outlet is just one alternative for providing protection to prevent excessive localized scour.

21. Appendix A is included in this report to present practical guidance for estimating the extent of localized erosion to be expected at culvert outlets and for comparing and selecting appropriate alternative schemes of protection at culvert and storm-drain outlets. For example, is the anticipated scour hole with an appropriate cutoff wall that protects the outlet adequate for energy dissipation? Is a paved flared outlet transition practical? Are the size and extent of riprap required for a stable horizontal blanket practicable? Is it practicable to comprise depth of scour and size of riprap by providing a preformed and riprap-lined scour hole? Is a lined channel expansion practical? Is an energy dissipator required? What are possible effective alternatives and the relative costs of each? The results of WES research efforts sponsored by the Directorate of Military Construction, OCE, during the past decade relative to these interests are therefore presented and it is considered that they provide useful guidance previously not available.

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Table 1

Basic Model Data of Conditions That Induced Failure of Sack Revetment Channel Expansions

Model* Culvert Size, ft	Discharge cfs	Tailwater Depth, ft**	Depth of Flow at Culvert Outlet, ft**	$\frac{Q}{D_o^{5/2}}$	F	$\frac{T_S}{D_o}$	$\frac{TW}{D_o}$	$\frac{T_S}{D_o} \times \frac{TW}{D_o}$
0.5 × 0.5	0.18	0.08	0.10	1.00	2.10	0.08	0.15	0.012
	0.21	0.12	0.14	1.20	1.45		0.24	0.019
	0.25	0.10	0.14	1.40	1.80		0.20	0.016
	0.35	0.17	0.19	2.00	1.50		0.34	0.027
	0.37	0.15	0.19	2.10	1.60		0.30	0.024
	0.41	0.25	0.24	2.32	1.24		0.50	0.040
	0.46	0.28	0.27	2.60	1.15		0.57	0.046
	0.61	0.38	0.36	3.47	0.99		0.76	0.061
	0.67	0.50	0.47	3.80	0.74		1.00	0.080
	0.83	0.50	0.47	4.70	0.90		1.00	0.080
	0.92	0.69	0.47	5.21	1.00		1.37	0.109
	1.10	1.00	0.50	6.30	1.10		2.00	0.160
	1.19	1.15	0.50	6.70	1.19		2.30	0.184
	1.20	0.80	0.50	6.80	1.20		1.60	0.128
1.0 × 1.0	0.50	0.002	0.14	0.50	1.70	0.04	0.14	0.0056
	0.50	0.090	0.12	0.50	2.10		0.09	0.0036
	0.65	0.12	0.15	0.65	1.90		0.12	0.0049
	0.70	0.12	0.17	0.70	1.75		0.12	0.0049
	0.75	0.16	0.18	0.75	1.73		0.16	0.0064
	1.00	0.28	0.28	1.00	1.17		0.28	0.011
	1.00	0.31	0.31	1.00	1.00		0.31	0.012
	1.00	0.15	0.26	1.00	1.36		0.15	0.006
	1.25	0.30	0.30	1.25	1.33		0.30	0.012
	1.50	0.34	0.35	1.50	1.30		0.34	0.014
	1.50	0.40	0.41	1.50	1.02		0.40	0.016
	1.75	0.45	0.45	1.75	1.03		0.45	0.018
	2.00	0.66	0.67	2.00	0.65		0.66	0.026
	2.00	0.59	0.59	2.00	0.78		0.59	0.024
	2.50	0.70	0.70	2.50	0.75		0.70	0.028
	2.50	0.66	0.67	2.50	0.81		0.66	0.026
	3.00	0.89	0.90	3.00	0.62		0.89	0.036
	3.00	0.75	0.76	3.00	0.80		0.75	0.030
	3.20	0.84	0.83	3.20	0.74		0.84	0.034
	3.70	1.00	1.00	3.70	0.65		1.00	0.040
	4.00	0.99	1.00	4.00	0.71		0.99	0.040
	5.00	1.30	0.99	5.00	0.90		1.30	0.052
2.0 x 2.0	2.49	0.26	0.26	0.44	1.66	0.03	0.13	0.0026
	3.00	0.38	0.38	0.53	1.13		0.19	0.0038
	3.51	0.45	0.45	0.62	1.02		0.22	0.0044
	3.73	0.65	0.65	0.66	0.63		0.32	0.0063
	4.02	0.75	0.76	0.71	0.54		0.37	0.0073
	4.98	0.80	0.89	0.88	0.52		0.40	0.0078
	6.00	1.10	1.13	1.06	0.44		0.55	0.011
	7.02	1.20	1.22	1.24	0.46		0.60	0.012
	8.04	1.30	1.30	1.42	0.48		0.65	0.013
	10.02	1.83	1.82	1.77	0.36		0.91	0.018

* Model culvert sizes of 0.5, 1.0, and 2.0 ft correspond to prototype culvert sizes of 4, 8, and 16 ft, respectively.
** Measured from invert of culvert.

Table 2

Basic Model Data of Conditions That Induced Failure of Cellular Block Channel Expansions

Model* Culvert Size, ft	Discharge cfs	Tailwater Depth ft**	Depth of Flow at Culvert Outlet ft**	$\frac{Q}{D_o^{5/2}}$	F	$\frac{T_B}{D_o}$	$\frac{TW}{D_o}$	$\frac{T_B}{D_o} \times \frac{TW}{D_o}$
0.5 × 0.5	1.2	0.25	0.50	6.7	1.20	0.17	0.50	0.085
	2.00	0.50	0.50	11.3	2.00		0.87	0.150
	2.00	0.44	0.50	11.3	2.00		1.00	0.170
	2.40	0.90	0.50	13.6	2.39		1.80	0.310
1.0 × 1.0	1.00	0.10	0.25	1.00	1.40	0.08	0.10	0.008
	2.20	0.36	0.40	2.20	1.53		0.37	0.029
	2.40	0.61	0.57	2.40	0.98		0.61	0.049
	2.40	0.19	0.40	2.40	1.67		0.19	0.015
	3.10	0.61	0.60	3.10	1.17		0.61	0.049
	3.10	0.63	0.63	3.10	1.10		0.63	0.051
	3.30	0.60	0.60	3.30	1.25		0.60	0.048
	4.00	1.00	1.00	4.00	0.70		1.00	0.080
	4.50	1.30	0.99	4.50	0.80		1.30	0.104
	5.30	1.00	1.0	5.30	0.94		1.00	0.080
	5.80	1.50	1.00	5.80	1.02		1.50	0.120
	6.20	1.50	1.00	6.20	1.10		1.50	0.120
2.0 x 2.0	4.95	0.64	0.52	0.87	1.18	0.04	0.32	0.013
	5.25	0.30	0.46	0.92	1.50		0.15	0.006
	6.30	0.06	0.50	1.11	1.56		0.03	0.010
	7.40	0.70	0.81	1.30	0.90		0.35	0.014
	10.20	1.20	1.20	1.78	0.67		0.60	0.024
	14.20	1.72	1.80	2.50	0.52		0.86	0.034

* Model culvert sizes of 0.5, 1.0, and 2.0 ft correspond to prototype sizes of 2, 4, and 8 ft, respectively.
** Measured from invert of culvert.

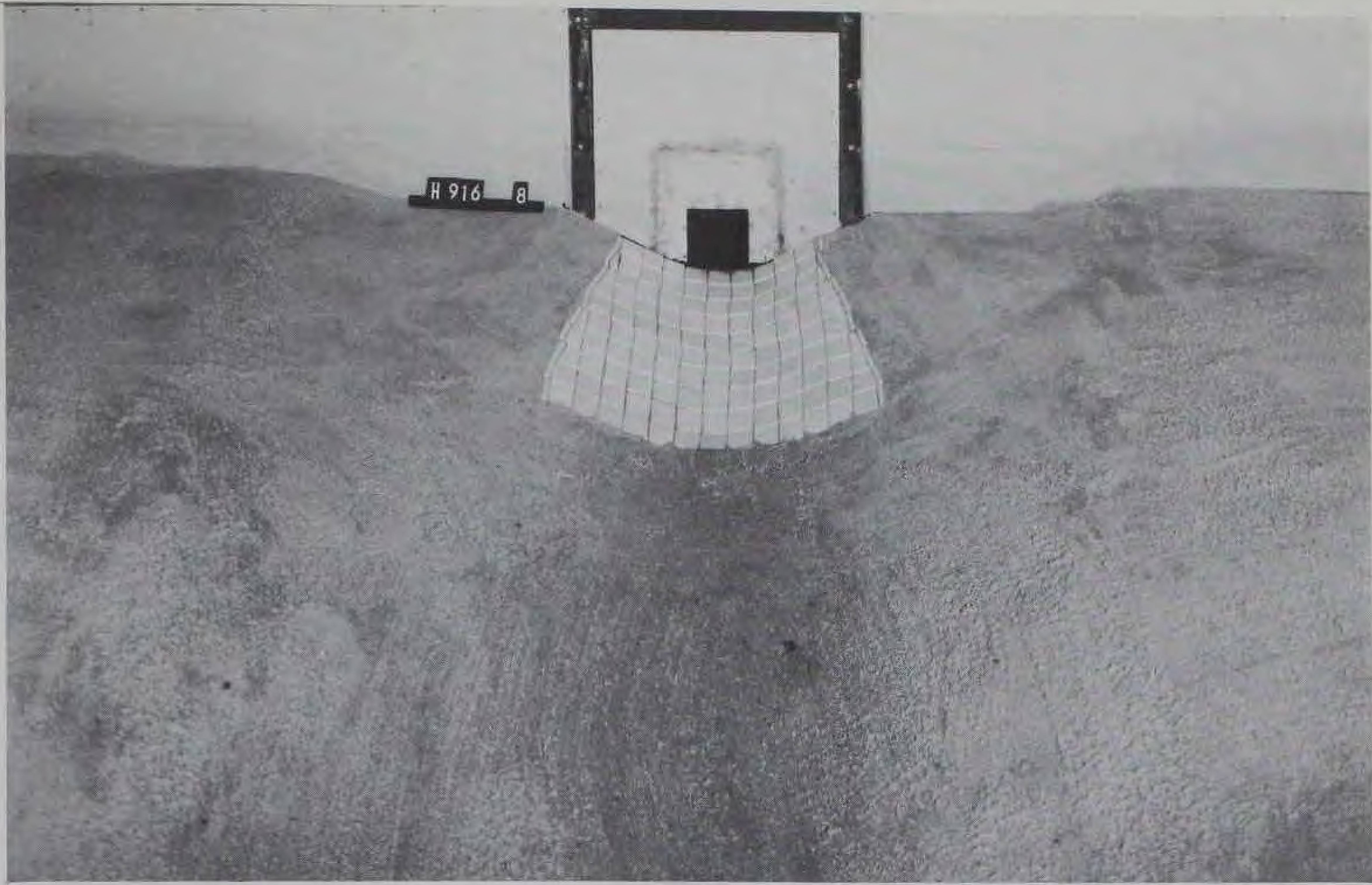
Table 3

Basic Model Data of Conditions That Induced Failure of

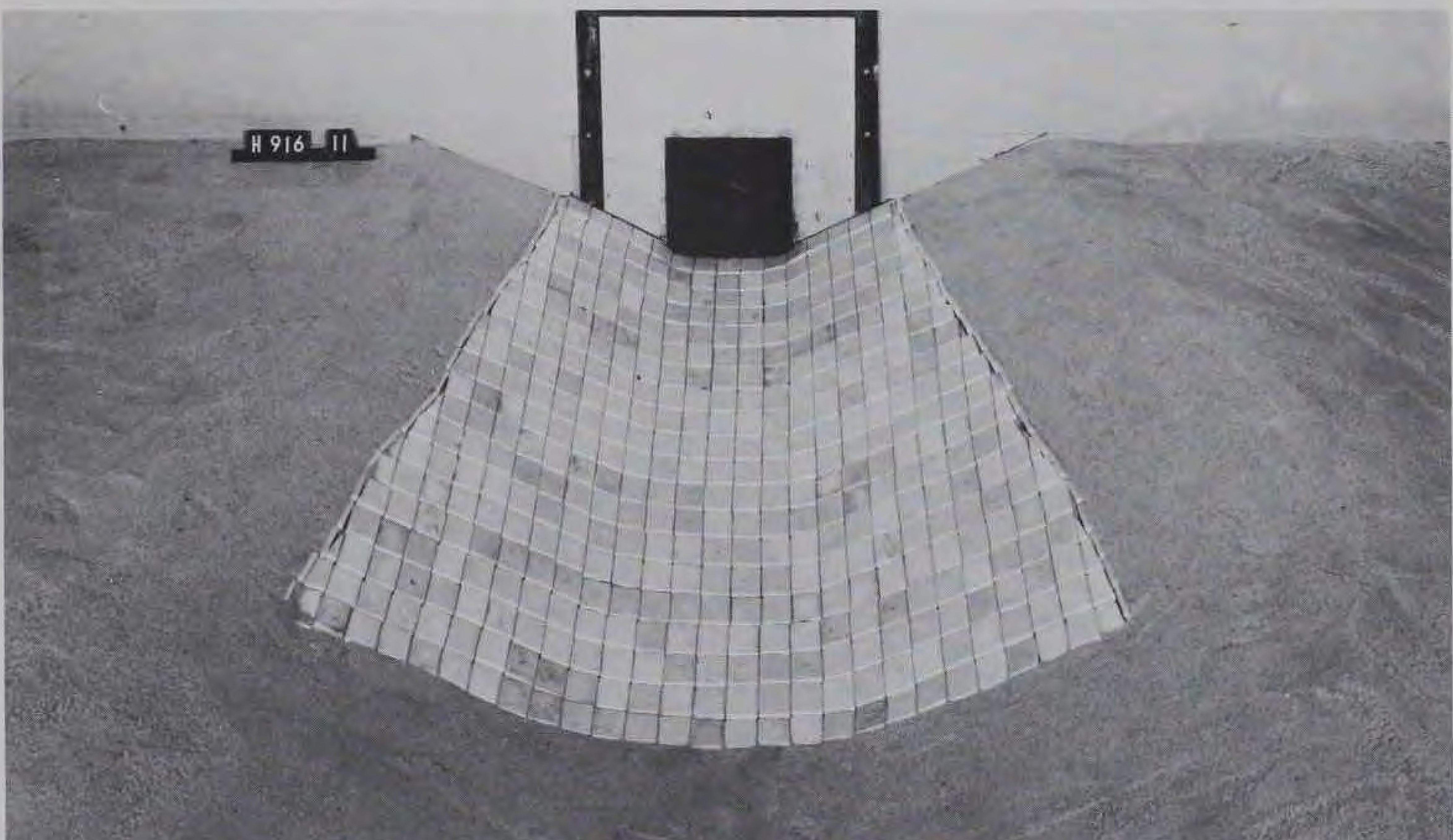
Rock Riprap Channel Expansions

Model* Culvert Size, ft	Discharge cfs	Tailwater Depth ft**	Depth of Flow at Culvert Outlet, ft**	Sieve Size, in.†	$\frac{Q}{D_o^{5/2}}$	F	$\frac{d_{50}}{D_o}$	$\frac{TW}{D_o}$	$\frac{d_{50}}{D_o} \times \frac{TW}{D_o}$
0.5 × 0.5	0.26	0.07	0.10	3/4-1/2	1.5	2.70	0.104	0.14	0.015
	0.62	0.35	0.25		3.5	1.75		0.56	0.058
	1.06	0.68	0.50		6.0	1.06		1.35	0.140
1.0 × 1.0	0.75	0.09	0.20	3/4-1/2	0.75	1.53	0.052	0.09	0.005
	2.00	0.37	0.50		2.00	1.00		0.38	0.019
	3.30	0.75	0.80		3.30	0.81		0.75	0.031
2.0 × 2.0	2.30	0.20	0.20	3/4-1/2	0.41	2.30	0.026	0.10	0.003
	4.80	0.75	0.48		0.85	1.27		0.35	0.009
	6.40	0.95	0.91		1.13	0.65		0.48	0.012
	9.60	1.50	1.48		1.70	0.47		0.75	0.019
2.0 x 2.0	1.5	0.07	0.25	2-1-1/2	0.27	1.06	0.073	0.08	0.002
	6.4	0.40	0.35		1.10	2.70		0.20	0.014
	9.0	0.70	0.65		1.60	1.52		0.35	0.025
	14.0	1.27	1.04		2.50	1.16		0.64	0.047

* Model culvert sizes of 0.5, 1.0, and 2.0 ft correspond to prototype sizes of 2, 4, and 8 ft, respectively.
** Measured from invert of culvert.
† Rocks are capable of passing and being retained by the respective sieve sizes indicated.

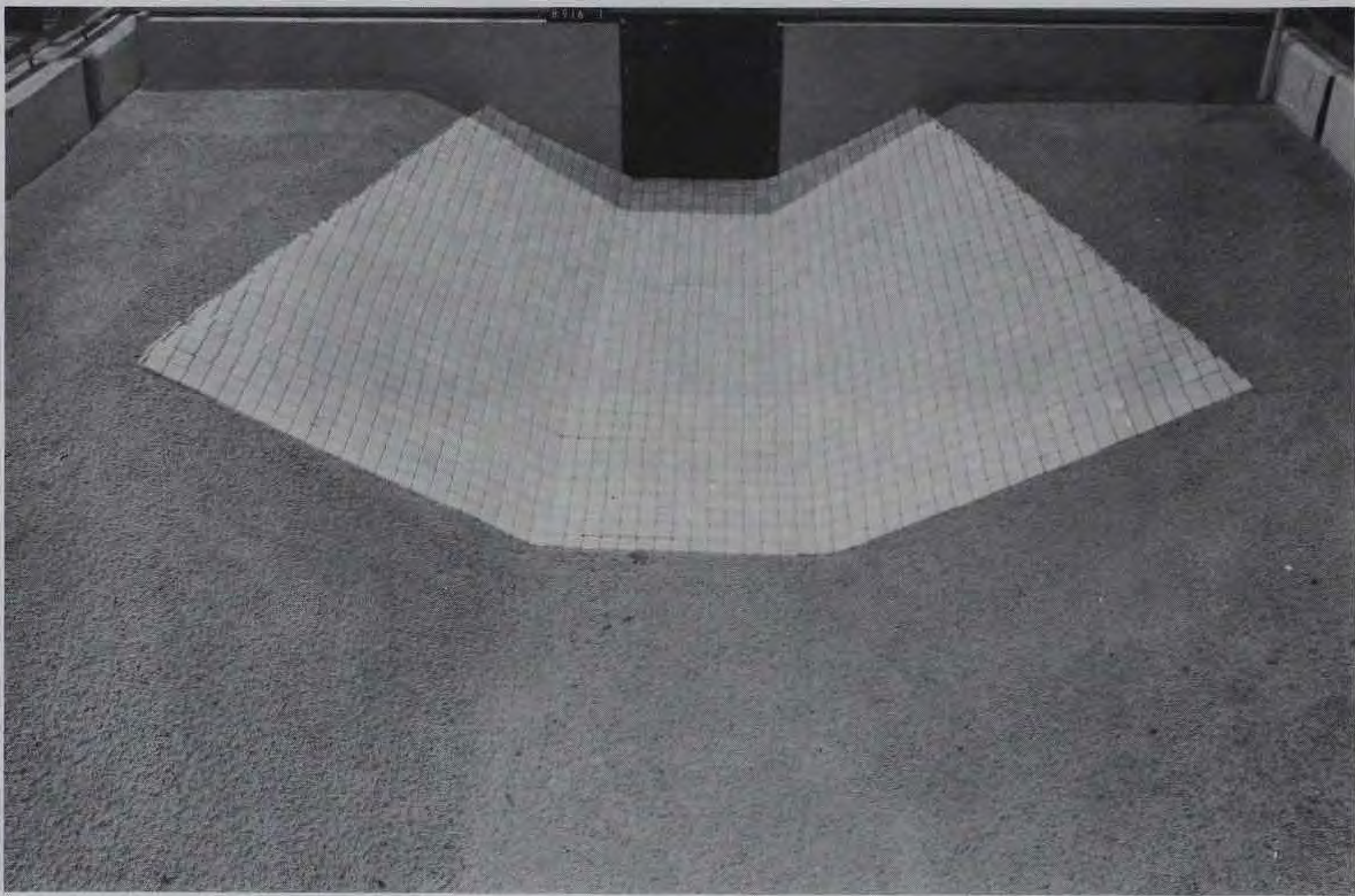


0.5-ft (4 ft prototype) culvert



1-ft (8 ft prototype) culvert

Photo 1. Sack revetment channel expansions
(sheet 1 of 2)



2-ft (16 ft prototype) culvert

Photo 1 (sheet 2 of 2)

During flow

After 20 min

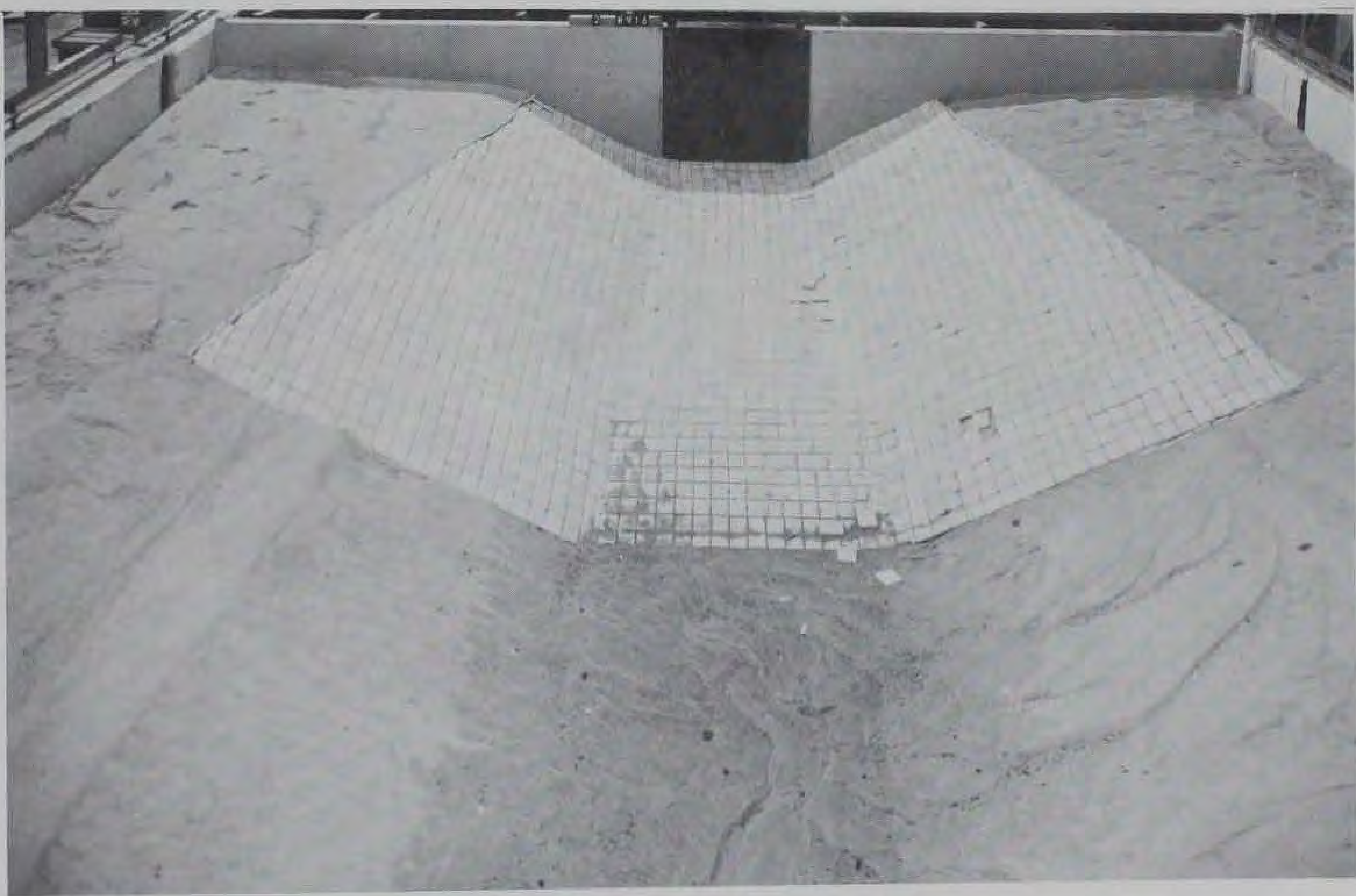
Photo 2. Simulated sack revetment channel expansion for 4-ft (prototype) culvert; discharge 118 cfs and TW 3.0 ft

During flow

After 20 min

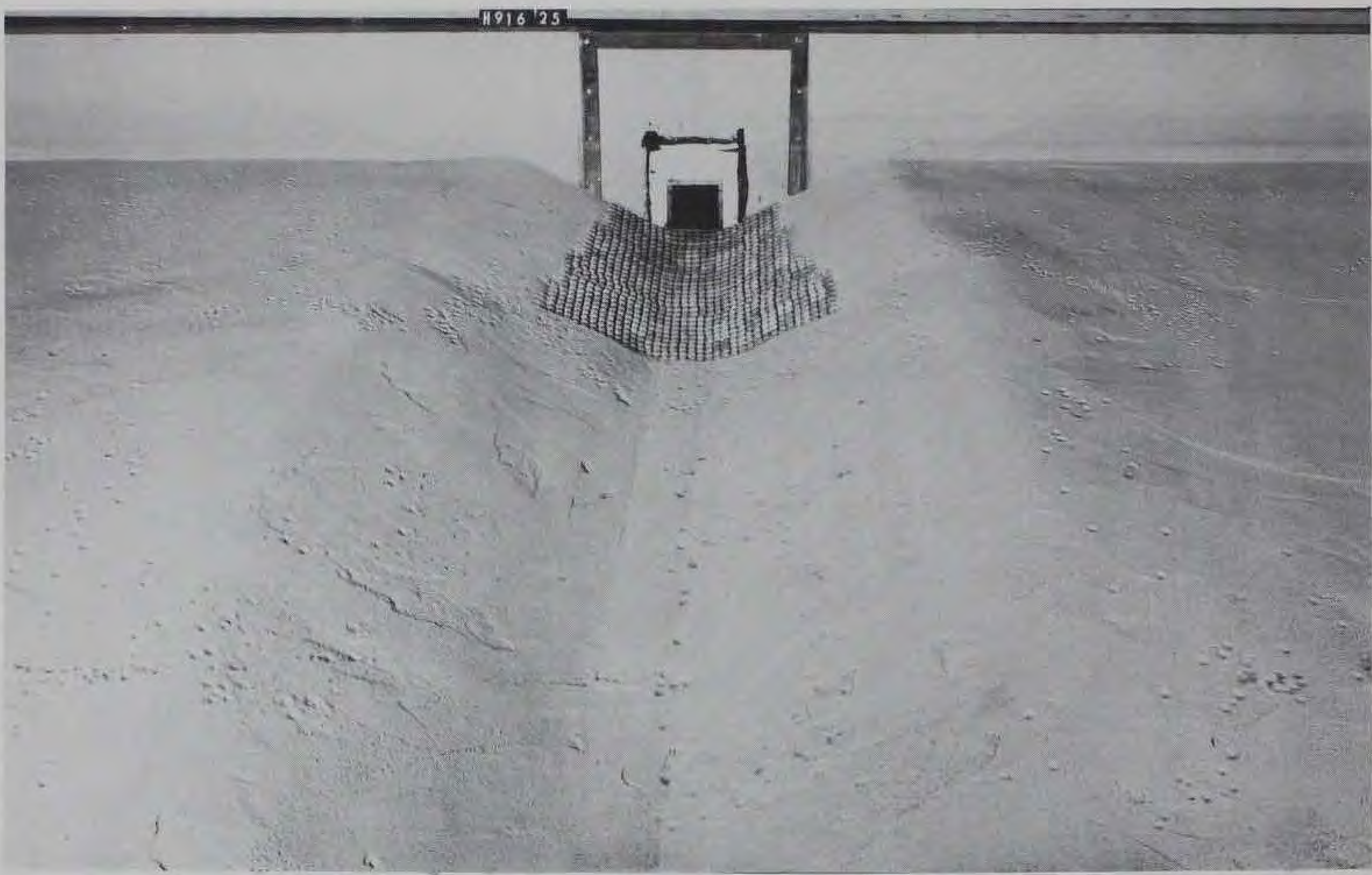
Photo 3. Simulated sack revetment channel expansion for 8-ft (prototype) culvert; discharge 543 cfs and TW 6.0 ft

During flow



After 10 min

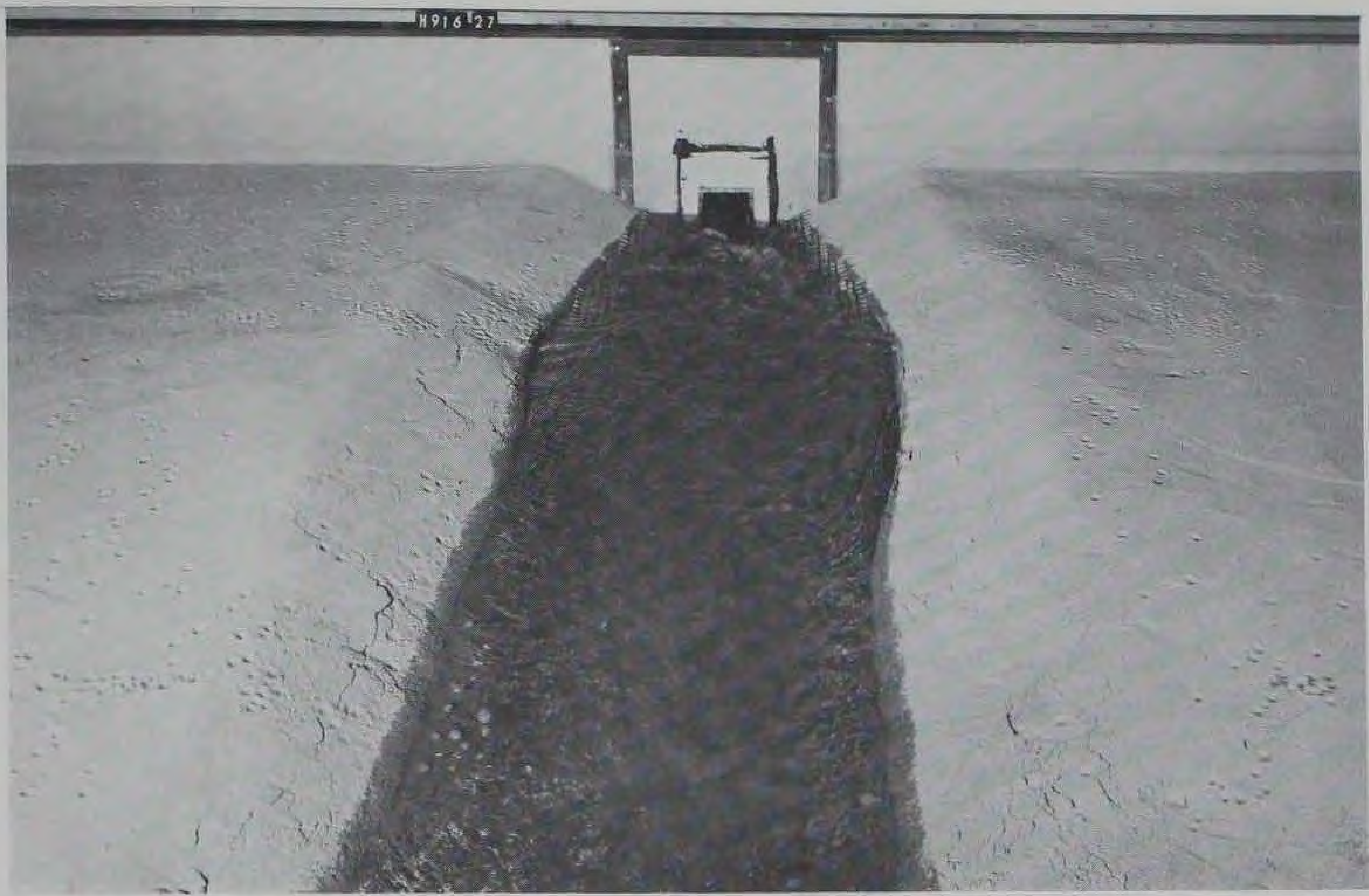
Photo 4. Simulated sack revetment channel expansion for 16-ft (prototype) culvert; discharge 634 cfs and TW 3.60 ft



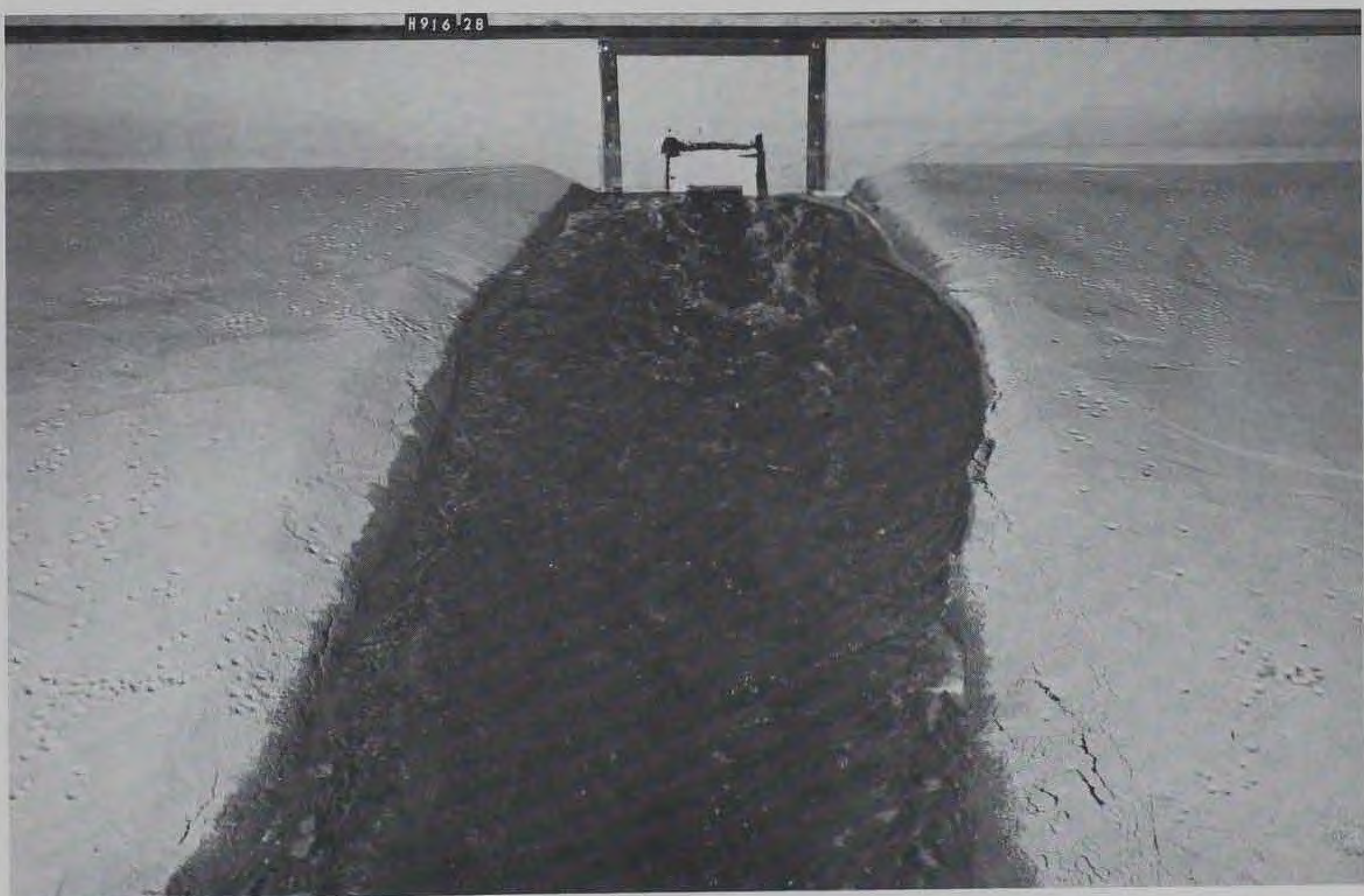
Prior to flow

Q = 13 cfs, d = 1 ft, TW = 0 ft

Photo 5. Simulated cellular block channel expansion before, during, and after various flow conditions through 2-ft culvert (sheet 1 of 3)

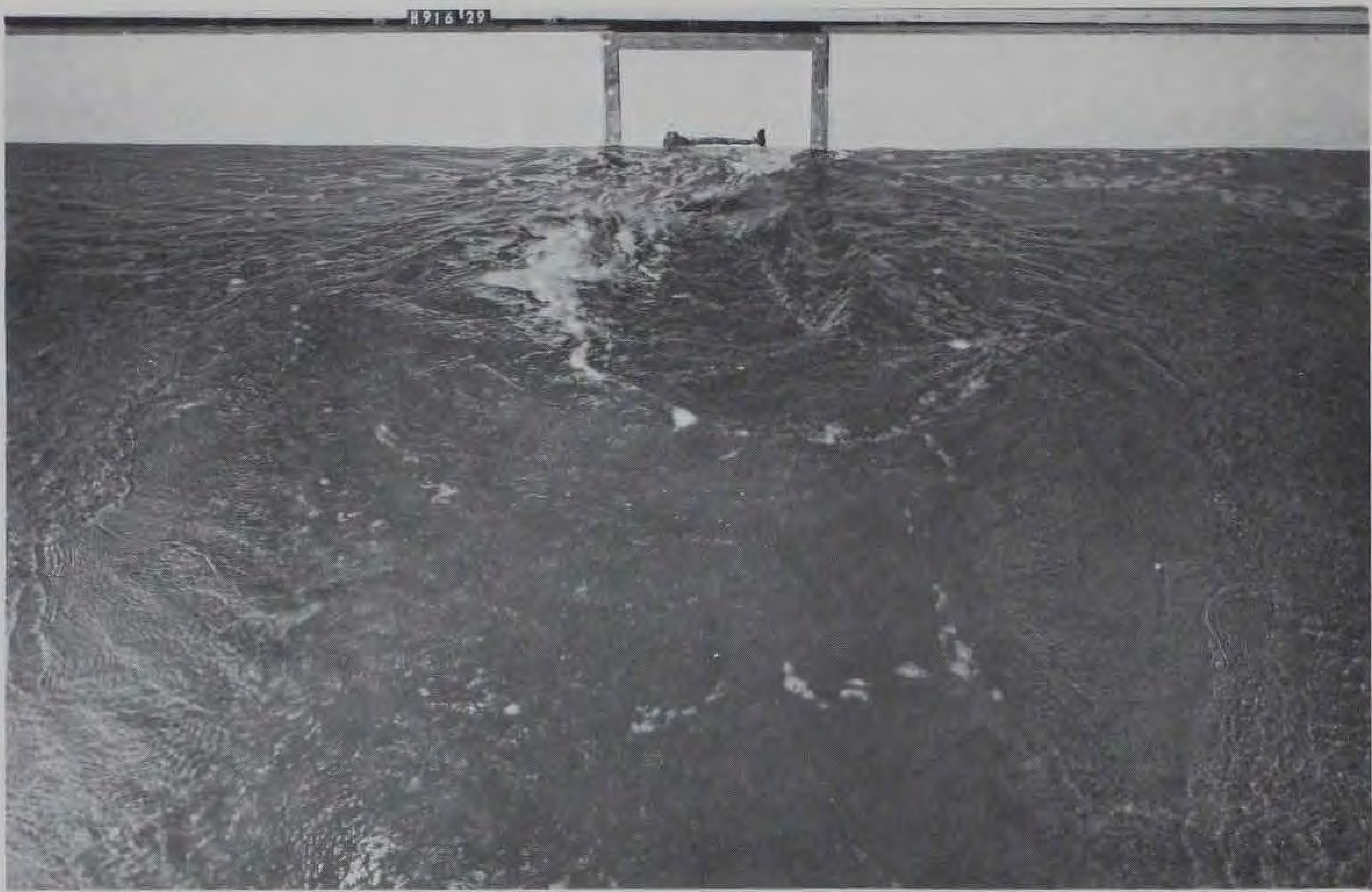


Q = 23 cfs, d = 1 ft, TW = 0.8 ft

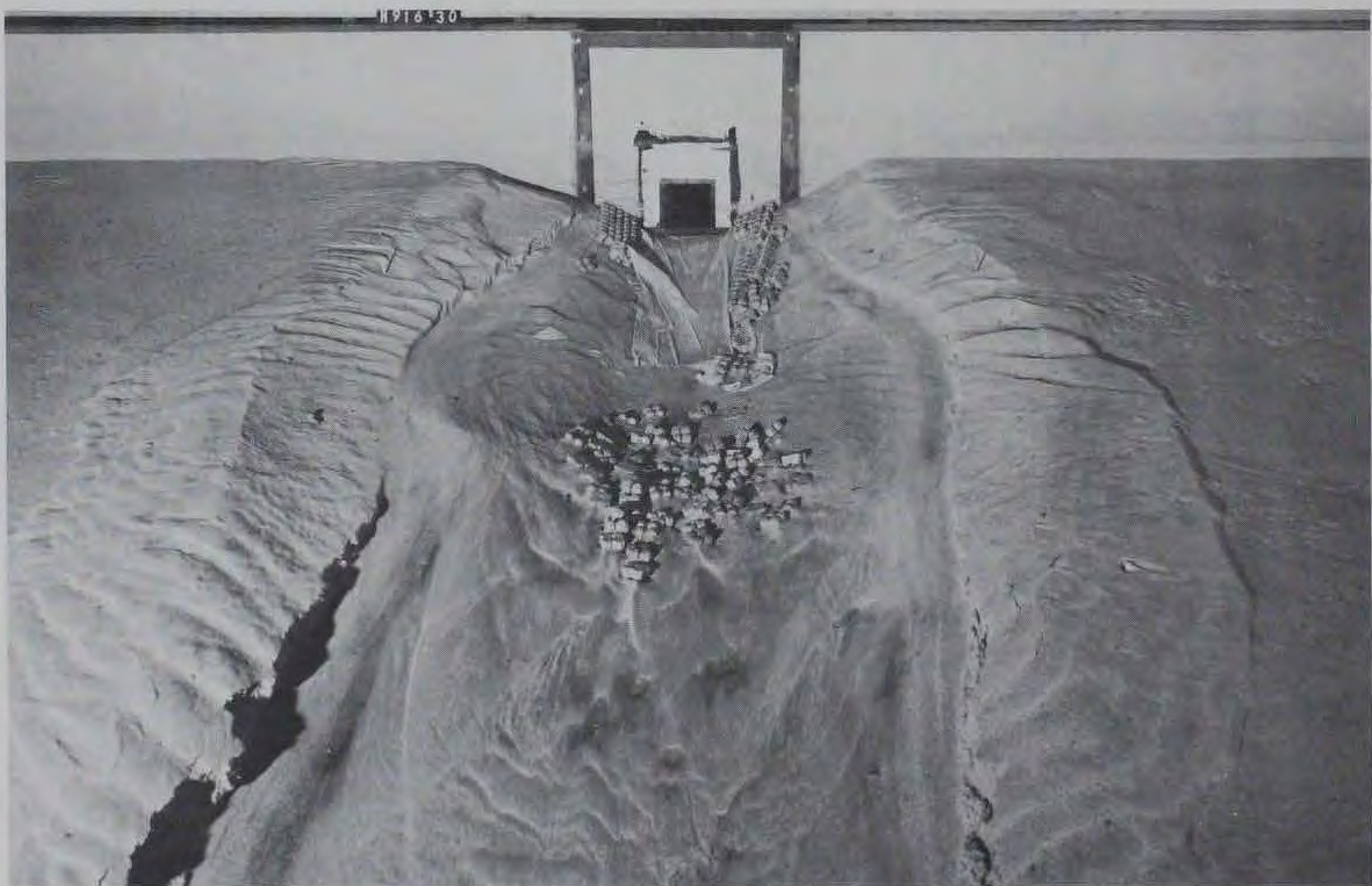


Q = 45 cfs, d = 2 ft, TW = 2 ft

Photo 5 (sheet 2 of 3)

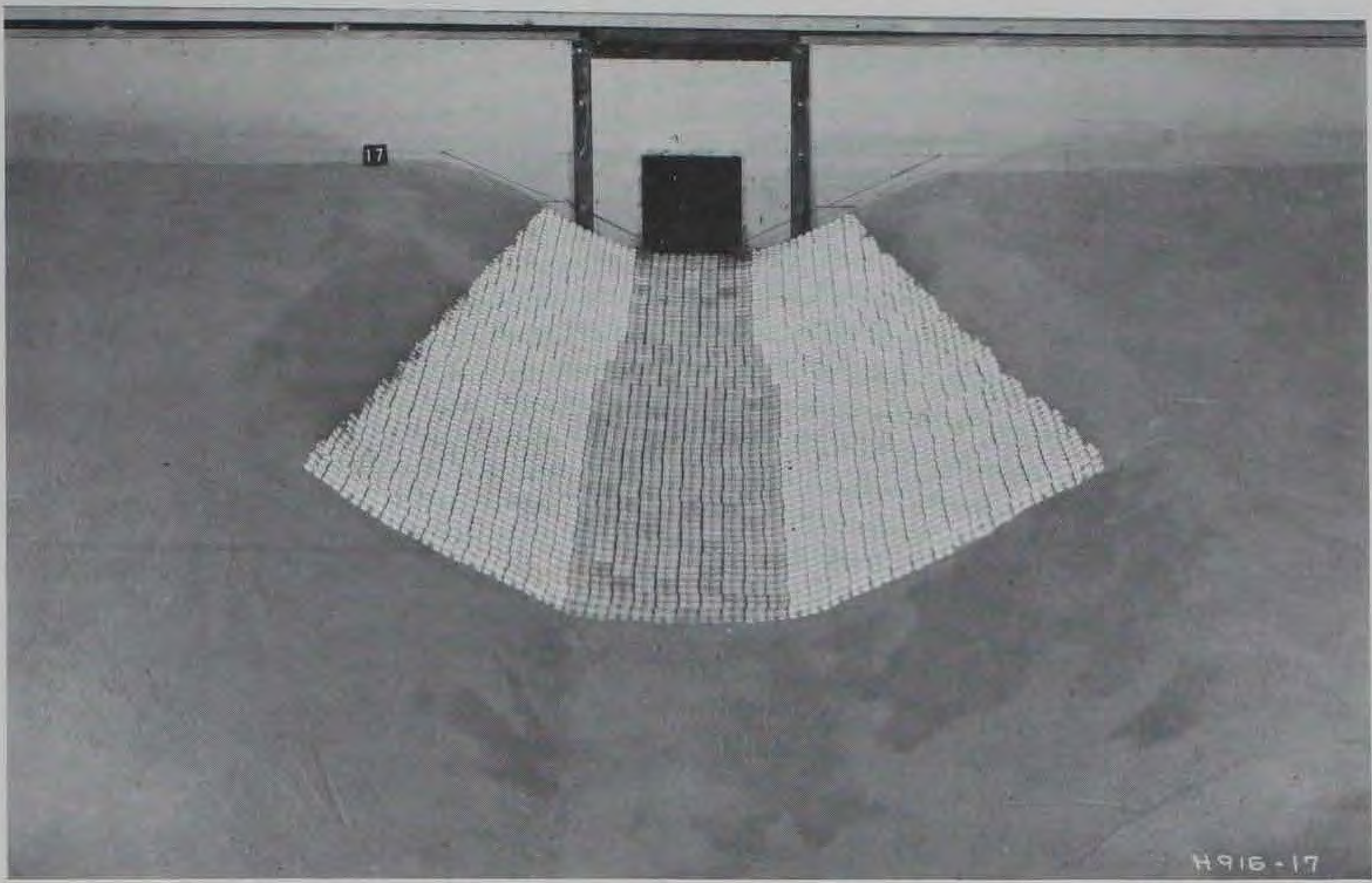


Q = 60 cfs, d = 2 ft, TW = 4 ft

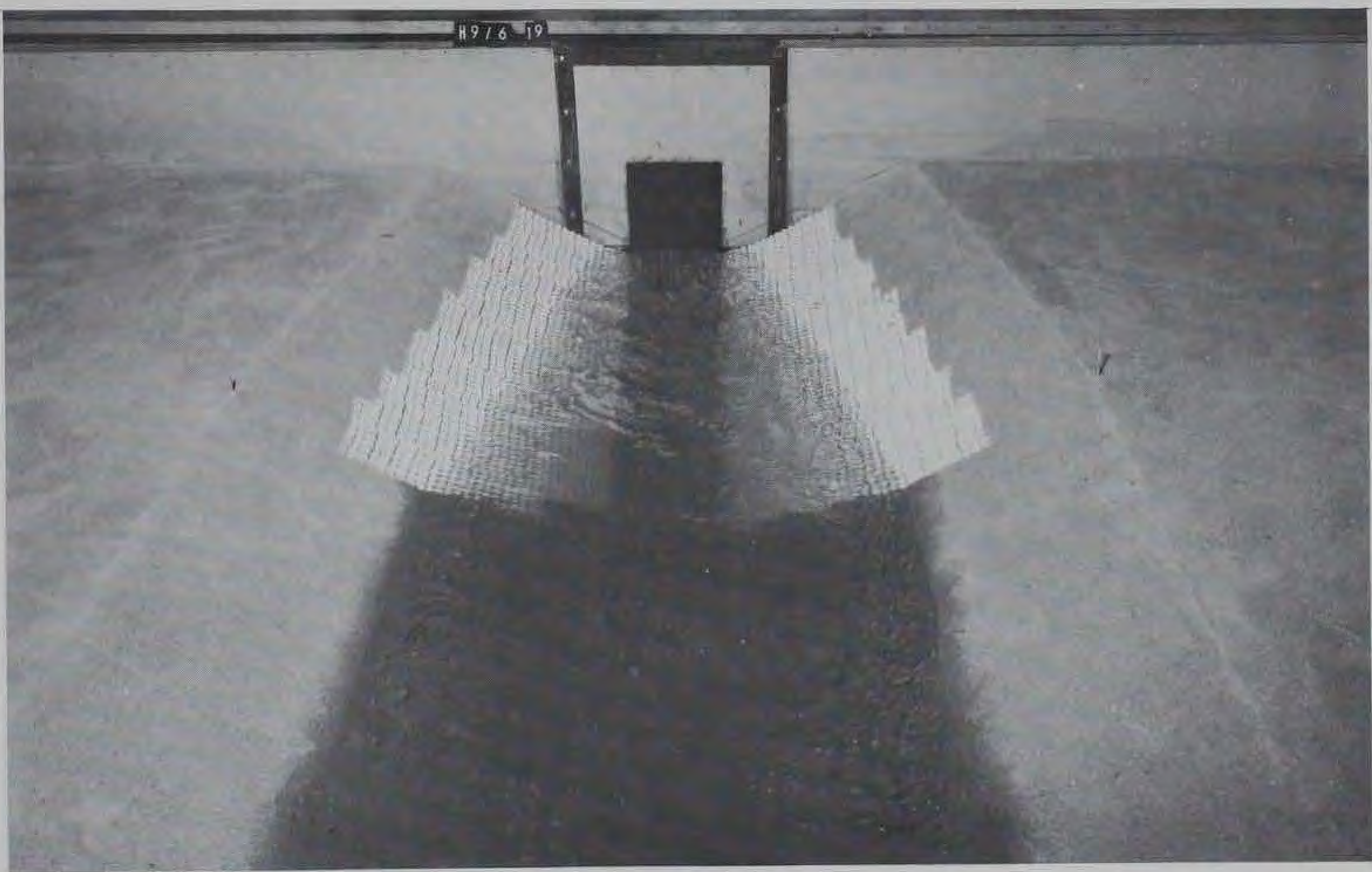


Q = 65 cfs, d = 2 ft, TW = 2 ft, t = 30 min

Photo 5 (sheet 3 of 3)



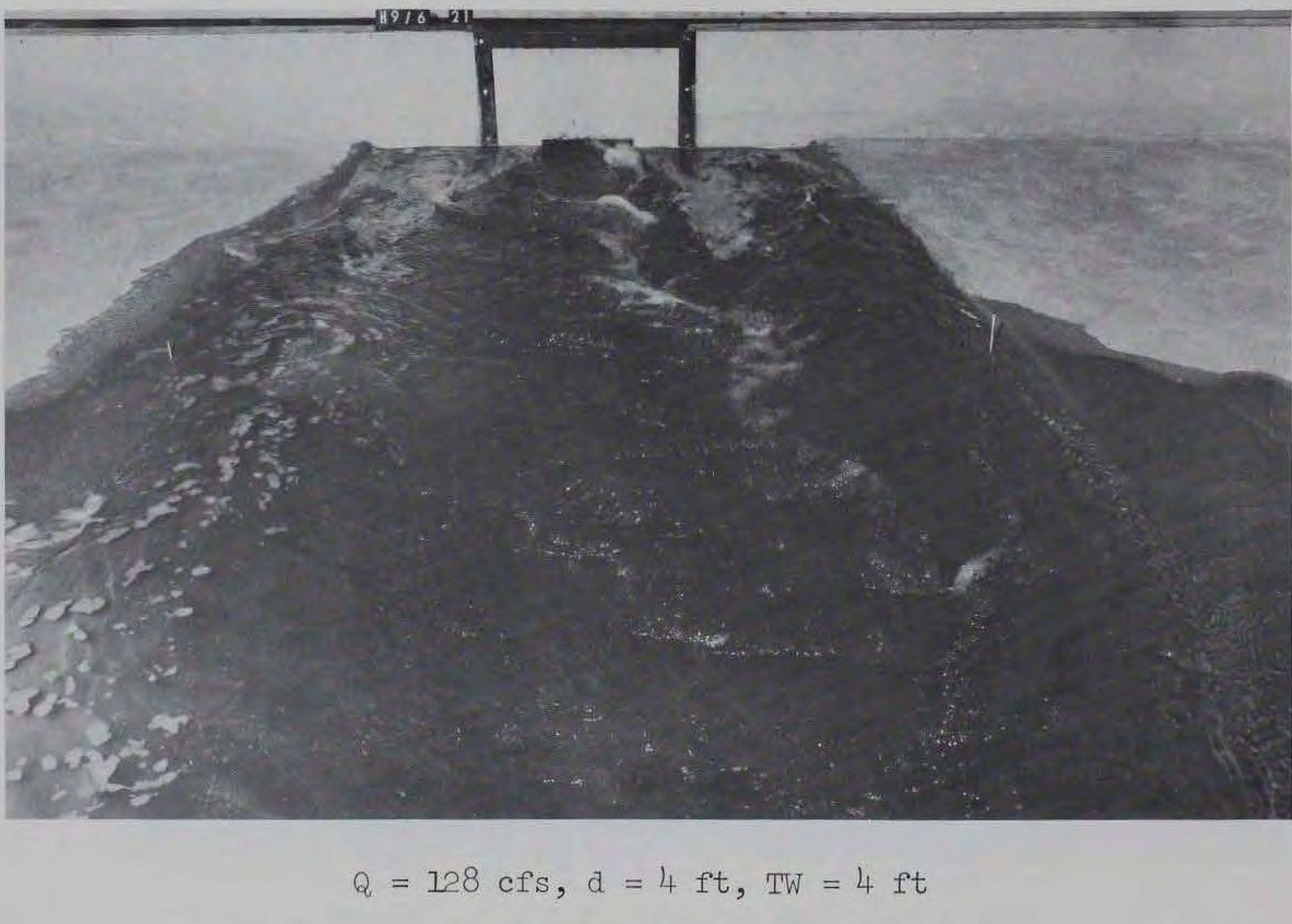
Prior to flow



Q = 26 cfs, d = 0.5 ft, TW = 0.5 ft

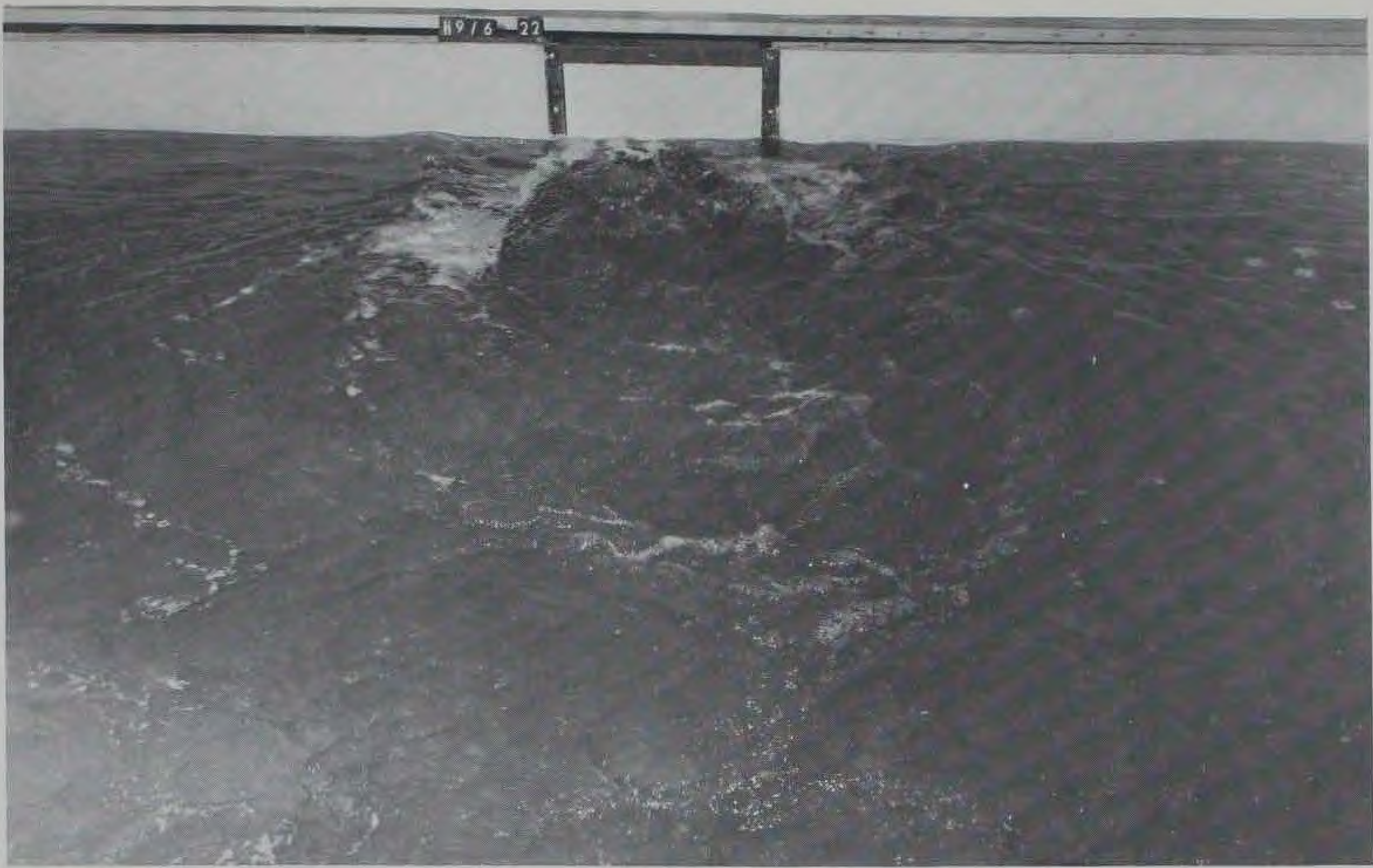
Photo 6. Simulated cellular block channel expansion before, during, and after various flow conditions through 4-ft culvert (sheet 1 of 3)

Q = 70 cfs, d = 1.8 ft, TW = 1.8 ft



Q = 128 cfs, d = 4 ft, TW = 4 ft

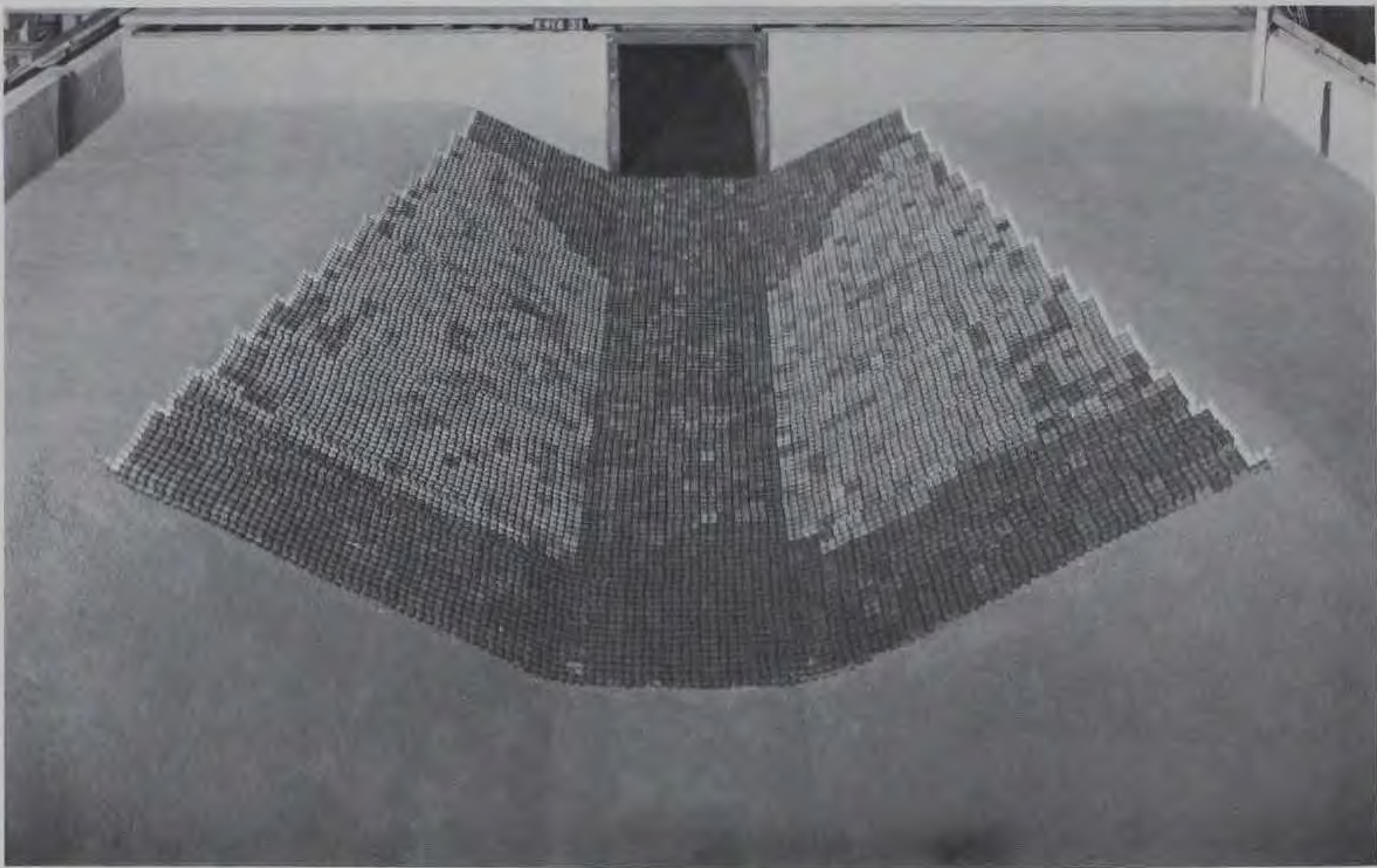
Photo 6 (sheet 2 of 3)



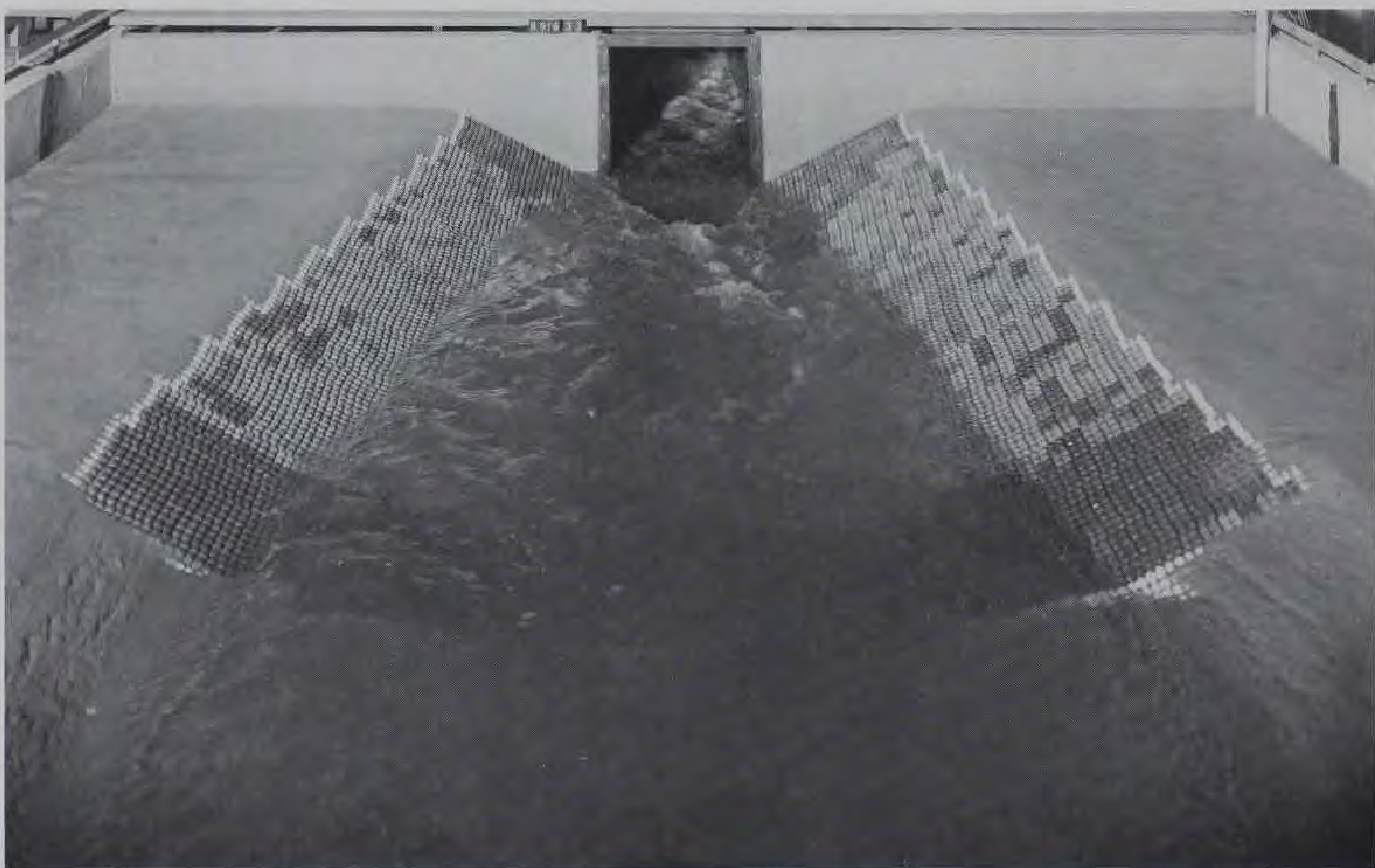
Q = 150 cfs, d = 4 ft, TW = 5.6 ft

Q = 80 cfs, d = 1.8 ft, TW = 1.6 ft, t = 30 min

Photo 6 (sheet 3 of 3)

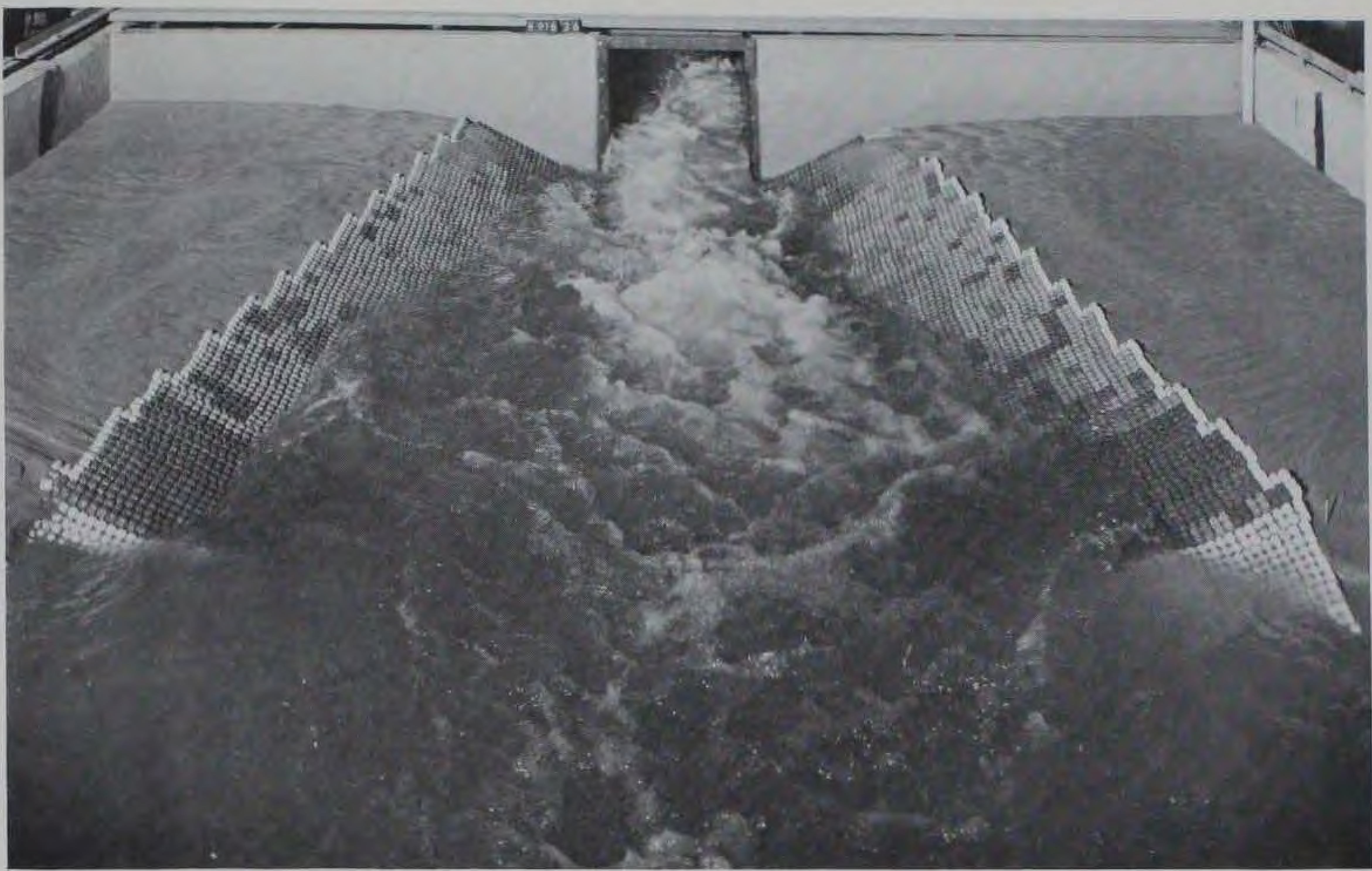


Prior to flow

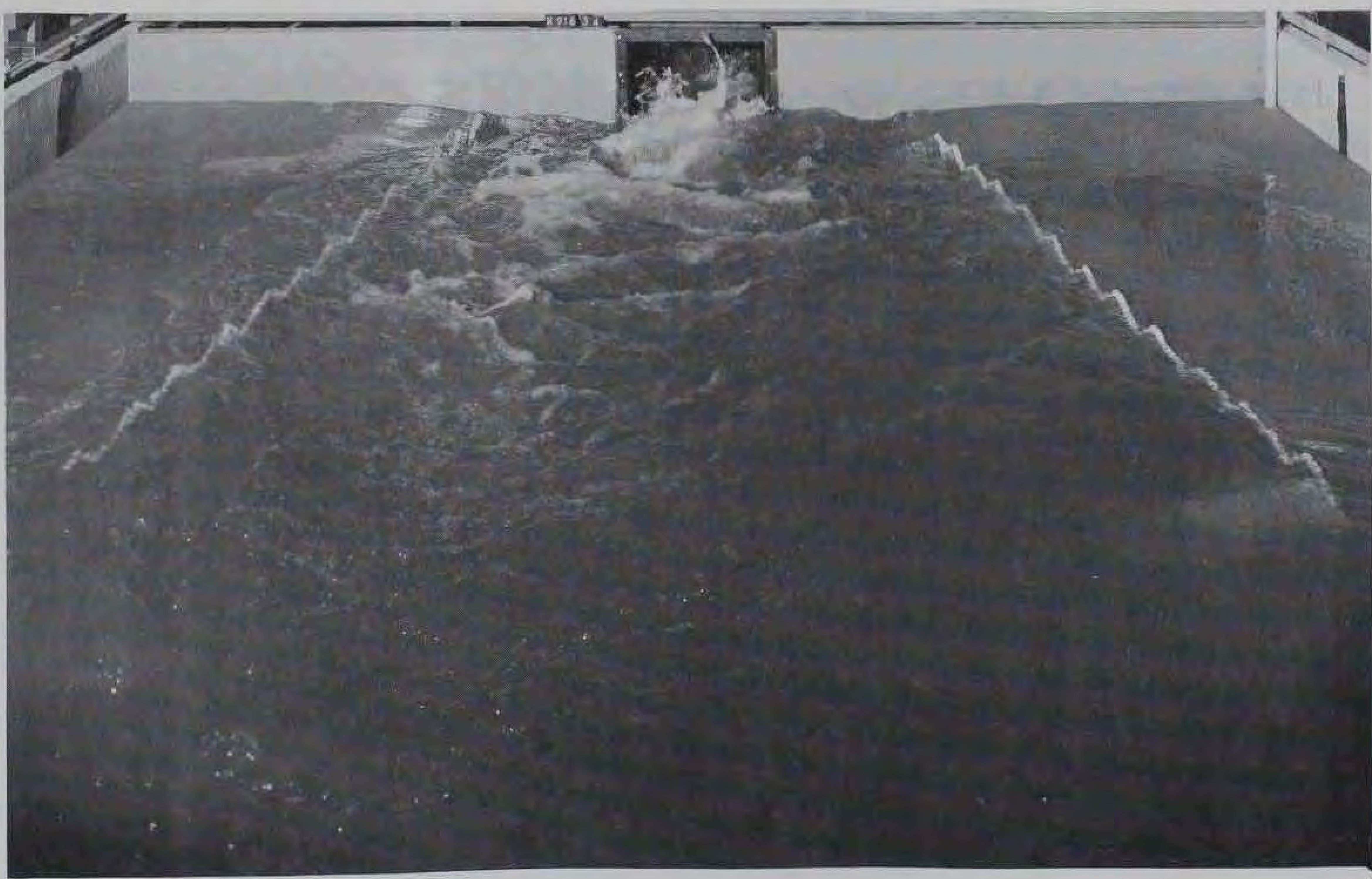


Q = 72 cfs, d = 0.8 ft, TW = 0.6 ft

Photo 7. Simulated cellular block channel expansion before, during, and after various flow conditions through 8-ft culvert (sheet 1 of 3)



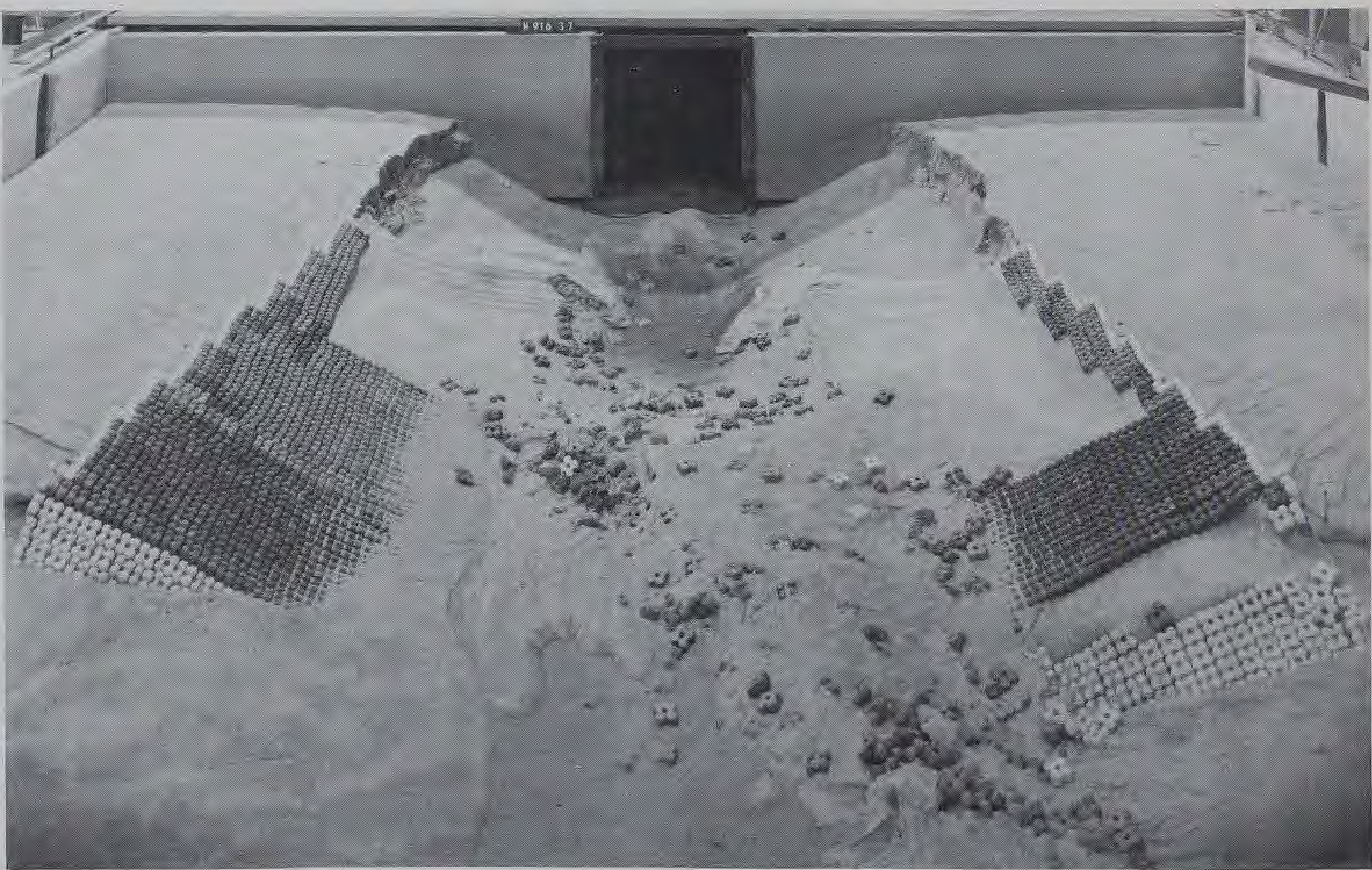
Q = 165 cfs, d = 1.6 ft, TW = 1.3 ft



Q = 256 cfs, d = 2.8 ft, TW = 4 ft

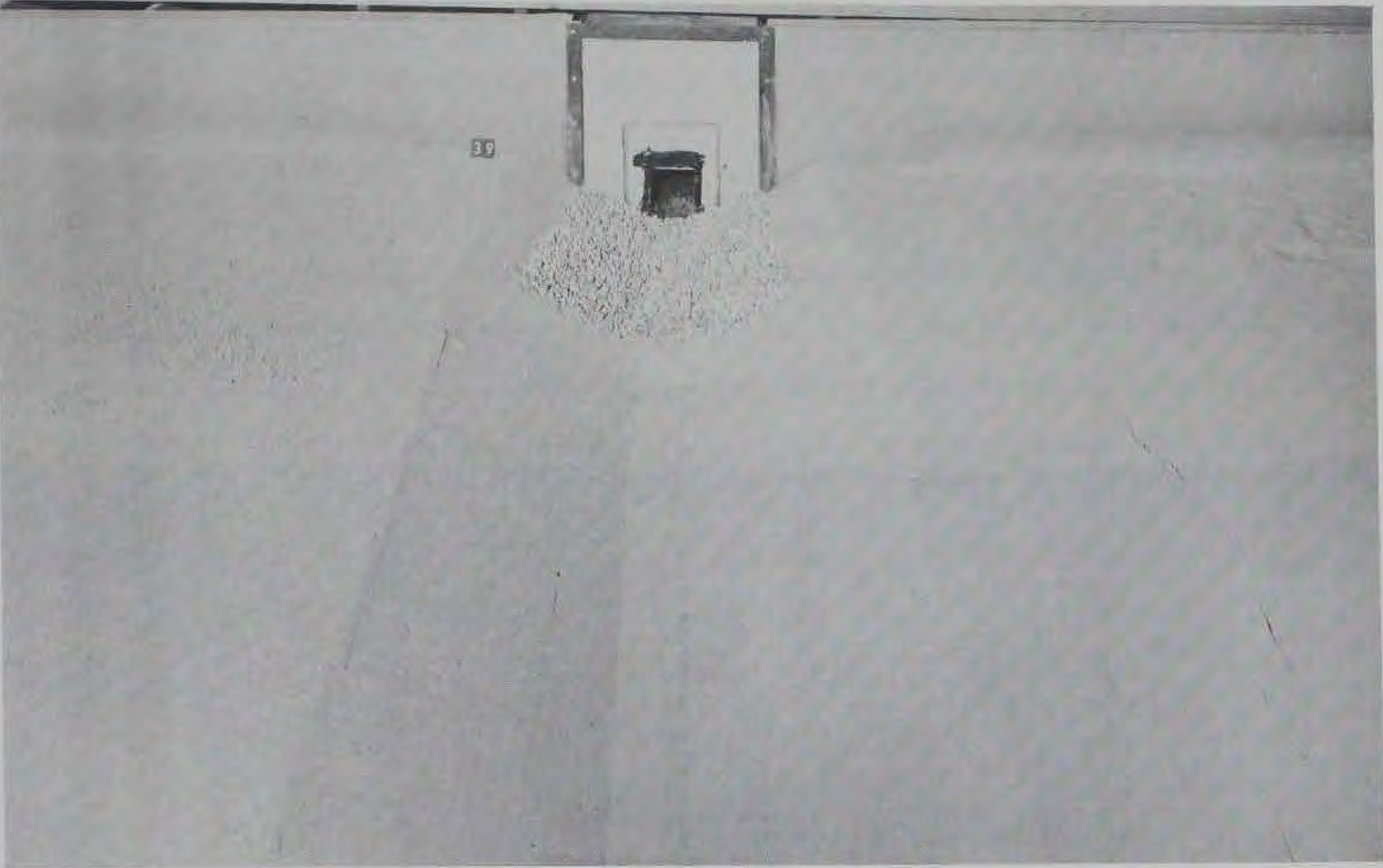
Photo 7 (sheet 2 of 3)

Q = 300 cfs, d = 6 ft, TW = 6 ft



Q = 165 cfs, d = 1.6 ft, TW = 1.3 ft, t = 30 min

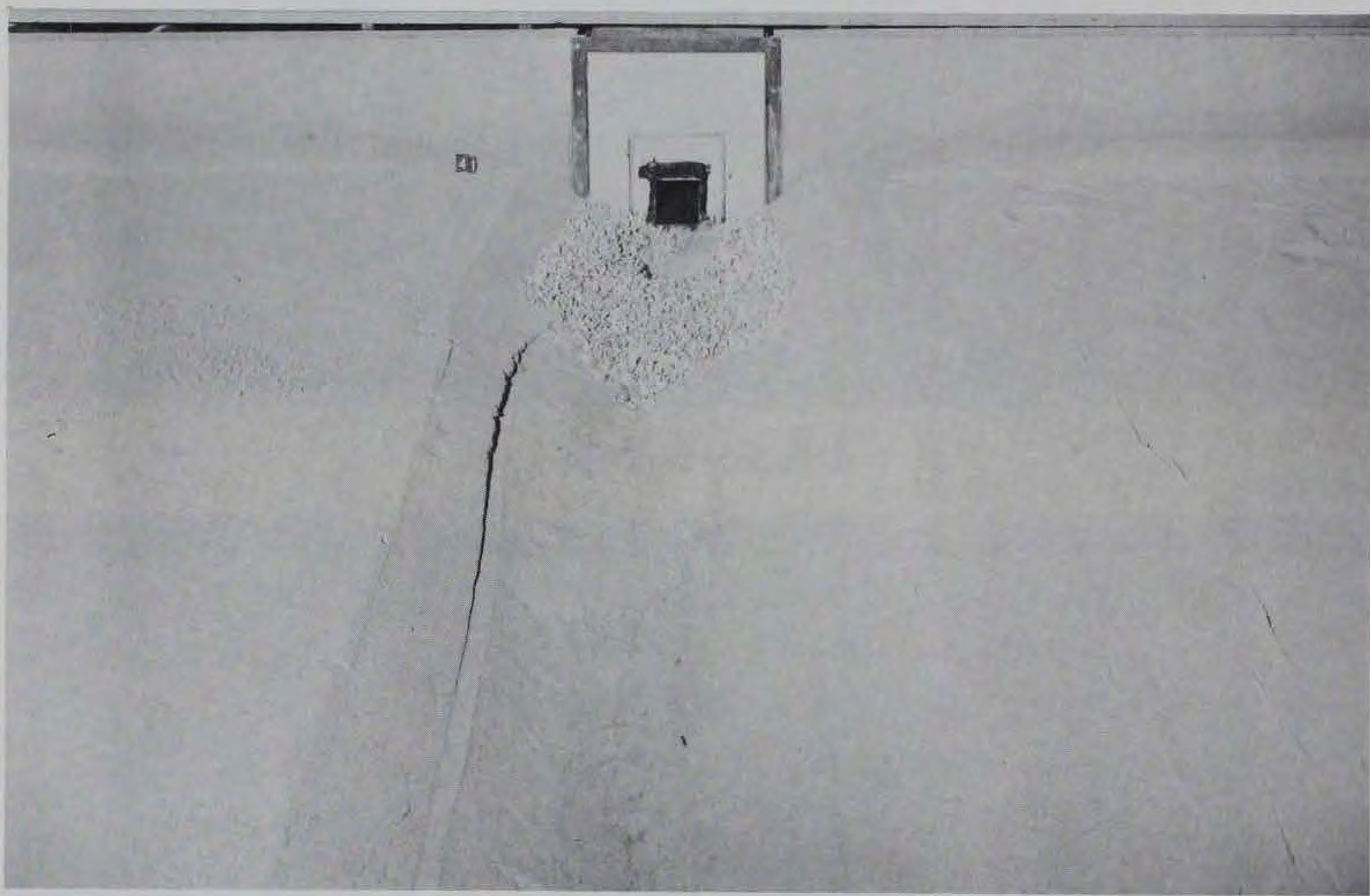
Photo 7 (sheet 3 of 3)



Prior to flow

$Q = 13$ cfs, $d = 1$ ft, $TW = 0$ ft

Photo 8. Simulated rock riprap ($d_{50} = 2.5$ in.) channel expansion before, during, and after various flow conditions through 2-ft culvert (sheet 1 of 2)



Q = 8.5 cfs, d = 0.4 ft, TW = 0.3 ft, t = 20 min

Photo 8 (sheet 2 of 2)

APPENDIX A: PRACTICAL GUIDANCE FOR ESTIMATING AND CONTROLLING EROSION AT STORM SEWER AND CULVERT OUTLETS

Introduction

1. This appendix summarizes and demonstrates application of the results of research conducted at the U. S. Army Engineer Waterways Experiment Station (WES) during the past decade to develop practical guidance for estimating and controlling erosion downstream of storm sewer and culvert 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 a cutoff wall, 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 outlets, the size and extent of various natural and artificial type revetments, and the appropriate dimensions of 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 storm sewer and culvert outlets.

Scour at Outlets

2. In general, two types of channel instability can develop downstream from storm sewer and culvert outlets, 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 as illustrated in Figure A1.

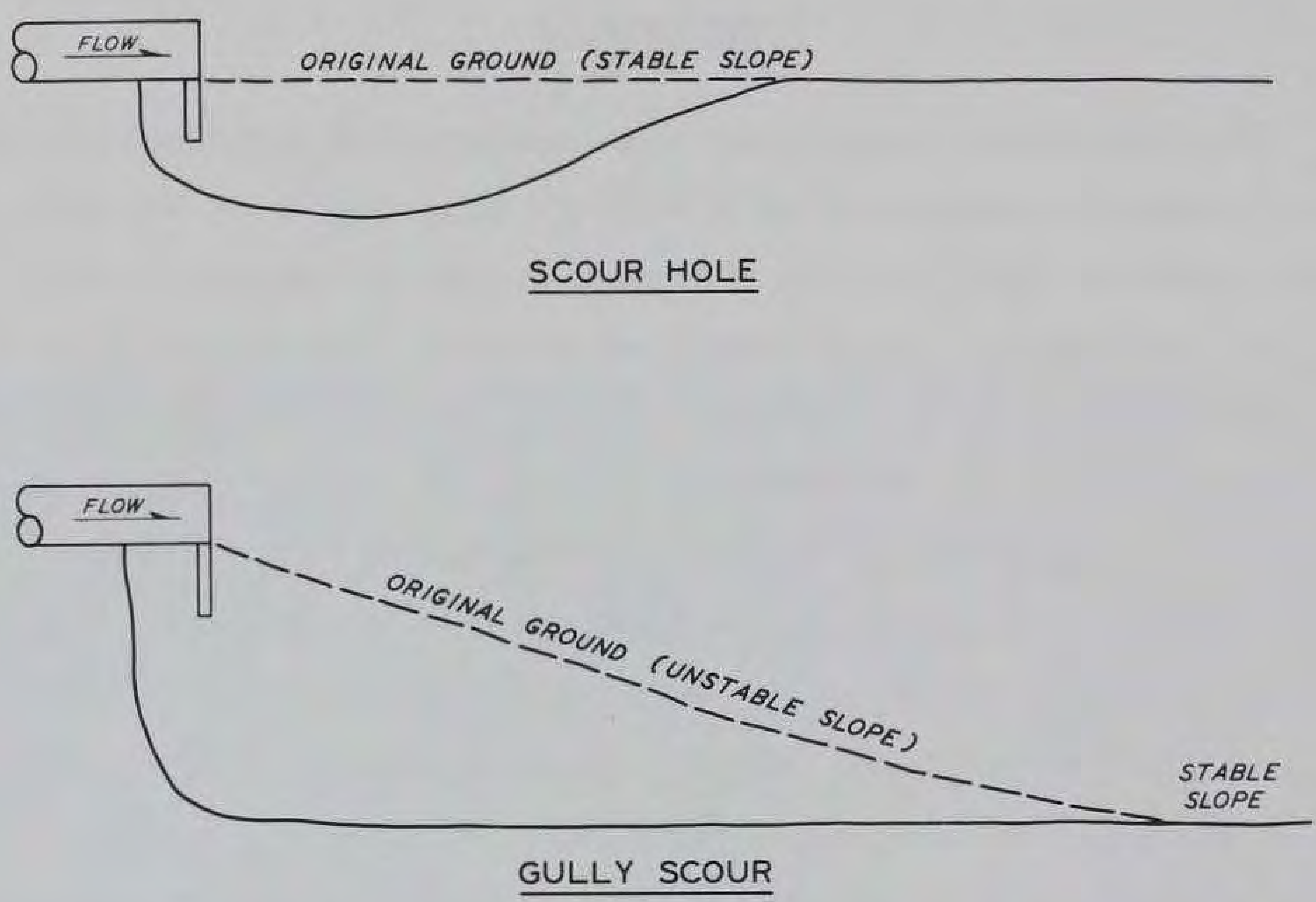


Figure A1. Types of scour at culvert outlets

Figure A2. Failure of outlet structure due to gully scour

3. Gully scour is to be expected when the Froude number of flow in the channel exceeds that required for stability. It begins at a control point downstream where the channel is stable and progresses upstream. If sufficient differential in elevation exists between the outlet and the section of stable channel, the outlet structure will be completely undermined as shown in Figure A2. The primary cause of gully scour is the practice of siting outlets high, with or without energy dissipators, relative to a stable downstream grade in order to reduce quantities of pipe and excavation. Erosion of this type may be of considerable extent depending upon the location of the stable channel section relative to that of the outlet in both the vertical and downstream directions. To prevent gully erosion, outlets and energy dissipators should be located at sites where the slope of the downstream channel or drainage basin is naturally mild enough to remain stable under the anticipated conditions or else it should be controlled by ditch checks, drop structures, and/or other means to a point where a naturally stable slope and cross section exist. Outlets and energy dissipators should not be located within channels or drainage basins experiencing deposition but adjacent to the perimeter and provided with an outlet channel that is skewed rather than perpendicular to the main channel or basin (Figure A3).

4. A scour hole or localized erosion is to be expected downstream of an outlet (Figure A4) even if the downstream channel is stable. The severity of damage to be anticipated depends upon the conditions existing or created at the outlet. In some instances, the extent of the scour hole may be insufficient to produce either instability of the embankment or structural damage to the outlet. However, in many situations flow conditions produce scour of the extent that embankment erosion (Figure 4a) as well as structural damage of the apron, end wall, and culvert (Figure 4b) is evident. Noteworthy surveys of conditions at culvert outlets have been accomplished by Keeley[1*] in Oklahoma and Scheer[2] in Montana.

5. The observations and empirical methods developed by Keeley,[1,3,4]

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* Raised numbers refer to similarly numbered items in the References at the end of the main text.

a. Single stilling well with paved perimeter

b. Multiple stilling wells without perimeter protection

Figure A3. Single and multiple stilling wells with and without perimeter protection

a. Embankment erosion

b. Structural damage of apron, end wall, and culvert

Figure A4. Damage resulting from localized erosion 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 1V-on-2H side slopes in a soil that would deposit and erode with Froude numbers of flow less than 0.15 and greater than 0.35, respectively, is shown in Figure A5.

6. Bohan also reported the results of research conducted at WES to determine the extent of localized scour that may be anticipated downstream of circular storm sewer and culvert outlets. These tests indicated that all of the tailwater conditions investigated could be grouped into two categories. Tailwater conditions of less than 0.5 D_o ft above the culvert invert produced approximately the same flow pattern and scour hole geometry and are termed minimum tailwater conditions; all tailwater conditions of 0.5 D_o ft and greater above the culvert invert produced approximately the same flow pattern and scour hole geometry and are termed maximum tailwater conditions. These results agreed very well with those presented by Seaburn and Laushey[6] which indicate that for a constant discharge the velocity just downstream of a circular culvert outlet remains constant for tailwater conditions from 0 to 0.5 D_o ft above the culvert invert. The velocity increases with increasing tailwater and

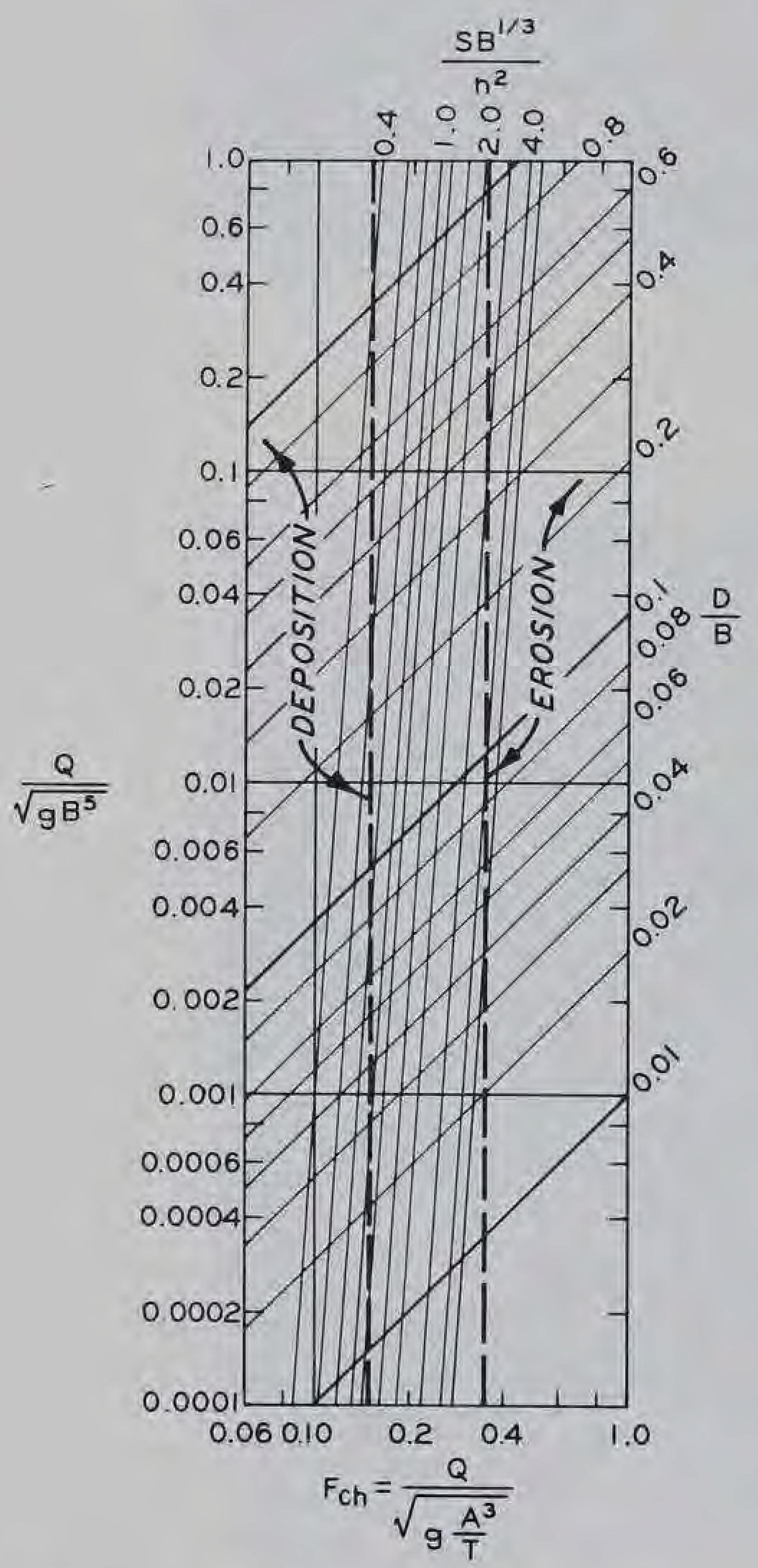


Figure A5. Characteristics of a trapezoidal channel with 1V-on-2H side slopes as a function of Froude number reaches a constant maximum velocity again at a tailwater approximately 1.0 D_o ft above the culvert invert.

7. 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 outlet and a discharge parameter, $Q/D_o^{5/2}$,* for circular and square outlets or $q/D_o^{3/2}$ for rectangular and other shaped outlets can be calculated; and the discharge parameter is just as representative of flow conditions as is the Froude number. The relations between the two parameters for both partial and full pipe uniform flow in square culverts are shown in Figure A6. 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 relations shown in Figures A7-A10 for estimating the extent of localized

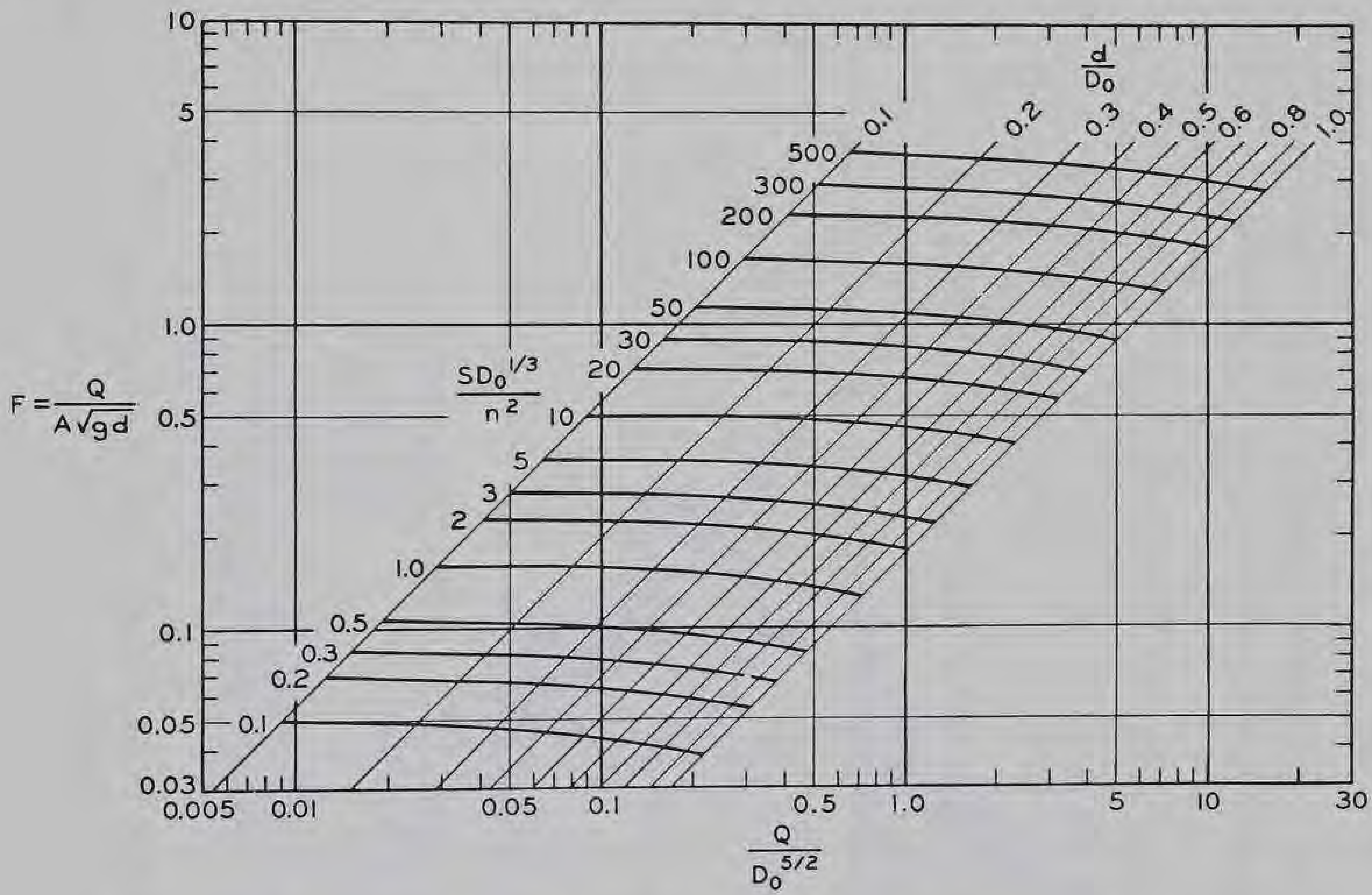


Figure A6. Square culvert - Froude number versus discharge

* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix B).

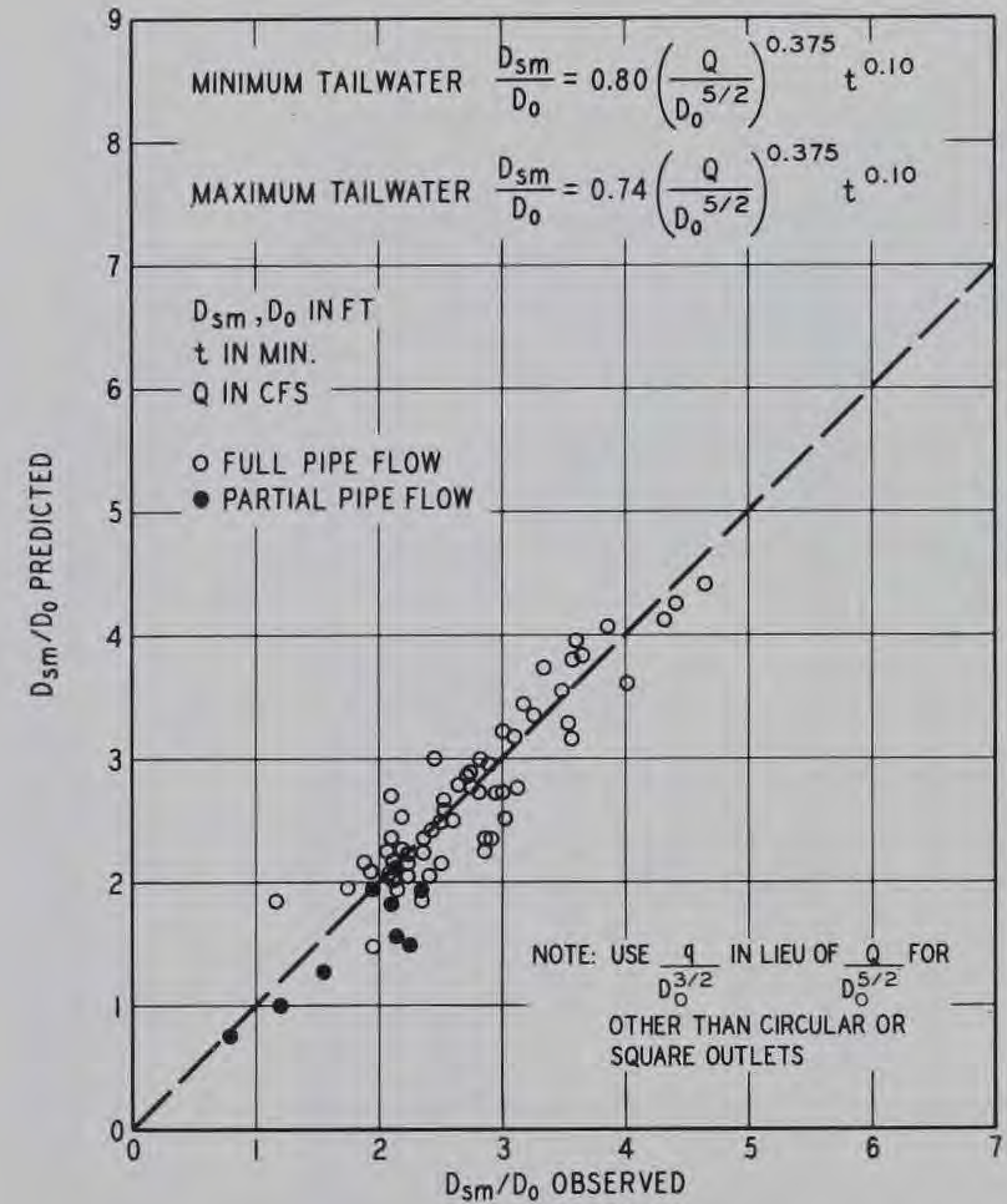


Figure A7. Predicted scour depth versus observed scour depth

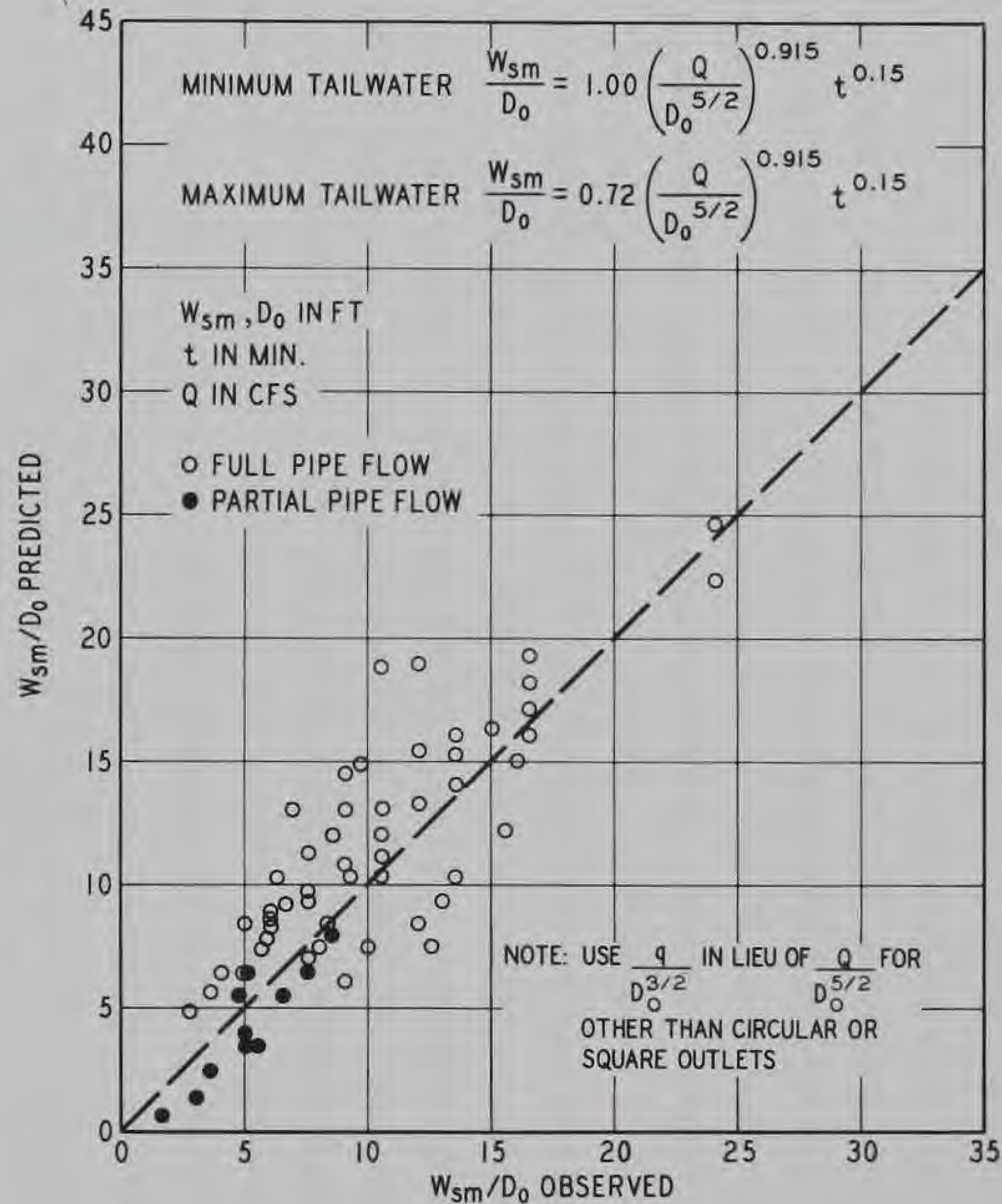


Figure A8. Predicted scour width versus observed scour width

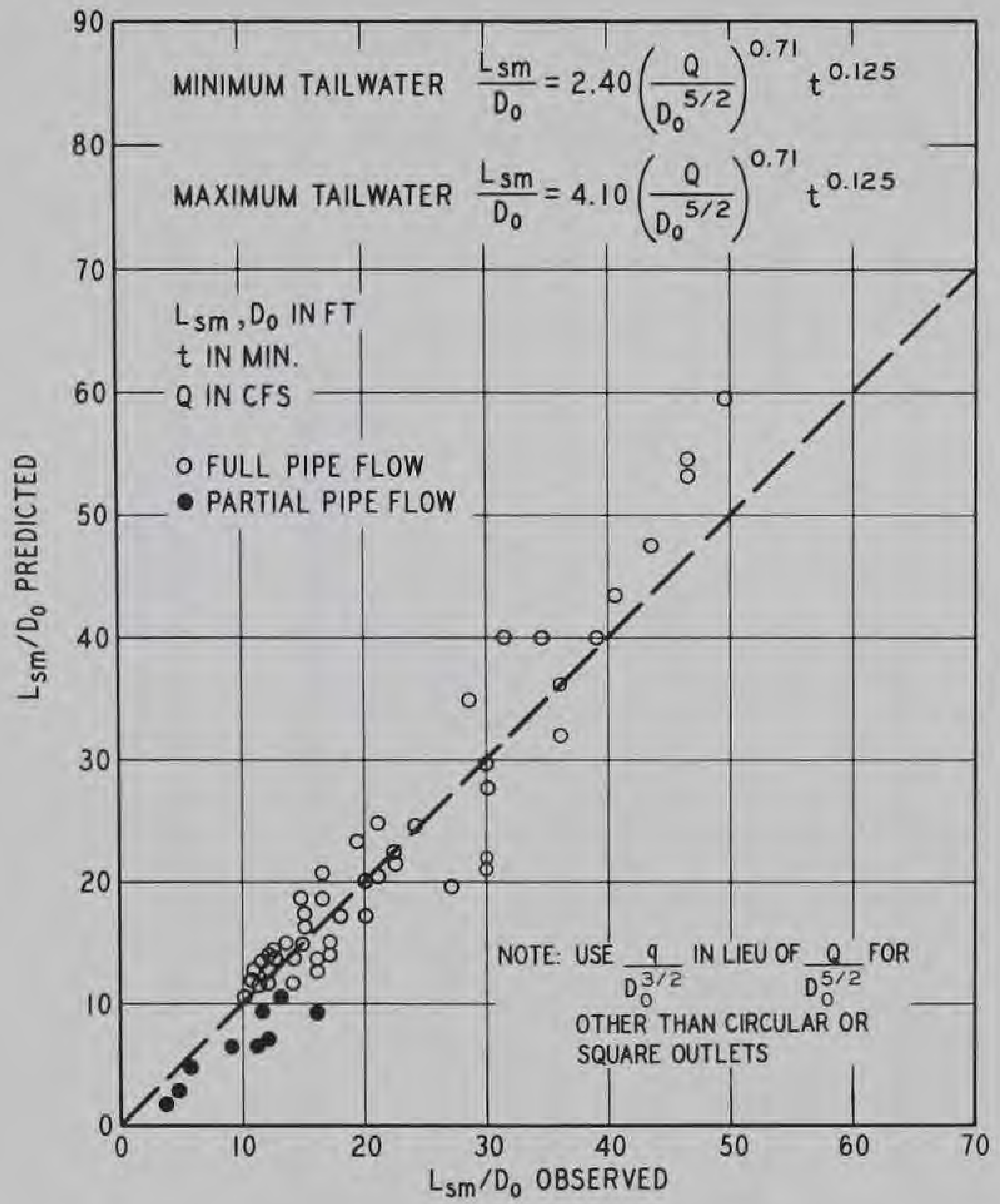


Figure A9. Predicted scour length versus observed scour length

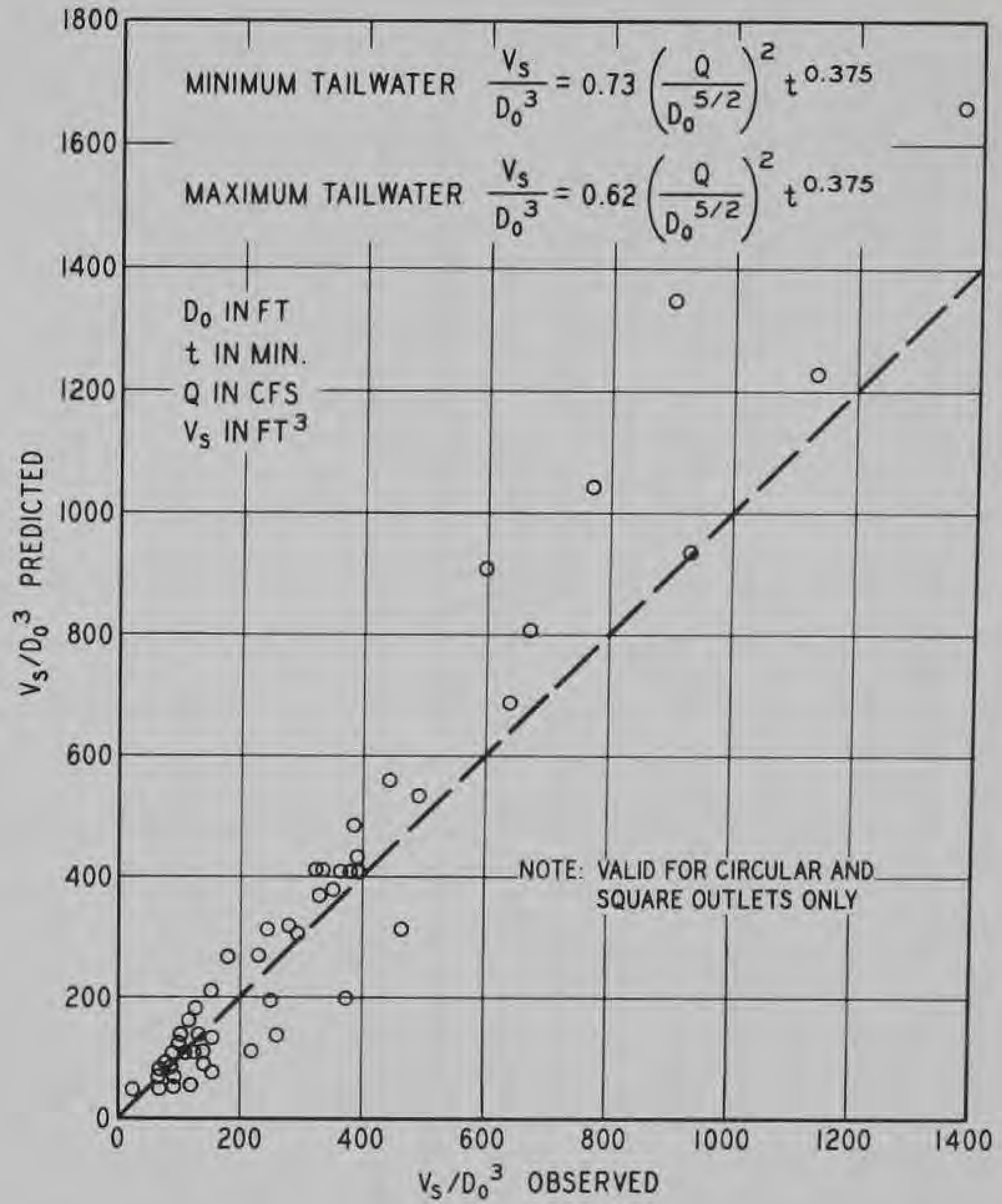


Figure A10. Predicted scour volume versus observed scour volume scour to be anticipated downstream of circular culvert and storm sewer outlets. The variables are defined in Appendix B, and comparisons of predicted and observed values are shown in Figures A7-A10.

8. Dimensionless scour hole geometries determined from model tests with 0.224-ft-, 0.33-ft-, and 1.00-ft-diam circular culverts, a sand with an average grain size of 0.25 mm, and tailwaters less than 0.5 D_o ft as well as equal to or greater than 0.5 D_o ft are presented in Figures A11 and A12, 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.

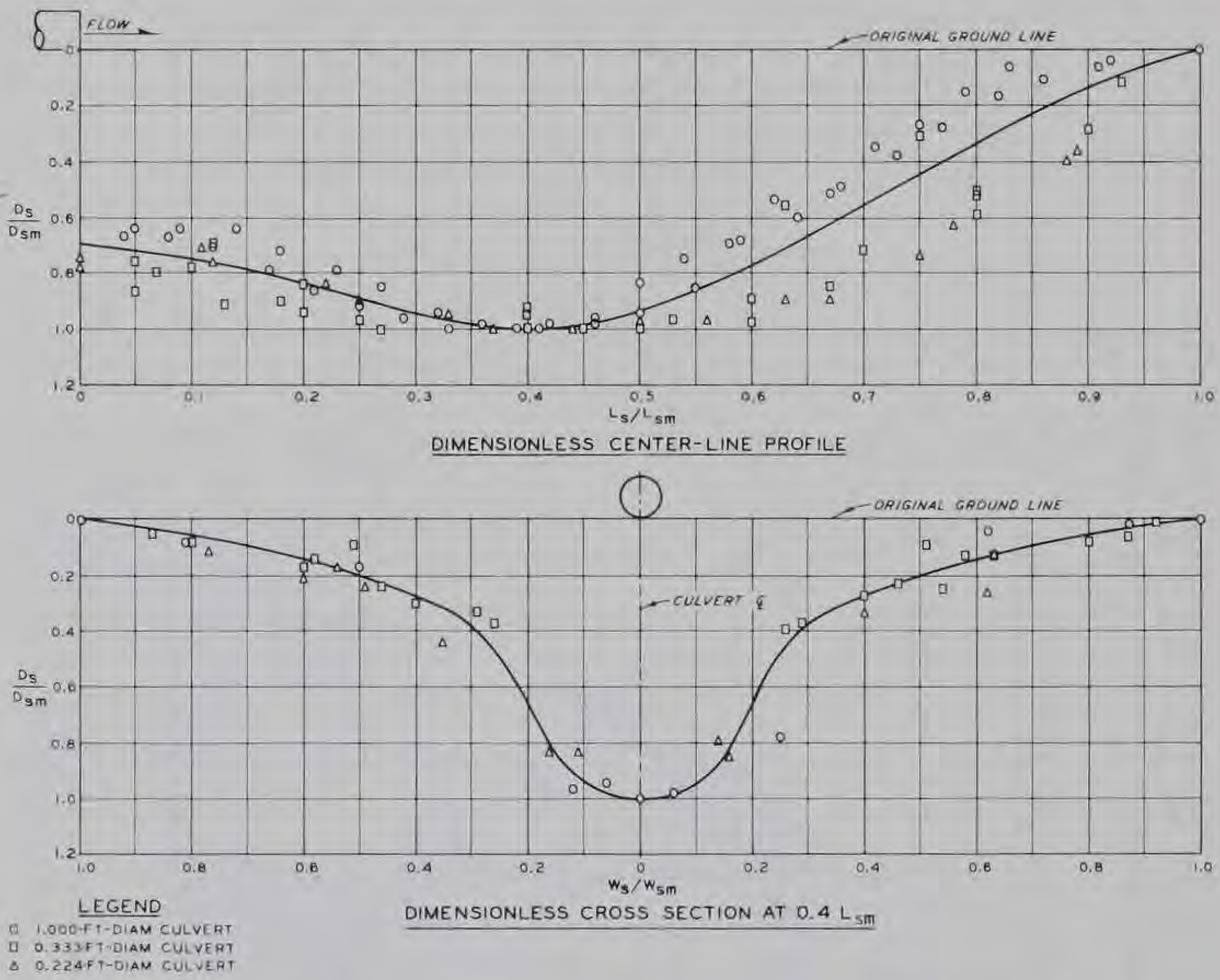


Figure A11. Dimensionless scour hole geometry for minimum tailwater

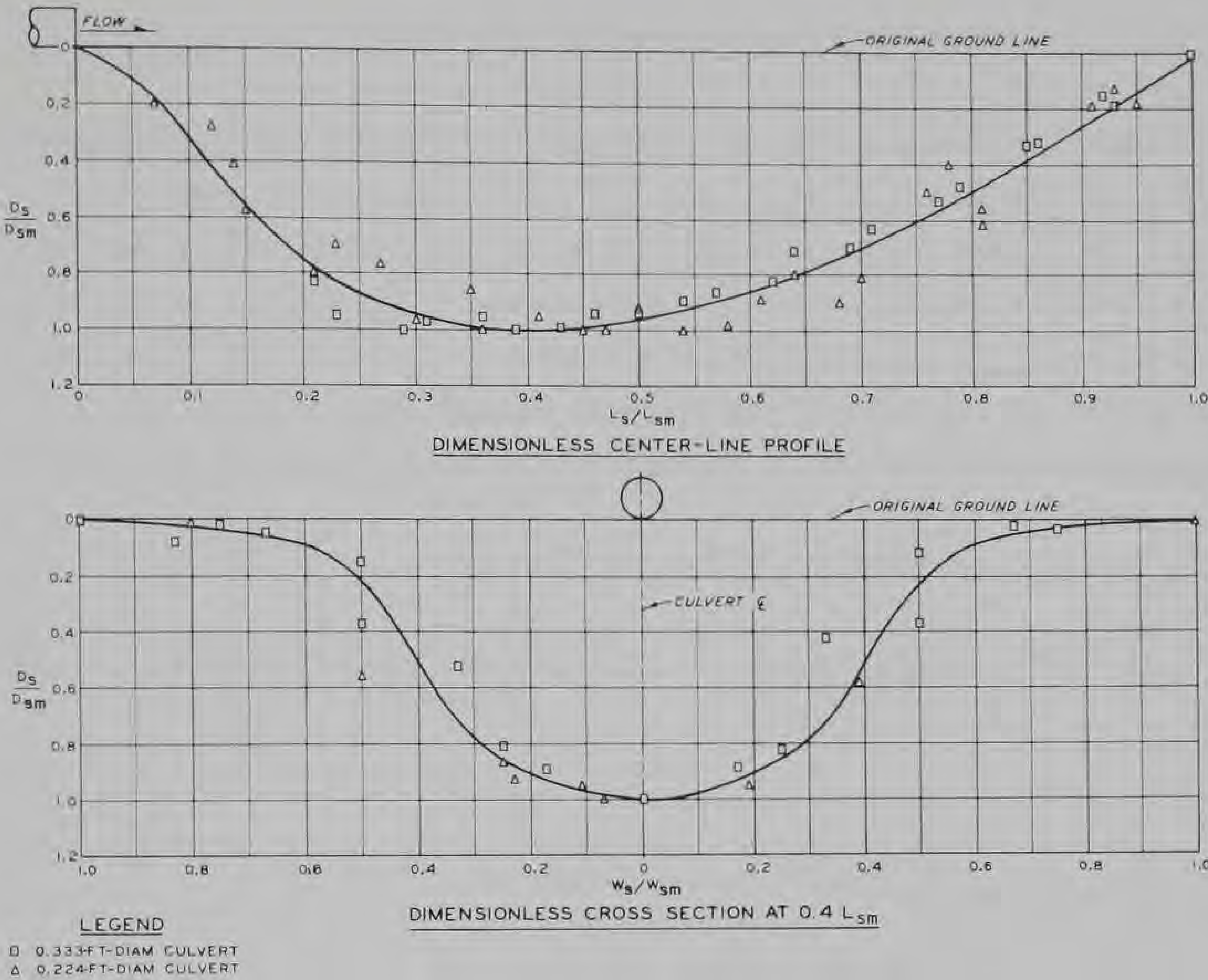


Figure A12. Dimensionless scour hole geometry for maximum tailwater

Cutoff Wall

9. 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 (Figure A11) and of appropriate width should be provided to prevent undermining.

Horizontal Blanket of Riprap

10. 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 dimensions, 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 relations:

$$\frac{d_{50}}{D_o} = 0.020 \frac{D_o}{TW} \left(\frac{Q}{D_o^{5/2}} \right)^{4/3} \quad \text{Circular and square outlets} \quad \text{(A1)}$$

$$\frac{d_{50}}{D_o} = 0.020 \frac{D_o}{TW} \left(\frac{q}{D_o^{3/2}} \right)^{4/3} \quad \text{Rectangular and other shaped outlets} \quad \text{(A2)}$$

The length of stone protection required downstream of an outlet can be estimated by the relations shown in Figure A13. The variables are defined in Table A1 and the recommended configuration of a horizontal blanket of riprap for control of erosion at an outlet is presented in Figure A14.

Preformed Scour Hole Lined with Riprap

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 Figure A15 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. Details of a scheme of riprap protection termed "preformed scour hole lined with riprap" are shown in Figure A16.

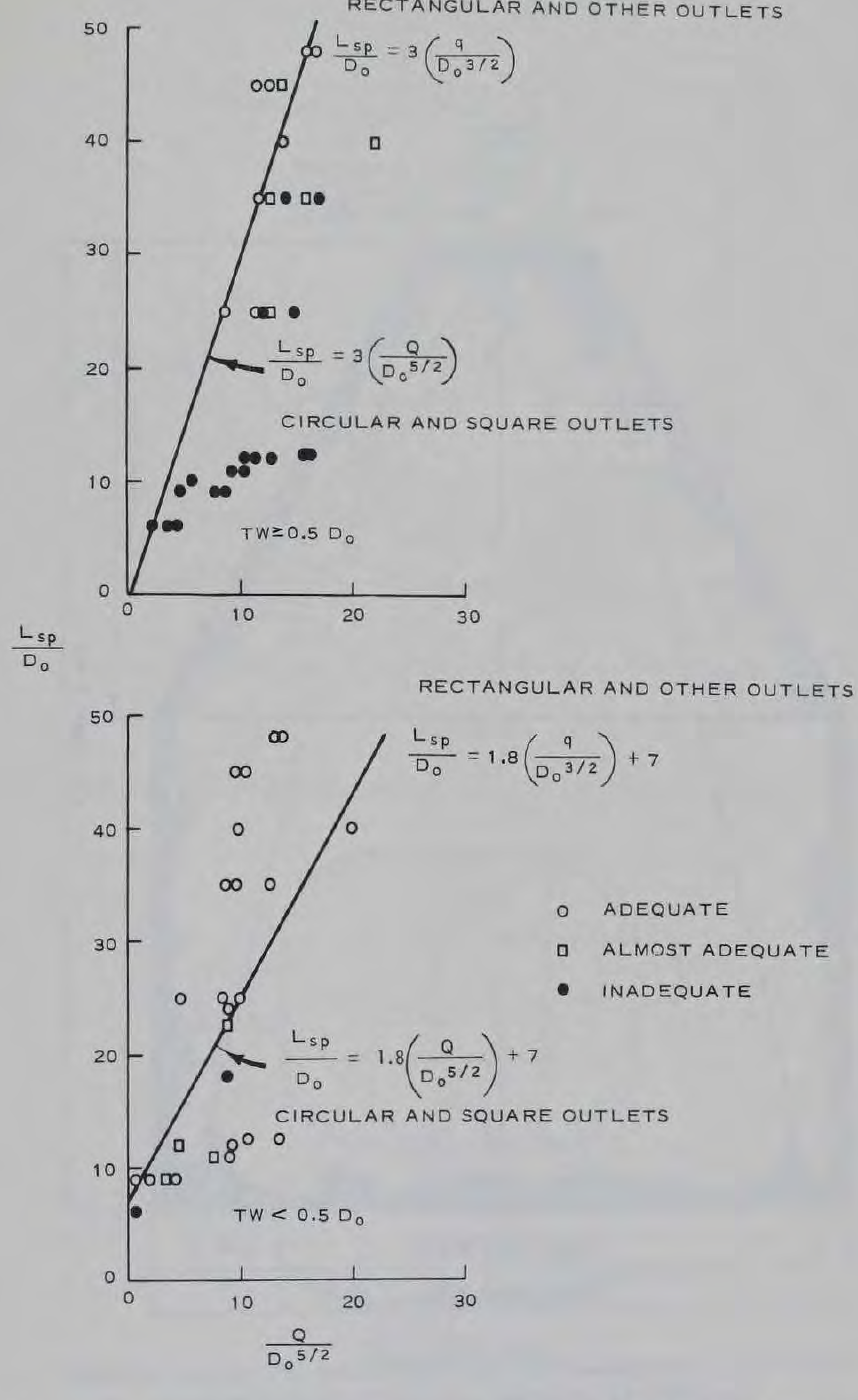


Figure A13. Length of stone protection, horizontal blanket

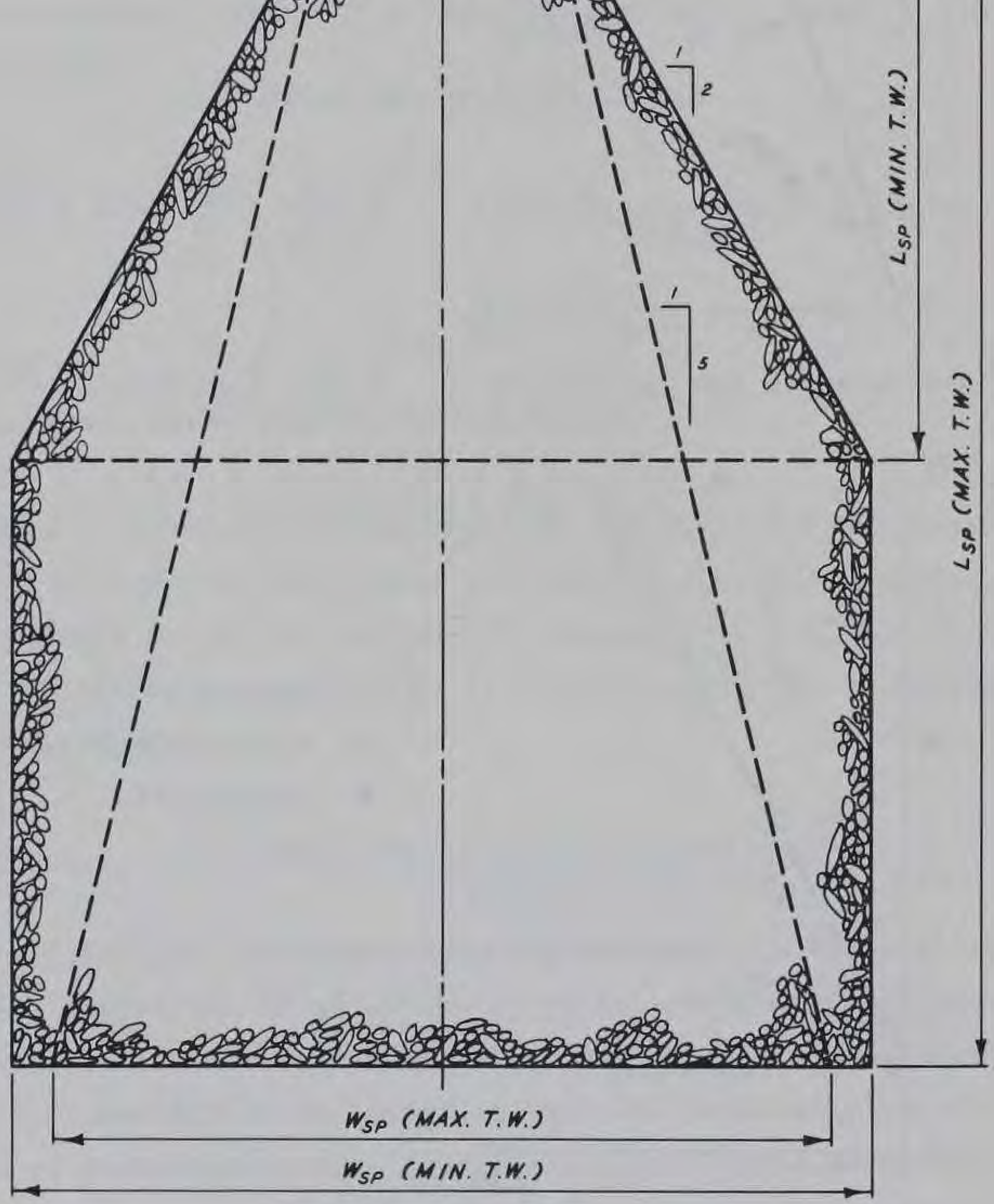


Figure A14. Recommended configuration of riprap blanket subject to minimum and maximum tailwaters

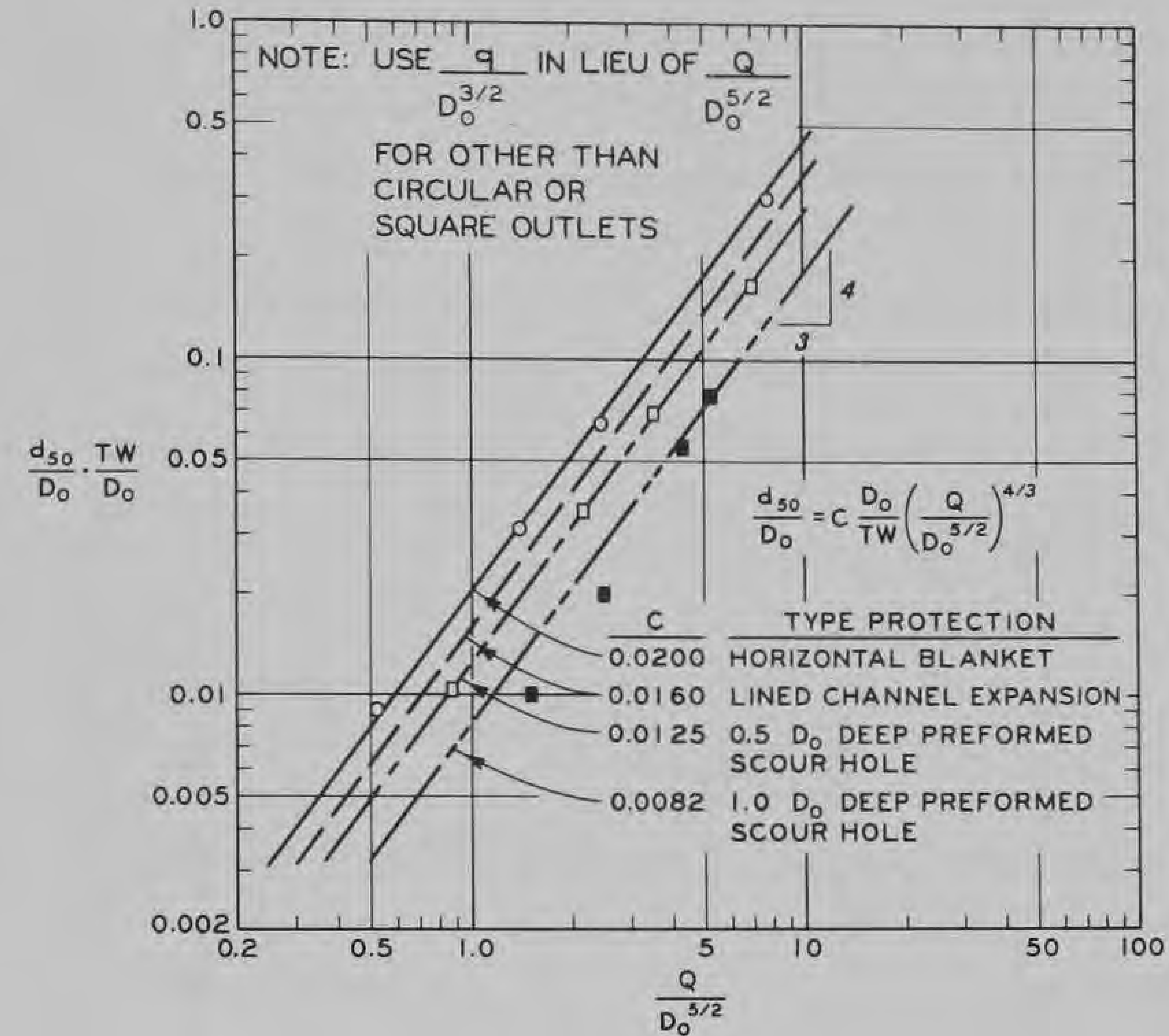


Figure A15. Recommended size of protective stone

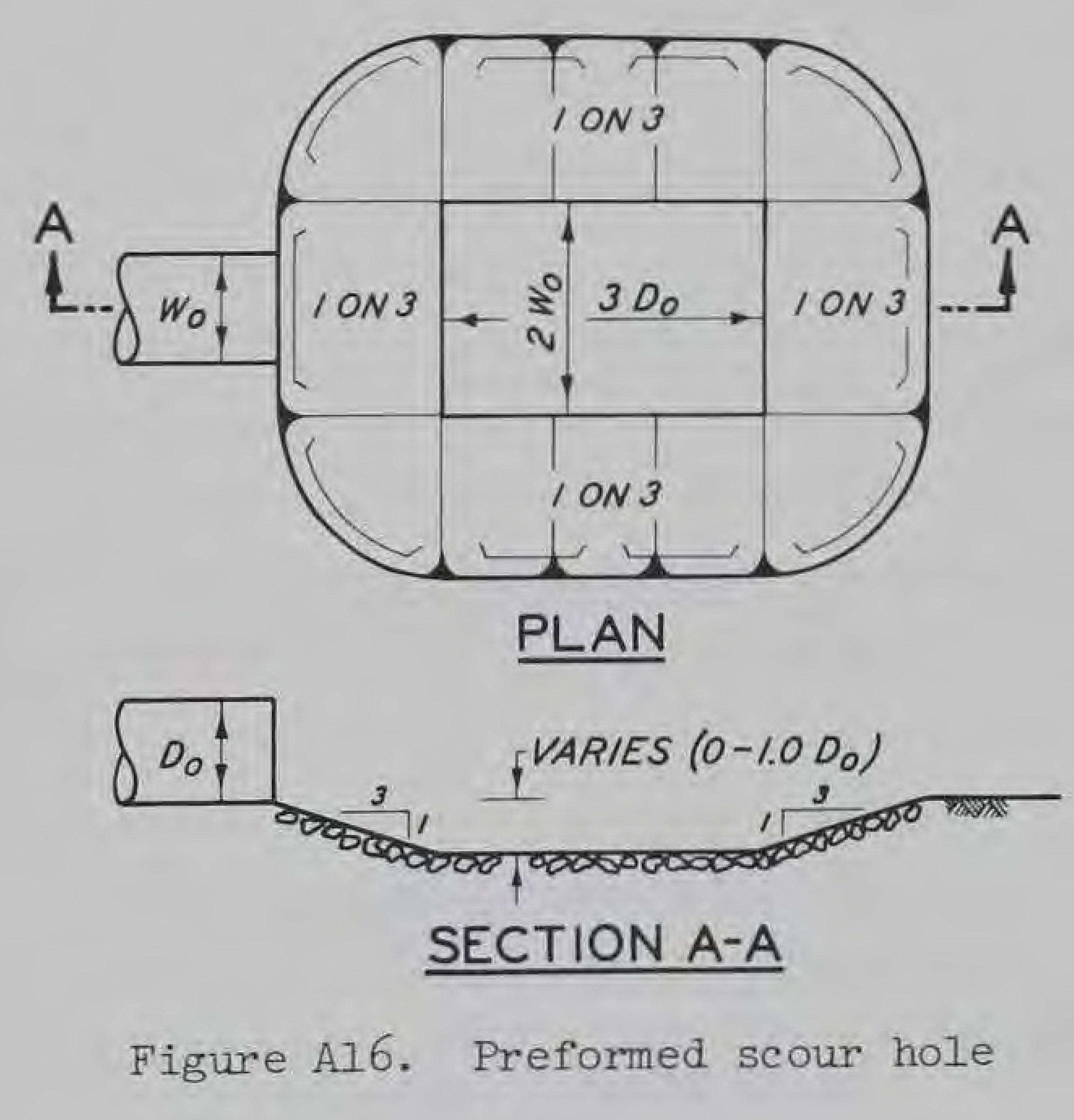


Figure A16. Preformed scour hole

Lined Channel Expansions

12. A research project sponsored by the Louisiana Department of Highways was recently completed at WES to investigate the feasibility of lining channel expansions downstream of square 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 Figure A17 was selected as a practical configuration. The dimensions of the lined channel expansion are related in terms of that of square box culverts.

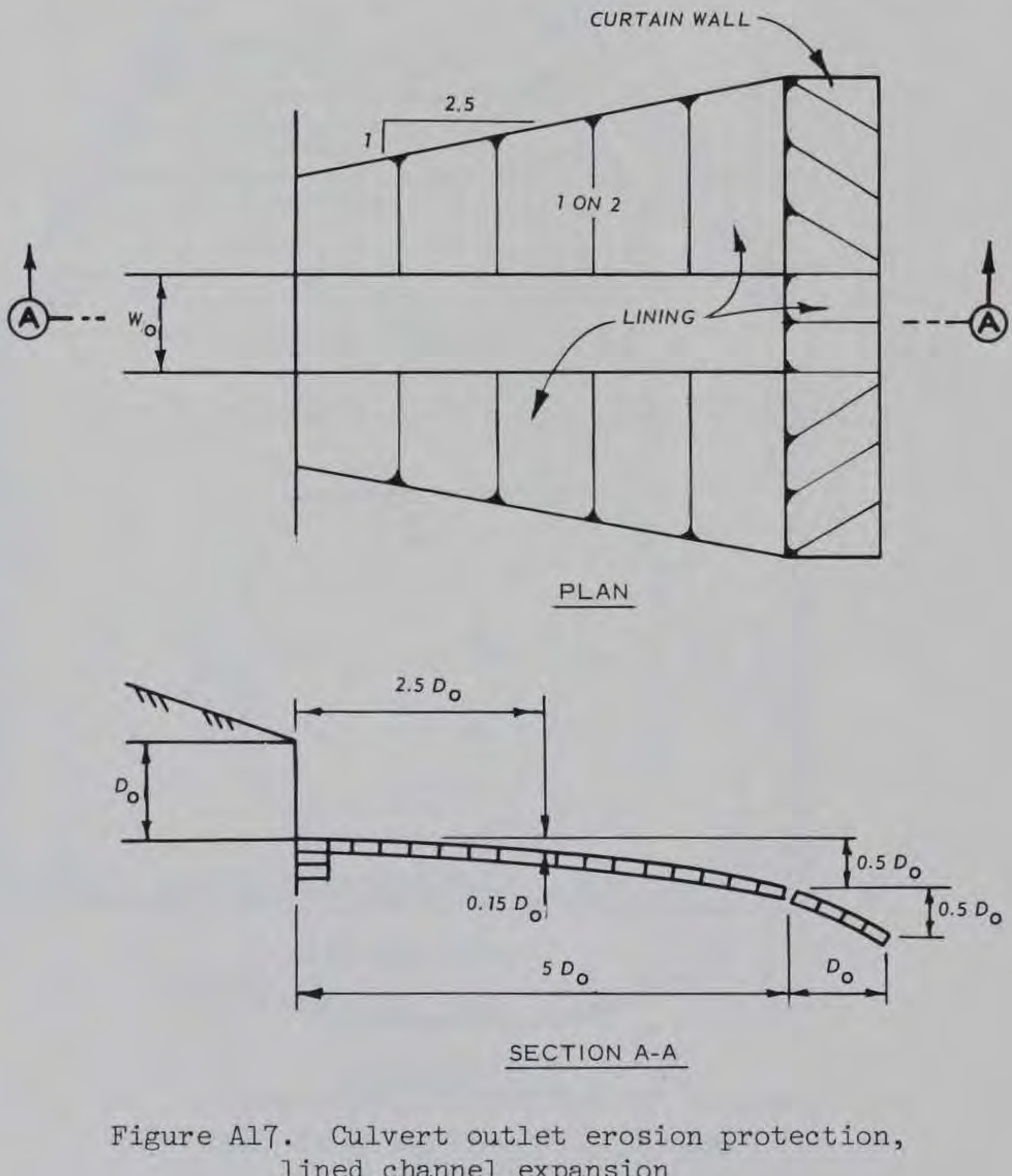


Figure A17. Culvert outlet erosion protection, lined channel expansion

For rectangular outlets, it is recommended that similarity be preserved in both the plan and elevation planes in terms of the respective width and height of the outlet.

13. Sack revetment with length, width, and thickness of 2, 1.5, and 0.33 ft, respectively, and weighing 120 lb was simulated at a scale of 1:8 as shown in Figure A18. Cellular blocks roughly 0.66 by 0.66 ft and 0.33 ft thick weighing 14 lb were simulated at a scale of 1:4 as shown in Figure A19. Rock of 6- to 8-in. diameter weighing 17 lb was simulated at a scale of 1:4 as shown in Figure A20. The results of tests to determine the conditions of discharge and tailwater required to displace or fail each of the revetments are shown in Figure A21 and indicate that the thickness of geometrically similar revetments can be calculated by the means of the following empirical equations:

$$\frac{d_{50}}{D_o} \text{ or } \frac{T_S}{D_o} \text{ or } \frac{T_B}{D_o} = 0.016 \frac{D_o}{TW}\left(\frac{Q}{D_o^{5/2}}\right)^{4/3} \quad \text{Square and circular outlets} \qquad \text{(A3)}$$

$$\frac{d_{50}}{D_o} \text{ or } \frac{T_S}{D_o} \text{ or } \frac{T_B}{D_o} = 0.016 \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3} \quad \text{Rectangular and other shaped outlets} \qquad \text{(A4)}$$

14. The variables are defined in Appendix B. The relative effectiveness of the lined channel expansion relative to the other schemes of riprap protection described previously is shown in Figure A15. The relations presented in Figure A15 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.

15. The maximum discharge parameters, $Q/D_o^{5/2}$ or $q/D_o^{3/2}$, of various schemes of protection can be calculated based on the results presented herein and comparisons relative to the cost of each type of

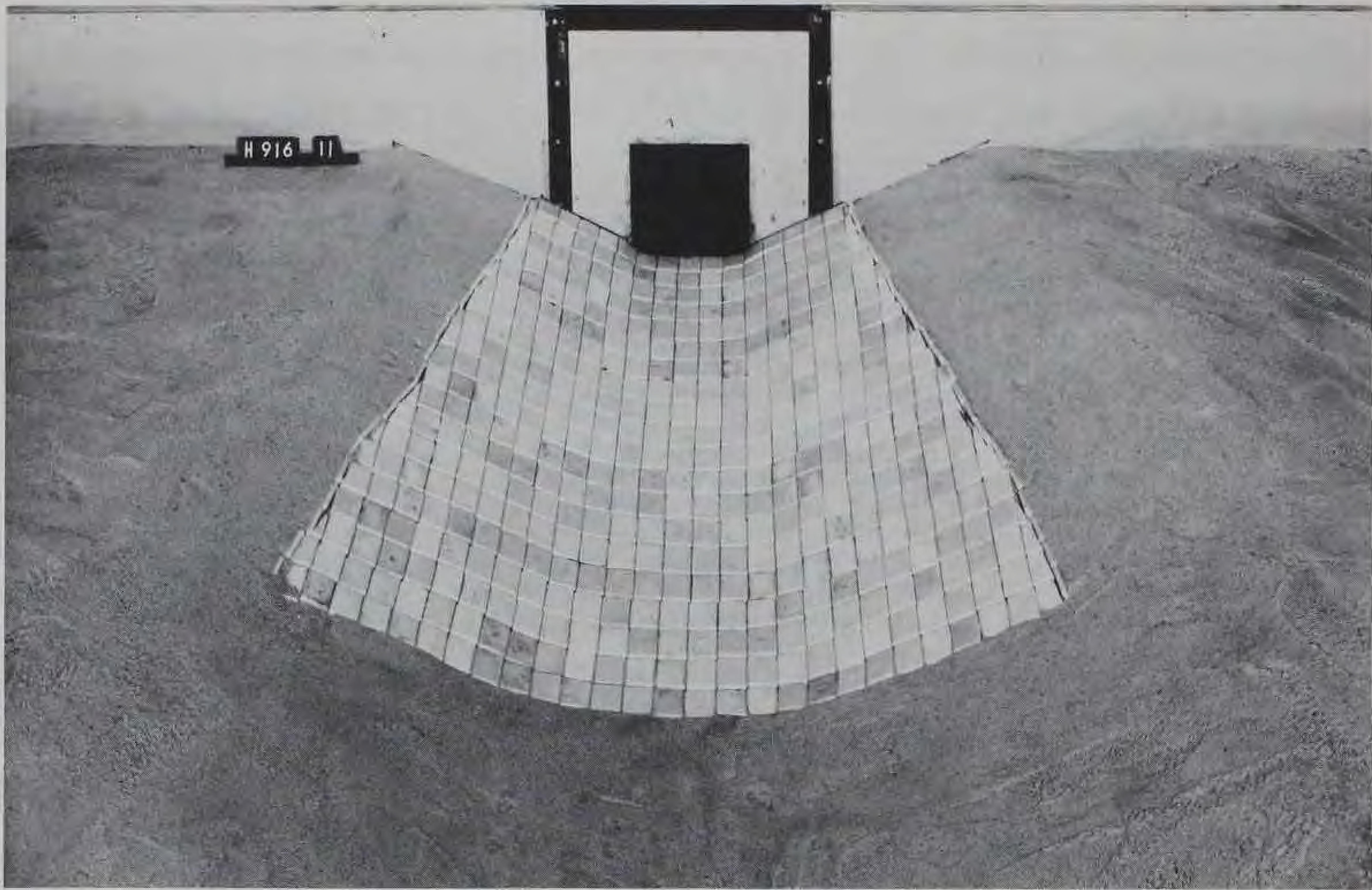


Figure A18. Channel expansion lined with sack revetment

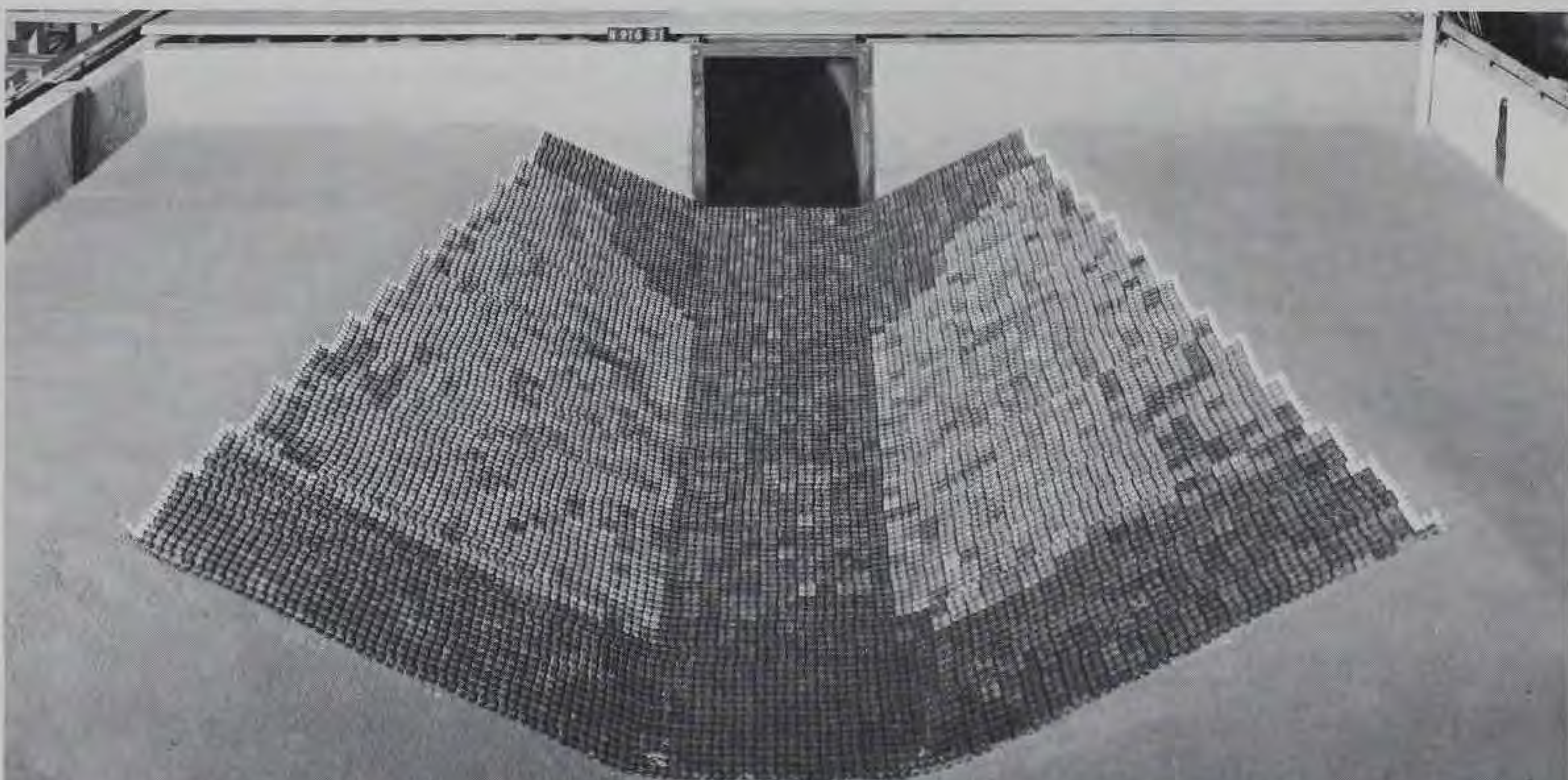


Figure A19. Channel expansion lined with cellular blocks

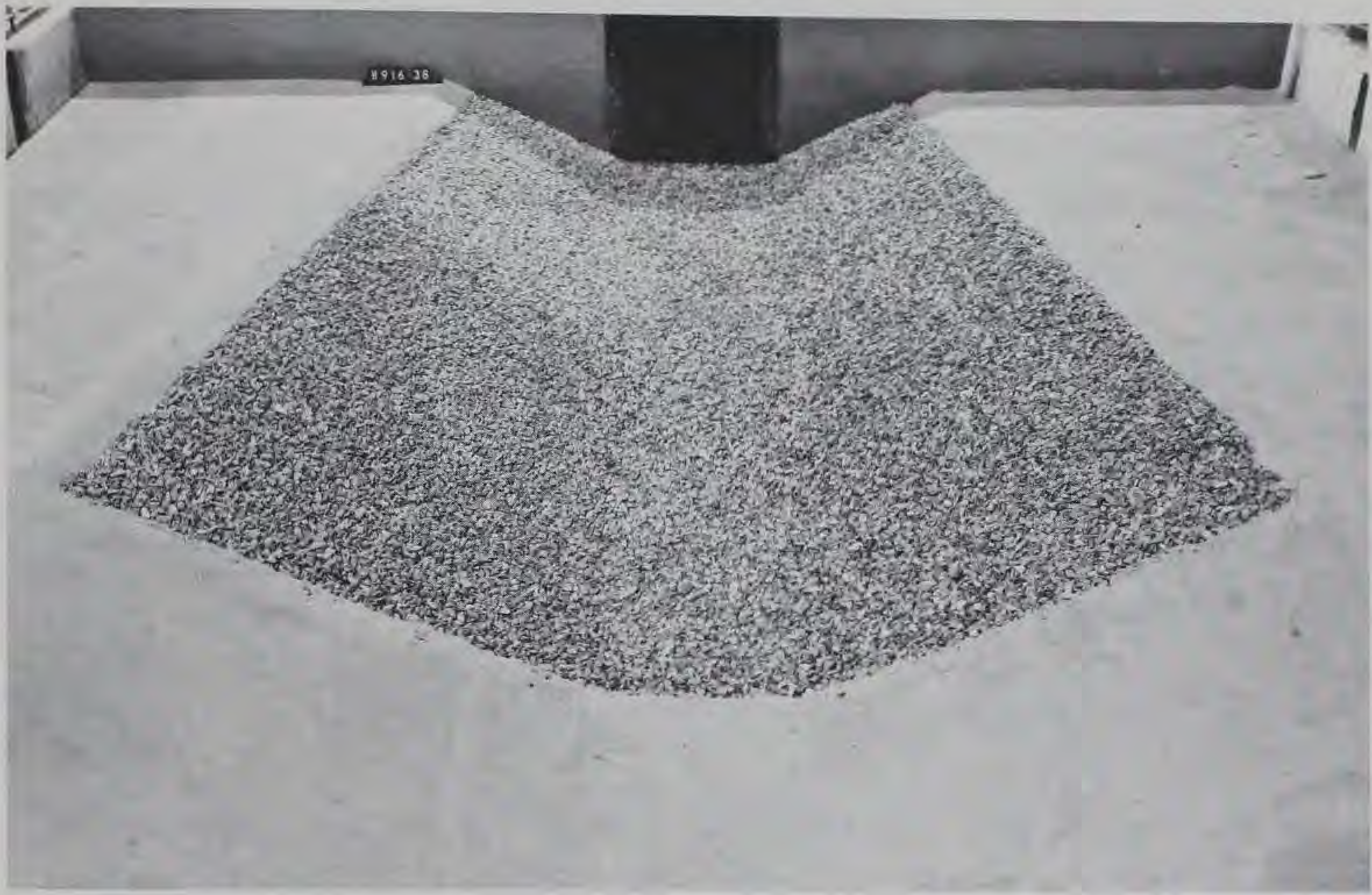


Figure A20. Channel expansion lined with riprap

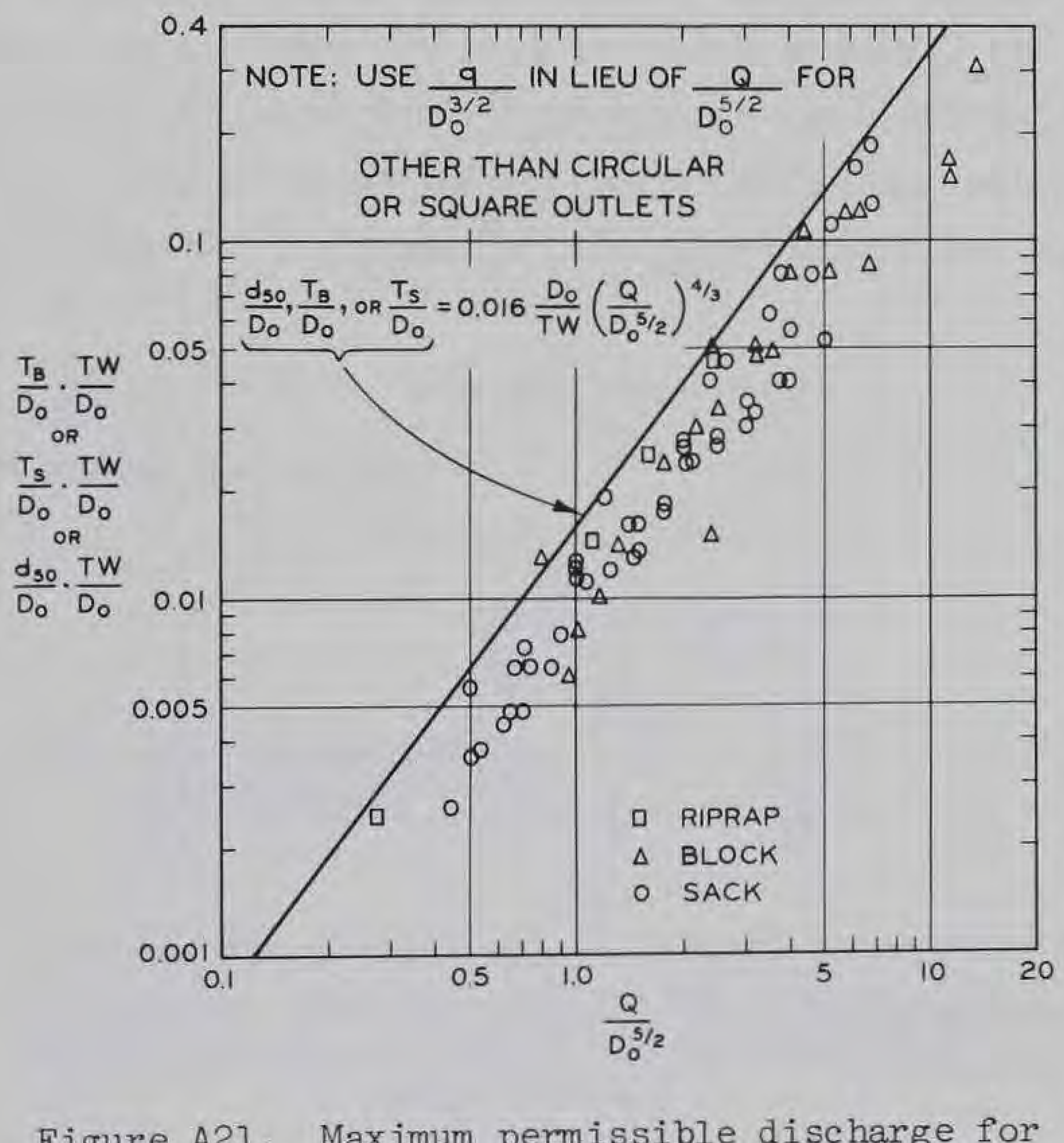


Figure A21. Maximum permissible discharge for lined channel expansions protection can be made to determine the most practical design of providing effective drainage and erosion control facilities for a given site. There will be conditions where the design discharge and economical size of culvert or storm sewer will result in a value of $Q/D_o^{5/2}$ or $q/D_o^{3/2}$, 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 the discharge parameter 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

16. Tests[7] were conducted to determine the maximum values of the discharge parameter (Table A1) 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 Figure A22. Results of the tests of these simple outlet transitions with the apron at the same elevation as the circular culvert invert are shown in Figure A23 which indicate that the maximum discharge parameter for a given outlet, length of transition, and tailwater can be calculated by the equations

$$\frac{Q}{D_o^{5/2}} = 1.60 \frac{TW}{D_o} \left(\frac{L}{D_o}\right)^{0.4(D_o/TW)^{1/3}} \quad \text{Circular and square outlets} \quad (A5)$$

$$\frac{q}{D_o^{3/2}} = 1.60 \frac{TW}{D_o} \left(\frac{L}{D_o}\right)^{0.4(D_o/TW)^{1/3}} \quad \text{Rectangular and other shaped outlets} \quad (A6)$$

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

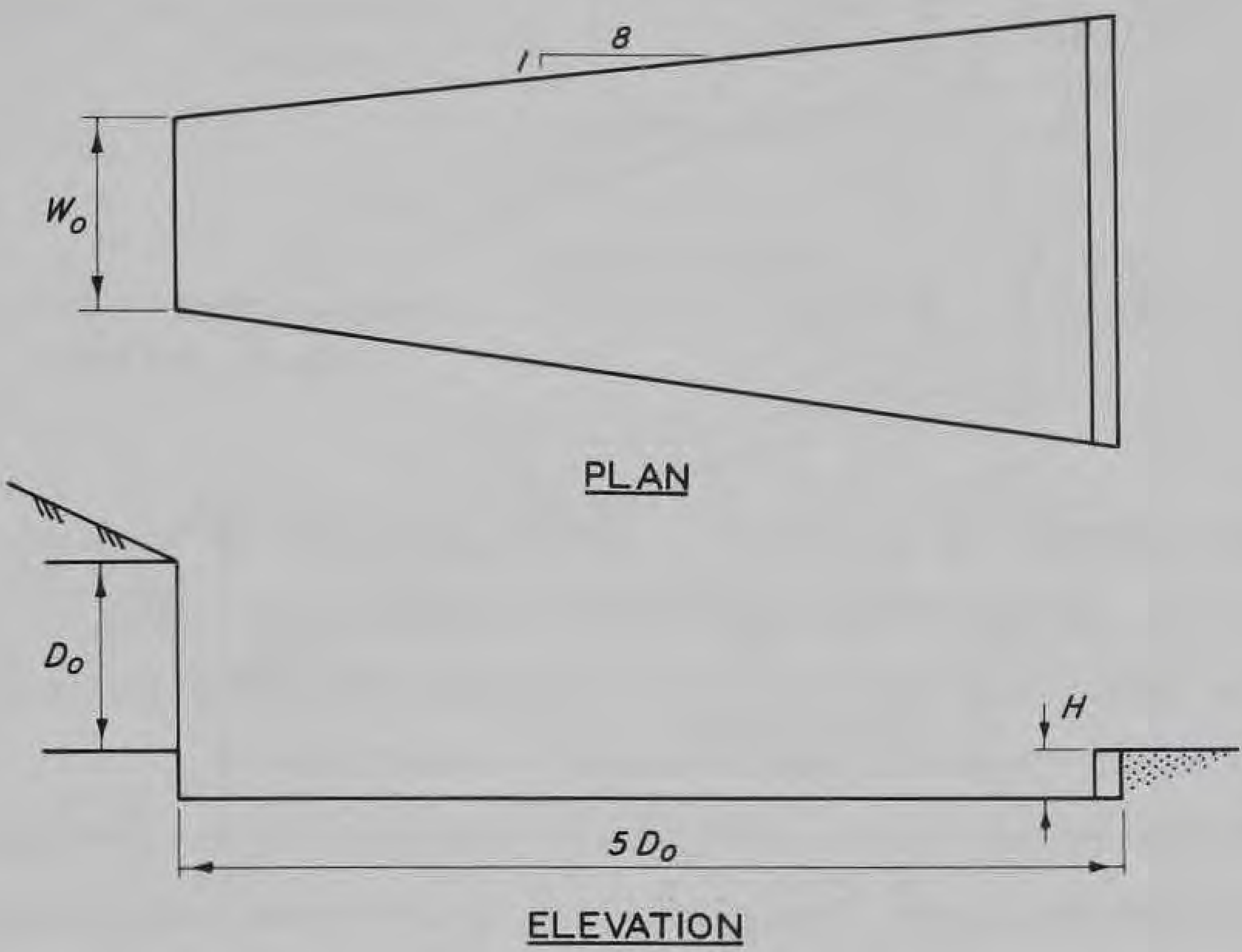


Figure A22. Flared outlet transition

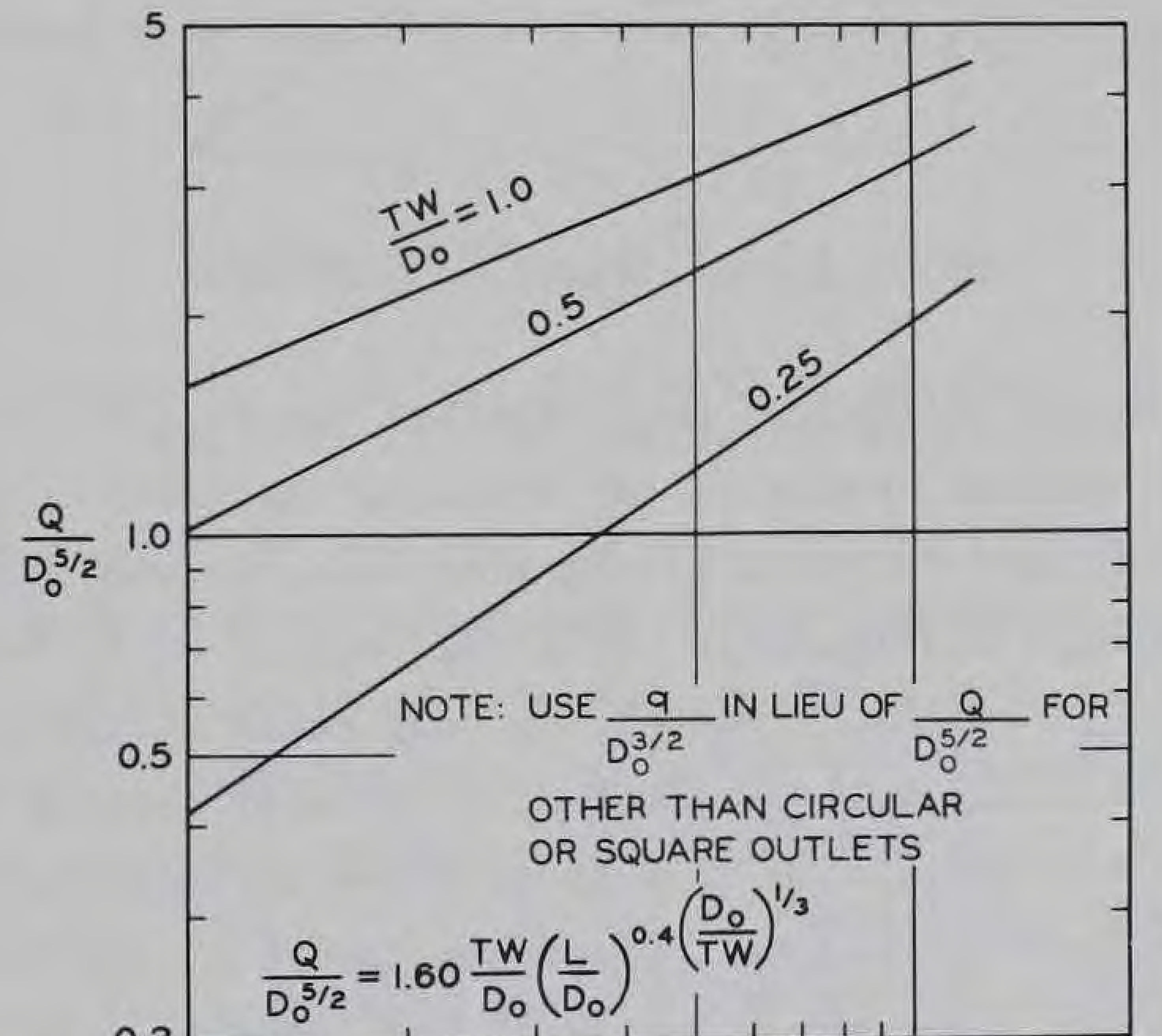


Figure A23. Maximum permissible discharge for various lengths of flared outlet transition and tailwaters

$$\frac{L}{D_o} = 0.30\left(\frac{D_o}{TW}\right)^2 \left(\frac{Q}{D_o^{5/2}}\right)^{2.5(D_o/TW)^{1/3}} \quad \text{Circular and square outlets} \qquad (A7)$$

$$\frac{L}{D_o} = 0.30\left(\frac{D_o}{TW}\right)^2 \left(\frac{q}{D_o^{3/2}}\right)^{2.5(D_o/TW)^{1/3}} \quad \text{Rectangular and other shaped outlets} \qquad (A8)$$

Variables are defined in Appendix B and Figure A23 shows that this type of protection is satisfactory only for low values of $Q/D_o^{5/2}$ or $q/D_o^{3/2}$. The arbitrary extent of scour depth equal to or less than 0.5 D_o was used to classify satisfactory conditions.

17. 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, Figure A24 indicates that this modification did not significantly improve energy dissipation or increase the applicable maximum values of the discharge parameter, $Q/D_o^{5/2}$ or $q/D_o^{3/2}$.

Commonly Used Energy Dissipators

18. Grace and Pickering[8] have reported the results of model tests to evaluate the maximum values of the discharge parameter, $Q/D_o^{5/2}$, applicable to circular culverts discharging into various sizes of three commonly used energy dissipators: stilling wells,[9] U. S. Bureau of Reclamation type VI basins,[10] and St. Anthony Falls stilling basins.[11]

19. The stilling well consists of a vertical section of circular pipe affixed to the outlet end of a storm sewer as shown in Figure A25. 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 Figure A25. 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.

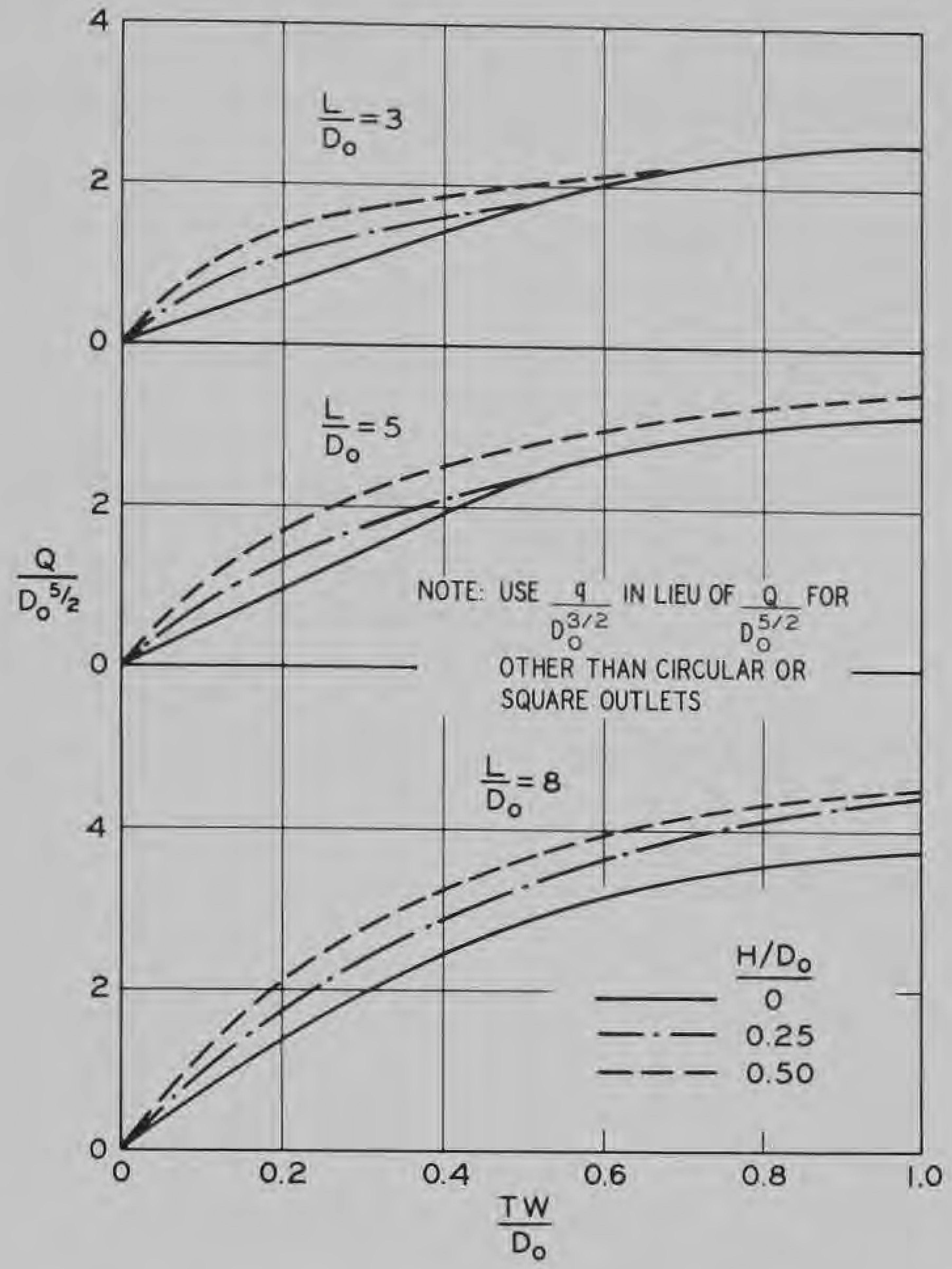
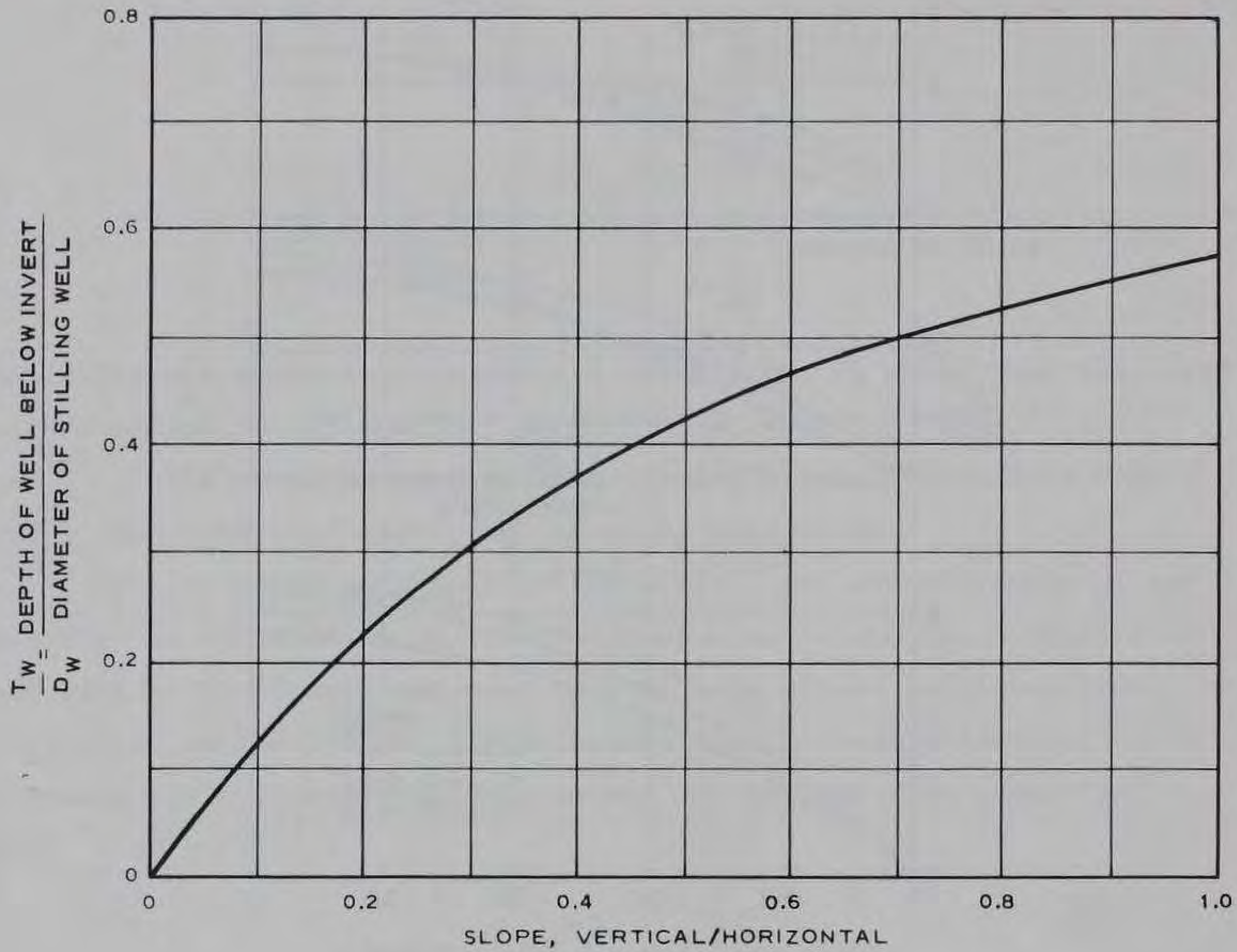


Figure A24. Relative effects of recessed apron and end sill on permissible discharge

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, protection is not needed. Energy dissipation is accomplished without the necessity of maintaining a specified tailwater depth in the vicinity of the outlet.

20. Details of the U. S. Bureau of Reclamation type VI basin and the St. Anthony Falls stilling basin are presented in Figures A26 and A27. 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 A2. These data are satisfied by the following equations which can be used to compute the diameter or width of each type



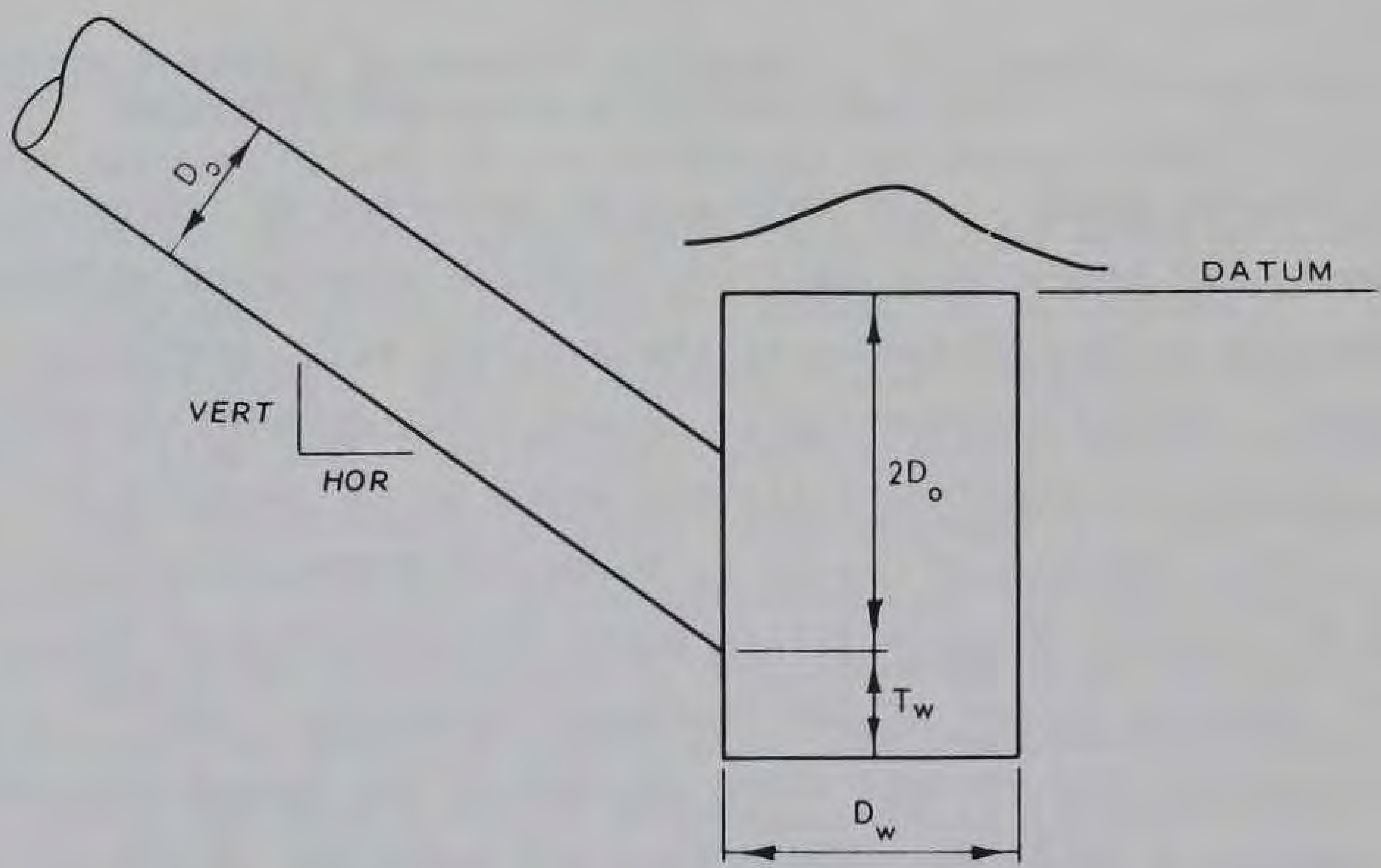
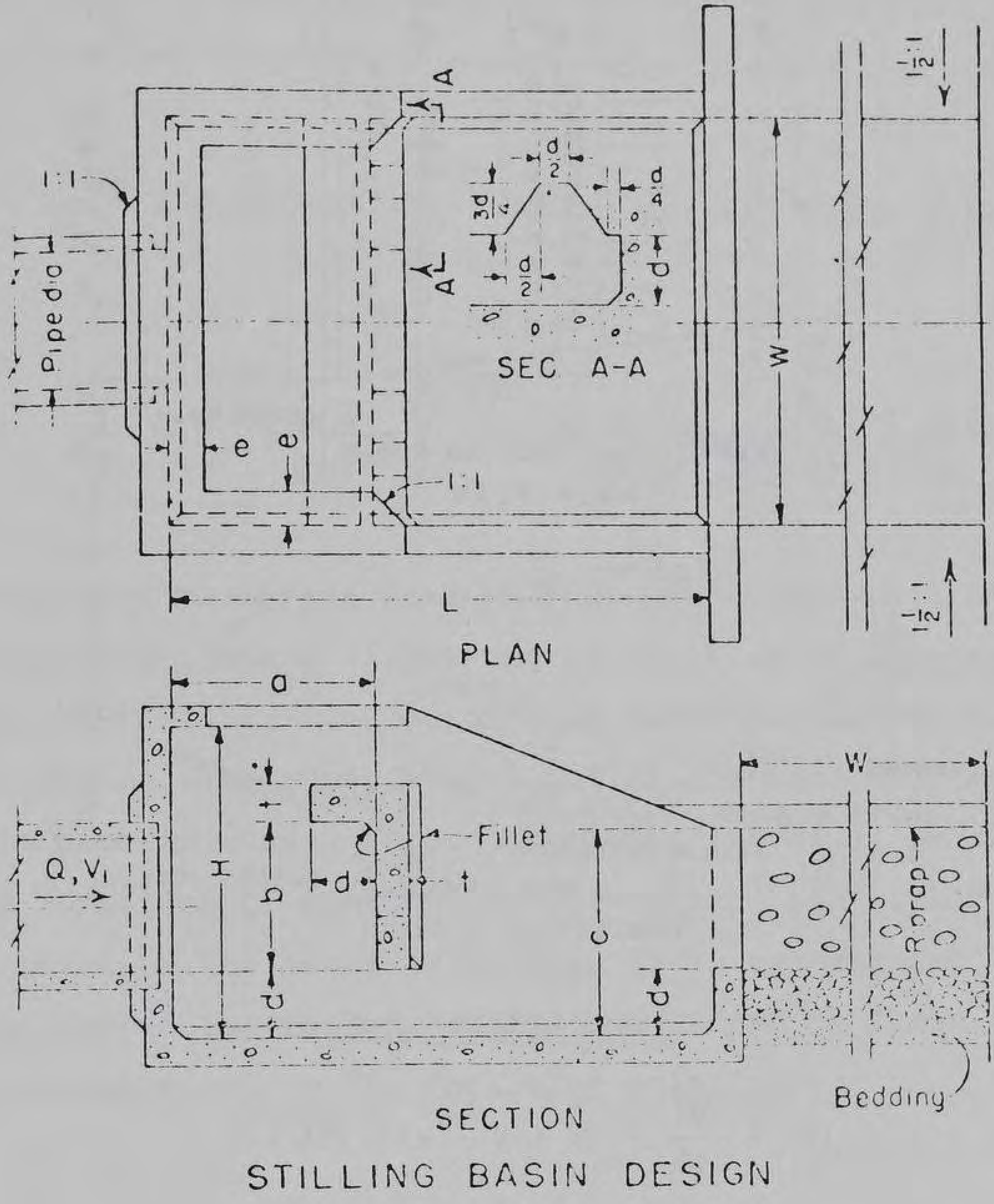


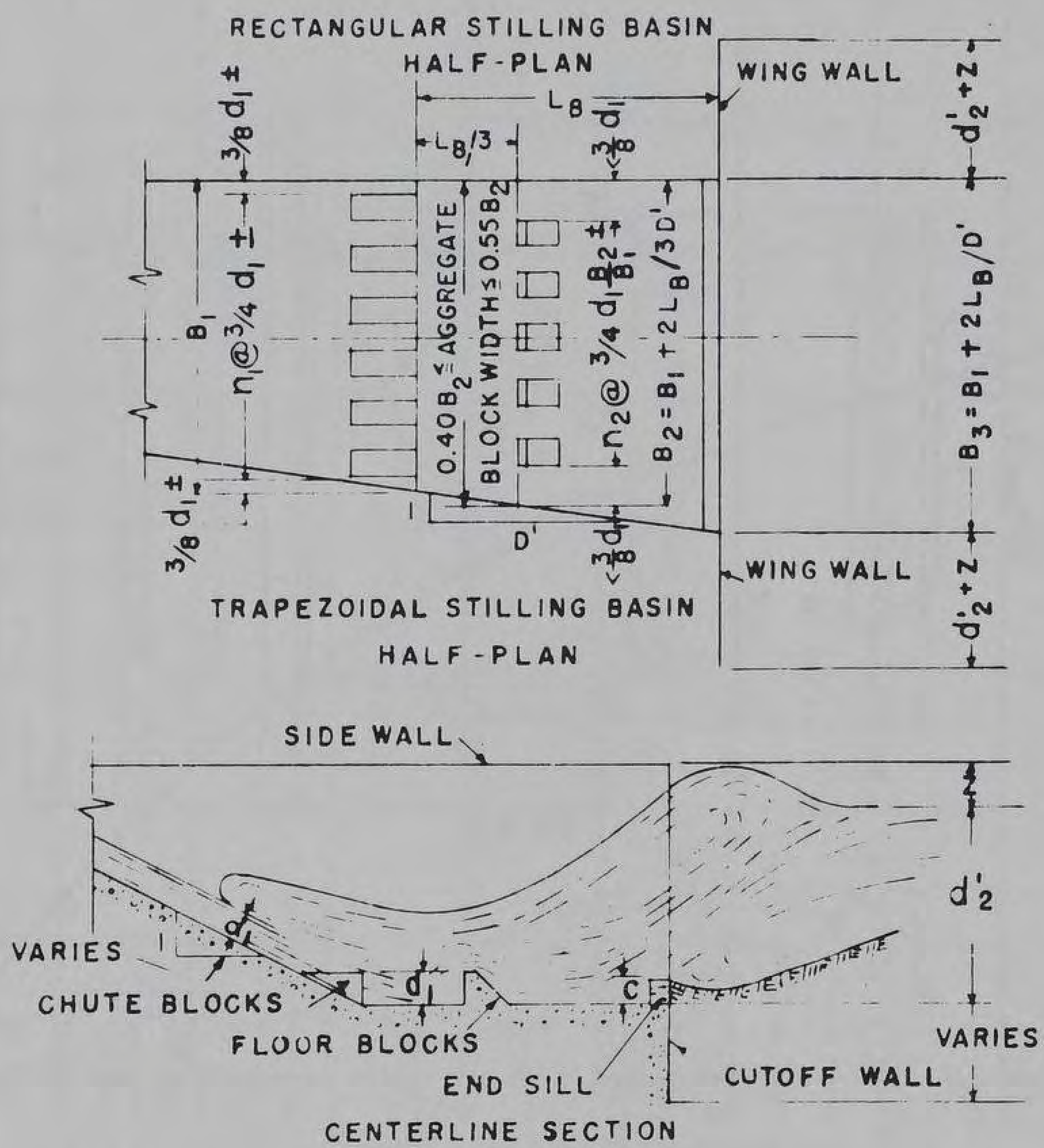
Figure A25. Stilling well



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)

Figure A26. 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) $c = 0.07 d_2$

Figure A27. Proportions of SAF stilling basin of energy dissipator relative to that of the incoming circular or square pipe:

$$\frac{D_W}{D_o} = 0.53 \left(\frac{Q}{D_o^{5/2}}\right)^{1.0} \quad \text{Stilling well} \qquad \text{(A9)}$$

$$\frac{W_{SAF}}{D_o} = 0.30 \left(\frac{Q}{D_o^{5/2}}\right)^{1.0} \quad \text{St. Anthony Falls stilling basin} \qquad \text{(A10)}$$

$$\frac{W_{VI}}{D_o} = 1.30 \left(\frac{Q}{D_o^{5/2}}\right)^{0.55} \quad \text{U. S. Bureau of Reclamation type VI basin} \qquad \text{(A11)}$$

The above relations should be used only for design of each of the respective energy dissipators downstream of circular or square outlets. The SAF stilling basin is the only one of the above energy dissipators recommended for use with other shaped outlets, and in such cases, the design should be conducted in accordance with the usual procedures for ensuring the formation of a hydraulic jump within the stilling basin rather than based on the above relation. It is recommended that the size of stone protection to be provided downstream of these energy dissipators be estimated by the following relation:

$$\frac{d_{50}}{D_e} = 1.0 \left(\frac{V_e}{\sqrt{gD_e}}\right)^3 \qquad \text{(A12)}$$

where D_e and V_e are the depth and velocity of flow exiting the energy dissipator. Guidance other than engineering judgment for estimating the length of stone protection required downstream of an energy dissipator is not available due to the lack of systematic investigations of this aspect of the problem. However, model studies of protection required downstream of spillway stilling basins indicate that a length of approximately 10 times the theoretical depth of flow required for a hydraulic jump is reasonably adequate.

Discussion

21. Contrary to the usual assumption, increased tailwater or excessive tailwater at outlets tends to concentrate rather than diffuse the efflux; and although the depth of scour may not be as severe, the length of scour relative to that observed with tailwaters less than one-half the height of the outlet is considerably greater. This is attributed to the fact that with tailwaters greater than or equal to one-half the outlet height, the efflux is confined by the relatively stagnant adjacent waters which are entrained with the efflux to effectively increase the unit discharge issue from the outlet.

22. Although the effect of outlet shape on the scour hole geometry was not investigated in detail, a comparison of the scour holes developed in 0.25-mm sand by a discharge of 0.87 cfs through each of four differently shaped outlets (circular, square, rectangular, and arch) with the same cross-sectional area (0.087 sq ft) and both minimum and maximum tailwater conditions indicated that outlet shape had no significant effect on the scour hole geometry. The tendency of the jet issued from an outlet to oscillate from side to side under conditions of maximum tailwater was observed with flows through each of the aforementioned conduit shapes. This oscillation was random and quite slow for all conditions except when flow from the arch-shaped outlet was discharged into maximum tailwaters after a scour hole had been developed with minimum tailwaters. For this condition, the oscillation was periodic and changed position about every 15 sec. Thus, it appears that a jet discharge from an arch-shaped outlet is less stable than those from the other outlet shapes investigated. This indicates that a greater extent of scour, particularly width of scour, may be expected downstream of arch outlets subject to both minimum and maximum tailwaters (see Figure A4).

23. Various degrees of success have been experienced with riprap and/or rubble or other forms of protection downstream of outlets and different opinions regarding the adequacy of protective stone have developed. One of the most common causes of failure of protective

material observed during field observations[12] was the lack of an adequate filter between the soil and the protective material. This permits progressive leaching of the soil and settlement of the blanket. The blanket can be grouted in areas subject to mild winters; however, an appropriate filter and weep holes should be provided for relief of hydrostatic pressure. Grouted riprap does not perform satisfactorily in areas where considerable freezing and thawing is experienced annually. Exit channel protection should be segregated from erodible soils by graded filters[13] and/or durable synthetic cloths.[14]

24. It is considered that the results presented herein, with the exception of the three commonly used energy dissipators which were developed for circular and square outlets, can be applied to other outlet shapes, provided geometric similarity is preserved in application of the recommended guidance. The discharge parameter should be calculated on the basis of the unit discharge per foot of width of the outlet, q, rather than the total discharge.

25. These results may also be applied to develop designs of protective measures downstream of multiple outlets, provided the spacing between outlets is relatively small (less than one-fourth the individual outlet widths). In such cases, it is recommended that analyses be conducted on the basis of a single outlet (one of the two outermost outlets) and that a total width of protection be provided which includes the total width of protection needed below a single outlet plus the width between the center lines of the two outermost outlets. If the spacing between outlets is appreciable, i.e. one-fourth or greater than the individual outlet widths, the individual jets and unit discharges of flow may be concentrated due to confinement by excessive tailwater or expansion and subsequent intersection downstream with minimum tailwater; and considerable turbulence may be generated which will increase the severity of attack on local boundaries. In such cases, it is recommended that the extent of the protective works be enlarged by a factor of judgment, i.e. 25 to 33 percent.

26. These generalized results offer considerable guidance since one can estimate the extent of scour to be anticipated in stable

channels of cohesionless soils and then decide what degree of protection is required. For example, is the anticipated scour hole with an appropriate cutoff wall that protects the outlet adequate for energy dissipation? Are the size and extent of riprap required for a stable horizontal blanket practicable? Is it practicable to compromise depth of scour and size of riprap by providing a preformed and riprap-lined scour hole? Is an energy dissipator required? Is it practicable to size the storm sewer or culvert on the basis of anticipated erosion and appropriate protective measures in lieu of hydraulic efficiency? Examples of the recommended application of the results are presented in Table A3.

Table A1

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 A2

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 A3

Examples of recommended application to estimate extent of scour in a cohesionless soil and alternative schemes of protection required to prevent local scour downstream of a circular and rectangular outlet with equivalent cross-sectional areas that will be subjected to a range of discharges for a duration of one hour.

Given:

Dimensions of rectangular outlet = W_o = 10 ft, D_o = 5 ft
Diameter of circular outlet, D_o = 8 ft
Range of discharge, Q = 362 to 1086 cfs
Discharge parameter for rectangular culvert, $q/D_o^{3/2}$ = 3.2 to 9.7

Discharge parameter for circular culvert, $Q/D_o^{5/2}$ = 2 to 6
Duration of runoff event, t = 60 min
Maximum tailwater el = 6.4 ft above outlet invert (>0.5 D_o)
Minimum tailwater el = 2.0 ft above outlet invert (<0.5 D_o)

Example 1 - Determine maximum depth of scour for minimum and maximum flow conditions:

RECTANGULAR CULVERT (see Figure A7)

MINIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.80 \left(\frac{q}{D_o^{3/2}} \right)^{0.375} t^{0.10}$$

$$D_{sm} = 0.80\ (3.2 - 9.7)^{0.375}\ (60)^{0.1}\ (5) = \underline{\underline{9.3\ \text{ft}}} - \underline{\underline{14.0\ \text{ft}}}$$

(Continued)

MAXIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.74 \left(\frac{q}{D_o^{3/2}}\right)^{0.375} t^{0.10}$$

$$D_{sm} = 0.74\ (3.2 - 9.7)^{0.375}\ (60)^{0.1}\ (5) = \underline{\underline{8.6\ \text{ft}}} - \underline{\underline{13.0\ \text{ft}}}$$

CIRCULAR CULVERT (see Figure A7)

MINIMUM TAILWATER

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

$$D_{sm} = 0.80\ (2 - 6)^{0.375}\ (60)^{0.1}\ (8) = \underline{\underline{12.5\ \text{ft}}} - \underline{\underline{18.9\ \text{ft}}}$$

MAXIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.74 \left(\frac{Q}{D_o^{5/2}}\right)^{0.375} t^{0.1}$$

$$D_{sm} = 0.74\ (2 - 6)^{0.375}\ (60)^{0.1}\ (8) = \underline{\underline{11.6\ \text{ft}}} - \underline{\underline{17.5\ \text{ft}}}$$

Example 2 - Determine maximum width of scour for minimum and maximum flow conditions:

RECTANGULAR CULVERT (see Figure A8)

MINIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 1.00 \left(\frac{q}{D_o^{3/2}}\right)^{0.915} t^{0.15}$$

$$W_{sm} = 1.00\ (3.2 - 9.7)^{0.915}\ (60)^{0.15}\ (5) = 27\ \text{ft} - 74\ \text{ft}$$

(Continued)

$$W_{smr} = W_{sm} + \frac{W_o}{2} - \frac{D_o}{2} = (27 - 74) + \frac{10}{2} - \frac{5}{2} = \underline{\underline{29.5 \text{ ft}}} - \underline{\underline{76.5 \text{ ft}}}$$

MAXIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 0.72 \left(\frac{q}{D_o^{3/2}}\right)^{0.915} t^{0.15}$$

$$W_{sm} = 0.72\ (3.2 - 9.7)^{0.915}\ (60)^{0.015} = 19 \text{ ft} - 53 \text{ ft}$$

$$W_{smr} = W_{sm} + \frac{W_o}{2} - \frac{D_o}{2} = (19 - 53) + \frac{10}{2} - \frac{5}{2} = \underline{\underline{21.5 \text{ ft}}} - \underline{\underline{55.5 \text{ ft}}}$$

CIRCULAR CULVERT (see Figure A8)

MINIMUM TAILWATER

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

$$W_{sm} = 1.00\ (2 - 6)^{0.915}\ (60)^{0.15}\ (8) = \underline{\underline{28 \text{ ft}}} - \underline{\underline{76 \text{ ft}}}$$

MAXIMUM TAILWATER

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

$$W_{sm} = 0.72\ (2 - 6)^{0.915}\ (60)^{0.15}\ (8) = \underline{\underline{20 \text{ ft}}} - \underline{\underline{55 \text{ ft}}}$$

(Continued)

Example 3 - Determine maximum length of scour for minimum and maximum flow conditions:

RECTANGULAR CULVERT (see Figure A9)

MINIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 2.40 \left(\frac{q}{D_o^{3/2}}\right)^{0.71} t^{0.125}$$

$$L_{sm} = 2.4\ (3.2 - 9.7)^{0.71}\ (60)^{0.125}\ (5) = \underline{\underline{46\ ft}} - \underline{\underline{101\ ft}}$$

MAXIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 4.10 \left(\frac{q}{D_o^{3/2}}\right)^{0.71} t^{0.125}$$

$$L_{sm} = 4.10\ (3.2 - 9.7)^{0.71}\ (60)^{0.125}\ (5) = \underline{\underline{78\ ft}} - \underline{\underline{171\ ft}}$$

CIRCULAR CULVERT (see Figure A9)

MINIMUM TAILWATER

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

$$L_{sm} = 2.4\ (2 - 6)^{0.71}\ (60)^{0.125}\ (8) = \underline{\underline{52\ ft}} - \underline{\underline{114\ ft}}$$

MAXIMUM TAILWATER

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

$$L_{sm} = 4.10\ (2 - 6)^{0.71}\ (60)^{0.125}\ (8) = \underline{\underline{90\ ft}} - \underline{\underline{195\ ft}}$$

(Continued)

Table A3 (Continued)

Example 4 - Determine profile and cross section of scour for maximum discharge and minimum tailwater conditions (see Figure A11):

CIRCULAR CULVERT

For L_{sm} = 114 ft and D_{sm} = 18.9 ft

L_s/L_{sm}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
L	0.0	11.4	22.8	34.2	45.6	57.0	68.4	79.8	91.2	102.6	114.0
D_s/D_{sm}	0.7	0.75	0.85	0.95	1.0	0.95	0.75	0.55	0.33	0.15	0.0
D_s	13.2	14.2	16.1	18.0	18.9	18.0	14.2	10.4	6.3	2.9	0.0

For W_{sm} = 76 ft and D_{sm} = 18.9 ft

W_s/W_{sm}	0.0	0.2	0.4	0.6	0.8	1.0
W_s	0.0	15.2	30.4	45.6	60.8	76.0
D_s/D_{sm}	1.0	0.67	0.27	0.15	0.05	0.0
D_s	18.9	12.6	5.1	2.8	0.95	0.0

RECTANGULAR CULVERT

For L_{sm} = 101 ft and D_{sm} = 14.0 ft

L_s/L_{sm}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
L	0.0	10.1	20.2	30.3	40.4	50.5	60.6	70.7	80.8	90.9	101.0
D_s/D_{sm}	0.7	0.75	0.85	0.95	1.0	0.95	0.75	0.55	0.33	0.15	0.0
D_s	9.8	10.5	11.9	13.3	14.0	13.3	10.5	7.7	4.6	2.1	0.0

For W_{sm} = 74 ft and D_{sm} = 14.0 ft

W_s/W_{sm}	0.0	0.2	0.4	0.6	0.8	1.0
W_s	0.0	14.8	29.6	44.4	59.2	74.0
D_s/D_{sm}	1.0	0.67	0.27	0.15	0.05	0.0
D_s	14.0	9.38	3.78	2.10	0.70	0.0
$W_{sr} = W_s$						
$+ \frac{W_o}{2} - \frac{D_o}{2}$	0-2.5	17.3	32.1	46.9	61.7	76.5

(Continued)

Example 5 - Determine depth and width of cutoff wall:

RECTANGULAR CULVERT, Maximum depth and width of scour = 14 ft and 76.5 ft

From Figure A11, depth of cutoff wall = 0.7 (D_{sm}) = 0.7 (14) = 9.8 ft

From Figure A11, width of cutoff wall = 2 (W_{smr}) = 2 (76.5) = 153 ft

CIRCULAR CULVERT, Maximum depth and width of scour = 18.9 ft and 76.0 ft

From Figure A11, depth of cutoff wall = 0.7 (D_{sm}) = 0.7 (18.9) = 13.2 ft

From Figure A11, width of cutoff wall = 2 (W_{sm}) = 2 (76) = 152 ft

Note: The depth of cutoff wall may be varied with width in accordance with the cross section of the scour hole at the location of the maximum depth of scour, see Figures A11 and A12.

Example 6 - Determine size and extent of horizontal blanket of riprap:

RECTANGULAR CULVERT

MINIMUM TAILWATER

From Figure A15, $$\frac{d_{50}}{D_o} = 0.020 \frac{D_o}{TW} \left(\frac{q}{D_o^{3/2}} \right)^{4/3}$$

$$d_{50} = 0.020\ (5/2)(3.2 - 9.7)^{4/3}\ (5) = \underline{1.2\text{ ft}} - \underline{5.2\text{ ft}}$$

From Figure A13, $$\frac{L_{sp}}{D_o} = 1.8 \left(\frac{q}{D_o^{3/2}} \right) + 7$$

$$L_{sp} = [1.8\ (3.2 - 9.7) + 7]\ 5 = \underline{64\text{ ft}} - \underline{122\text{ ft}}$$

MAXIMUM TAILWATER

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

(Continued)

Table A3 (Continued)

$$d_{50} = 0.020\ (5/6.4)\ (3.2 - 9.7)^{4/3}\ (5) = \underline{\underline{0.37\ ft}} - \underline{\underline{0.76\ ft}}$$

$$\frac{L_{sp}}{D_o} = 3\ \left(\frac{q}{D_o^{3/2}}\right)$$

$$L_{sp} = 3\ (3.2 - 9.7)\ 5 = \underline{\underline{48\ ft}} - \underline{\underline{145\ ft}}$$

CIRCULAR CULVERT

MINIMUM TAILWATER

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

$$d_{50} = 0.020\ (8/2)\ (2 - 6)^{4/3}\ (8) = \underline{\underline{1.6\ ft}} - \underline{\underline{7.0\ ft}}$$

$$\frac{L_{sp}}{D_o} = 1.8\left(\frac{Q}{D_o^{5/2}}\right) + 7$$

$$L_{sp} = [1.8\ (2 - 6) + 7]\ 8 = \underline{\underline{85\ ft}} - \underline{\underline{142\ ft}}$$

MAXIMUM TAILWATER

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

$$d_{50} = 0.020\ (8/6.4)\ (2 - 6)^{4/3}\ (8) = 0.50\ ft - 2.18\ ft$$

$$\frac{L_{sp}}{D_o} = 3\ \left(\frac{Q}{D_o^{5/2}}\right)$$

(Continued)

Table A3 (Continued)

$$L_{sp} = 3\ (2 - 6)\ 8 = \underline{\underline{48\ ft}} - \underline{\underline{144\ ft}}$$

Use Figure A14 to determine recommended configuration of horizontal blanket of riprap subject to minimum and maximum tailwaters.

Example 7 - Determine size and geometry of riprap-lined preformed scour holes 0.5- and 1.0-D_o deep for minimum tailwater conditions:

RECTANGULAR CULVERT (see Figure A15)

0.5-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0125\ \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3}$$

$$d_{50} = 0.0125\ (5/2)\ (3.2 - 9.7)^{4/3}\ (5) = \underline{\underline{0.73\ ft}} - \underline{\underline{3.2\ ft}}$$

1.0-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0082\ \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3}$$

$$d_{50} = 0.0082\ (8/2)\ (2 - 6)^{4/3}\ (8) = \underline{\underline{0.66\ ft}} - \underline{\underline{2.9\ ft}}$$

CIRCULAR CULVERT

0.5-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0125\ \frac{D_o}{TW}\left(\frac{Q}{D_o^{5/2}}\right)^{4/3}$$

$$d_{50} = 0.0125\ (8/2)\ (2 - 6)^{4/3}\ (8) = \underline{\underline{1.0\ ft}} - \underline{\underline{4.4\ ft}}$$

(Continued)

1.0-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0082 \frac{D_o}{TW}\left(\frac{Q}{D_o^{5/2}}\right)^{4/3}$$

$$d_{50} = 0.0082\ (8/2)(2 - 6)^{4/3}\ (8) = \underline{\underline{0.66\ ft}} - \underline{\underline{2.9\ ft}}$$

See Figure A16 for geometry.

<u>Example 8 - Determine size and geometry of riprap-lined-channel expansion for minimum tailwaters (see Figure A21):</u>

RECTANGULAR CULVERT

$$\frac{d_{50}}{D_o} = 0.016 \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3}$$

$$d_{50} = 0.016\ (5/2)\ (3.2 - 9.7)^{4/3}\ (5) = \underline{\underline{0.94\ ft}} - \underline{\underline{4.1\ ft}}$$

CIRCULAR CULVERT

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

$$d_{50} = 0.016\ (5/2)\ (2 - 6)^{4/3}\ (8) = \underline{\underline{0.81\ ft}} - \underline{\underline{3.5\ ft}}$$

See Figure A17 for geometry.

<u>Example 9 - Determine length and geometry of a flared outlet transition for minimum tailwaters:</u>

RECTANGULAR CULVERT

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

$$L = \left[0.3\ (5/2)^2\ (3.2 - 9.7)^{2.5(2/5)^{1/3}}\right] 5 = \underline{\underline{80\ ft}} - \underline{\underline{616\ ft}}$$

(Continued)

CIRCULAR CULVERT

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

$$L = \left[0.3\ (8/2)^2\ (2 - 6)^{2.5(2/8)^{1/3}}\right] 8 = \underline{\underline{114\ ft}} - \underline{\underline{645\ ft}}$$

See Figure A22 for geometric details; above equations developed for $H = 0$ or horizontal apron at outlet invert elevation without an end sill.

Example 10 - Determine diameter of stilling well required downstream of the 8-ft-diam outlet:

From page A27

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

$$D_W = 0.53\ (2 - 6)\ 8 = \underline{\underline{8.5\ ft}} - \underline{\underline{25.4\ ft}}$$

See Figure A25 for additional dimensions.

Example 11 - Determine width of USBR type VI basin required downstream of the 8-ft-diam outlet:

From page A27

$$\frac{W_{VI}}{D_o} = 1.30\left(\frac{Q}{D_o^{5/2}}\right)^{0.55}$$

$$W_{VI} = \left[1.3\ (2 - 6)^{0.55}\right] 8 = \underline{\underline{15.2\ ft}} - \underline{\underline{27.9\ ft}}$$

See Figure A26 for additional dimensions.

Example 12 - Determine width of SAF basin required downstream of the 8-ft-diam outlet

From page A27

$$\frac{W_{SAF}}{D_o} = 0.30\left(\frac{Q}{D_o^{5/2}}\right)^{1.0}$$

(Continued)

$$W_{SAF} = 0.30\ (2 - 6)\ 8 = \underline{4.8\ ft} - \underline{14.4\ ft}$$

See Figure A27 for additional dimensions.

Example 13 - Determine size of riprap required downstream of 8-ft-diam culvert and 14.4-ft-wide SAF basin with discharge of 1086 cfs:

$$q = \frac{Q}{W_{SAF}} = \frac{1086}{14.4} = 75\ cfs/ft$$

$$V_1 = \frac{Q}{A} = \frac{1086}{0.785(8)^2} = 21.6\ fps$$

$$d_1 = \frac{q}{V_1} = \frac{75}{21.6} = 3.5\ ft$$

$$d_2 = 8.4\ ft\ \text{(from conjugate depth relations)}$$

MINIMUM TAILWATER REQUIRED FOR A HYDRAULIC JUMP = 0.90 (8.4) = 7.6 ft

From page A27

$$\frac{d_{50}}{D_e} = 1.0 \left(\frac{V_e}{\sqrt{gD_e}} \right)^3$$

$$V_e = \frac{q}{D_e} = \frac{75}{7.6} = 9.9\ fps$$

$$d_{50} = 1.0 \left[\frac{9.9}{\sqrt{32.2(7.6)}} \right]^3 7.6$$

$$d_{50} = \underline{1.9\ ft}$$

APPENDIX B: NOTATION

A Cross-sectional area of flow, ft^2

A_c Rectangular culvert aspect ratio, W_o/D_o

A_d Ratio of depth of flow to height of rectangular or square culvert or diameter of circular culvert d/D_o

A_r Ratio of area of flow to the square of the culvert height, $A_c A_d$

B Base width of channel, ft

C Coefficient

d Depth of uniform flow in culvert, ft

d_1 Depth of flow upstream of hydraulic jump, ft

d_2 Theoretical depth of flow required for hydraulic jump, ft

d_{50} Diameter of average size stone, ft

D Depth of flow in channel, ft

D_e Depth of flow exiting energy dissipator, ft

D_o Height of rectangular, width and height of square, and diameter of circular culverts, ft

D_s Depth of scour, ft

D_{sm} Maximum depth of scour, ft

D_W Diameter of stilling well, 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

K, K_2 Coefficients

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 per foot of outlet width, cfs/ft

Q Discharge, cfs

S Slope of channel bottom for partial pipe flow and slope of energy gradient for full pipe flow

t Duration of flow, minutes

T Top width of flow in channel, ft

T_B Thickness of geometrically similar cellular block, ft

T_S Thickness of geometrically similar sack revetment, ft

T_W Depth of stilling well below invert of incoming pipe, ft

TW Tailwater depth above invert of culvert outlet, ft

V Average velocity of flow in channel, fps

V_e Average velocity of flow exiting energy dissipator, fps

V_s Volume of scour, ft^3

V_1 Average velocity of flow upstream of hydraulic jump, fps

W_o Width of rectangular, square, or circular culvert, ft

W_s Width of scour from center line of single circular or square outlet

W_{sm} One-half maximum width of scour from center line of single circular or square outlet, ft

W_{smr} One-half maximum width of scour from center line of single rectangular outlet or a multiple outlet installation, ft

$$W_{smr} = W_{sm} + \frac{W_o}{2} - \frac{D_o}{2}$$

W_{sp} Width of stone protection, ft

W_{sr} Width of scour from center line of single rectangular outlet or a multiple outlet installation, ft

$$W_{sr} = W_s + \frac{W_o}{2} - \frac{D_o}{2}$$

W_{VI} Width of U. S. Bureau of Reclamation type VI basin, ft

W_{SAF} Width of St. Anthony Falls stilling basin, ft