SUBDIVISION REGULATION APPENDICES

TOWN OF WATERTOWN
PLANNING & ZONING COMMISSION

Original Effective Date: May 1, 1955
Revisions to: September 30, 2011

Note: Some of the Subdivision Appendices are included at the end of the Subdivision Regulations document and are not included in this document.

TOWN OF WATERTOWN

SUBDIVISION REGULATIONS APPENDICES

For Informational Purposes
And Are Not Part of the Subdivision Regulations

APPENDIX A

Title Block and Construction Details

APPENDIX A

TABLE OF CONTENTS

NOTES

1. USE THE SAME LINE QUALITY AS THAT SHOWN IN THE EXAMPLE TITLE BLOCK.
2. SEE DETAIL NO. 2 FOR LOCATION OF TITLE BLOCK.
3. LEAVE FILE NO. BLANK.

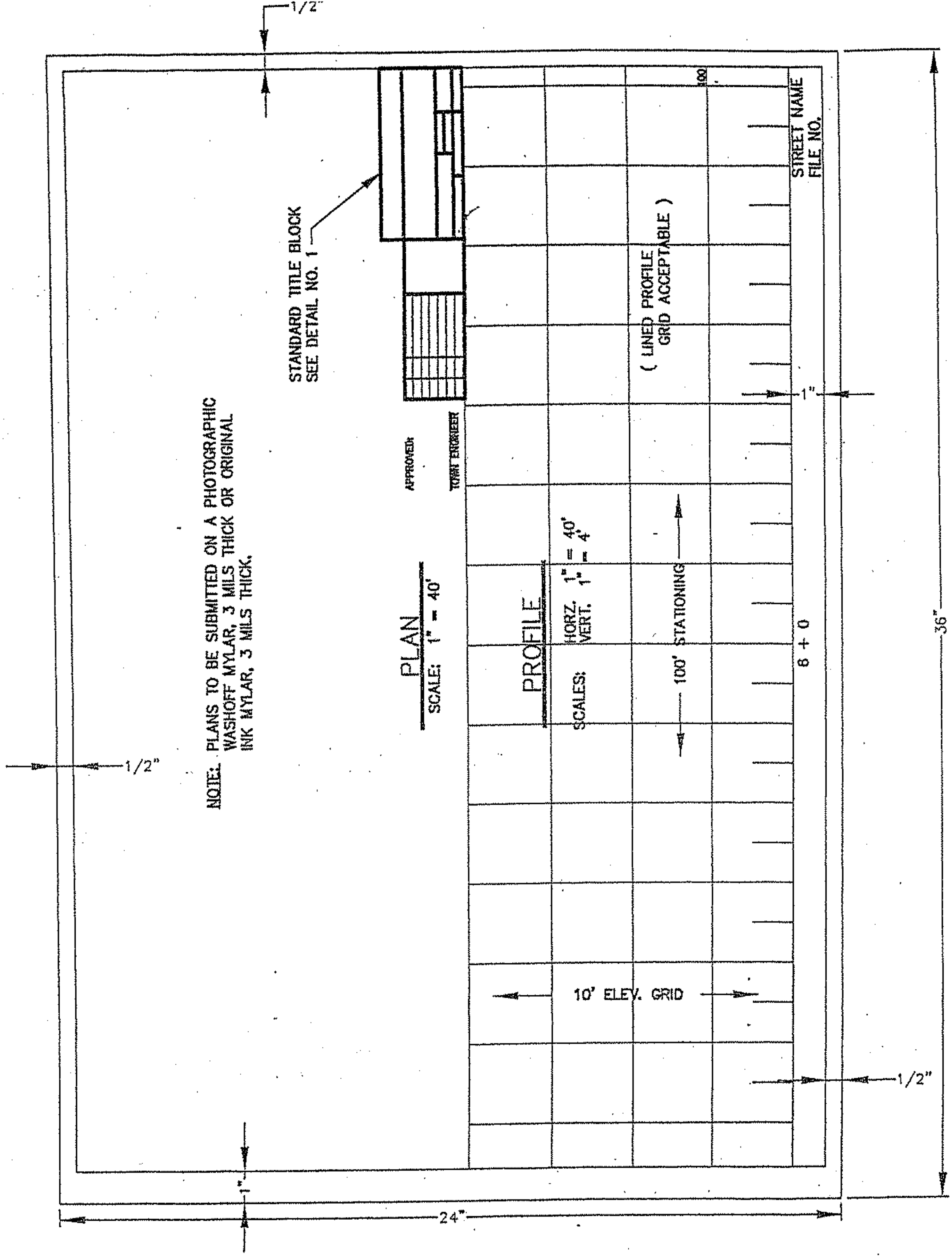
			(STAMP)
DATE	BY	REVISION	

MATCH LINE

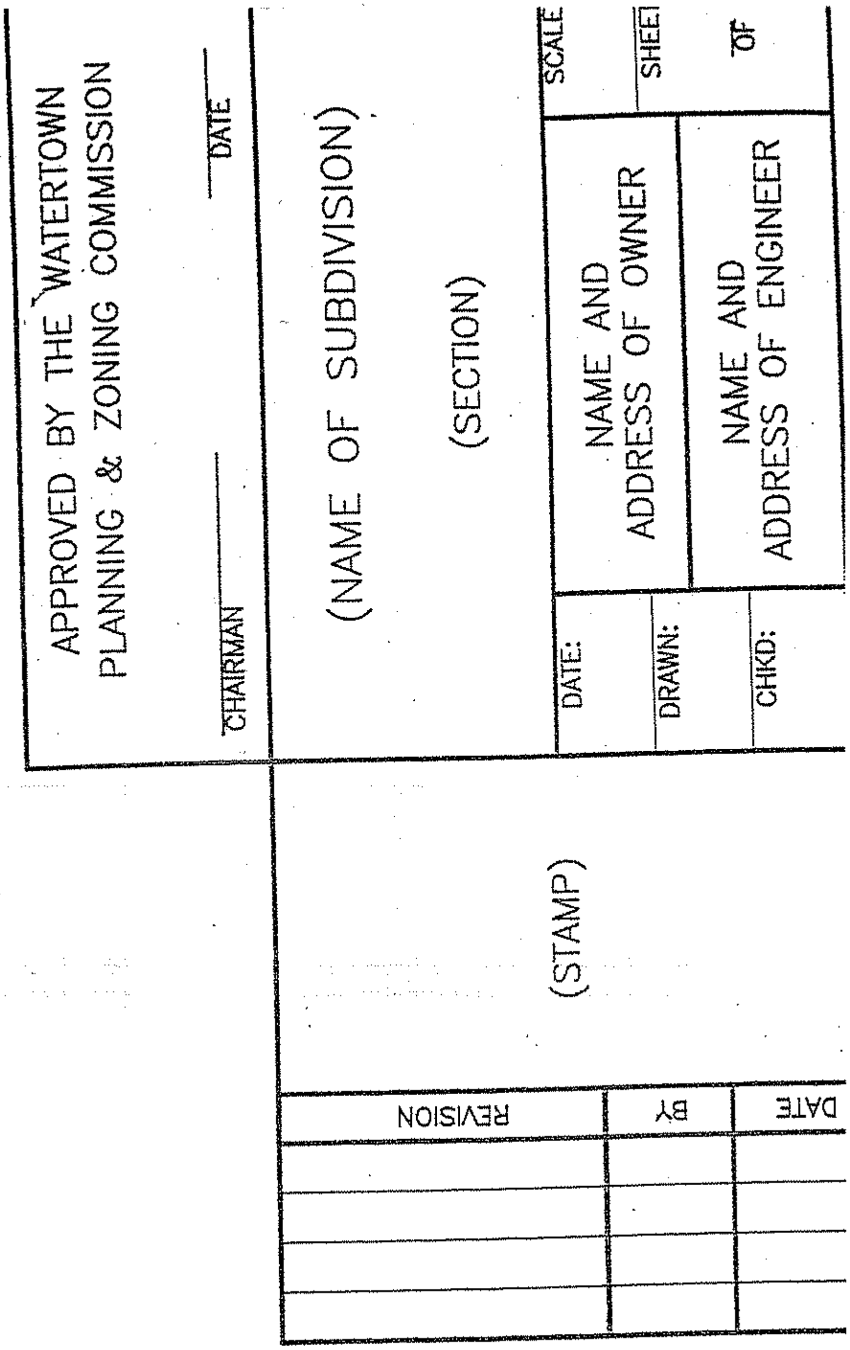
MATCH LINE

TOWN OF WATERTOWN ROADWAY IMPROVEMENTS		
(STREET NAME) (STATIONING OF STREET)		
(NAME & ADDESS OF ENGINEER)	DRWN. BY: CHKD. BY:	SHEET OF
DATE:	FIELD BOOK: PG.:	FILE NO.:

TOWN OF WATERTOWN ENGINEERING DEPT. WATERTOWN, CT	*STANDARD TITLE BLOCK (For Streets)*	SCALE: FULL	DATE: 1/96	REVISION –
		DETAIL NO. 1	CAD FILE SUBDREGS\DET1	
			APPENDIX A– 1	

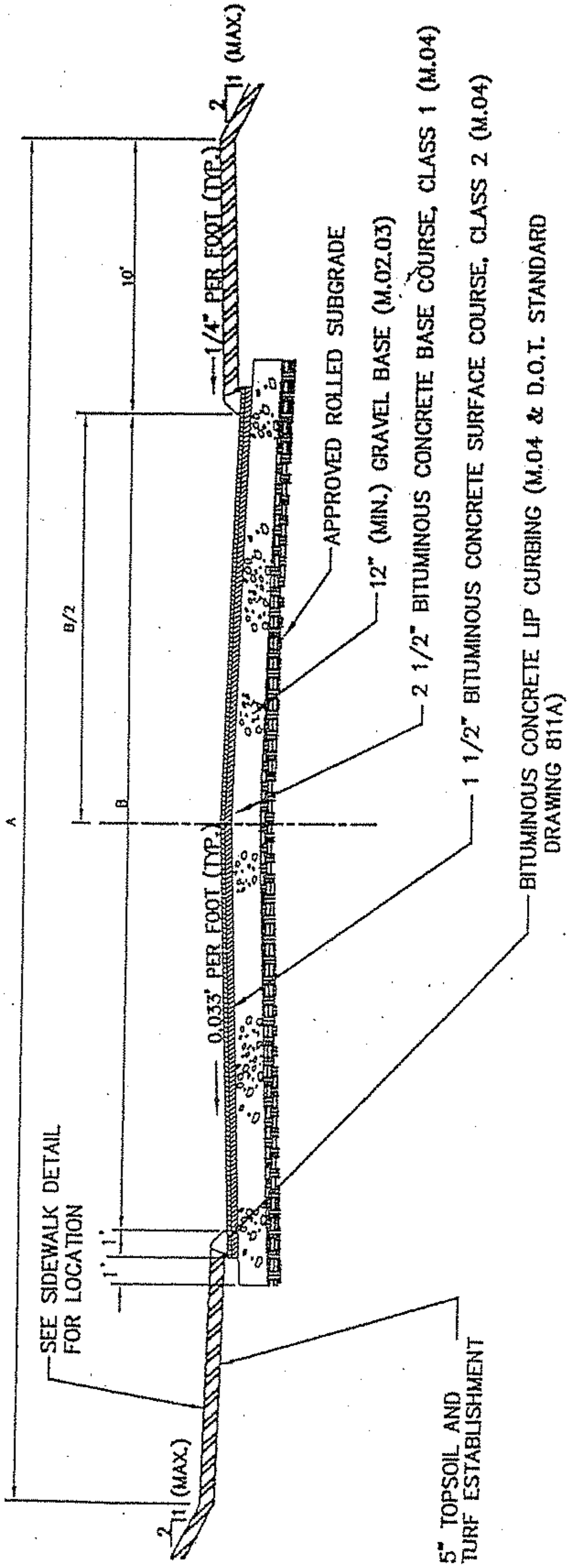


TOWN OF WATERTOWN ENGINEERING DEPT. WATERTOWN, CT	STANDARD SHEET LAYOUT FOR STREETS	SCALE: N.T.S.	DATE: 1/96	REVISION —
		DETAIL NO. 2	CAD FILE SUBDREGS\DET2 APPENDIX A— 2	



NOTES:
1. USE THE SAME LINE QUALITY AS THAT SHOWN IN SAMPLE TITLE BLOCK.
2. LEAVE FILE NO. BLANK.

TOWN OF WATERTOWN ENGINEERING DEPT. WATERTOWN, CT	STANDARD TITLE BLOCK FOR SUBDIVISIONS	SCALE: FULL	DATE: 1/96	REVISION –
		DETAIL NO. 3	CAD FILE SUBDREGS\DET3 APPENDIX A– 3	

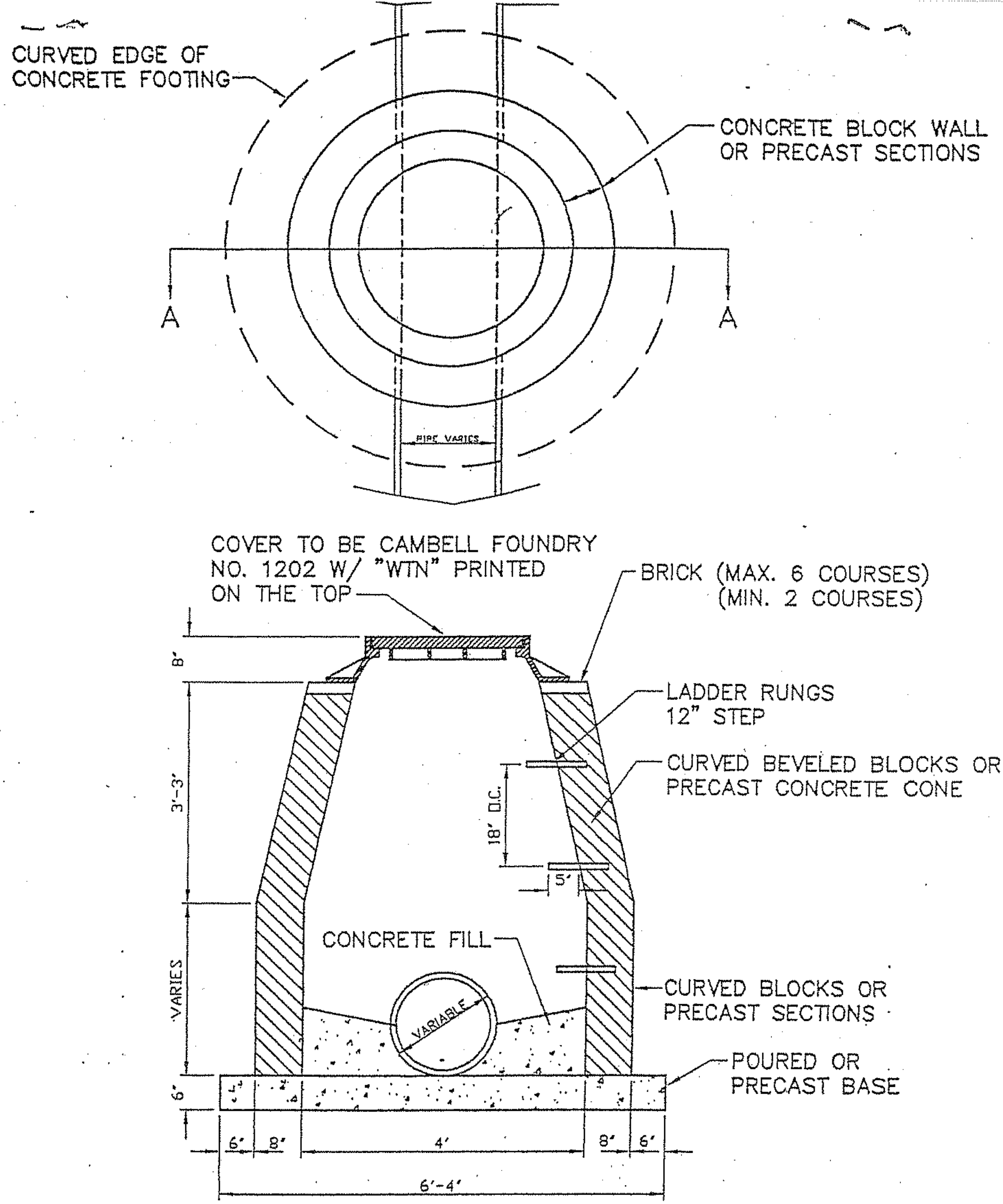


		LOCAL	COMMERCIAL & INDUSTRIAL	THOROUGH FARE	PRIVATE
RIGHT OF WAY	A	50'	60'	60'	50'
PAVING WIDTH (CURB TO CURB)	B	30'	40'	40'	30'

SPECIFICATION REFERENCE: CT D.O.T. FORM 814

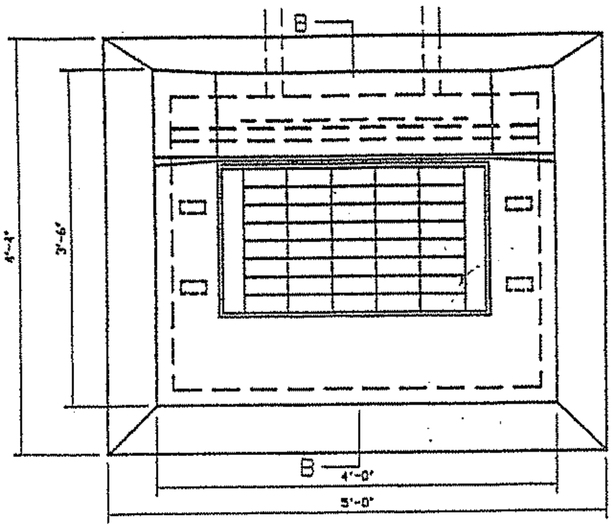
(5-98 REV. TOPSOIL - NOTE)
(5-97 REV. CROSS SLOPE - TYPO)

TOWN OF WATERTOWN	STANDARD STREET CROSS SECTION	SCALE: NONE	DATE: 1/96	REVISION 5-97
ENGINEERING DEPT. WATERTOWN, CT		DETAIL NO. 4	CAD FILE SUBDREGS\DET4 APPENDIX A- 4	



SECTION A–A

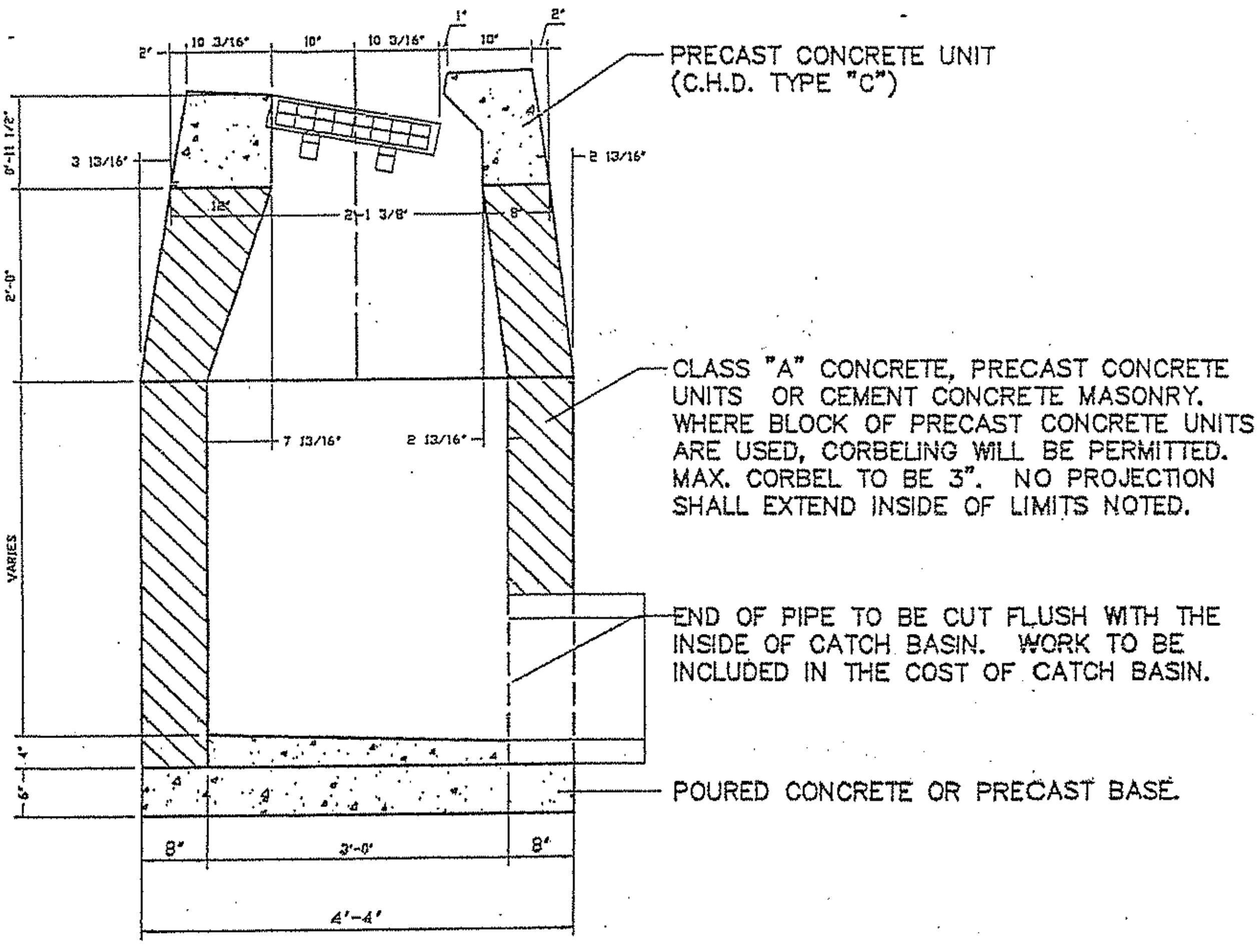
TOWN OF /ATERTOWN	*STANDARD STORM MANHOLE*	SCALE: 1/2"=1'-0"	DATE: 1/96	REVISION —
;INEERING DEPT. ATERTOWN, CT		DETAIL NO. 5	CAD FILE \SUBDREGS\DET5	
			APPENDIX A– 5	



PLAN VIEW

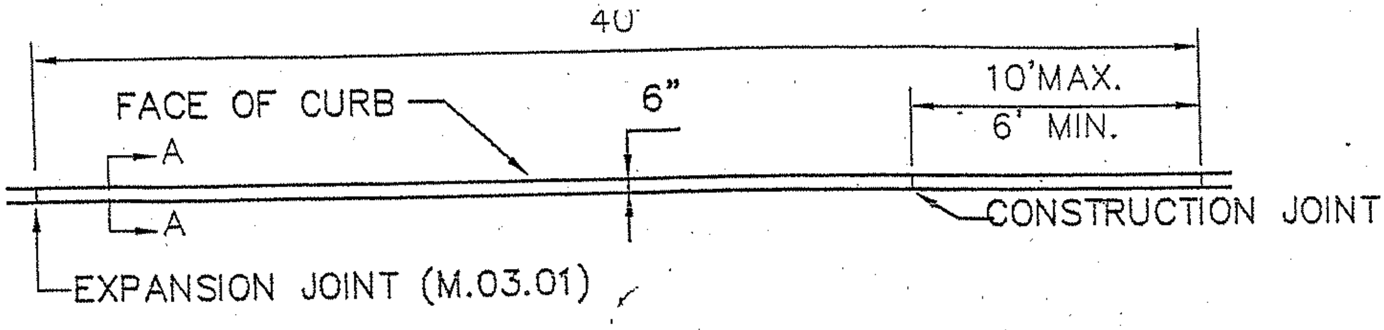
NOTE:

1. WALLS OF ALL CATCH BASINS OVER 10' DEEP SHALL BE INCREASED TO 12" THICKNESS.
2. SUMPS MAY BE REQUIRED AT LOCATIONS SPECIFIED BY THE TOWN ENGINEER.
3. BACKFILL BASINS WITH GRAVEL. LEAVE WEEP JOINTS AT LEVELS ABOVE TOP OF PIPE.

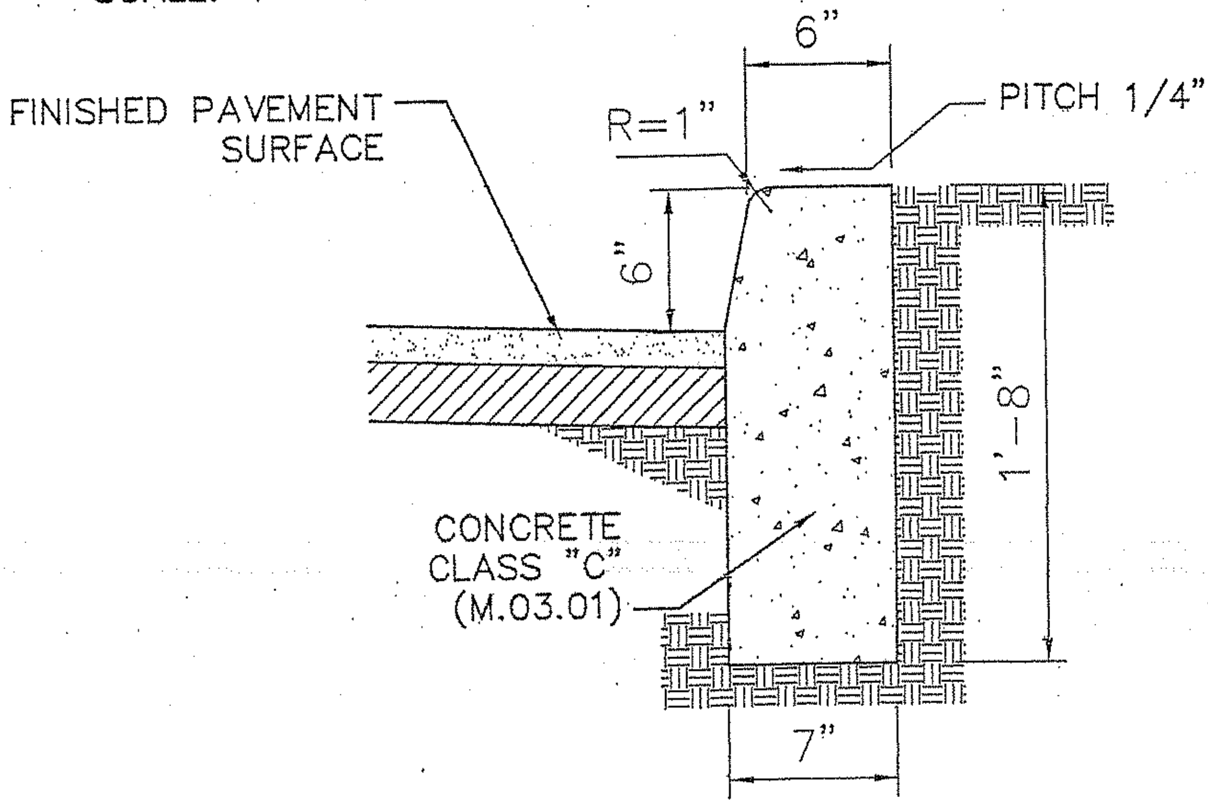


SECTION B–B

TOWN OF WATERTOWN	STANDARD TYPE "C" DROP INLET	SCALE: 1/2"=1'–0"	DATE: 1/96	REVISION —
ENGINEERING DEPT. WATERTOWN, CT		DETAIL NO. 6	CAD FILE SUBDREGS\DET6	APPENDIX A– 6



PLAN VIEW
SCALE: 1" = 8'



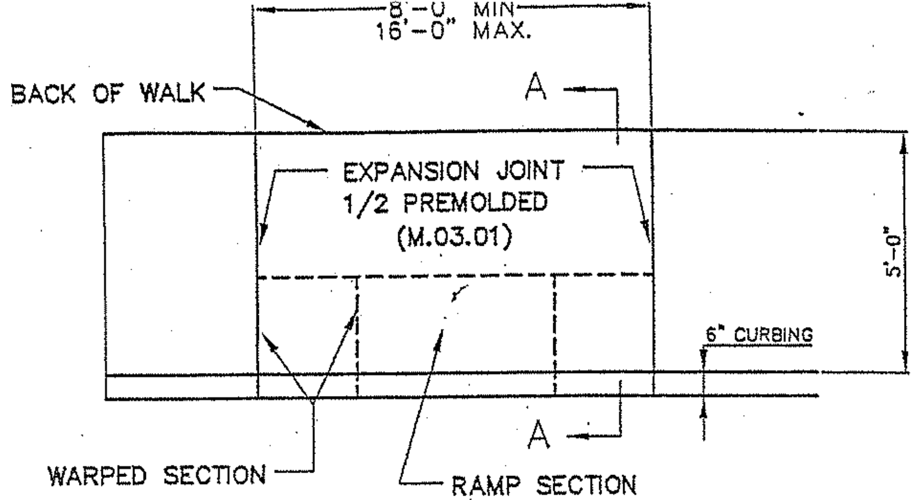
SECTION A-A
SCALE: 1 1/2" = 1' - 0"

GENERAL NOTES

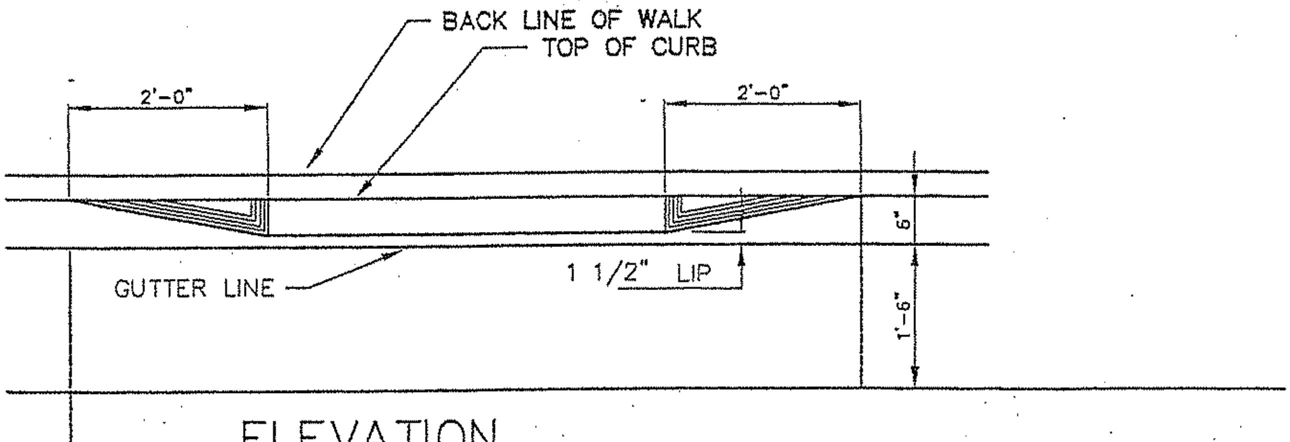
1. CONCRETE SHALL BE "CLASS C" AND SHALL CONTAIN 5 TO 7 PERCENT ENTRAINED AIR.
2. EXPANSION JOINTS SHALL BE MADE OF PREFORMED BITUMINIOUS JOINT FILLER 1/2" THICK AND SHALL BE INSTALLED EVERY 40 FEET.
3. ALL EXPOSED SURFACES SHALL BE FLOAT FINISHED.
4. MINIMUM LENGTH OF CURB SECTION SHALL BE 6 FEET.

SPECIFICATION REFERENCE: CT D.O.T. FORM 814

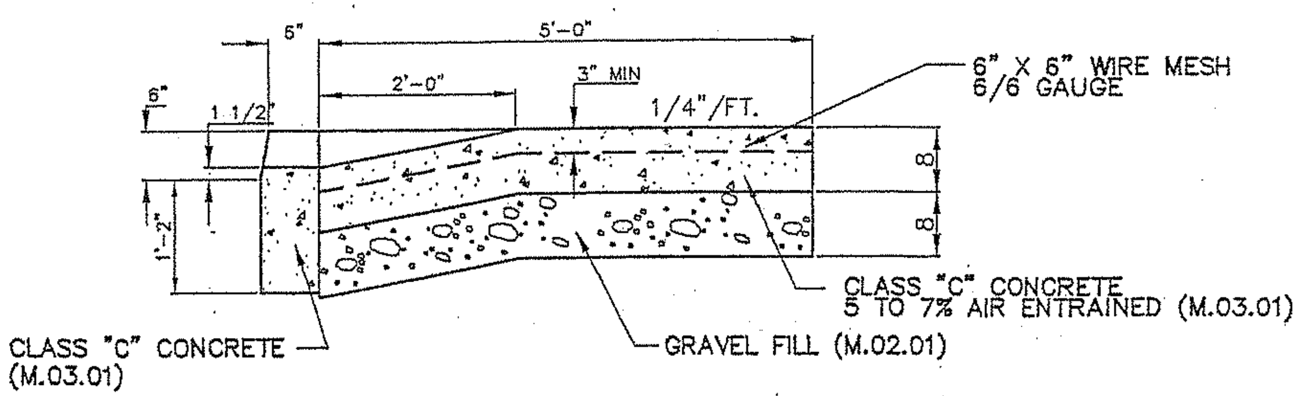
TOWN OF WATERTOWN	*CEMENT CONCRETE CURBING*	SCALE: 1.5"=1'-0"	DATE: 1/96	REVISION -
ENGINEERING DEPT. WATERTOWN, CT		DETAIL NO. 7	CAD FILE SUBDREGS\DET7	
			APPENDIX A- 7	



PLAN VIEW
1/4" = 1'-0"



ELEVATION
1/2" = 1'-0'



SECTION A-A
1/2" = 1'-0"

NOTE: THIS DETAIL APPLIES WHERE CEMENT CONCRETE SIDEWALK ADJOINS CURBING

SPECIFICATION REFERENCE
CT D.O.T. FORM 814

TOWN OF WATERTOWN	*STANDARD DRIVEWAY CONC. RAMP*	SCALE: 1/2"=1'-0"	DATE: 1/96	REVISION —
ENGINEERING DEPT. WATERTOWN, CT		DETAIL NO. 8	CAD FILE SUBDREGS\DET8	
			APPENDIX A— 8	

GENERAL NOTES:

1. DRIVEWAY ENTRANCE SHALL BE A MINIMUM OF 12' (3658) WIDE, EXCLUDING CURBING WHEN PRESENT.
2. SIDEWALK RAMPS SHALL BE A MINIMUM OF 36" (914) TO 40" (1016) MAXIMUM, WITH A MAXIMUM SLOPE OF 12:1. THERE SHALL BE NO LIP AT THE DRIVEWAY SIDEWALK INTERFACE.
3. WELDED WIRE FABRIC MATS WITH REINFORCING AT CLOSER SPACING MAY BE USED.

ALL METRIC DIMENSIONS ARE IN MILLIMETERS (mm) UNLESS OTHERWISE NOTED

REV.	DATE	REVISION DESCRIPTION
1	6/01/10	REVISED BORDER TITLE
2	6/01/10	REVISED HALF ELEVATION DETAILS
-	-	-
-	-	-
-	-	-

THE INFORMATION, INCLUDING ESTIMATED QUANTITIES OF WORK, SHOWN ON THESE SHEETS IS BASED ON LIMITED INVESTIGATIONS BY THE STATE AND IS IN NO WAY WARRANTED TO INDICATE THE CONDITIONS OF ACTUAL QUANTITIES OF WORK WHICH WILL BE REQUIRED.

Plotted Date: 5/21/2010

NOT TO SCALE

STATE OF CONNECTICUT
DEPARTMENT OF TRANSPORTATION

Filename: CTDOT_HIGHWAY_STD.dgn Model: HW-921_01

SUBMITTED BY: NAME/DATE/TIME: Leo Fontaine 2010.05.28 10:29:33 -04'00'

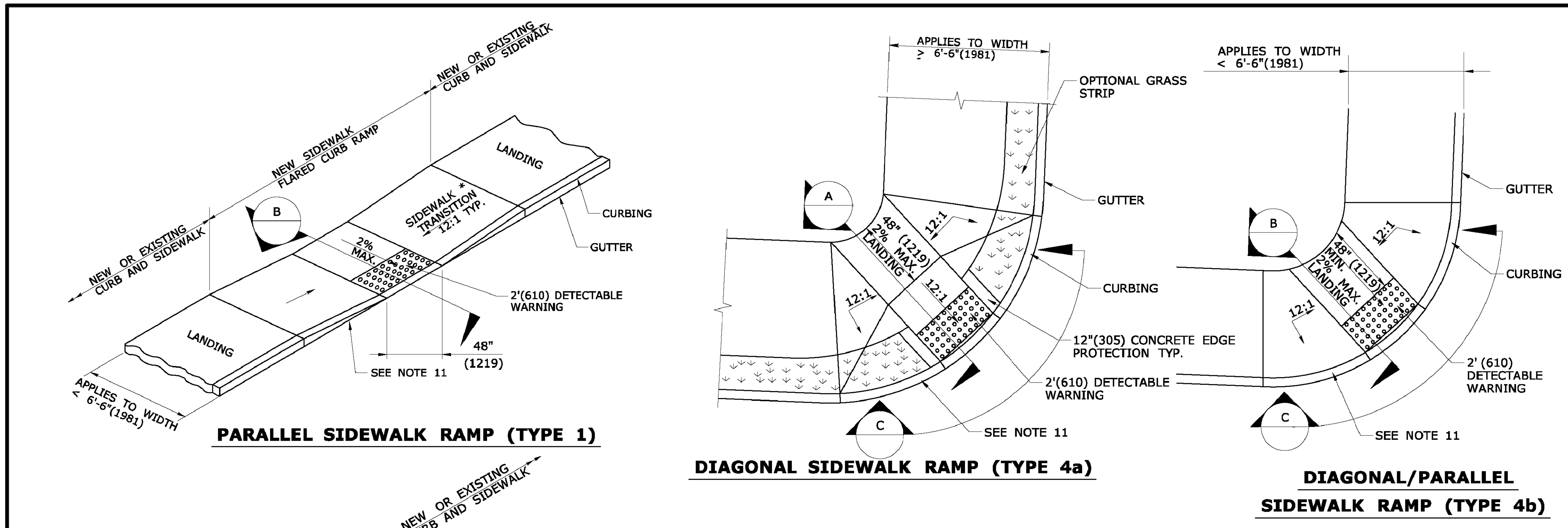
APPROVED BY: NAME/DATE/TIME: James H. Norman

CTDOT STANDARD SHEET
OFFICE OF ENGINEERING

STANDARD SHEET TITLE: DRIVEWAY RAMPS AND SIDEWALKS

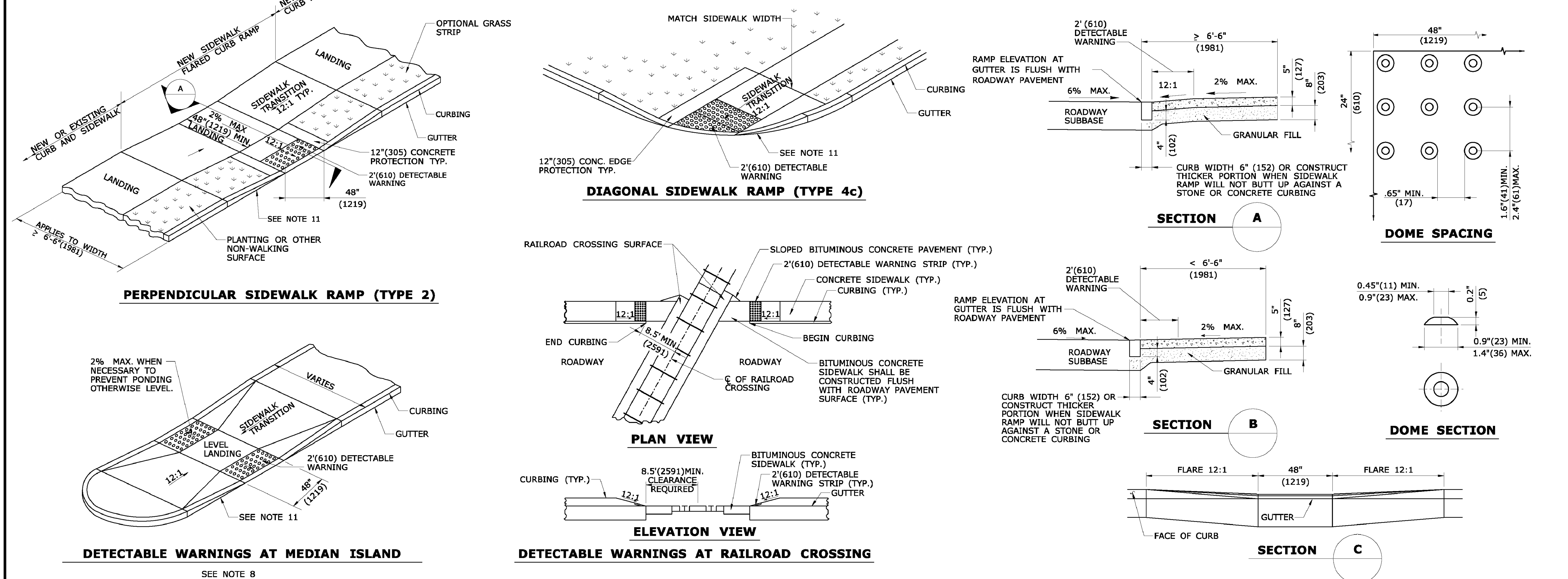
STANDARD SHEET NO.: HW-921_01

A-9-a



GENERAL NOTES:

1. MAXIMUM SLOPES OF ADJOINING GUTTERS AND ROAD SURFACES IMMEDIATELY ADJACENT TO THE SIDEWALK RAMP OR ACCESSIBLE ROUTE SHOULD NOT EXCEED 20:1.
2. CARE SHALL BE TAKEN TO ASSURE UNIFORM GRADE ON THE RAMP, FREE OF SAGS AND ABRUPT GRADE CHANGES.
3. ALL RAMPS SHALL BE CONSTRUCTED OF CLASS "C" CONCRETE IN ACCORDANCE WITH CONNECTICUT STANDARD SPECIFICATIONS ARTICLE M.03.01.
4. SIDEWALK RAMPS SHALL HAVE A COARSE BROOM FINISH TRANSVERSE TO THE SLOPE OF THE RAMP.
5. DIAGONAL SIDEWALK RAMPS AT MARKED CROSSINGS SHALL BE WHOLLY CONTAINED WITHIN THE MARKINGS, EXCLUDING ANY FLARED SIDES.
6. REMOVAL OF EXISTING SIDEWALK FOR NEW RAMP INSTALLATIONS SHALL BE TO THE NEAREST EXPANSION / CONTRACTION JOINT OR DUMMY JOINT. 12:1 MAY NOT BE ACHIEVABLE DUE TO SIDEWALK GRADE. IN RECOGNITION OF THIS, A MINIMUM LIMIT OF 15' (4.57m) FOR A PARALLEL RAMP SHALL BE USED. REMOVAL SHALL NOT BE FURTHER THAN 2' (610) FROM THE PROPOSED RAMP UNLESS DIRECTED BY THE ENGINEER. SAW CUT REQUIRED FOR DUMMY JOINTS SHALL BE INCLUDED IN THE COST OF "CONCRETE SIDEWALK".
7. EXPANSION JOINTS IN CONCRETE SHALL MATCH THOSE IN ADJACENT SIDEWALKS BUT IN NO CASE SHALL THE SPACING BETWEEN EXPANSION JOINTS EXCEED 12' (3.66m) UNLESS OTHERWISE NOTED.
8. RAISED MEDIAN ISLANDS IN MARKED CROSSINGS SHALL HAVE SIDEWALK RAMPS AT BOTH SIDES AND A LEVEL AREA AT LEAST 4' (1219) LONG BETWEEN THE RAMPS. IF THIS CAN NOT BE ACHIEVED, THE RAISED ISLAND SHALL BE CUT THROUGH LEVEL WITH THE ROADWAY AS SHOWN ON THE PLANS OR AS DIRECTED BY THE ENGINEER.
9. SIDEWALK RAMPS, WHEN CONSTRUCTED IN CONJUNCTION WITH SIDEWALK, SHALL BE PAID FOR UNDER THE ITEM "CONCRETE SIDEWALK", INCLUDING CURBING WITHIN THE LIMITS OF THE NEW SIDEWALK RAMP AND DETECTABLE WARNING STRIPS.WHEN JUST A SIDEWALK RAMP IS CONSTRUCTED, IT SHALL BE PAID FOR UNDER THE ITEM "SIDEWALK RAMP" INCLUDING CURBING WITHIN THE LIMITS OF THE NEW SIDEWALK AND DETECTABLE WARNING STRIP.
10. CURBING WITHIN THE LIMITS OF THE NEW SIDEWALK RAMP SHALL BE CONSTRUCTED IN CONFORMANCE WITH THE REQUIREMENTS OF FORM 816 SECTIONS 8.11 AND 8.13.
11. TRANSITION TO FULL HEIGHT CURB. INSTALL STONE CURBING IF ADJACENT CURBING IS STONE. INSTALL CONCRETE CURBING IF ADJACENT CURBING IS CONCRETE OR BITUMINOUS.
12. INSTALL THE EDGE OF THE DETECTABLE WARNING STRIP 6" (152) FROM THE EDGE OF ROAD.
13. TO PERMIT WHEELCHAIR WHEELS TO ROLL BETWEEN DOMES, ALIGN DOMES ON A SQUARE GRID IN THE DIRECTION OF PEDESTRIAN TRAVEL.



ALL METRIC DIMENSIONS ARE IN MILLIMETERS (mm) UNLESS OTHERWISE NOTED

REV.	DATE	REVISION DESCRIPTION
-	-	-
-	-	-
-	-	-
-	-	-
2	6/11	REVISE MAX GRADE CALL-OUTS TO SAY 2%
1	10/10	Revised Note 4 and removed note 11

THE INFORMATION, INCLUDING ESTIMATED QUANTITIES OF WORK, SHOWN ON THESE SHEETS IS BASED ON LIMITED INVESTIGATIONS BY THE STATE AND IS IN NO WAY WARRANTED TO INDICATE THE CONDITIONS OF ACTUAL QUANTITIES OF WORK WHICH WILL BE REQUIRED.

Plotted Date: 5/10/2011

NOT TO SCALE

STATE OF CONNECTICUT
DEPARTMENT OF TRANSPORTATION

Filename: CTDOT_HIGHWAY_STD_JUNE2011.dgn Model: 69 - HW-921_02

SUBMITTED BY: NAME/DATE/TIME:

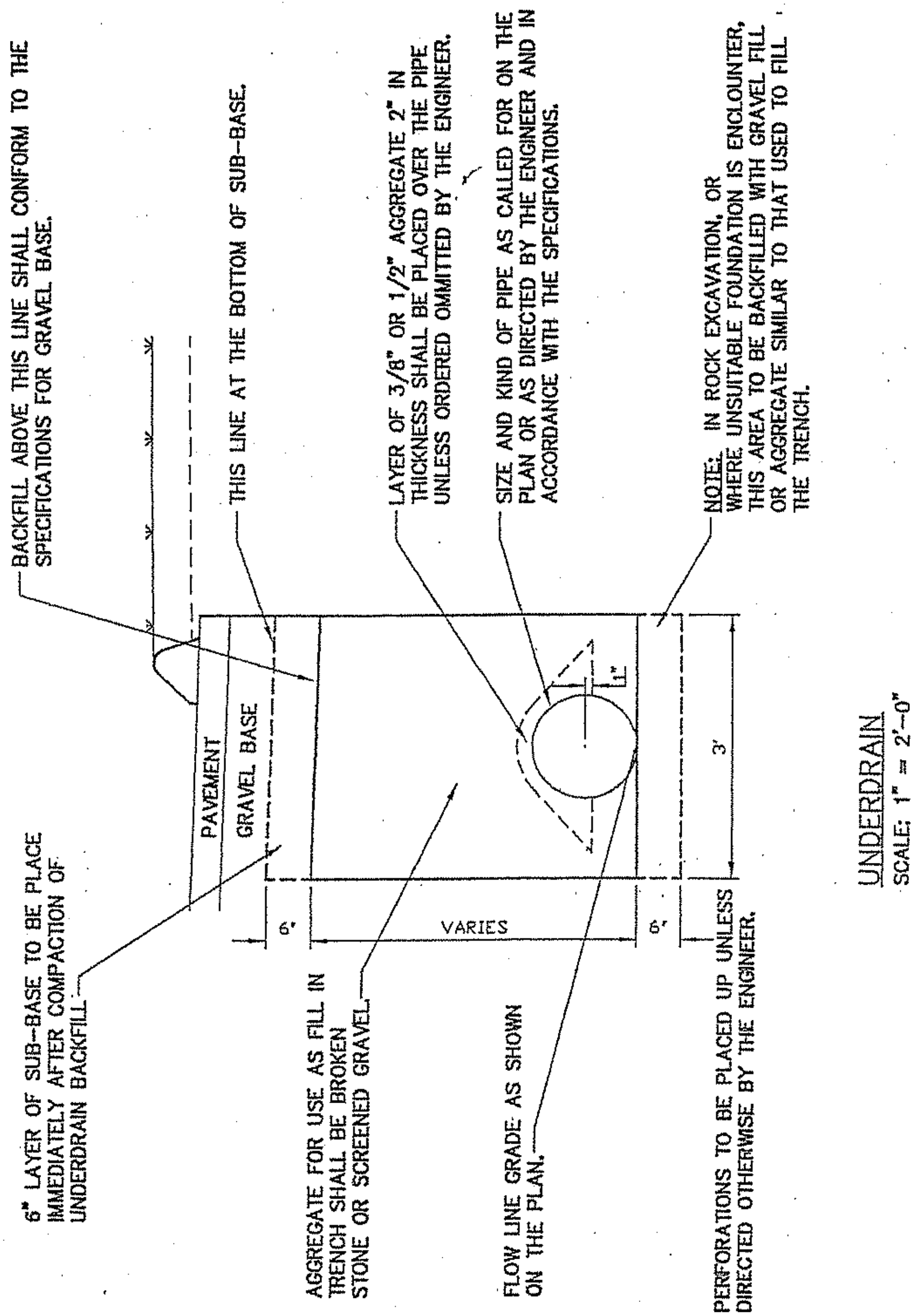
APPROVED BY: NAME/DATE/TIME:
James H. Norman
2011.06.09 15:37:11 -04'00'

CTDOT
STANDARD SHEET
OFFICE OF ENGINEERING

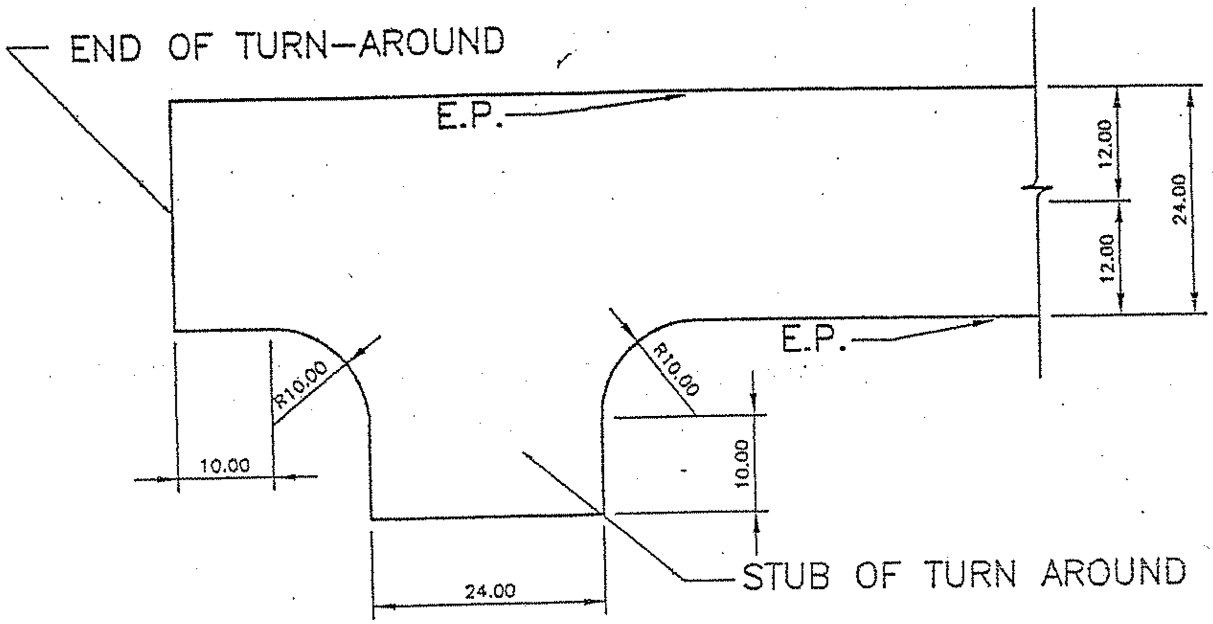
STANDARD SHEET TITLE:
SIDEWALK RAMPS

STANDARD SHEET NO.:
HW-921_02

A-9-b

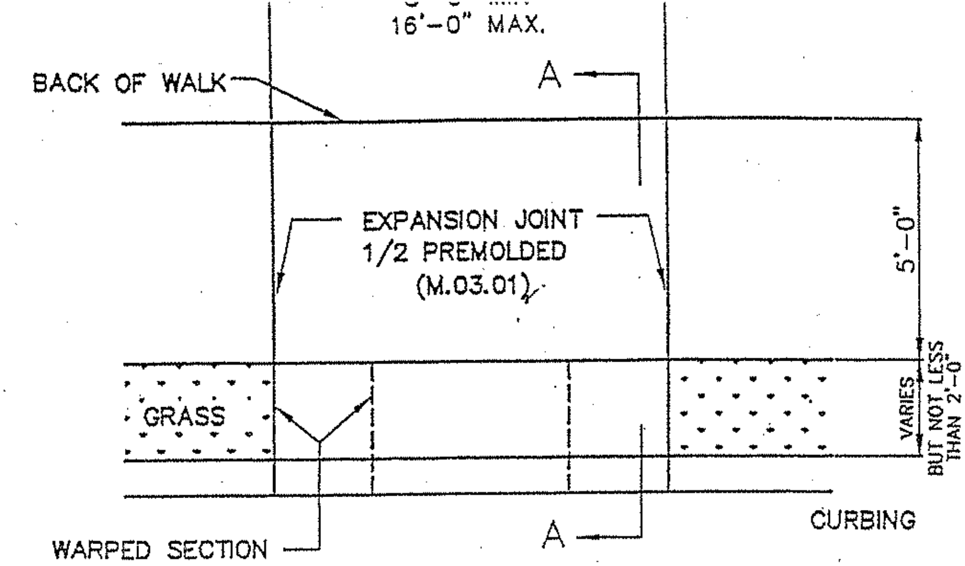


TOWN OF WATERTOWN	STANDARD UNDERDRAIN	SCALE: 1/2"=1'-0"	DATE: 1/96	REVISION –
ENGINEERING DEPT. WATERTOWN, CT		DETAIL NO. 10	CAD FILE SUBDREGS\DET10	
			APPENDIX A– 10	

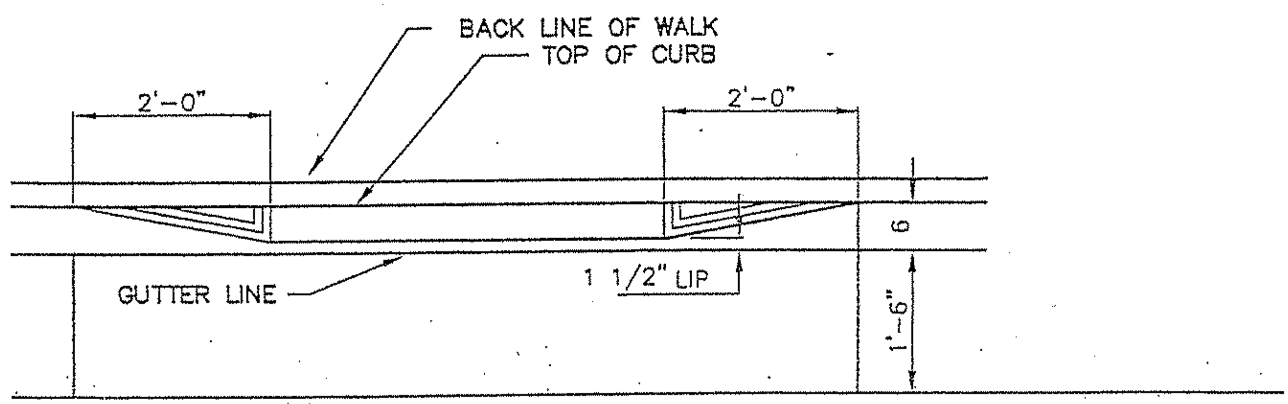


NOTE: E.P. = EDGE OF PAVEMENT

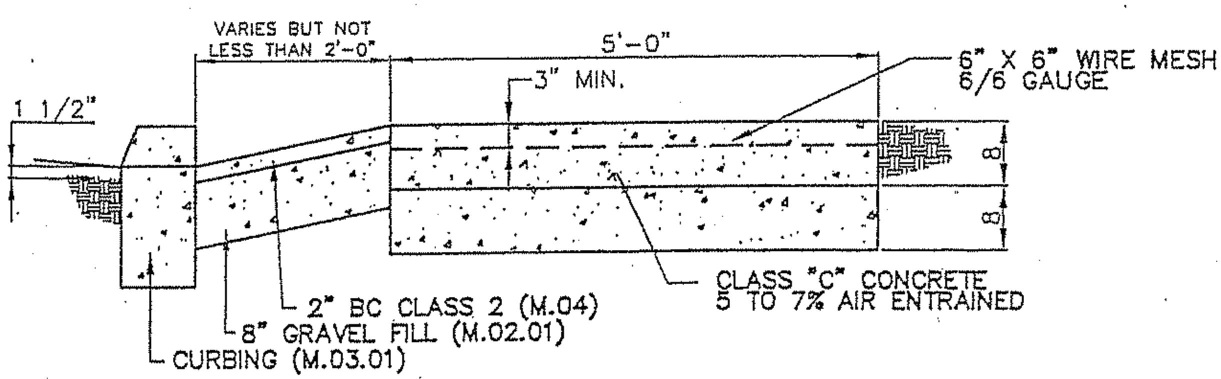
TOWN OF WATERTOWN ENGINEERING DEPT. WATERTOWN, CT	STANDARD HAMMERHEAD TURNAROUND	SCALE: 1"=20'	DATE: 1/96	REVISION –
		DETAIL NO. 11	CAD FILE SUBDREGS\DET11 APPENDIX A– 11	



PLAN VIEW
1/4" = 1'-0"



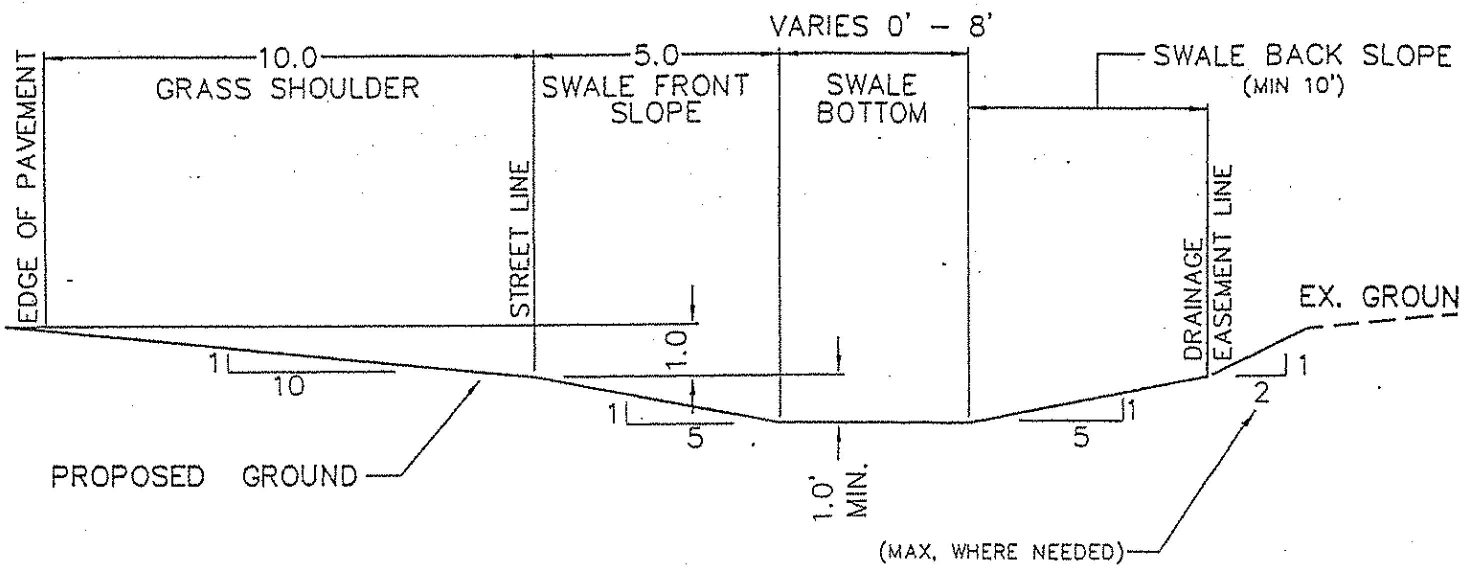
ELEVATION
1/2" = 1'-0'



SECTION A–A
1/2" = 1'-0"

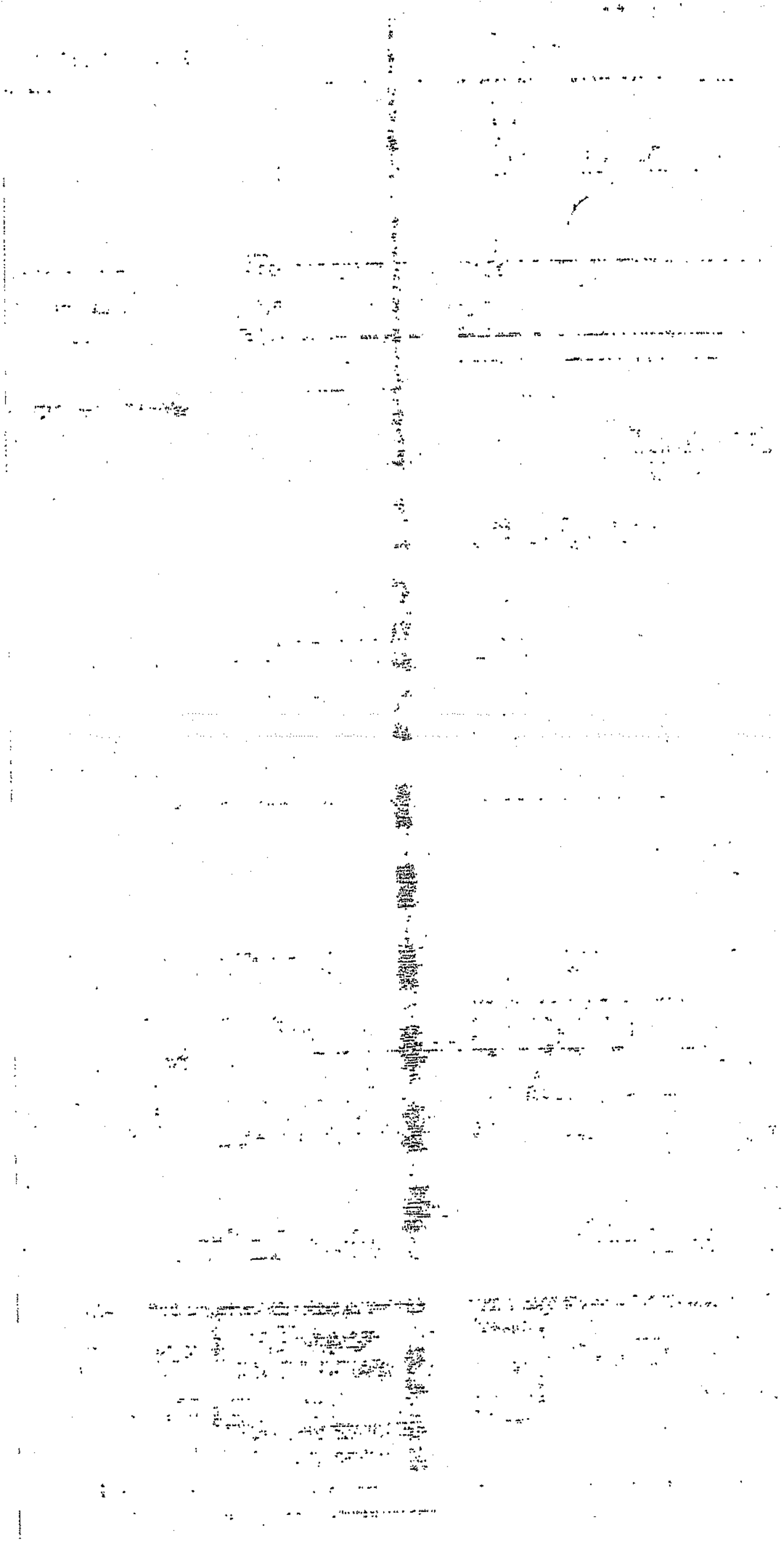
NOTE: SPECIFICATION REFERENCE
CT D.O.T. FORM 814

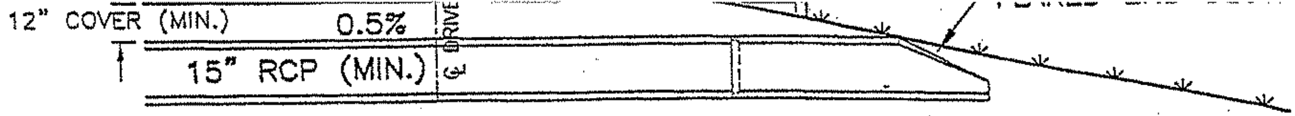
TOWN OF WATERTOWN ENGINEERING DEPT. WATERTOWN, CT	STANDARD DRIVEWAY RAMP W/ GRASS STRIP	SCALE: AS NOTED	DATE: 1/96	REVISION –
		DETAIL NO. 12	CAD FILE SUBDREGS\DET12 APPENDIX A– 12	



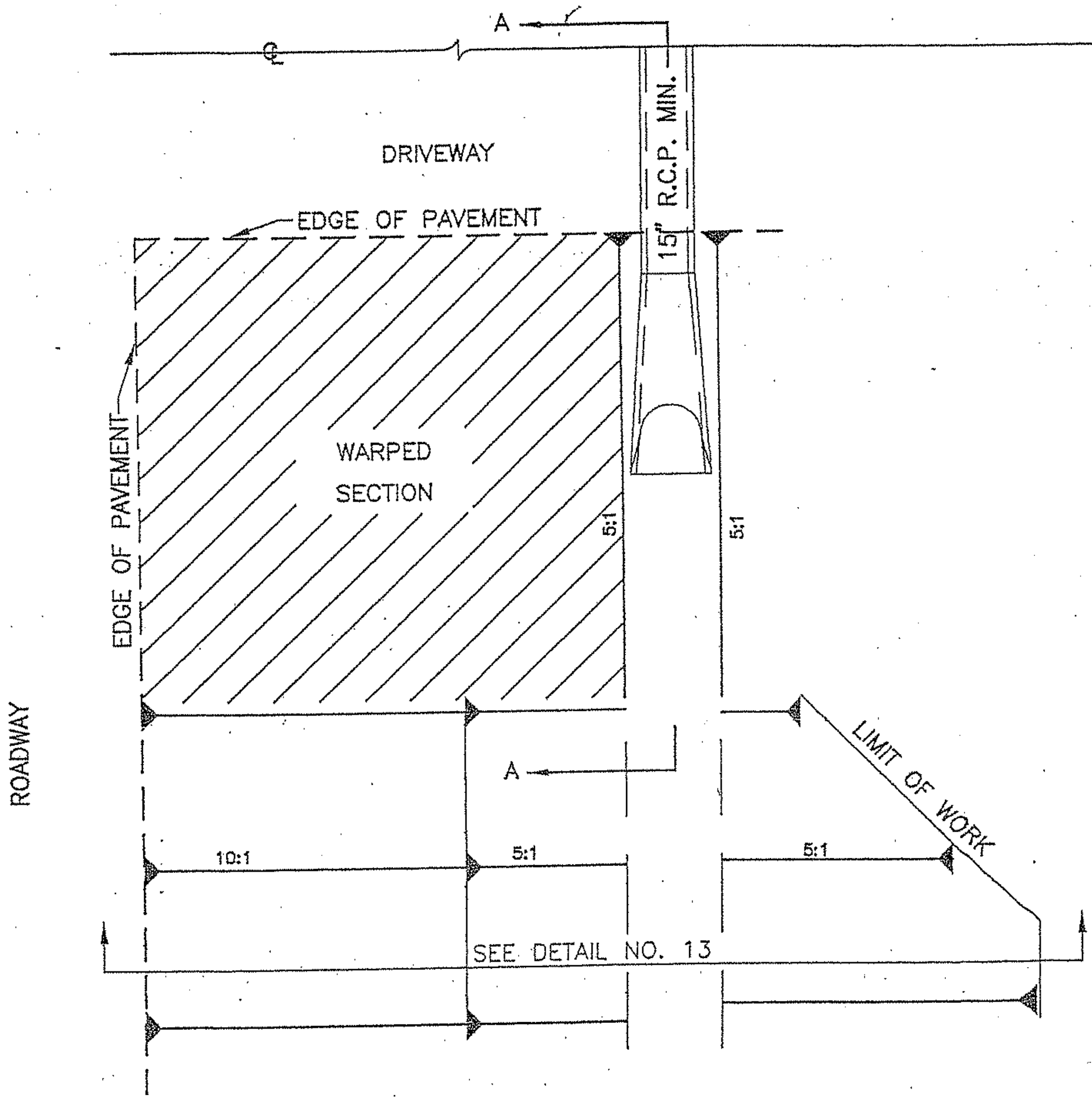
(5–97 REV. BACKSLOPE)

TOWN OF WATERTOWN ENGINEERING DEPT. WATERTOWN, CT	ROADSIDE SWALE DETAIL	SCALE: 1" = 4'	DATE: 1/96	REVISION 5 –97
		DETAIL NO. 13	CAD FILE SUBDREGS\DET13	
			APPENDIX A– 13	





SECTION A – A
SCALE: 1"=5'



PLAN VIEW
SCALE: 1"=5'

TOWN OF WATERTOWN	*DRIVEWAY CULVERT DETAIL*	SCALE: 1" = 5'	DATE: 1/96	REVISION –
ENGINEERING DEPT. WATERTOWN, CT		DETAIL NO. 14	CAD FILE SUBDREGS\DET1	
			APPENDIX A– 14	

APPENDIX B

Procedure for Evaluating Solar Access

PROCEDURE FOR EVALUATING SOLAR ACCESS

Drawings

PROCEDURE FOR EVALUATING SOLAR ACCESS

Section 1. Data Requirements for Solar Access Evaluation: The availability of south wall solar access protection shall be evaluated for all proposed building locations using the solar access setback overlay. In order to use the solar access setback overlay it is necessary to first determine the following:

1. The orientation and slope of the land to the south side of the proposed building site.
2. The direction of true north on the map.
3. The scale of the map.

Based on these factors the applicant shall evaluate solar access assuming the following heights for buildings, and trees located within lines drawn at a 45 degree azimuth of true south from the southerly corners of the south wall of the building:

Shadow Casting Objects	Assumed Height for Purposes of Evaluating Solar Access
1. Buildings	35 feet
2. Evergreen Trees	50 feet

The solar access setback overlays have been developed for application on subdivision maps that have a scale of one inch equals 100 feet and one inch equals 40 feet. If other mapping scales are used for the subdivision map, the applicant must develop his/her own solar access setback overlays using the shadow projection data contained in Table 1.

Section 2. Procedure for Evaluating Solar Access The applicant shall select the appropriate solar access setback overlay by determining the slope and orientation of land to the south of the proposed building. A total of 30 different overlays are available for the eight points of the compass and for five different slope conditions. Select the overlay which comes nearest to the exact orientation and slope of the land. Place the overlay on the subdivision map so that the south arrow on the overlay points in the opposite direction from the true north arrow on the map. Then line up the grid line at the apex of the solar access setback overlay so that it touches the corner of the south wall of the proposed building for which solar access is being evaluated. Next, move the solar access setback overlay to the opposite corner of the south wall. If any building falls within the 35 foot solar access setback line using this procedure the applicant must reconsider the location of one or both proposed buildings to provide unobstructed solar access to the south wall of the proposed building for which solar access is being evaluated. (See Figure 1.)

After evaluating the possible shadows cast by buildings the applicant shall evaluate the shadows that could be cast by evergreen trees. Use the 50 foot zone on the solar access setback overlay to determine the minimum setback for evergreen trees. No evergreen tree shall be allowed in the zone delineated by the 50 foot line on the solar access setback overlay unless the applicant has included solar easements or restrictive covenants with the deeds of each lot to guarantee each lot owner control over solar access to the south wall of the proposed building between the hours of 8:34 A.M. local time and 3:08 P. M. local time.

Section 3 <u>Review and Variance by Planning and Zoning Commission</u> The Planning and Zoning Commission will review the proposed building locations to ensure that solar access is available for 75 percent of the time between 8:34 A.M. and 3:08 P. M. local time on December 21st. Where this minimum level of solar access protection is not available, after due consideration has been given to locating the proposed building in the most favorable area on the lot for protecting solar access, then the Commission may waive the solar access requirements of the subdivision regulations. All lots that do not meet the solar access requirements of the regulations shall be listed on the subdivision map with the notation "Full south wall solar access not available on lots....."

Shadow Length Table for December 21st for A One Foot Pole
for 41° 20' Latitude and Slopes in Connecticut
(Assumes Morning and Afternoon Evaluations Correspond to 45 Degree Azimuths)

	N			NE			E			SE			S			SW			W			NW		
Slope	A.M.	NOON	P.M.	A.M.	NOON	P.M.	A.M.	NOON	P.M.	A.M.	NOON	P.M.	A.M.	NOON	P.M.	A.M.	NOON	P.M.	A.M.	NOON	P.M.	A.M.	NOON	P.M.
0%	5.29	2.14	5.29	5.29	2.14	5.29	5.29	2.14	5.29	5.29	2.14	5.29	5.29	2.14	5.29	5.29	2.14	5.29	5.29	2.14	5.29	5.29	2.14	5.29
5%	6.50	2.40	6.50	5.29	2.32	7.19	4.46	2.14	6.50	4.18	1.99	5.29	4.46	1.93	4.46	5.29	1.99	4.18	6.50	2.14	4.46	7.19	2.32	5.29
10%	8.44	2.72	8.44	5.29	2.52	11.22	3.85	2.14	8.44	3.46	1.06	5.29	3.85	1.76	3.85	5.29	1.06	3.46	8.44	2.14	3.85	11.22	2.52	5.29
15%	12.04	3.15	12.04	5.29	2.77	25.55	3.39	2.14	12.04	2.95	1.74	5.29	3.39	1.62	3.39	5.29	1.74	2.95	12.04	2.14	3.39	25.55	2.77	5.29
20%	20.96	3.74	20.96	5.29	3.07	***	3.03	2.14	20.96	2.57	1.64	5.29	3.03	1.50	3.03	5.29	1.64	2.57	20.96	2.14	3.03	***	3.07	5.29
25%	80.93	4.60	80.93	5.29	3.44	***	2.73	2.14	80.93	2.28	1.55	5.29	2.73	1.39	2.73	5.29	1.55	2.28	80.93	2.14	2.73	***	3.44	5.29

Note: The a.m. time refers to 8:43 solar time, the p.m. time refers to 3:17 solar time and the noon time refers to 12:00 Noon solar time. The a.m. and p.m. times correspond to 45 degree azimuths that are used to define the day's period of usable radiation. About 80% of the total available sunshine on December 21st falls between the hours of 8:43 a.m. and 3:17 p.m. solar time. The Table gives the shadow length on December 21st of a one (1) foot pole for varying slopes and orientations. Approximate shadow lengths for slopes not listed in the Table may be interpolated.

Afternoon shadow lengths on Northeast slopes of 20% or greater and morning shadow lengths on Northwest slopes of 20% or greater do not offer any solar access opportunities.

SHADOW LENGTH FOR SLOPE 0%

41° 30' NORTH LATTITUDE

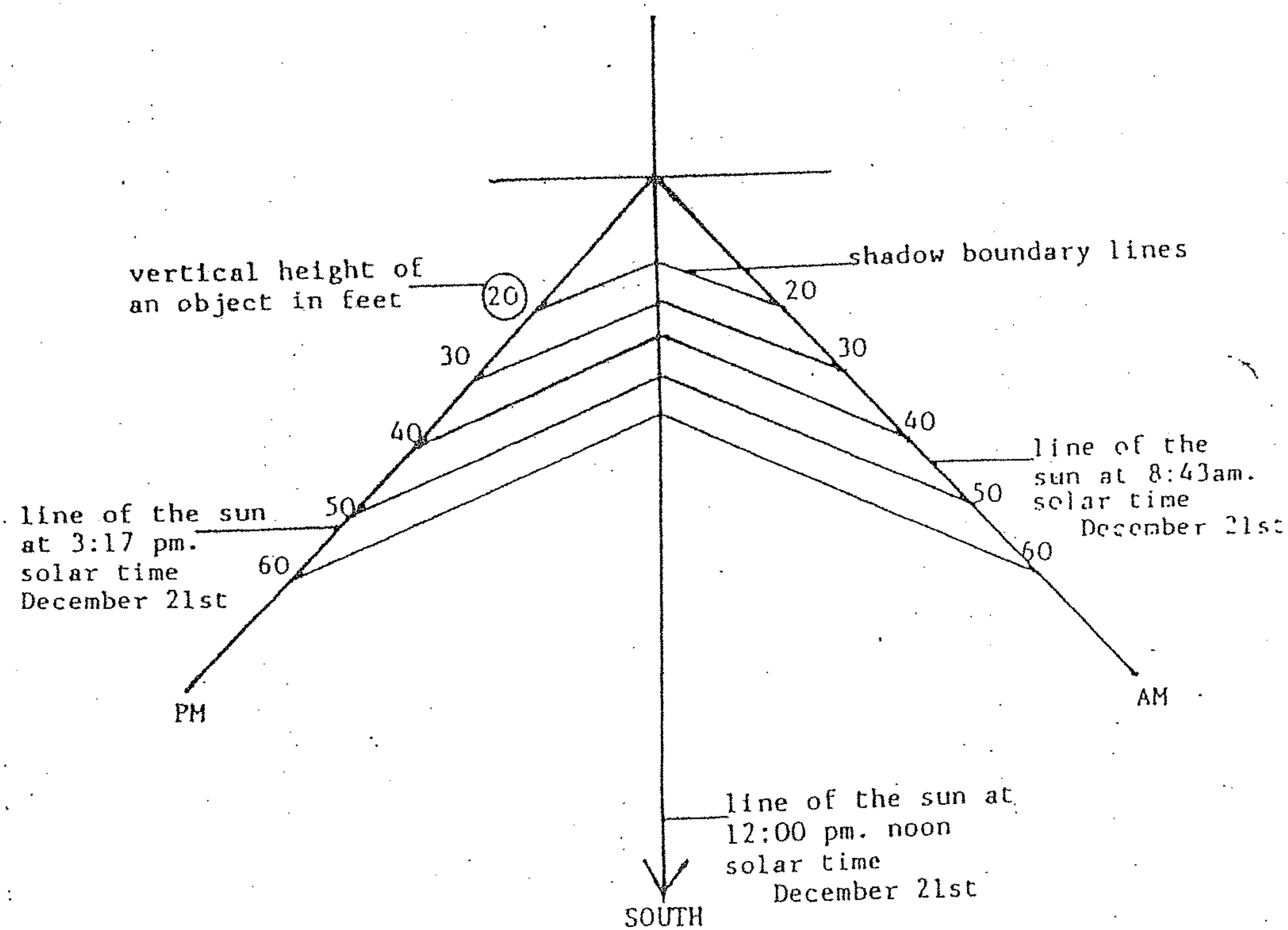
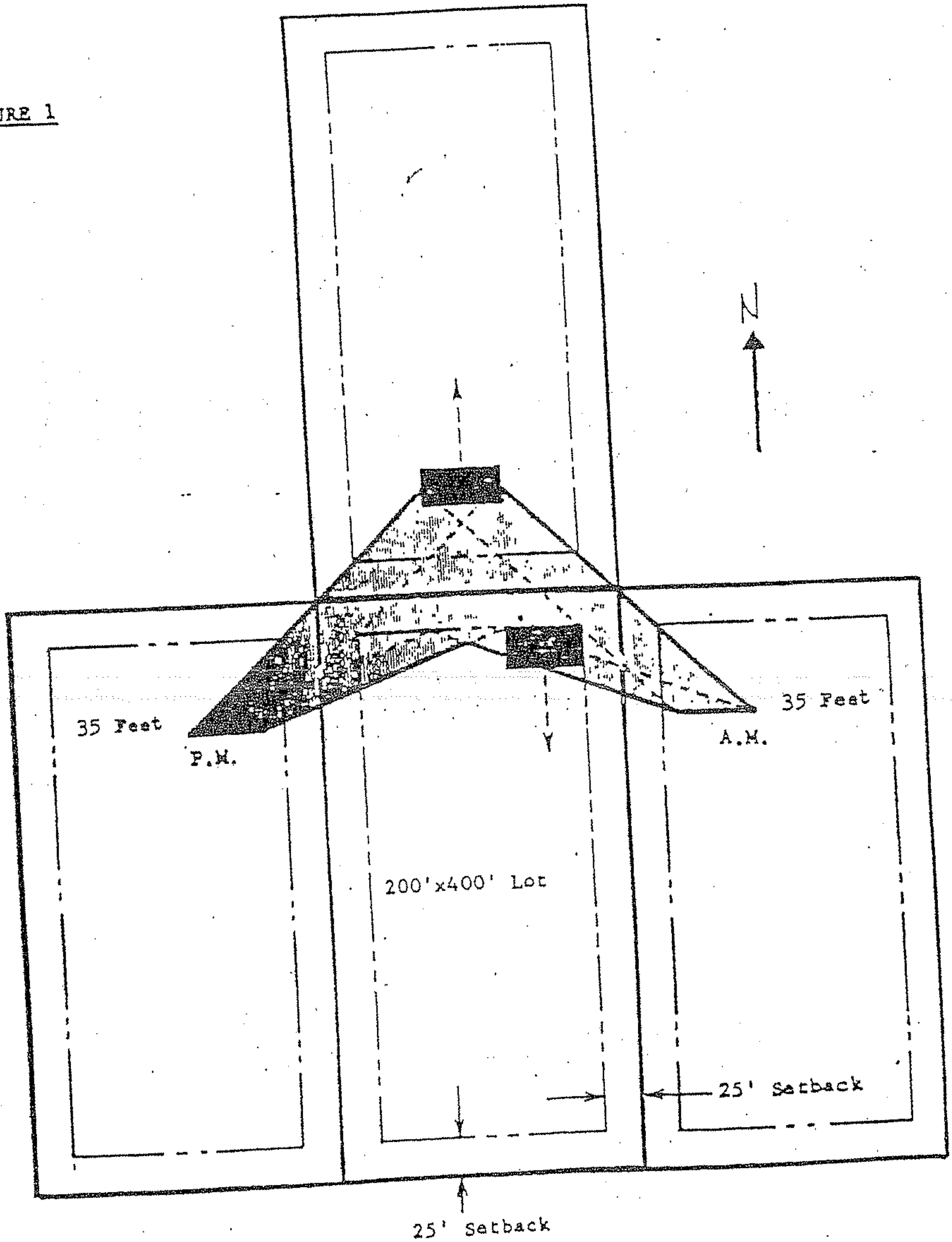


FIGURE 1



Scale: 1" = 100'

Site Specific Evaluation of Solar Access on Flat Land

APPENDIX B-5

APPENDIX C

Vertical Curves

Crest Vertical Curves. To design a crest vertical curve the following formulas should be used:

L = K*A or L = 3*V whichever is larger

$$K = \frac{S^2}{1329}$$

where:

L =	minimum length of vertical curve, ft
A =	algebraic difference between the two
K =	horizontal distance in feet required to effect a 1% change in gradient.
S =	stopping sight distance from Table - Appendix E, page E-4.
V =	Design speed.

The selection of the grade "G" to determine the appropriate "S" at a crest vertical curve will depend on which grade is steeper and whether the roadway is one way or two way. On a 1-way roadway, "G" will always be the grade on the far side of the crest when considering the direction of travel. On a 2-way roadway, "G" will always be the steeper of the two grades on either side of the crest.

Sag Vertical Curves. To design a sag vertical curve the following formulas should be used:

L = K*A or L = 3*V whichever is larger.

$$K = \frac{S^2}{400 + 3.5S}$$

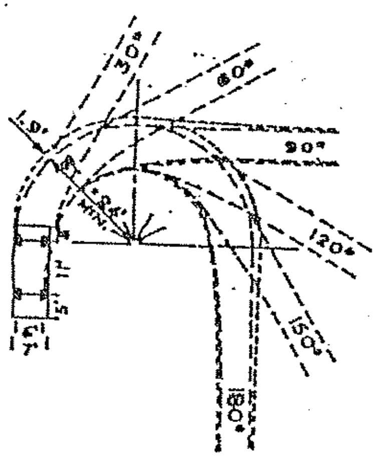
The selection of grade "G" to determine the appropriate "S" at a sag vertical curve will depend on which grade is flatter and whether the roadway is one way or two way. On a 1-way roadway, "G" will always be the grade on the far side of the sag when considering the direction of travel. On a 2-way roadway, "G" will always be the flatter of the two grades on either side of the sag.

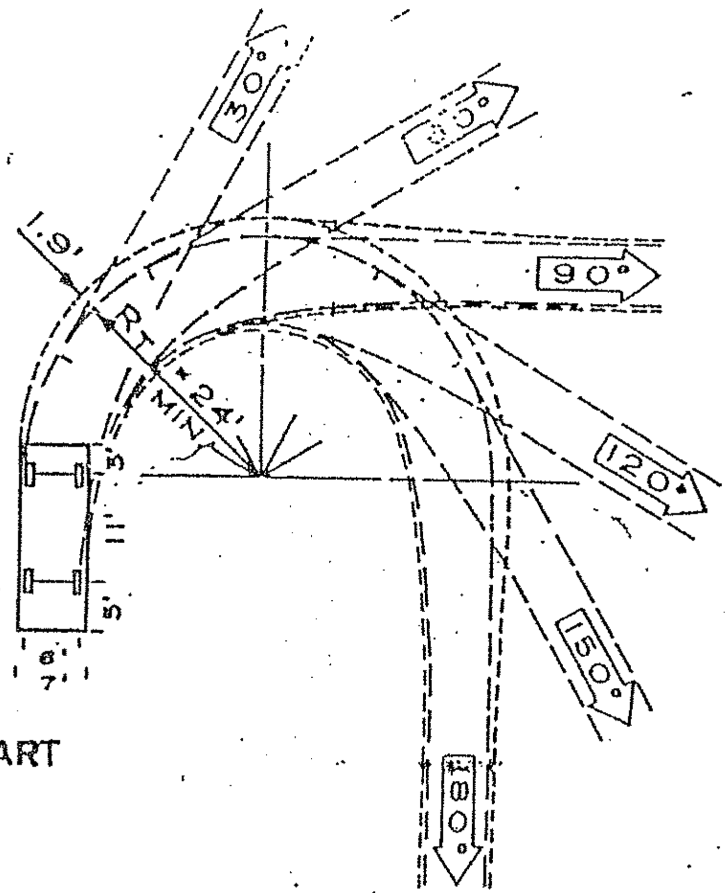
Occasionally, it may be warranted to design a sag vertical curve to meet the comfort criteria. This design should only be used on fully lighted sections of highway and where it is impractical to provide the headlight sag distance. The formula for this criteria is:

$$L = \frac{AV^2}{46.5}$$

APPENDIX D

Turning Templates





FOR ACUTE ANGLES
OR FROM A STANDING START

R ≐ 24'
1" = 40'

R ≐ 24'
1" = 20'

APPENDIX E

Intersection Sight and Stopping Distances

Intersection Sight Distance

The intersection sight distances (ISD) are provided in Table . As illustrated in Figure , the ISD criteria are based on the distance "X" the turning vehicle must travel from the "reference" line to clear the opposing traffic. This allows the application of the ISD model to multilane highways. The designer should also consider the following when determining the ISD criteria:

1. The minimum "X" distance will be 22 ft, even if the actual "X" is less than this value.

2. Each successive column approximately represents an additional lane of opposing traffic (12 ft).

3. The eye location is desirable 20 ft and, at a minimum, 10 ft behind the reference line. The eye location is independent of "X".

4. The table assumes that a right-turning vehicle will turn into the outer travel lane in that direction. A left-turning vehicle will turn into the inner travel lane in that direction.

5. If the opposing direction of travel includes an exclusive right- or left-turn lane(s), these will be included in the "X" distance when reading into the table.

6. For the values of "X" which are between columns, the designer should read into the next highest column.

7. If a divided highway has a median width of 25 ft or more, the ISD application can be evaluated in two movements.

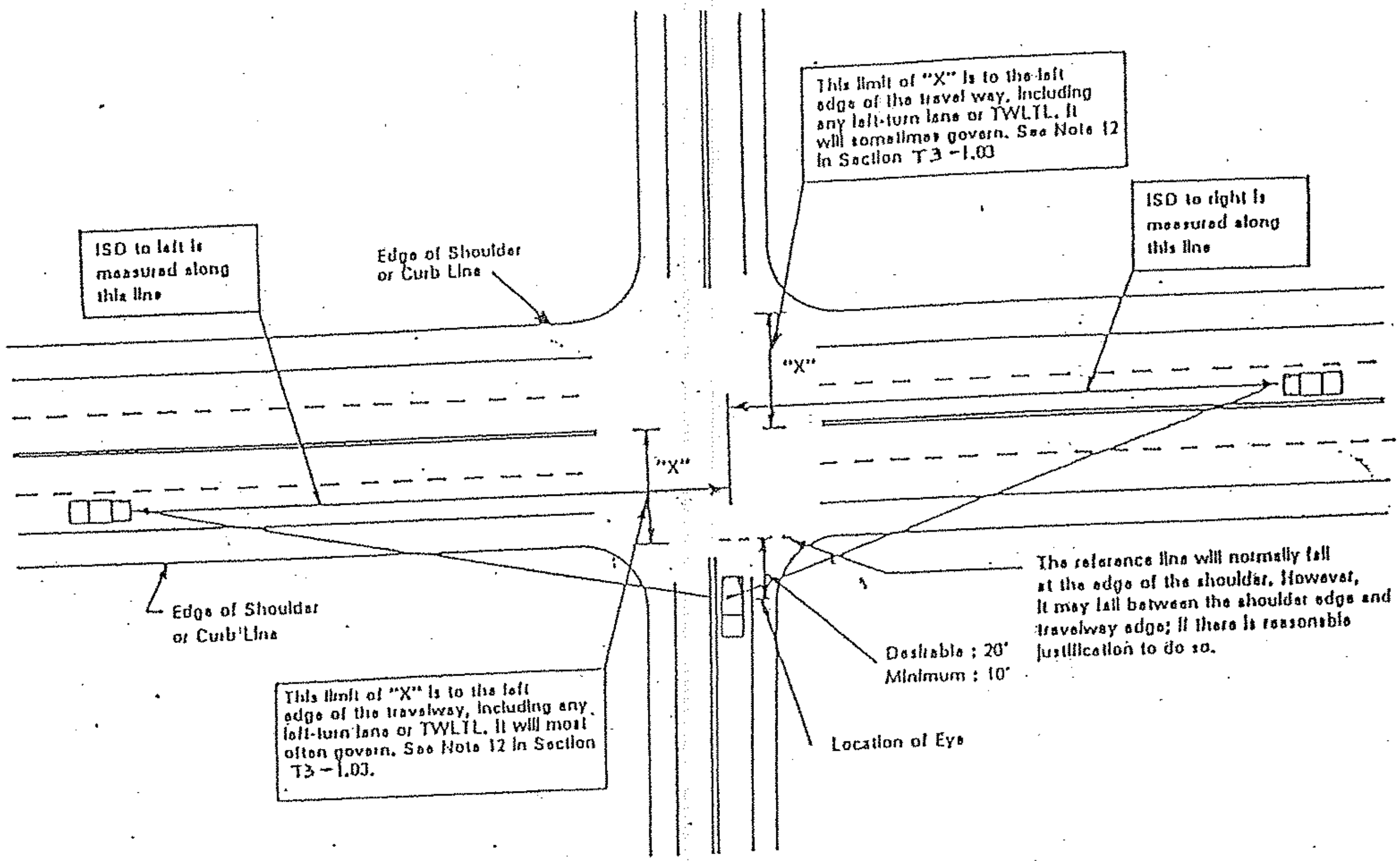
8. It is assumed that the roadway being entered is relatively level over the ISD distances.

9. If the angle of intersection is less than 60°, the designer should adjust the "X" distance and ISD accordingly.

10. At some intersections, the designer may want to increase the ISD distances to account for large numbers of buses or trucks which may use the intersection.

11. The height of eye and object is 3.5 ft.

12. For 4-leg intersections <u>and</u> for minimum ISD to the right, the designer must determine the applicable "X" value to read into Table . If "X" is the same for both directions of travel, then this value will be used. However, if the main road has unbalanced lanes, the "X" distance will be different for the two directions of travel. In this case, the designer will use the larger of the two values to read into Table for minimum ISD to the right.



INTERSECTION SIGHT DISTANCE
(Application)

Figure

Table

INTERSECTION SIGHT DISTANCE CRITERIA

Application	Road Class. *	D.S. (mph) **	X=Width of Opposing Lanes				
			≦22′	34′	46′	58′	70′
Desirable ISD (To the Lt. and Rt.)	L	30	310	390	440	480	515
	C, I	35	405	500	555	600	640
	T	45	635	755	820	875	925
Minimum ISD (To the Right)	L	30	230	280	320	350	375
	C, I	35	285	380	425	460	490
	T	45	455	575	635	680	720
Minimum ISD (To the Left)	L	30	210	240	255	285	300
	C, I	35	285	285	300	330	350
	T	45	455	455	455	455	455

*Road Class. = Road Classification

**D.S. = Design Speed

L = Local

C = Commercial

I = Industrial

T = Thoroughfare

Table

STOPPING SIGHT DISTANCE

Road Class.	Design Speed	Average Running Speed	f	Downgrades -9% Upper	Lower	-6% Upper	Lower	-3% Upper	Lower
L	30	28	0.35	230	230	220	220	210	210
C, I	35	32	0.34	300	275	280	255	265	240
T	45	40	0.31	490	415	455	380	425	350

Road Class.	Design Speed	Average Running Speed	f	Level 0% Upper	Lower
L	30	28	0.35	200	200
C, I	35	32	0.34	250	225
T	45	40	0.31	400	325

Road Class.	Design Speed	Average Running Speed	f	Upgrades +3% Upper	Lower	+6% Upper	Lower	+9% Upper	Lower
L	30	28	0.35	200	200	190	190	180	180
C, I	35	32	0.34	245	220	235	210	225	200
T	45	40	0.31	385	310	375	300	365	290

Notes:
1. For design speeds of 50 mph or higher, use the level SSD values when $-1\% < G < +1\%$.
2. For design speeds less than 50 mph, use the level SSD values when $-2\% < G < +2\%$.
3. For grades intermediate between columns, use a straight-line interpolation to calculate SSD. For example:

$V = 50$ mph
$G = -4.3\%$

$$\text{Lower SSD} = 430 + \left(\frac{4.3 - 3}{6 - 3}\right)(470 - 430)$$

L = Local
C = Commercial
I = Industrial
T = Thoroughfare

APPENDIX F

Soil Erosion And Sediment Control

APPENDIX F

Soil Erosion And Sediment Control

Erosion and sediment control planning should be an integral part of the site planning process. The potential for soil erosion should be a significant consideration when deciding upon the layout of buildings, parking lots, roads and other facilities. Costly erosion and sediment control measures can be minimized if the site design is adapted to existing site conditions and good conservation principles are used. The plan should also be integrated into plans developed for the control or management of storm water.

This chapter will take the planner through the first three steps of the site planning process prior to the actual preparation of the plan: (1) collecting site information and data, (2) analyzing the data, and (3) design selection incorporating three broad categories of erosion and sediment control measures -- vegetative, structural, and nonstructural.

A. DATA COLLECTION

The data collection process begins with preliminary site inspections to evaluate the physical features of the site. Prior to on-site data collection, appropriate base maps should be assembled. Topographic, soil survey, land use and zoning maps are particularly helpful. Consider the use of aerial photography for documenting existing conditions.

1. SITE LOCATION MAP

In addition to giving the position of a property in legal terms, a site location map shows the site's relationship to roads and other environmental features such as major drainageways and drainage divides. The location of any drainage or utility easements on the parcel should be shown on this map.

2. TOPOGRAPHY

A small-scale topographic map of the site should be prepared to show the existing contour elevations at intervals of from 1 to 5 feet depending upon the slope of the terrain. A scale of 1 inch = 100 feet is generally suitable. Topographic maps are available locally from the Connecticut Department of Environmental Protection, Natural Resources Center. On larger tracts of land (generally greater than 25 acres in size) a photogrammetric contour map with two-foot contour intervals can be useful for planning, especially for areas proposed for intensive development which have site condition limitations.

3. SOILS

Major soil type(s) on the site should be determined and shown on the topographic map. General soils information can be obtained from a soil survey published for the county. Commercial soils evaluations, which provide a more comprehensive soil survey, are recommended for large sites. Soil boundaries marked in the field can then be plotted directly onto the map for ease of interpretation. A private soil scientist can also prepare a detailed wetlands map from this information. A map showing areas of prime farmland soils can be developed from the soil survey map.

4. VEGETATION

The existing vegetative patterns on the site should be shown. Such features as tree clusters, grassy areas, and unique vegetation should be shown on the map. In addition, existing denuded or exposed soil areas, such as borrow pits, should be indicated.

5. ADJACENT AREAS

Areas adjacent to the site should be delineated on the topographic map. Such features as perennial and intermittent streams, roads, houses or other buildings, or wooded areas should be shown. Wetlands, watercourses and downstream culverts which will receive runoff from the site should be surveyed to determine their ability to retain or discharge runoff. Identify sensitive downstream areas, especially on parcels with stream flows of 5 cfs or greater. Consider 1,000 feet downstream as a minimum, depending upon soil conditions, soil types, and area disturbed. Give attention to possible future development upstream that may affect the rate and volume of runoff contributing to the project site.

B. DATA ANALYSIS

When all of the data in Step 1 are considered together, the site's potentials and limitations can then be defined. The site planner should be able to determine those areas which have potential erosion hazards or areas sensitive to development. Prior to lot layout the following are points to consider in the site analysis.

1. TOPOGRAPHY

The primary topographic considerations are slope gradient and slope length. The longer and steeper the slope, the greater the erosion potential.

Chapter 10 has an explanation of the Universal Soil Loss Equation (USLE) and its use on developing areas.

2. DRAINAGE PATTERNS

Natural drainage patterns exist on the land. These patterns, which consist of overland flow, swales and depressions, and natural watercourses, should be identified in order to plan around critical areas where water will concentrate. Where it is possible, natural drainageways should be used to convey runoff through and off the site to avoid the expense and problems of constructing an artificial drainage system. Man-made ditches and waterways will be subject to erosion if they are not properly stabilized. Care should also be taken to ensure that increased runoff from the site will not erode or exceed the capacity of the existing natural drainage system. Possible sites for storm water detention should be considered at this time. Every effort should be made to keep post-development runoff rates equal to or less than predevelopment rates by on-site detention. Soil Conservation Service Technical Releases 20 and 55, or other appropriate methods can be used to evaluate existing and post-development conditions(1).

3. SOILS

Soil properties such as flood hazard, natural drainage, depth to bedrock, depth to seasonal water table, permeability, texture, and erodibility exert a strong influence on land development decisions. Chapter 10 contains basic guidelines for using the Universal Soil Loss Equation for site planning. A list of Connecticut soils and their hydrologic soil groups are included in Chapter 9, Figure 9-9.

4. VEGETATION

The vegetation patterns should be analyzed and a landscape plan prepared. Any existing vegetation which can be saved will help prevent erosion. Trees and other vegetation protect the soil, as well as beautify the site after construction. If the existing vegetation cannot be saved, the planner should consider staging construction, and/or using temporary seeding, or temporary mulching. Staging of construction involves stabilizing one part of the site before disturbing another. In this way the entire site is not all disturbed at once and the time without vegetative cover is minimized. Temporary seeding and mulching involve seeding or mulching areas which would otherwise lie open for long periods of time. The time of exposure is limited, and therefore, the erosion hazard is reduced.

5. ADJACENT AREAS

An analysis of adjacent properties should focus on areas downslope from the construction project. Wetlands and watercourses which will receive direct runoff from the site should be a major concern. The potential for sediment pollution of these areas should be considered as well as the potential for downstream channel erosion due to increased volume, velocity and peak flow rate of storm water runoff from the site. The potential for sediment deposition on adjacent properties from sheet, rill, and gully erosion should also be analyzed so that appropriate sediment trapping measures can be planned.

C. SITE PLANNING

After analyzing the data and determining the site limitations, the planner can then develop a site plan. Town commissions should permit planners and developers to implement innovative site plans that locate the buildings, roads, and parking lots, and develop landscaping plans which exploit the strengths and overcome the limitations of the site. The planner should use the principles listed in Chapter 2 to develop an erosion and sediment control strategy. The criteria in Chapter 4 establish a minimum level of control for all projects. The site planner should determine which of the criteria are applicable to the site, and select appropriate conservation measures from the matrix in Chapter 5. The following are some points to consider in making these decisions.

1. FIT DEVELOPMENT TO THE TERRAIN

The development of an area should be tailored to the existing site conditions. This will avoid unnecessary land disturbance, minimizing the erosion hazards and costs. Limit areas of clearing and grading by concentrating construction activities on the least critical or sensitive areas. Align roads on the contour and consider using them to divert surface water, thereby reducing slope lengths and decreasing erosive water movement. Minimize impacts of soil limitations by planning structures to fit in the best suited areas.

2. DIVIDE THE SITE INTO DRAINAGE AREAS

Determine how runoff will travel over the site. Consider how erosion and sedimentation can be controlled in each small drainage area before looking at the entire site. Remember, it is easier to control erosion than to contend with sediment after it has been carried downstream. Avoid siting buildings in drainageways.

3. CLUSTER BUILDINGS TOGETHER

This minimizes the amount of disturbed area, concentrates utility lines and connections in one area, and provides more open natural space. The cluster concept not only lessens the erodible area, but reduces runoff, and generally reduces development costs. Plan grading and landscaping around buildings and septic systems to divert water away from them.

4. MINIMIZE IMPERVIOUS AREAS

Keep paved areas such as parking lots and roads to a minimum. This complements cluster developments in eliminating the need for duplicating parking areas, access roads, and other impervious areas. The more land that is kept in vegetative cover, the more water will infiltrate into the soil minimizing runoff and erosion.

5. UTILIZE THE NATURAL DRAINAGE SYSTEM

If the natural drainage system of a site can be preserved instead of being replaced with storm sewers or concrete channels, the potential for downstream damages from increased runoff can be minimized, making compliance with storm water management criteria easier. Consider these areas for siting of temporary sediment basins during the construction phase. Do not locate sediment basins in running streams that carry water flow from large drainage areas. In such situations, sediment basins should be located so that they will intercept runoff prior to its entry into the stream. Avoid diverting one drainage system into another without closely investigating whether the receiving system will be overtaxed and create downstream flooding or erode the natural vegetation.

6. SELECT EROSION AND SEDIMENT CONTROL MEASURES

From the matrix in Chapter 5 erosion and sediment control can be divided into three broad categories: vegetative, nonstructural, and structural measures. Chapters 6, 7 and 8 of these guidelines should be used for the selection and design of these measures.

a. Vegetative Measures

The first and most important line of defense is to prevent erosion. This is accomplished by protecting the soil surface from raindrop impact and overland flow of runoff. The best way to protect the soil surface is to preserve the existing vegetation. Where land disturbance is necessary, refer to Chapter 6 for measures to use for stabilization.

Erosion and sediment control plans must contain provisions for permanent stabilization of disturbed areas. Selection of permanent vegetation should include the following considerations:

(1) Planting requirements
(2) Adaptability of species to site conditions
(3) Aesthetic appearance of completed plantings
(4) Maintenance requirements

b. Nonstructural Measures

During construction -- or as a protective cover prior to vegetating a site -- inexpensive, yet highly effective nonstructural methods can be employed to provide rapid soil cover. These measures can also provide a means to establish a growing medium for vegetation. Attention to specific uses of these measures and their timely application is important in minimizing erosion from wind or water and the resulting off-site sediment transport.

c. Structural Measures

Structures are generally more costly and less efficient than vegetative controls. However, they are often necessary since not all disturbed areas can be protected with vegetation. Structural measures are often used as a second or third line of defense to capture suspended sediment before it leaves the site.

7. PLAN FOR STORM WATER MANAGEMENT

Where increased runoff will cause increased erosion of downstream channels, the site planner must select appropriate storm water management measures to reduce peak flows to predevelopment condition. Every effort should be made to reduce increased runoff.

REFERENCES

1. U.S. Department of Agriculture. Computer Program for Project Formulation - Hydrology, Technical Release Number 20. Revised 1984. Urban Hydrology for Small Watersheds, Technical Release Number 55, 1986. Soil Conservation Service, Washington, DC.

NOTES

A. DEFINITION OF PLAN

An erosion and sediment control plan is a document which explains and illustrates the measures which will be taken to control erosion and sediment problems on construction sites. The plan has a written portion known as a narrative and an illustrative portion known as a map or site plan.

A plan is defined in PA 83-388 of 1983 as follows:

> Sec. 3 (5) "Soil erosion and sediment control plan" means a scheme that minimizes soil erosion and sedimentation and includes but is not limited to a map and narrative. The map shall show topography, cleared and graded areas, proposed area alterations and the location of and detailed information concerning erosion and sediment measures and facilities. The narrative shall describe the project, the schedule of major activities on the land, the application of conservation practices, design criteria, construction details and the maintenance program for any erosion and sediment control facilities that are installed;"

B. PLAN FORMAT

The soil erosion and sediment control plan should be an integral part of the overall site plan. However, it needs to be consolidated, so it can be separated from the site plan for review and certification.

To facilitate plan review, certification and implementation, and the construction inspection process, the following format is suggested:

1. The information needed for construction <u>should be</u> on the construction drawings and not in the design calculations or background information.

2. The construction drawings <u>should all be</u> the same size sheets.

3. The soil erosion and sediment control measure construction drawings <u>should be</u> a part of the overall construction drawings for the project.

4. The construction details for measures <u>should be</u> shown on a separate sheet from the plan view sheets.

5. The stages of development, sequence of major operations on the land, and maintenance program during construction are in the narrative portion of the plan but also <u>should be</u> on the construction drawings.

6. General information about the project and design calculations <u>should be</u> in the narrative portion with the exception of a small, simple plan.

7. The design calculations <u>should be</u> in the narrative separate from the construction drawings. Design calculations are normally not needed for inspection, but design calculations need to be available in case revisions are necessary during construction.

8. The background information should be in the narrative separate from the construction drawings.

C. PLAN OUTLINE

The plan must include the items required by the law as given above. The items following include those required by the law and other items that should be considered when developing the plan and included in the plan if appropriate.

This plan outline should not be used as a basis for plan approval. It is intended to be of assistance in preparing and approving erosion and sediment control plans, and to be a reminder of major items that usually need to be considered when developing a plan.

1. VICINITY MAP

   a. Project location
   b. Roads, streets
   c. North arrow
   d. Scale
   e. Major drainageways
   f. Major land uses of surrounding areas

2. PROJECT FEATURES

   a. Property lines
   b. Limit and acreage of development application
   c. Limit and acreage of disturbed area
   d. North arrow
   e. Scale
   f. Legend
   g. Planned and existing roads and buildings with their location and elevations
   h. Land use of surrounding areas
   i. Access roads; temporary and permanent

3. NATURAL FEATURES

   a. Soils
   b. Rock outcrops
   c. Seeps, springs
   d. Inland and coastal wetlands
   e. Floodplains
   f. Streams, lakes, ponds, drainageways, dams
   g. Existing vegetation
   h. Natural features of adjacent areas

4. TOPOGRAPHIC FEATURES

   a. Contours; present and planned (normally 2 foot intervals)
   b. Areas of cut or fill
   c. Planned grades and slope steepness

5. DRAINAGE SYSTEM

a. Existing and planned drainage pattern
b. Existing and planned drainage area map (include off-site areas that drain through project)
c. Size of drainage areas
d. Size and location of culverts and storm sewers
e. Design calculations and construction details for culverts, storm sewers, etc.
f. Size and locations of existing and planned channels or waterways with design calculations and construction details to control erosion of the channel or waterway
g. Existing peak flows with calculations
h. Planned peak flows with calculations
i. Changes in peak flows
j. Off-site effects of increased peak flows or volumes
k. Measures with design calculations and construction details to control off-site erosion caused by the project
l. Survey and soil information below culverts and storm sewer outlets
m. Measures with design calculations and construction details to control erosion below culverts and storm sewer outlets
n. Measures with design calculations and construction details to control groundwater, i.e. seeps, high water table, etc.

6. UTILITY SYSTEM

a. Location of existing and planned septic systems
b. Location and size of existing and planned sanitary sewers
c. Location of other existing and planned utilities, telephone, electric, gas, etc.

7. CLEARING, GRADING, VEGETATIVE STABILIZATION

a. Areas to be cleared, staging and sequence of clearing
b. Disposal of cleared material
c. Areas to be graded, staging and sequence of grading
d. Areas and acreage to be vegetatively stabilized
e. Planned vegetation with details of plants, seed, mulch, fertilizer, planting dates, etc.
f. Temporary erosion protection of disturbed areas
g. Temporary erosion protection when time of year or weather prohibit establishment of permanent vegetative cover

8. EROSION CONTROL MEASURES

a. Construction drawings and details for temporary and permanent measures
b. Design calculations
c. Maintenance requirements of measures during construction of project
d. Person responsible for maintenance during construction of project
e. Maintenance requirements of permanent measures when project is complete
f. Organization or person responsible for maintenance of permanent measures when project is complete

9. NARRATIVE

a. Nature, purpose and description of project
b. Potentially serious erosion or sediment problems
c. The stages of development if more than one stage is planned
d. The sequence of major operations on the land, such as installation of erosion control measures, clearing, grading, temporary stabilization, road base, road paving, building construction, permanent stabilization, removal of temporary erosion control measures
e. The time required for the major operations identified in the sequence
f. The planned dates for the project. These are often subject to change depending on markets, financing and permit approvals, therefore the sequence of all major operations and time required for major operations is more important in minimizing erosion and sediment problems.

All the necessary planning work should be done during the site planning process. This step consists of consolidating the pertinent information and developing it into a specific erosion and sediment control plan for the project.

A. MAP AND NARRATIVE

The plan consists of two parts: a map and a narrative. The map illustrates the topography of the area, the limits for clearing and grading, other proposed alterations of the area, the location of the erosion and sediment control measures and facilities, and the location of project components. The narrative describes the project, giving the purposes, schedule or phasing of major construction activities, schedule of application of measures, and measure design data and a maintenance program for the installed measures. If the narrative is not so lengthy that it would clutter up the map, both the narrative and map may be on the one plan.

The major elements to be considered in the development of a plan are:

1. A GENERAL STATEMENT ABOUT THE PROJECT

   This statement should include the date the project is to begin and the expected date when final stabilization will be completed. A description of the erosion and sediment control program to be used should be included.

2. TOPOGRAPHIC FEATURES

   This will show the location of streets and highways, municipalities, major streams, and other landmarks. Include the acreage of the project, contours at an interval and scale that will adequately describe the area, critical environmental areas such as rock outcrops, wetlands, floodplains, groundwater recharge, streams, lakes, ponds, and streambelts as well as the nature and extent of existing vegetation.

3. SOILS SHOULD BE IDENTIFIED ON THE MAP

   All soils identified on the site should be shown by delineation and standard soil survey symbol on the erosion and sediment plan map.

4. THE AMOUNT OF RUNOFF AND CHANGES IN THE AMOUNT OF RUNOFF FROM THE PROJECT AREA SHALL BE DESCRIBED IN THE NARRATIVE

   The methods of calculation and worksheets should be included.

5. THE MAP SHOULD SHOW THE PROPOSED ALTERATION OF THE AREA

   The map should illustrate limits of clearing and grading, areas of cuts and fills, roads, buildings, pond areas and other structures, and storm water management facilities.

6. THE NARRATIVE OUTLINES THE SEQUENCE AND STAGING OF LAND DISTURBING ACTIVITIES

This section includes the sequence of land clearing operations, removal and/or stockpiling of topsoil, major earth moving and grading, control facility installation and program of operations.

7. MEASURES TO BE USED DURING CONSTRUCTION

The temporary erosion and sediment control and permanent erosion and sediment control measures for long-term protection are to be included in the narrative and shown on the map. This will show the purpose, types and location of measures and facilities, dimensional details of facilities, design considerations and calculations for structural measures, and the maintenance schedule.

8. A STATEMENT ABOUT THE OFF-SITE EFFECTS

Note, for example, the effects of adequate and inadequate sized culverts, and downstream effects from increased peak flows.

9. THE MAINTENANCE PROGRAM FOR THE CONTROL FACILITIES ARE TO BE DESCRIBED IN THE NARRATIVE

Points to cover are the inspection program including the frequency and schedule, restabilization, repair or reconstruction of damaged structural measures; the method and frequency of removal and disposal of solid waste materials from the control facilities or the project area, and the method of disposing of temporary structural measures after they have served their purpose.

The narrative should also explain provisions made for sediment to be removed from the control facilities and to be disposed of at a location that will not cause additional problems to the surrounding area.

B. CONTROL MEASURE SELECTION PROCESS

The accompanying flow chart and planning matrix (Figure 5-1) can be used to guide the selection of soil erosion and sedimentation control measures. Following the chart in steps from left to right, the user can identify the potential problems and solutions for control of these problems. To use the flow chart and matrix, follow five basic steps:

Step 1: Identify Control Problem - On any construction site the objective in erosion and sediment control is to prevent off-site sedimentation damage. The three basic methods used to control erosion on construction sites are soil stabilization, runoff control, and sediment control. Controlling erosion should be used as the first line of defense where soil properties and topography of the site make the design of sediment trapping facilities impractical or where much of the site will not be disturbed and much of the existing vegetation can be preserved. Controlling erosion is very effective for small disturbed areas such as single lots or small areas of a development that do not drain to a sediment trapping facility.

Sediment trapping facilities should be used on large developments where major grading is planned, where it is impossible or impractical to control erosion, and where sediment particles are relatively large. By using a combination of erosion control and sediment control measures, costs can usually be kept to a minimum.

Step 2: Identify Problem Areas - Once a method of control is selected, potential erosion and sediment problem areas are identified. Areas where erosion is to be controlled will usually fall into categories of slopes, graded areas or drainageways. Slopes include graded rights-of-way, stockpile areas, and all cut or fill slopes. Graded areas include all stripped areas other than slopes. Drainageways are areas where concentrations of water flow naturally or artificially and the potential for gully erosion is high. Problem areas where sediment is to be controlled fall into categories of large or small drainage areas. Small drainage areas are normally one acre or less in size where filtering of sediment can be accomplished. Large areas require that the sediment be settled rather than filtered.

Step 3: Identify Required Strategy - The third step in erosion and sediment control planning is to select the most appropriate strategy to solve the problem. The planning matrix may facilitate the selection process.

There may be several strategies used individually or in combination to provide the solution. For example, if there is a cut slope to be protected from erosion, the strategies may be to protect the ground surface, divert water from the slope or shorten it. Any combination of the above can be used. If no rainfall except that which falls on the slope has the potential to cause erosion and if the slope is relatively short, protecting the soil surface is often all that is required to solve the problem.

Step 4: Identify Control Measure Group - Once required strategies to solve the erosion and sediment problem are identified, the planning matrix leads to the group or groups of control measures that will accomplish one strategy. Control measures within each group have similar purpose, scope, application, design criteria, standard plans, and construction specifications. Therefore, any measure within a group may solve the problem in question.

Step 5: Select Specific Control Measure - The final step in erosion and sediment control planning can be accomplished by completing the final design. This involves adaptation of any control measure within a group to solve the specific erosion and sediment problem. Select the one measure which is most economical, practical, efficient, and adaptable to the site.

Once the specific control measure has been selected, the plan key symbol given in the matrix can be placed on the erosion and sediment control site plan to show where the measure will be used. Standardized design, plan, and construction specification sheets can then be completed for each control measure. This completes the planning for soil erosion and sedimentation control.

Figure 5-1 - Control Measure Selection Process

IDENTIFY CONTROL PROBLEM	IDENTIFY PROBLEM AREAS	IDENTIFY REQUIRED STRATEGY	IDENTIFY CONTROL MEASURE GROUP	SELECT SPECIFIC CONTROL MEASURE	PLAN KEY
CONTROL SOIL MOVEMENT	Graded Areas			Temporary Vegetative Cover	TV
Sheet and Rill Erosion	Slopes		Vegetative	Permanent Vegetation Cover	PV
Wind Erosion	Small Areas	Protect Surface	Soil	Sodding	SO
Protect Onsite Areas	Exposed Areas	Manage Surface Water	Cover	Trees, Shrubs, Vines & Ground Cover	GC
Natural Resource Degradation	Travel Areas			Vegetative Streambank Protection	VP
	Borrow and Stockpile Areas		Nonvegetative Soil Cover	Temporary Mulching	MU
				Permanent Mulching	PM
		Manage Site Resources Protect Amenities	Environmental Enhancement	Tree Protection	TP
				Topsoiling	TO
				Land Grading	LG
CONTROL WATER MOVEMENT	Drainageways	Direct Runoff	Diversions	Diversion	DV
Gully Erosion	Watercourses	Convey Runoff	Waterways	Grassed Waterway	GW
Channel and Stream Erosion	Steep Slopes			Temporary Channel Lining	TL
Protect Onsite and Offsite Areas	Long Slopes			Permanent Lined Waterway	LW
Natural Resource Degradation		Stabilize Outlets	Outlets	Outlet Protection	OP
		Intercept Ground Water	Enclosed Drainage	Subsurface Drain	SD
				Riprap	RR
				Gabions	G
		Stabilize Steep Slopes	Stabilization	Reinforced Concrete Retaining Wall	RW
		Stabilize Watercourses	Structures	Precast Cellular Blocks	CB
				Prefabricated Retaining Walls	PW
				Grade Stabilization Structure	GS
CONTROL SEDIMENT MOVEMENT	Large Areas	Trap Sediment	Sediment Control	Sediment Basin	SB
Protect Offsite Areas	Small Areas	Detain Runoff		Detention Basin	DB
Wind Erosion	Waterbodies			Temporary Stream Crossing	SC
Natural Resource Degradation	Travel Areas	Control Sediment	Mud and Dust Control	Dust Control	DC
	Borrow and Stockpile Areas			Construction Entrance	CE
		Filter Sediment	Sediment Filters	Sediment Barriers	ST
				Silt Curtain	SI
STEP 1	STEP 2	STEP 3	STEP 4	STEP 5	

Source: U.S. Department of Agriculture, Soil Conservation Service, Storrs, Connecticut.

MATERIALS FOR USE IN IMPROVING
EROSION AND SEDIMENT CONTROL PLAN IMPLEMENTATION
October 1988

IV. CONSTRUCTION SEQUENCE

A construction sequence or schedule is a chronological listing of the construction activities necessary to install the development according to the developers plan. The sequence should be developed on the "first things first" and "last things last" premise with proper attention given to the inclusion of adequate erosion and sediment control measures.

A properly developed construction sequence which is followed will do two basic things:

1. Provide for efficient use of labor, material and equipment.

2. Minimize on-site disturbance and off-site impacts.

Scheduling of construction activities should include considerations such as sequence of construction, construction techniques, landscaping, and future operations and maintenance. By properly sequencing the construction, both the extent of exposed-ground and the duration of exposure can be minimized. Phasing, which allows for clearing, grading, and the stabilization of one portion of the site before clearing and grading begins on another, will limit the number and severity of erosion problems.

Erosion and sediment control starts during the planning and design process for the development. Incorporation of a construction sequence in the erosion and sediment control plan facilitates the implementation of the plan resulting in improving erosion and sediment control. Items to consider in developing a construction sequence and schedule include:

1. Install the erosion and sediment control measures that will exist during the life span of projects as soon as possible.

2. Clear only what is necessary.

3. Stockpile topsoil and spoil when appropriate. Establish temporary cover if the material will remain unspread for longer than one month.

4. Establish permanent streets, roads, underground utilities, and drainage systems as quickly as possible.

5. Establish final grades as rapidly as possible and establish permanent cover.

6. Maintain vegetative buffer strips along streams.

7. Establish temporary cover on all disturbed areas where final grade or vegetation will not be established until the following construction season.

8. Clean out and maintain all sediment control structures on a regula basis to ensure proper operation and storage capacity.

A model construction sequence is provided to help illustrate a typical sequence of construction developed to minimize erosion and sedimentation. I is important to recognize that all plans and proposals are site specific and are, therefore, unique. There are certain operations and events that are characteristic of nearly all plans and can serve as the milestones for enforcement. The model provided is intended as a guide for developing construction sequences. It is not intended to be standard language for all erosion and sediment control plans, but rather to serve as a starting point which to develop a construction sequence. For a specific development, milestone dates for all or major items can be shown to make construction scheduling and monitoring easier.

TYPICAL CONSTRUCTION SEQUENCE

Pre-construction review - discuss erosion and sediment control requirements; sensitive areas; requirements for field adjustments; procedures for modifications to construction sequence; bonding and coverage; pre-blast surveys; limits of clearing; erosion and sediment control language.

Site Work:

- Install construction entrance(s).
- Flag the limits of clearing for the phase, if appropriate, in the field
- Install temporary erosion and sediment controls for all critical areas not planned for grading changes.
- Clear, grub, chip, or log the site to the limits of clearing.
- Disposal of stumps and boulders should occur in accordance with approve plans.
- Inspect the condition of temporary erosion and sediment control measure
- Prepare dewatering, stilling, and settling basins.
- Install permanent drainage and erosion control features: swales, splas pools, detention or retention basins. Permanently stabilize prior to use.
- Place rip-rap lining where required.
- Install underground utilities and storm drainage system to the phase limits, if appropriate.
- Install outfall mechanism(s) - maintain erosion and sediment control measures.

- Construct roads, drives, and parking areas.
- Install septic systems, sewer connections, curtain drains (shallow excavations), and building foundations.
- Temporarily stabilize those areas where final grading is complete; where no further vehicular traffic is anticipated - i.e. septic system, yard areas, and along drives.
- Secure building permits - commence building construction.
- Maintain erosion and sediment control measures during construction.
- Ensure that all disturbed areas are permanently stabilized prior to issuance of certificate of occupancy. This includes ALL landscaping requirements.

For Subdivisions Done in Phases:

- Return to "Flag limits-of-clearing" - repeat entire cycle for all subsequent phases. Perform only those functions necessary to maintain the integrity of the construction sequence, and the erosion and sedimentation control system.

PLAN REVIEW WORKSHEET

This worksheet is designed to facilitate the development and review of erosion and sediment control plans. Local commissions should be consulted for regulatory requirements concerning erosion and sediment control planning.

Checked (·) items are those that have been provided on the current erosion and sediment control plan. Items identified with an asterisk (*) should be incorporated into final plans.

Name or Development ______________________________

Materials received ______________________________

____

____

____

Total Area ____________ Location ______________________

Total Number of Lots ____________

Engineer ______________________________

Date Received ____________ Site Visit __________ Reviewed by __________

Submitted by ______________________________

NARRATIVE SECTION DESCRIBING:

____ The development
____ Major land uses of adjoining areas
____ The number of total acres and acres to be disturbed in the project
____ The schedule of grading and construction activities including start and completion dates
____ Application sequence of all E&S control measures
____ The design criteria for all proposed E&S control measures
____ Construction details and installation procedures for all proposed E&S control measures
____ The operations and maintenance program for all proposed E&S control measures
____ The name of the person or organization that will be responsible for the installation and maintenance of the E&S control measures
____ Organization or person responsible for maintenance of permanent measures when project is completed. Measures include: ______________________________

____

Adopted from the Connecticut Guidelines for Soil Erosion and Sediment Control, published by the Connecticut Council on Soil and Water Conservation, January 1985.

A SITE PLAN AT A SUFFICIENT SCALE SHOWING:

Natural Features

____ Existing topography
____ Existing vegetation
____ Soils information, including test pit data, if available
____ Identification of wetlands, watercourses, major drainageways, and water bodies on the site
____ Name of soil scientist who performed wetlands delineations and flag numbers
____ Rock outcrop areas
____ Seeps, springs
____ Major aquifers
____ Floodplains (100 year) and floodways
____ Channel encroachment line (DEP permit required)
____ Coastal zone boundary
____ Public water supply watershed boundaries
____ Possible Army Corps Sec. 404 or Sec. 10 Permit Areas (Contact Corps at 1-800-343-4789).

Project Features

____ The location of the proposed development
____ A plan legend
____ Adjacent property
____ Property lines
____ Lot lines and setback lines
____ Lot and/or building numbers
____ Planned and existing roads
____ Proposed structures
____ Location of existing and planned utilities
____ Location of wells and septic systems
____ Proposed topography
____ North arrow

Clearing, Grading, Vegetative Stabilization

____ The sequence of grading, construction, and sediment and erosion control activities
____ The location of and construction details for all proposed E&S control measures
____ Recommended measures include ____

____

____ Limits of disturbed areas
____ Extent of areas to be graded
____ Disposal procedure for cleared material
____ Location of stockpiled topsoil and subsoil
____ Temporary erosion control in method for protection of disturbed areas when time of year or weather prohibit establishment of permanent vegetative cover
____ Seeding mixture, rates, and seeding dates

____ Seedbed preparation (including topsoiling specifications)
____ Fertilizer and lime application rates
____ Mulch application rate
____ Mulch anchoring measures

Drainage System

____ Existing and planned drainage pattern
____ Drainage areas used in design of stormwater management system
____ Size and location of culverts and storm sewers
____ Drainage calculations for review by town engineer
____ Stormwater management measures and construction details
____ Groundwater control measures (footing drains, curtain drains)
____ Planned water diversions and dams (DEP permit may be required)

House Site Developments

____ Sediment and erosion control measures for individual lot development

Additional Comments

III. INSPECTION WORKSHEET

This worksheet is suggested for personnel responsible for inspection.

PROJECT NAME: ______________________________

LOCATION: ______________________________

PROJECT DESCRIPTION: ______________________________
(Brief description, condominiums, subdivision, etc.)

PARCEL AREA (Acres) ______________________________

RESPONSIBLE PERSONNEL: (Person with responsibility for implementing soil erosion and sediment control plan)

NAME ______________________________

ADDRESS ______________________________

CITY ______________________________

PHONE ______________________________

EROSION AND SEDIMENT CONTROL PLAN PREPARER: ______________________________

INSTALLATION CHECKLIST:

* WORK DESCRIPTION E&S CONTROL MEASURES	** LOCATION	DATE MEASURE INSTALLED	INITIALS OF INSTALLER	DATE MEASURE REMOVED	INITIALS OF PERSON REMOVING MEASURE

*Sequentially list (dates not necessary) measures to be installed. This list should be developed from the narrative and must include all work items.

**Describe location of each proposed measure so that it can be referenced to the plan map. Use of alphabetical measure names can be utilized here. Abbreviated names found in guidelines are preferable - for example: (Construction entrance to Paxton Road = C.E. Paxton Road.

CHECKLIST FOR MAINTENANCE OF MEASURES

LOCATION	DESCRIPTION OR NUMBER	DATE OF MAINTENANCE	INITIALS OF RESPONSIBLE PERSON

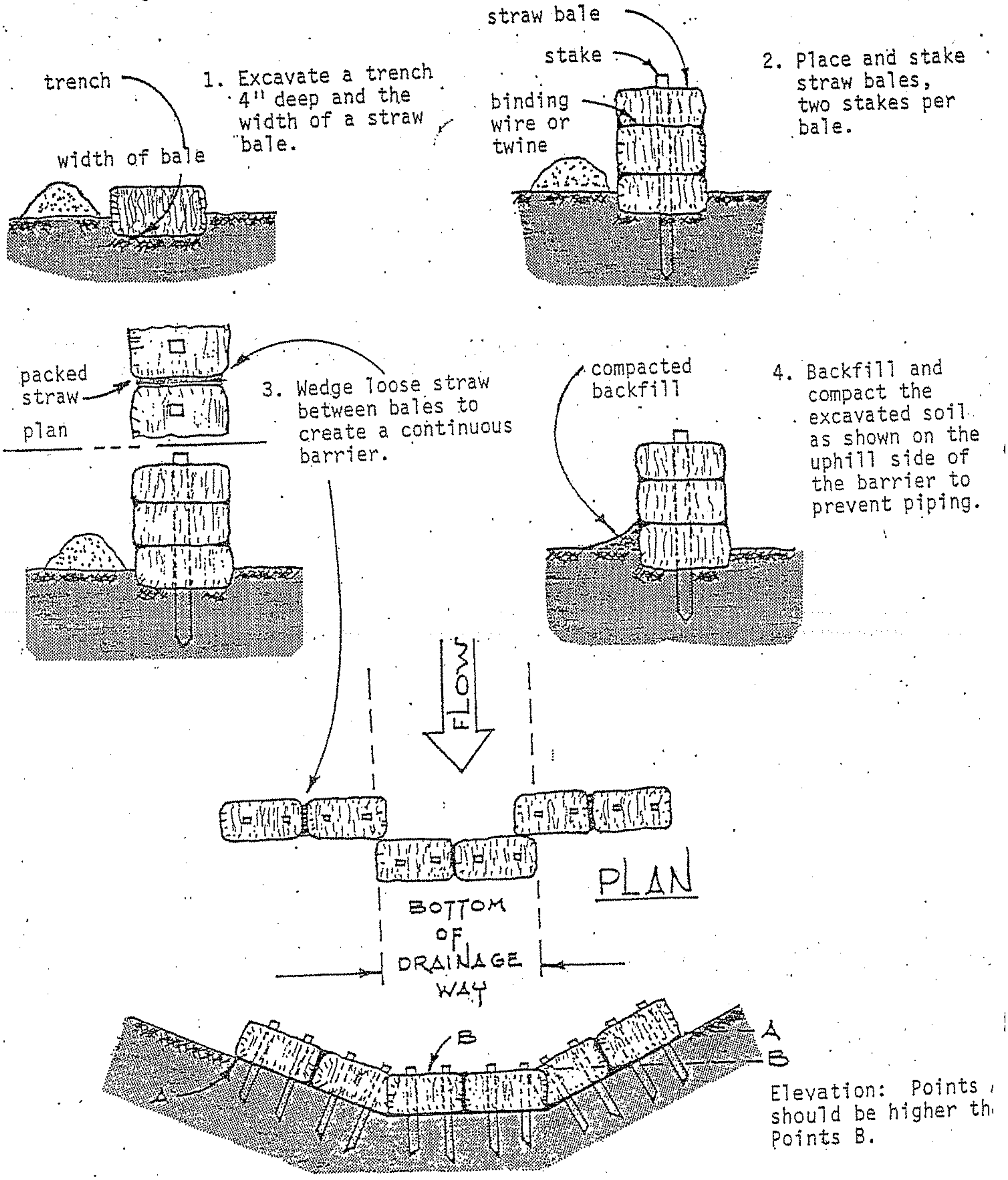
PROJECT DATES: ____________ DATE ________ INITIALS ________

DATE OF GROUNDBREAKING FOR PROJECT: ____________________

DATE OF FINAL STABILIZATION: ____________________

Appendix F-21

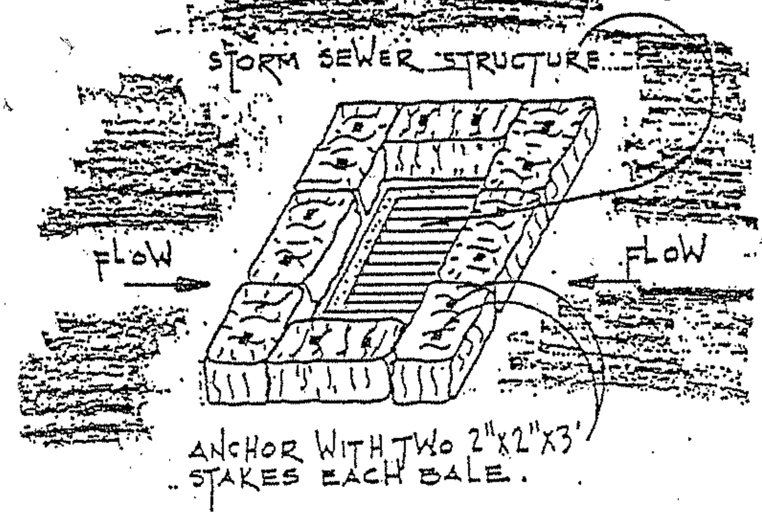
Figure 7-7 - Placement and Construction of a Straw Bale Barrier



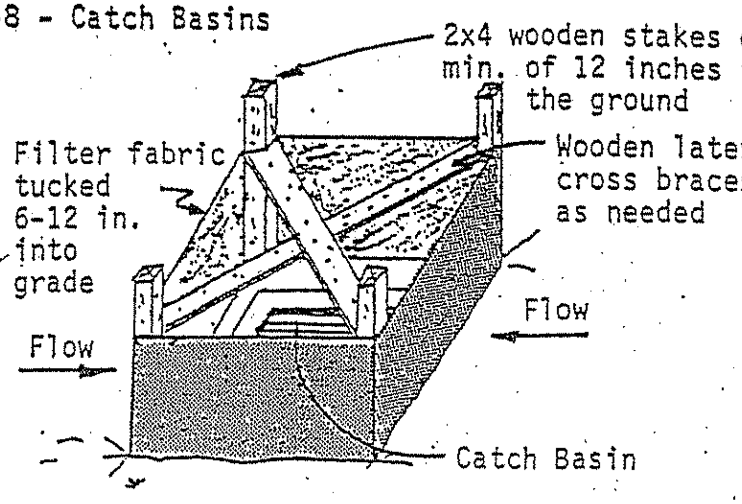
Source: U.S. Department of Agriculture, Soil Conservation Service, Storrs, Connecticut.

(Revised 2/14/86)

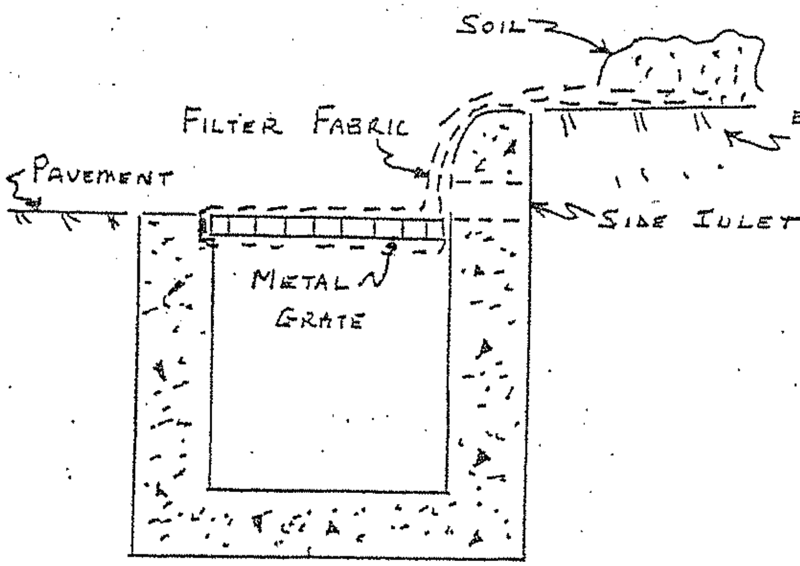
Figure 7-8 - Catch Basins

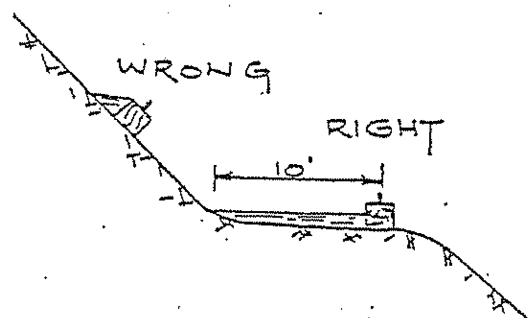


Hay Bale Installation at Catch Basins



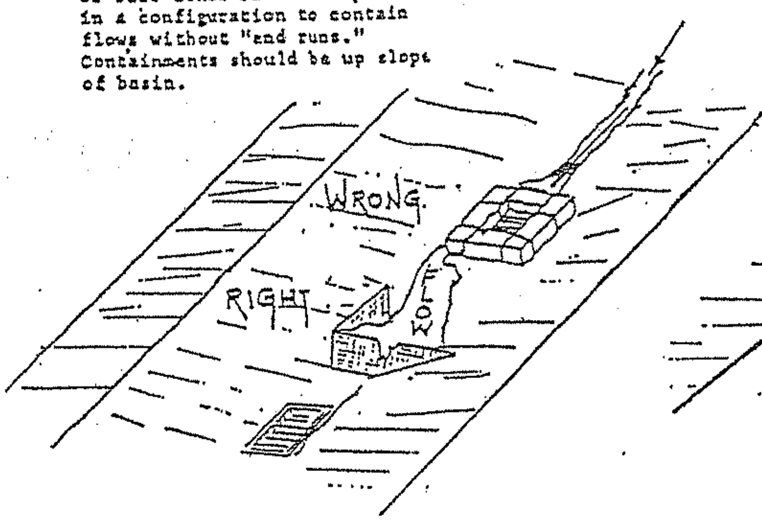
Silt Fence Installation at Catch Basins



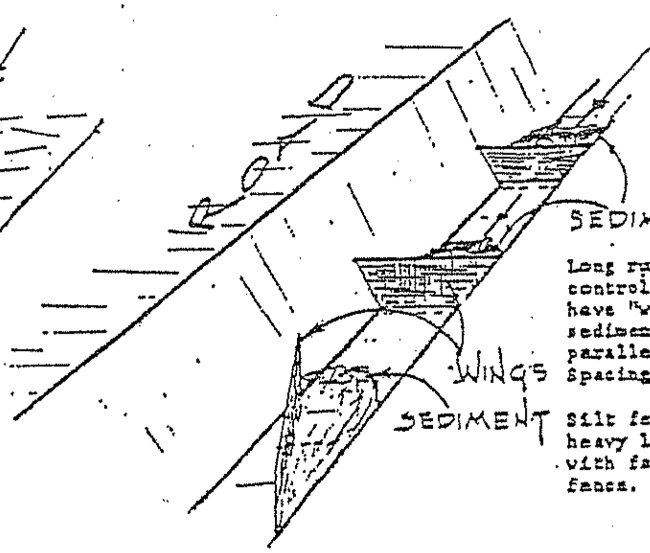


CATCH BASIN

Basins on sloping roads should not be ringed. Bales or silt fence should be placed in a configuration to contain flows without "end runs." Containments should be up slope of basin.



SEDIMENT CONTROL

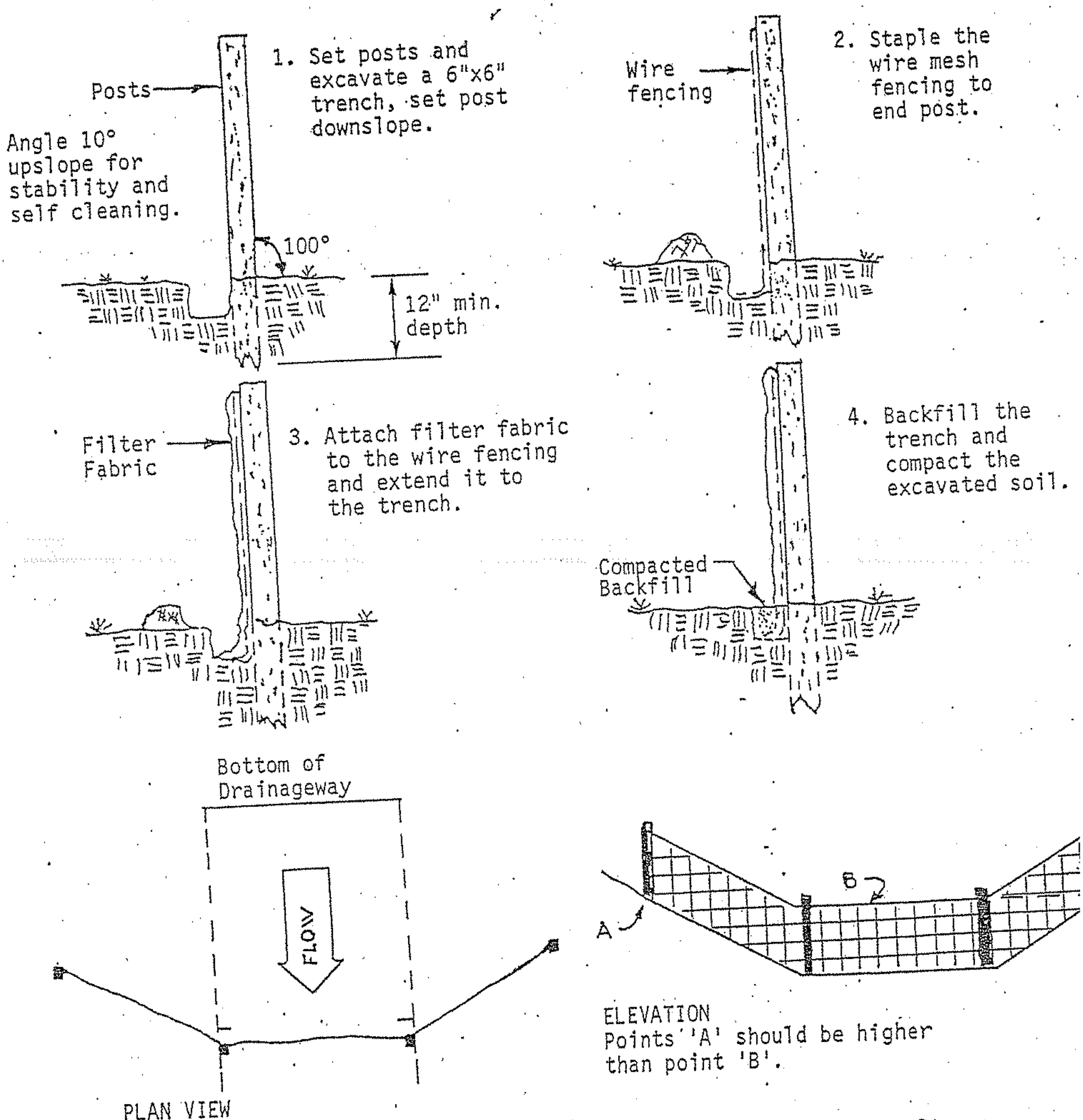


Long running sediment control systems should have "wings" to prevent sediment from running parallel with the system. Spacing as required.

Silt fence subjected to heavy loads can be rein with farm fence and or s fence.

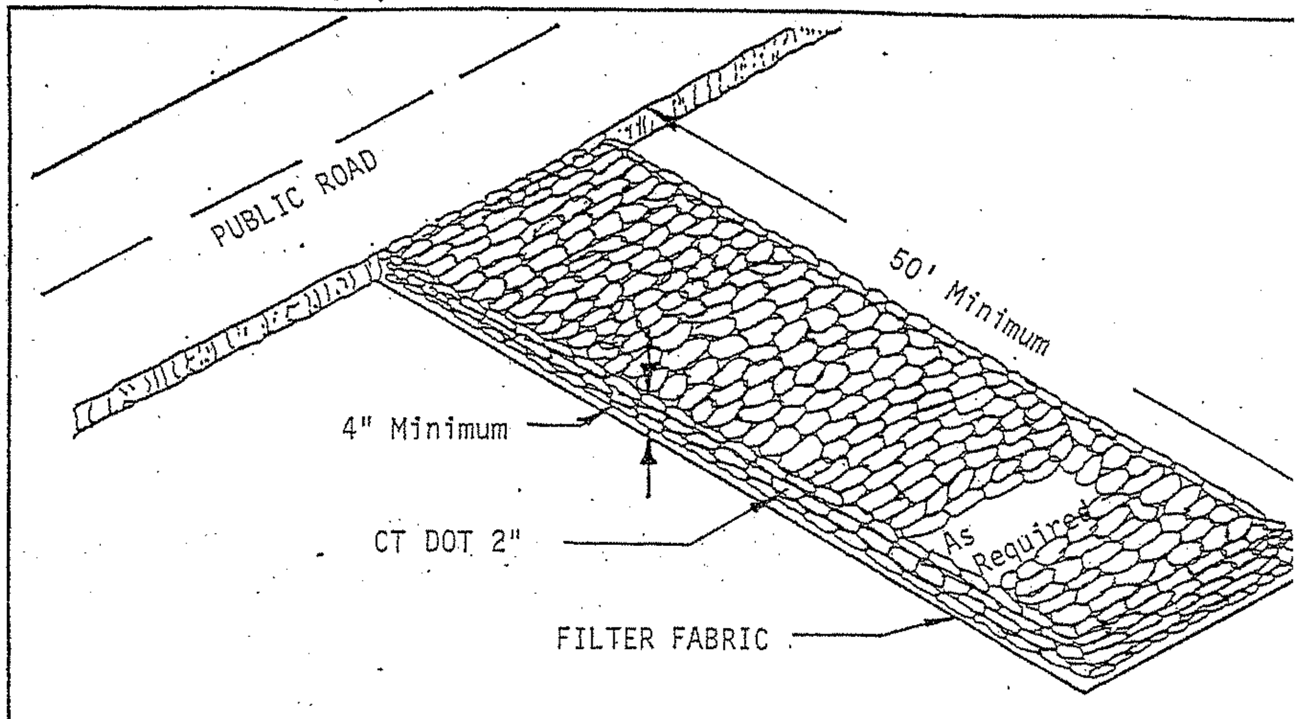
Source: U.S. Department of Agriculture, Soil Conservation Service, Storrs, Connecticut.

Figure 7-9 - Placement and Construction of a Synthetic Filter Barrier



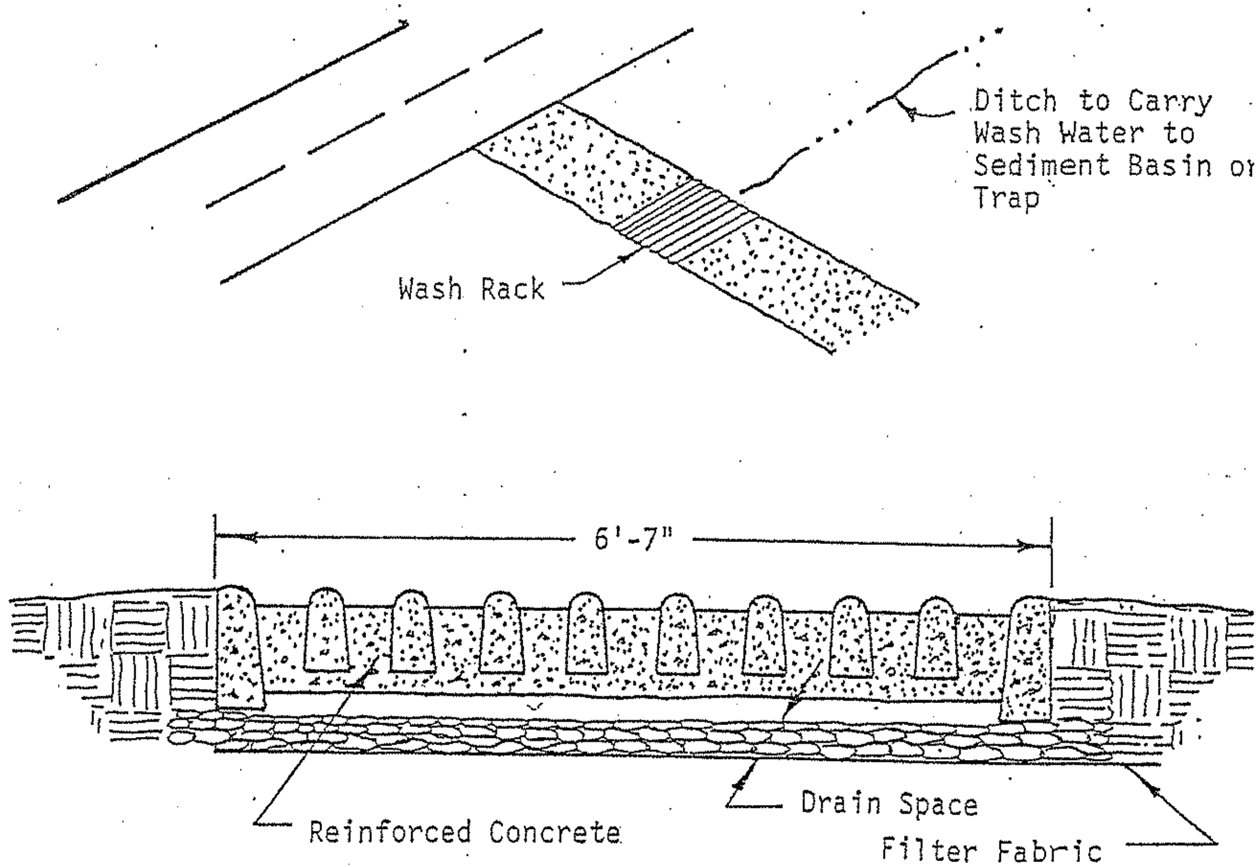
Source: U.S. Department of Agriculture, Soil Conservation Service, Storrs, Connecticut.

Figure 8-59 - Construction Entrances



CONSTRUCTION ENTRANCE

CONSTRUCTION ENTRANCE WITH WASH RACK



Detail of Wash Rack

Source: Smith Cattleguard Company

APPENDIX G

D.O.T. Gutter Flow And Storm Sewer Methods

DETERMINATION OF RUNOFF BY THE RATIONAL METHOD

The Rational Method of determining runoff is based on the premise that the peak rate of discharge from an area wil be proportional to the rate of rainfall, modified by the size and characteristics of the area. The Rational Method is to be used for watersheds under 200 acres only.

A field investigation of the drainage basin should be made in all cases and the time of concentration estimated. The time of concentration is the time it would take rain water, falling on the most distant part of the watershed, to reach the location of the drainage facility being designed. Nomographs which may be of assistance in calculating this time are included as Figures A and B. The factor for determining the total time of concentration should be computed by adding together the estimated times and the proportionate lengths of flow over the various conditions shown. A judgement must be made and the time of concentration arrived at by weighing the factors contributing to runoff. In general, Figure A should be used for overland flow in the upper reaches of the watershed, and Figure B used for lower reaches where the flow has concentrated into a channel. Combining the two time periods will give total Tc.

The minimum time of concentration to be used for a completely paved area will be 5 minutes. Generally in fill sections with curbing the computed "Tc" to the first structure will not exceed 5 minutes. For median and shelf areas or any areas mostly unpaved the Tc will be a minimum of 10 minutes.

The rainfall intensity for the storm having the appropriate frequency and of duration equal to the total time of concentration should be selected from Figure C.

The Coefficient of imperviousness may be estimated from the following table:

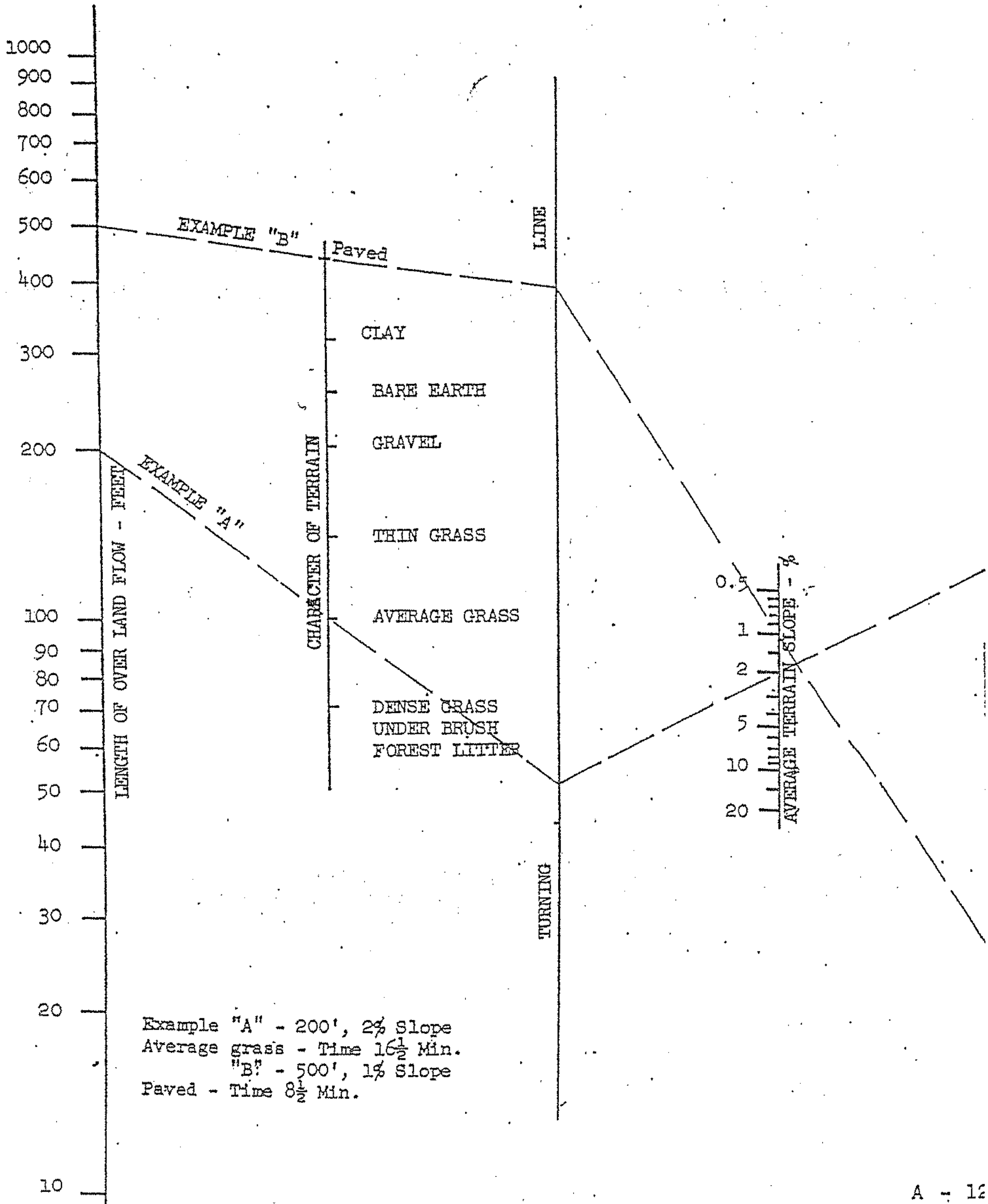
Paved Areas	0.9
Steep Grassed Slopes (>4:1)	0.4
Moderate Grassed Slopes (>6:1,<4:1)	0.3
Flat Grassed Slopes (<6:1)	0.2
Rock	0.8
1/4 Acre Residential	0.45
1/2 Acre Residential	0.35

The peak discharge from an area, computed by this method is the product of the number of acres, times the rate of rainfall in inches per hour, times the coefficient of imperviousness. The product is expressed in cubic feet per second.

The procedure may be used for determination of the runoff expectable from highway surface and immediately adjacent overlying land areas.

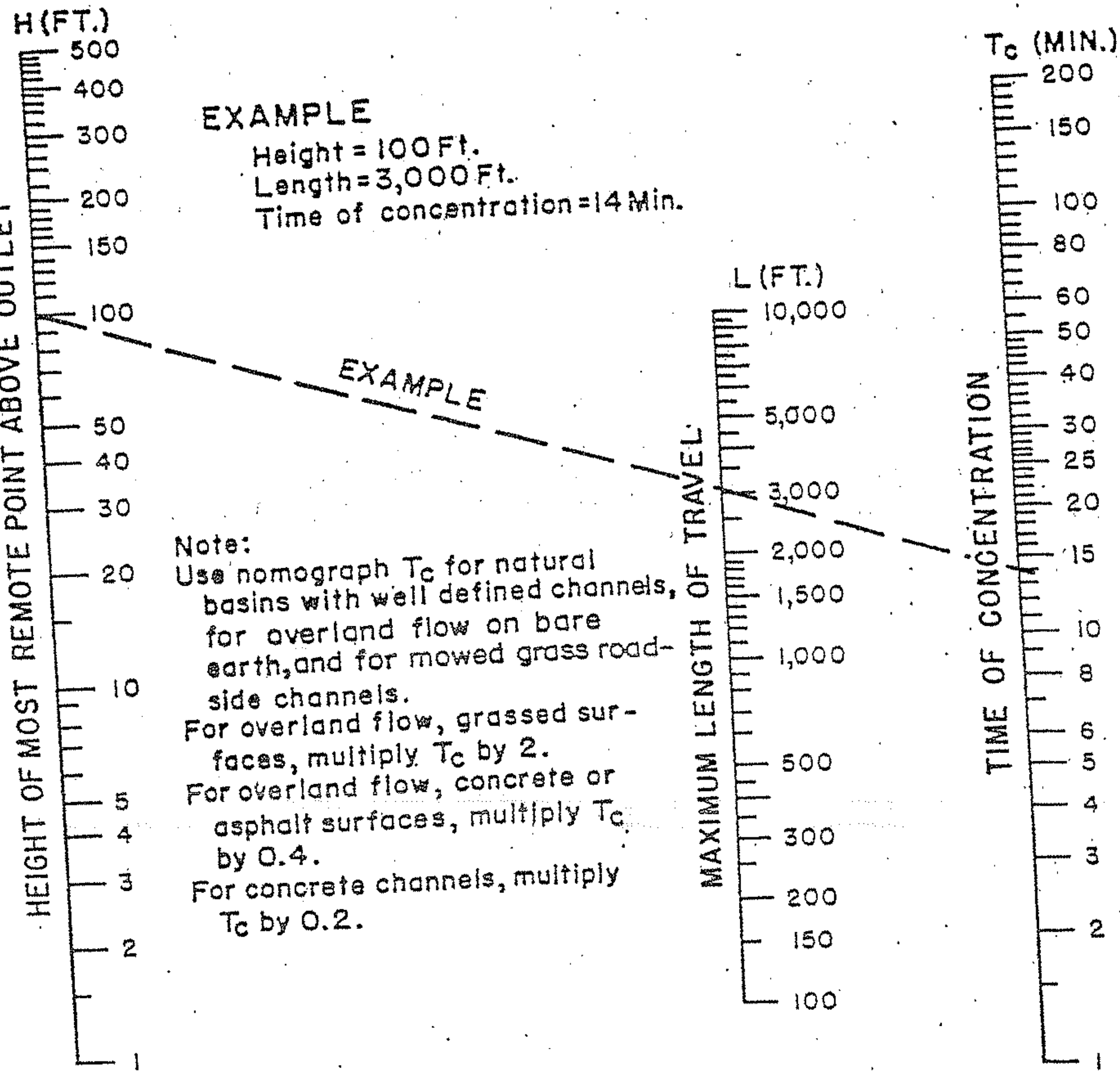
TIME OF CONCENTRATION

(OVERLAND FLOW ONLY)



Example "A" - 200', 2% Slope
Average grass - Time 16½ Min.
"B" - 500', 1% Slope
Paved - Time 8½ Min.

FIG. A

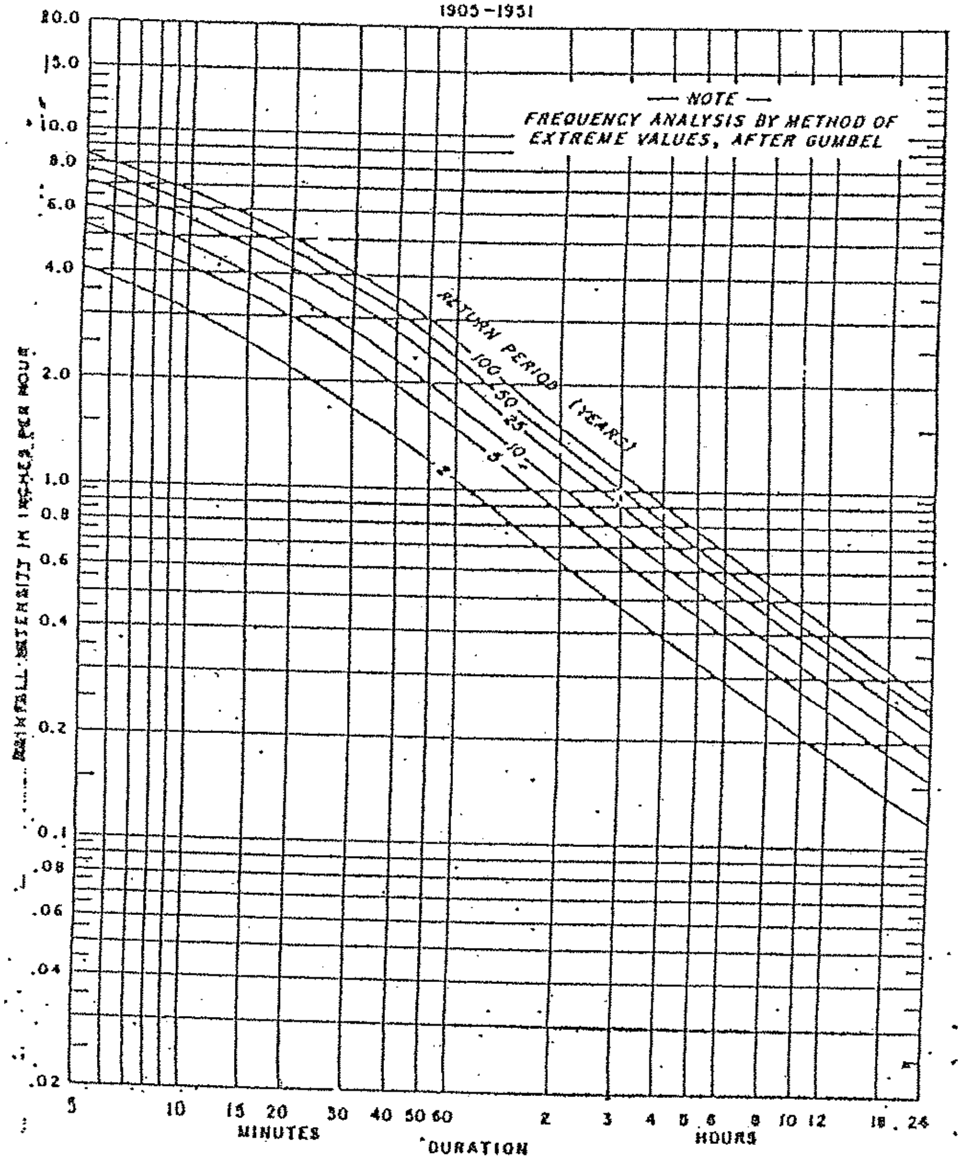


Based on study by P. Z. Kirpich,
Civil Engineering, Vol. 10, No. 6, June 1940, p. 362

TIME OF CONCENTRATION OF SMALL DRAINAGE BASINS

FIG B

HARTFORD, CONNECTICUT
1905-1951



NEW HAVEN, CONNECTICUT
1905-1950

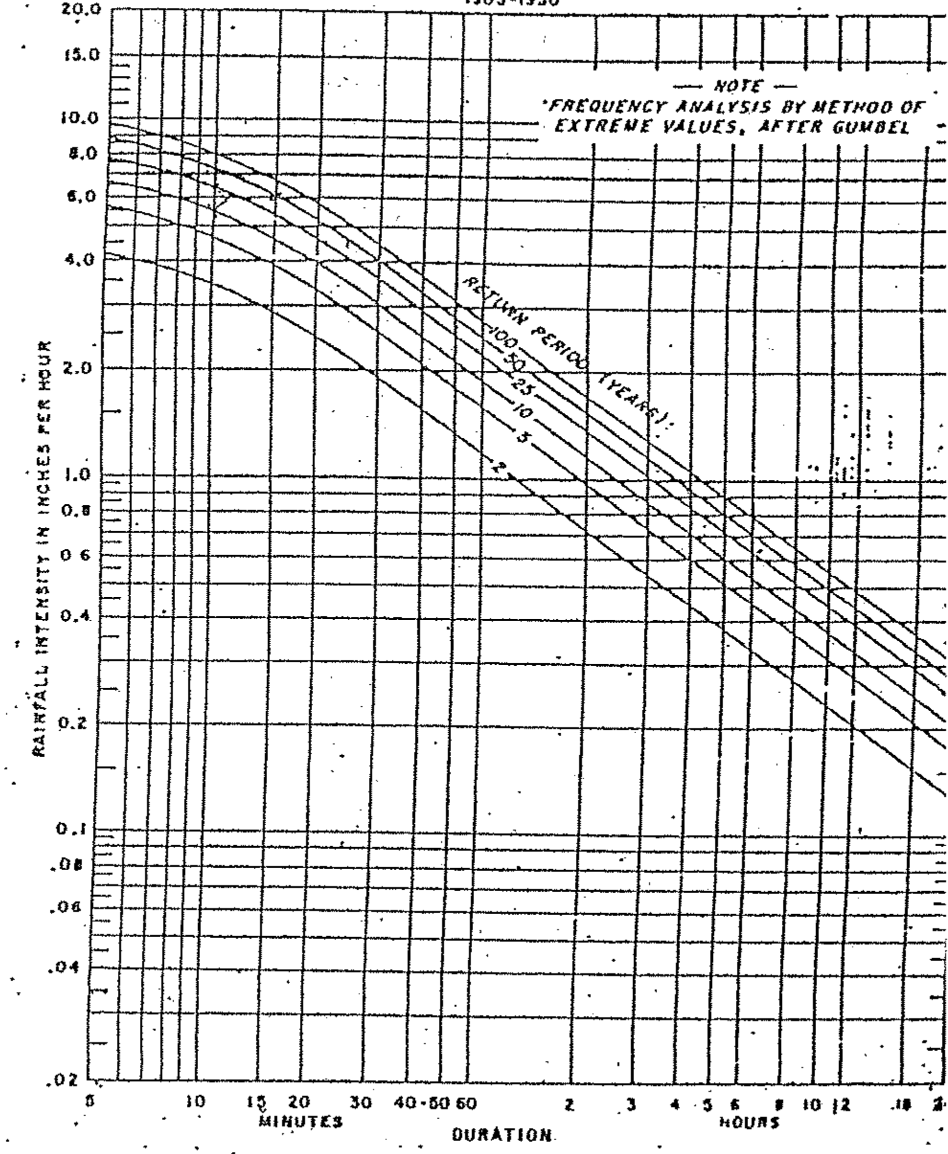


FIG C

SURFACE AND SUBSURFACE DRAINAGE

Highway drainage is divided into two categories, surface drainage anc subsurface drainage. The two categories are for different purposes but frequently share the same facilities.

Surface Drainage

Surface drainage shall provide for the interception and disposal of rainwater and snow melt originating on the highway surface and immediate adjacent overlying areas.

Hydraulics and Interception of Flow

The amount of flow intercepted by a catch basin is dependent upon many factors; including the type of grate, the amount of depression, potential for clogging and velocity of flow. The primary factor is the type of grate that is used. Experience with various grates indicate that the portion of the flow within the width of the grate will usually be intercepted. Lateral flow over the side of the grate is negligible and should not be considered on normal installations. The remainder of the flow outside the grate width will bypass to the next catch basin.

Procedure for Gutter Flow Analysis

Inlet Station - Identify inlet by station and location from centerline.

Time to Inlet - Time required for surface flow to concentrate at inlet.

Area in Acres - Area contributing runoff to inlet.

Runoff Coefficient (I) - Coefficient of area contributing to inlet.

AI - The product of the area and the runoff coefficient.

Sum of AI - The sum of the AI for the inlet.

Total AI - The AI bypassing the previous inlet and the AI for the inlet. (#6 + #15 = #7).

Rainfall Intensity (R) - The intensity determined by the Time to inlet. (#2)

Q to inlet - The product of the Total AI, (#7), and the Rainfall Intensity. (#8) (Q = AIR)

Grade of Gutter - grade to be expressed in feet per foot.

Cross slope of Shoulder - slope to be expressed in feet per foot.

Depth of flow - depth of water at gutter.

Width of flow - the width the water will flow. When the width of flow exceeds the shoulder width, determine depth of flow at the edge of travelway and enter the Flow Characteristic Curves to find the width of travelway flooded. Add this width to the shoulder width to find total width of flow.

Q Bypassing Inlet - the portion of flow that is beyond the width of the grate will be used to determine the bypass Q. No consideration will be given to the minimal amount that enters along the longitudinal edge of the grate.

AI Bypassing Inlet - determined by dividing the "Q bypassing the inlet", (#14), by Rainfall Intensity (#8).

AI entering system - the "Total AI", (#7), minus the "AI bypassing inlet". (#15).

Computer programming for gutter flow analysis is acceptable for use. The computer print-out should contain the same information that is shown on the Gutter Flow Analysis Form.

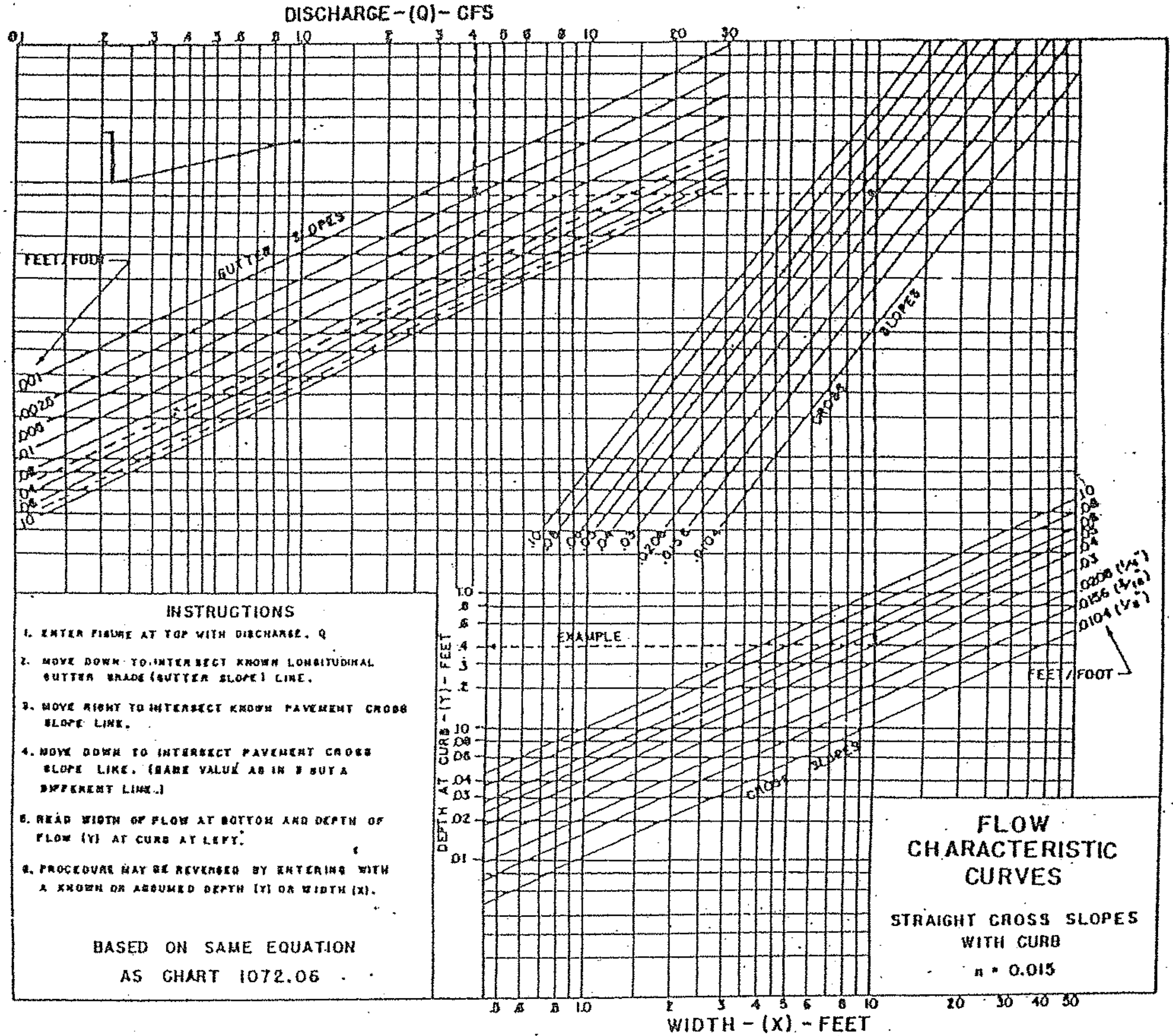
Project ____________________ Designed by ____________________

Town ____________________ Route ____________________ Checked by ____________________

Sheet No. ____

Gutter Analysis

Inlet Station and Offset	Time to Inlet	Area in Acres	Runoff Coefficient	AI	Sum of AI	Total AI	Rainfall Intensity	Q to Inlet	Grade of Gutter	Cross Slope of Shoulder	Depth of Flow at Gutter	Width of Flow	Q Bypassing Inlet	AI Bypassing Inlet	AI Entering Catch Basin
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16


DISCHARGE - (Q) - CFS
FEET/FOOT
GUTTER SLOPES
CROSS SLOPES
EXAMPLE
DEPTH AT CURB - (Y) - FEET
WIDTH - (X) - FEET
INSTRUCTIONS
1. ENTER FIGURE AT TOP WITH DISCHARGE, Q
2. MOVE DOWN TO INTERSECT KNOWN LONGITUDINAL GUTTER GRADE (GUTTER SLOPE) LINE.
3. MOVE RIGHT TO INTERSECT KNOWN PAVEMENT CROSS SLOPE LINE.
4. MOVE DOWN TO INTERSECT PAVEMENT CROSS SLOPE LINE. (SAME VALUE AS IN 3 BUT A DIFFERENT LINE.)
5. READ WIDTH OF FLOW AT BOTTOM AND DEPTH OF FLOW (Y) AT CURB AT LEFT.
6. PROCEDURE MAY BE REVERSED BY ENTERING WITH A KNOWN OR ASSUMED DEPTH (Y) OR WIDTH (X).
BASED ON SAME EQUATION AS CHART 1072.06
FLOW CHARACTERISTIC CURVES
STRAIGHT CROSS SLOPES WITH CURB
n = 0.015

Storm Sewers

Introduction

The design of Storm Sewer systems is a logical interrelation of the technical elements of gutter flow criteria, inlet capabilities and pipe sizing with the topographic conditions that exist at the project site.

Design Basis

Storm sewers will be designed using the rational formula for estimating design discharges. When the sewer system outlet is combined with a culvert crossing the highway, criteria for the culvert crossing will apply to the design of the outlet, however the design of the system leading to the outlet will be based on the rational formula.

Except where indicated by a special study, pipes will be designed to flow "just full" or less than full.

In locations where the roadway is in cut, consideration shall be given to the need for ditches above the slope limits, ditches incised into the cut slope face, or a combination of both, as needed to prevent a concentration of overland drainage from eroding the slope.

Selection of Factors and Outline of Drainage Areas

The designer should outline the general contributing drainage area on available mapping (U.S.G.S., 200 scale photogrammetry, etc), and define imperviousness factors for the individual areas.

Attention should be directed to existing systems within the watershed which may divert portions of the area as defined on the mapping. The field trip should determine preliminary outlet and trunk line locations.

Inlets and other drainage structures shall conform to the details shown on the Department's Standard Drawings.

Type 'C' Catch Basin - Roadway surface drainage shall normally enter storm drainage systems through catch basins at the curb line, where Type 'C' Catch Basins will be the type normally specified ... On streets being re-

Type 'C-L' Catch Basins - will generally be used in medians, swales, negative shelves, channelization islands, parking areas and other locations where vehicles may traverse them. These catch basins are usually depressed to increase their capacity beyond that which would normally pass over the width of the grate.

When these basins are designed with water ponded over the grate, the capacity is usually restricted due to litter, leaves, etc. and a percentage of clogging must be considered.

Clogging Percentage

50% - Depressed sag catch basin, parking lots, and other locations

20% - medians and swales where minimal tree growth is expected.

Double Type 'C-L' Catch Basins Double Grate can be used where greater capacity is needed. Check whether the grate opening or the pipe opening is the hydraulic control.

Type 'D' & 'D-G' Endwalls - have to be located beyond the area that can be traversed by vehicles. The capacity of these endwalls are computed by the weir formula, $Q = CLH^{3/2}$, where 'C', is the coefficient, is equal to 3.33; L is the length of the weir in feet and H is height of water above weir in feet. Caution must be used to prevent the water surface developed by the outlet pipe from submerging the weir.

Endwalls and End Sections - must be located similar to the 'D' and 'D-G' Endwalls. The capacities of these are described in H.E.C. No. 5. Precast end sections will normally be used instead of endwalls.

Adjacent area drainage [illegible] or cross culverts through culvert ends, endwalls of various types or catch basins as required to provide a proper entrance for the water and an adequate safeguard to persons and property. The selection shall be made in accordance with sound engineering practice, considering the amount of discharge to be accommodated, the topography of the inlet location, the skew, if any, of the culvert with respect to the embankment and the potential hazard to the traveling public.

<u>Sumps in Catch Basins</u> - normal practice is to extend the depth of a catch basin two feet below the outlet flowline. This provides a sump for the sand and silts to deposit and be removed by maintenance forces. The sand and silt would otherwise be conveyed to the outlet where it could cause a blockage or environmental damage.

Catch basins located on watercourses or pipes larger than 36" diameter shall not have sumps and will be designated as C.B. w/o sump. The reasons for the deletion of sumps with large pipes is that the volumes of water are usually large and turbulent which will not allow for sand to settle out.

<u>Spacing and Locating Inlets</u>

Inlets are located to intercept concentration of flows, to limit the amount of flooding, or to control the movement of water.

Catch Basins in a defined gutter shall be generally spaced in accordance with the Gutter Flow Analysis and the permissible inundation of shoulder and travelway as previously noted.

Catch Basins should be generally located immediately preceding a bridge structure to intercept flow before it enters the bridge joint. Also, catch basins should be located below a bridge where there is no extension of the curb to prevent continuous scouring.

feet from driveway returns to prevent loss of vehicular traction.

Catch Basins are required at intersections where the grades may cause pockets. To determine the exact location of these catch basins and to determine their capacity it will be necessary to develop contours of these intersections which can be incorporated in the final design.

The capacity of a catch basin in a sag location will be determined by Hydraulic Capacity of Grate Inlets.

The Type 'C' Catch Basin, Double Grate-Type II, which allows much greater capacity in a sag location, will be used where warranted by the gutter analysis.

Designing Storm Sewers

After locations of inlets, pipe runs and outfalls have been determined the next step is the computation of discharge to be conveyed by each pipe run and to determine the size and gradient of pipe for each run. It should be remembered that the quantity of water in a system is not necessarily the sum of the interception of the inlets but as a rule is somewhat less than this total. It is well to be aware that as the time of concentration increases in the system, the rainfall intensity decreased. For all ordinary conditions, pipes should be sized on the assumption that they will flow full or practically full under design conditions but will not be placed under a pressure head.

For uniformity of method of hydraulic analysis it is recommended that the Manning modification of the Chezy flow formula be used for computing flow characteristics of open channels and conduits. Flow characteristics at inlets and other restrictions should be calculated by the use of appropriate variations of the Bernoulli equation. Graphic solution of these procedures can be facilitated and expedited by the use of pertinent charts and graphs published by various government agencies and by manufacturers or manufacturers associations.

Miscellaneous Requirements Storm Sewer Pipe Design

Storm Sewers will be designed to flow "just full". The headwaters in structures shall be limited to one foot below the top of grate, taking into consideration the possible affect of headwater in the next downstream structure.

Where a change in size of pipe is made at a structure the crowns of these pipes will normally be aligned on grade.

Underdrain pipes of 6" size should be laid in straight segments or gradual curves if possible. Where bends of underdrain are necessary to enter a structure they should be no greater than 30 degrees.

Long skew crossings of storm sewer laterals under pavement should be avoided.

Where it is necessary to lay storm sewer pipe or culverts on a slope greater than 10 percent, C.C.M.P. shall be used. C.C.M. Pipes down fill slopes shall have an elbow at the bottom (but not at the top where there is a structure near the top of the fill unless this will result in excessive depth of trench).

All roadway drainage, including the side and slope ditches shall be carried to a suitable outlet, preferably an existing stream. Where outletting to an existing stream is impractical, or where no stream is available, appropriate drainage rights must be obtained.

All existing pipes to be abandoned under the travelway are to be removed.

In all cases where drainage is diverted from one watershed area to another, as is frequently the case in incised highways, the designer shall note the diversions in his computations and on his preliminary plans.

Utility conflicts may require design changes. New installations should be kept at least one foot from any utilities.

Each outlet must be carefully designed with erosion protection as needed and carried down steep slopes to lesser slopes where outlet erosion will not occur. Riprap or modified riprap shall be used at all outlets not flowing over exposed rock or into watercourses or ponds.

Subsurface Drainage

Adequate provisions for subsurface drainage will be included in the design.

1) Underdrains shall consist of a trench cut below the elevation of the bottom of the subbase, containing a suitable perforated or slotted pipe and backfilled with a pervious material in accordance with the Standard Specifications and/or the recommendations of the Engineer of Soils and Foundations.

2) The pipe shall be not less than 6 inches in nominal diameter and may carry surface drainage. Where the pipe carries surface drainage in addition to subsurface drainage, the size shall be not less than 12 inches. At locations where the capacity required exceeds the capacity of the largest underdrain pipes of the appropriate type, the subsurface water and the surface drainage shall be carried in separate pipes.

3) Outlets for underdrain pipe shall be connected directly to drainage structures where practical. If no drainage structure is available, the outlet pipe shall be terminated with a standard underdrain outlet endwall as shown in the Standard Drawings. Uphill ends of underdrains carrying only subsurface drainage shall be extended into a drainage structure, if one is available within 25 feet, and plugged.

Procedure for Storm Sewer System Design

1. Line Segment - Identification of line usually between inlets by stationing and offset.

2. Time to Inlet - Time for surface flow to concentrate for first inlet. If the area is such that it takes less than the minimum time of 5 minutes then 5 minutes shall be used until the accumulated time exceeds 5 minutes.

3. Time in pipe - time required to pass through line segment.

4. Accumulated Time - Time of concentration effective at location. The longest time is to be used. This can be overland flow to an inlet; accumulation of time in pipe; or a branch line entering a system.

5. AI entering Catch Basin - AI determined by "Gutter Flow Analysis Form".

6. Sum of AI in system - sum of the AIs entering inlets effective at location.

7. Rainfall Intensity - The intensity determined by the Accumulated Time (4).

8. 'Q' in system - The product of sum of AI in system, (7) and the Rainfall Intensity, (5).

9. Pipe size - self-explanatory.

10. Length of Pipe - self-explanatory.

11. Slope - to be expressed to the nearest thousandths of a foot.

12. Average velocity - that which will be obtained in pipe of size, type and slope specified at design discharge.

13. Full Capacity - discharge which can be carried by pipe of size and type specified, flowing full.

14. Headwater - height water will reach above the flowline that will develop at the design discharge in the structure.

15. 'n' - roughness Coefficient: n = .012 for R.C.P.; n = .019 for C.C.M.P. with paved invert.

Storm Se System Design

Project ______ Designed by ______

Town ______ Route ______ Checked by ______ Sheet No. ______

1 Line Segment	2 Time to Inlet	3 Time in Pipe	4 Accumulated Time	5 AI Entering Catch Basin	6 Sum of AI in System	7 Rainfall Intensity	8 Q in System	9 Pipe Size	10 Length of Pipe	11 Slope	12 Average Velocity	13 Full Capacity	14 Headwater	15 'n'

APPENDIX G-17

CAPACITY OF GRATE INLETS IN A SAG

A grate inlet in a sag operates first as a weir having a crest length roughly equal to the outside perimeter (P) along which the flow enters. Bars are disregarded and the side against the curb is not included in computing P. Weir operation continues to a depth (d) of about 0.4 foot above the top of grate and the discharge intercepted by the grate is:

$$Q_i = 3.0\, Pd^{1.5} \qquad (1)$$

Where Q_i = rate of discharge into the grate opening, in cubic feet per second

P = perimeter of grate opening, in feet, disregarding bars and neglecting the side against the curb

d = depth of water at grate, in feet

When the depth at the grate exceeds about 1.4 feet, the grate begins to operate as an orifice and the discharge intercepted by the grate is:

$$Q_i = 0.67A\ (2gd)^{0.5} = 5.37Ad^{0.5} \qquad (2)$$

Where Q_i = rate of discharge into the grate opening, in cubic feet per second

A = clear opening of the grate, in square feet

g = acceleration of gravity, 32.2 feet per second^2

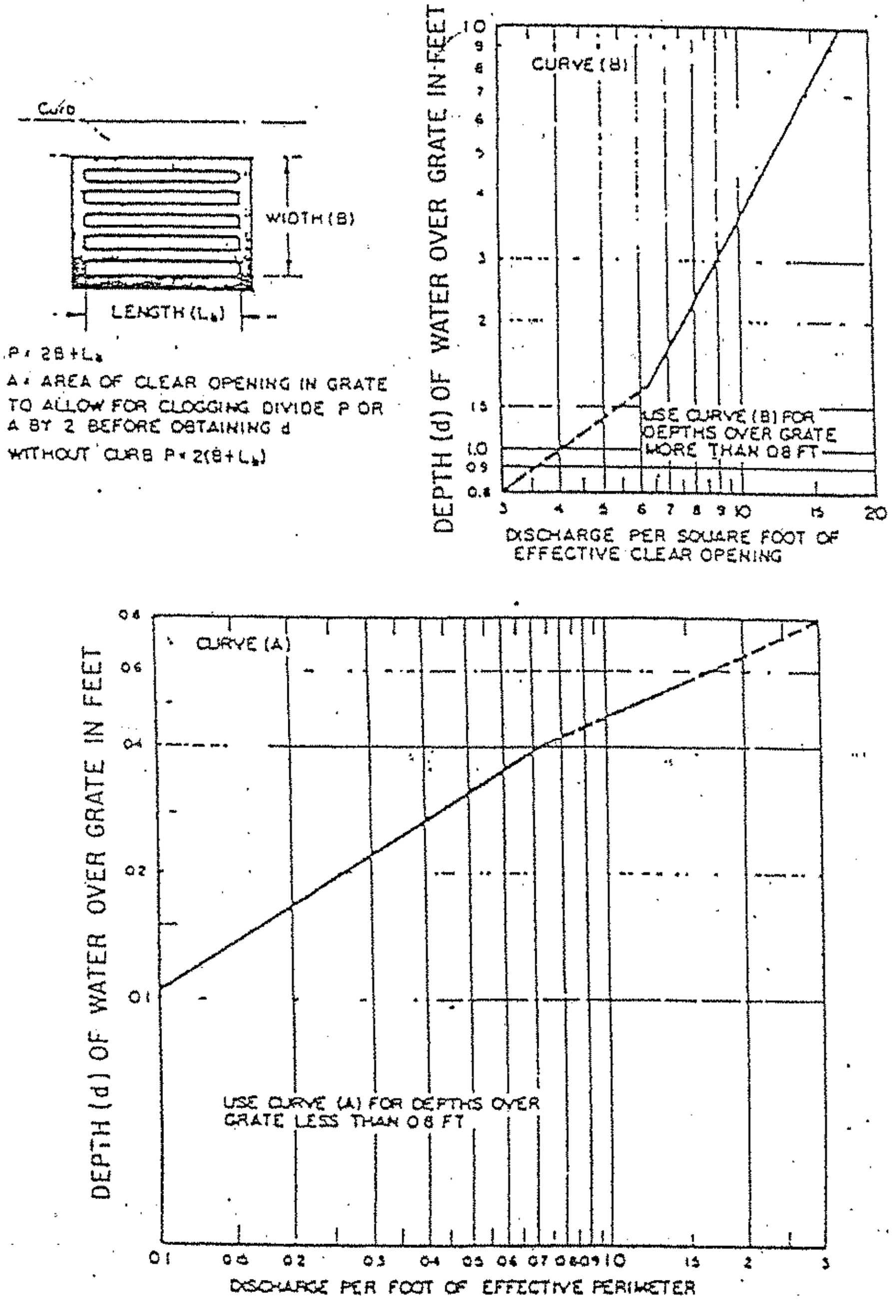
d = depth of ponded water above top of grate, in feet

Between depths over the grate of about 0.4 and about 1.4 feet the operation of the grate inlet is indefinite due to vortices and other disturbances. The capacity of the grate is some where between that given by equations (1) and (2).

Because of the vortices and the tendency of trash to collect on the grate, the clear opening or perimeter of a grate inlet should be at least twice that required by equations (1) and (2) in order to remain below the design depth over the grate. Where danger of clogging is slight a factor of safety less than two might be used. If a combination inlet is used, the grate need only be as large as given by equations (1) and (2) because the curb opening provides the safety factor from clogging.

Equations (1) and (2) can be solved graphically with the following charts.

The dashed lines represent the range where neither weir nor orifice operation is fully effective.



BUREAU OF PUBLIC ROADS
REV. AUG 1968

HYDRAULIC CAPACITY OF GRATE INLET IN SUMP

APPENDIX H

This Appendix Left Intentionally Blank

APPENDIX I

Design of Highway Culverts

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-IP-85-15 HDS No. 5		

4. Title and Subtitle	5. Report Date
Hydraulic Design of Highway Culverts	September 1985
	6. Performing Organization Code
	8. Performing Organization Report No.
7. Author(s) Jerome M. Normann, Robert J. Houghtalen and William J. Johnston	
9. Performing Organization Name and Address Jerome M. Normann and Associates Norfolk, Virginia 23503	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address Office of Implementation, HRT-10 Federal Highway Administration 6200 Georgetown Pike McLean, Virginia 22101	14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager: John M. Kurdziel (HRT-10)
Technical Assistants: Philip L. Thompson, Dennis L. Richards, J. Sterling Jones

16. Abstract

Hydraulic Design Series No. 5 combines culvert design information previously contained in Hydraulic Engineering Circular (HEC) No. 5, No. 10, and No. 13 with hydrologic, storage routing, and special culvert design information. The result is a comprehensive culvert design publication. Hydrologic analysis methods are described, and references cited. Culvert design methods are presented for both conventional culverts and culverts with inlet improvements. Storage routing techniques are included which permit the designer to account for ponding effects upstream of the culvert. Unique culvert applications, erosion and sediment control, debris control, structural aspects, and long span culverts are discussed and references cited. Inlet control, outlet control, and critical depth design charts, many of which are newly developed, are included for a variety of culvert sizes, shapes, and materials. New dimensionless culvert design charts are provided for the design of culverts lacking conventional design nomographs and charts. The appendices of the publication contain the equations and methodology used to construct the design charts, information of the hydraulic resistance of culverts, and methods of optimizing culvert design using performance curves and inlet depression. Calculation forms are provided for most of the design methodologies in the manual.

17. Key Words	18. Distribution Statement
Culverts, hydrology, storage routing inlet control, outlet control, critical depth, tapered inlets.	This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	272	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

For those interested in using the metric system, the inch-pound units used in this manual may be converted to metric units by the following factors.

From		Multiply by	To obtain	
Unit	Abbrev.		Unit	Abbrev.
cubic foot per second	ft^3/s	0.02832	cubic meter per second	m^3/s
foot	ft	0.3048	meter	m
square foot	ft^2	0.0929	square meter	m^2
cubic foot	ft^3	0.0283	cubic meter	m^3
inch	in	2.54	centimeter	cm
square mile	mi^2	2.59	square kilometer	km^2
acre		0.4047	hectare	
foot per second	ft/s	0.3048	meter per second	m/s

TABLE OF CONTENTS

LIST OF FIGURES

Figure No.		Page

Figure No.		Page
VI-14	Riprap protection at culvert outlet	119
VI-15	Sediment deposition in culvert	119
VI-16	Debris deflector	121
VI-17	Barrel skew angle	121
VI-18	Inlet skew angle	122
VI-19	Barrel and inlet skew	123
VI-20	Fill warped to avoid inlet skew	124
VI-21	Double barrel box culvert	124
VI-22	Multiple barrel culvert with one low flow barrel	125
VI-23	Bridge versus culvert at same location	126
VI-24	Corrugated metal box culvert (Kaiser)	127
VI-25	Precast double barrel box culvert	127
VI-26	LTEC design process	129
VI-27	LTEC solution surface	129
VI-28	Guardrail adjacent to culvert headwall	130
VI-29	Endwall for safety grate	131
VI-30	Safety grate flush with culvert entrance	131
VI-31	Culvert installations	132
VI-32	Pressure distribution - rigid culverts	132
VI-33	Unanchored mitered end	133
VI-34	Slope paving around a mitered end	133
VI-35	Long span culvert (ARMCO)	134
VI-36	Long span culvert (ARMCO)	135
VI-37	Typical long span culvert shapes	135
VI-38	Abrasion in culvert barrel	136
VI-39	Flow chart for calculator programs	139
VI-40	Flow chart for CDS No. 4	141
VI-41	Macro-flow diagram for HY-6	142
A-1	Dimensionless performance curve for structural plate elliptical conduit, long axis horizontal, thin wall projecting entrance.	151
B-1	Shapes of annular corrugations.	157
B-2	Shape of 5- by 1-inch corrugation.	158
B-3	Manning n versus diameter for corrugated metal conduits.	160
C-1	Outlet control performance curves.	166
C-2	Box culvert outlet control performance curves.	167
C-3	Inlet control performance curves - various inlet configurations.	168
C-4	Optimization of performance in inlet control.	169
C-5	Possible face design selections - tapered inlet.	170
C-6	Tapered inlet design options for 8 ft by 6 ft reinforced box culvert.	172

LIST OF TABLES

GLOSSARY

a	Cross-sectional area of orifice, ft^2
a'	Constant in rainfall intensity formula
A	Full cross-sectional area of culvert barrel or channel, ft^2
A_b	Area of bend section of slope-tapered inlet, ft^2
A_f	Area of inlet face section of tapered inlet, ft^2
A_p	Area of flow prism, ft^2
A_t	Area of tapered inlet throat section, ft^2
A_w	Watershed area, acres
b	Face dimension of side bevel, in
b'	Constant in rainfall intensity formula
B	Span of culvert barrel, ft
B_b	Width of bend section of a slope-tapered inlet, ft
B_f	Width of face section of a tapered inlet, ft
c	Coefficient for submerged inlet control equation
C	Runoff coefficient for use in the Rational equation
C_b	Discharge coefficient for bend section control
C_d	Coefficient of discharge for flow over an embankment
C_f	Discharge coefficient for face section control
C_r	Free flow coefficient of discharge for flow over an embankment
C_t	Discharge coefficient for throat section control
CMP	Corrugated metal pipe
d	Face dimension of top bevel, in
d_c	Critical depth, ft
D	Interior height of culvert barrel, ft
D_e	Equivalent diameter, $D_e = 4R$, ft
D_{50}	Size of streambed material which exceeds 50% of the material by weight; i.e., the median size, in or ft
E	Height of face of tapered inlet, excluding bevel, ft
EL_c	Elevation of weir crest, ft
EL_f	Invert elevation at face, ft
EL_{hc}	Headwater elevation required for flow to pass crest in crest control, ft
El_{hd}	Design headwater elevation, ft
EL_{hf}	Headwater elevation required for flow to pass face section in face control, ft

EL_{hi}	Headwater elevation required for culvert to pass flow in inlet control, ft
EL_{ho}	Headwater elevation required for culvert to pass flow in outlet control, ft
EL_{ht}	Headwater elevation required for flow to pass throat section in throat control, ft
EL_o	Invert elevation at outlet, ft
EL_{sf}	Stream bed elevation at face of culvert, ft
EL_{so}	Stream bed elevation at outlet of culvert, ft
EL_t	Invert elevation at throat, ft
EL_{tw}	Tailwater elevation, ft
f	Darcy resistance factor
F_r	Froude number
FALL	Depression of inlet control section below the stream bed, ft. (Measured from stream bed to face invert for culvert, to throat invert for culvert with tapered inlet.)
G	The number of different materials (roughnesses) in the perimeter of a conduit with composite roughness
g	Acceleration due to gravity, 32.2 f/s/s
HGL	Hydraulic grade line
h	Height of hydraulic grade line above centerline of orifice, ft
h_f	Friction head loss, ft
h_o	Height of hydraulic grade line above outlet invert, ft
h_t	Height of tailwater above crown of submerged road, ft
H	Sum of inlet loss, friction loss, and velocity head in a culvert, ft
H_L	Total energy required to pass a given discharge through a culvert, ft
H_b	Head loss at bend, ft
H_c	Specific head at critical depth ($d_c + V_c^2/2g$), ft
H_e	Entrance head loss, ft
H_f	Friction head loss in culvert barrel, ft
H_g	Head loss at bar grate, ft
H_j	Head loss at junction, ft
H_l	Friction head loss in tapered inlet, ft
H_o	Exit head loss, ft
H_v	Velocity head = $V^2/2g$, ft
HW	Depth from inlet invert to upstream total energy grade line, ft
HW_b	Headwater depth above the bend section invert, ft
HW_c	Headwater depth above the weir crest, ft

HW_d	Design headwater depth, ft
HW_i	Headwater depth above inlet control section invert, ft
HW_f	Headwater depth above the culvert inlet face invert, ft
HW_o	Headwater depth above the culvert outlet invert, ft
HW_r	Total head of flow over embankment, ft (Measured from roadway crest to upstream surface level.)
HW_t	Depth from throat invert to upstream total energy grade line, ft
I	Rate of inflow into a storage basin, ft^3/s
	Rainfall intensity, in/hr
k	Flow constant for an orifice, $Q = kah^{0.5}$, $ft^{0.5}/s$
k_e	Entrance loss coefficient
k_t	Correction factor for downstream submergence during roadway overtopping
K	Coefficient for unsubmerged inlet control equation
K_b	Dimensionless effective pressure term for bend section control
K_f	Dimensionless effective pressure term for inlet face section control
K_g	Dimensionless bar shape factor for calculating grate head losses
K_t	Dimensionless effective pressure term for inlet throat control
L	Actual culvert length, ft
L_a	Approximate length of culvert, including tapered inlet, but excluding wingwalls, ft
L_r	Width of roadway prism crest, ft
L_1, L_2, L_3, L_4	Dimensions relating to tapered inlets, ft
M	Exponent in unsubmerged inlet control equation
n	Manning roughness coefficient
$\bar{n}$	Weighted Manning n value
N	Number of barrels
O	Rate of outflow from a storage basin, ft^3/s
p	Wetted perimeter, ft
p_f	Wetted perimeter of tapered inlet face, ft
p_t	Wetted perimeter of tapered inlet throat, ft
P	Length from crest of depression to face of culvert, ft
q_o	Discharge over segment of embankment, ft^3/s
Q	Discharge, ft^3/s
Q_b	Flow through culvert as opposed to flow over embankment, ft^3/s

HW_d	Design headwater depth, ft
HW_i	Headwater depth above inlet control section invert, ft
HW_f	Headwater depth above the culvert inlet face invert, ft
HW_o	Headwater depth above the culvert outlet invert, ft
HW_r	Total head of flow over embankment, ft (Measured from roadway crest to upstream surface level.)
HW_t	Depth from throat invert to upstream total energy grade line, ft
I	Rate of inflow into a storage basin, ft^3/s
	Rainfall intensity, in/hr
k	Flow constant for an orifice, $Q = kah^{0.5}$, $ft^{0.5}/s$
k_e	Entrance loss coefficient
k_t	Correction factor for downstream submergence during roadway overtopping
K	Coefficient for unsubmerged inlet control equation
K_b	Dimensionless effective pressure term for bend section control
K_f	Dimensionless effective pressure term for inlet face section control
K_g	Dimensionless bar shape factor for calculating grate head losses
K_t	Dimensionless effective pressure term for inlet throat control
L	Actual culvert length, ft
L_a	Approximate length of culvert, including tapered inlet, but excluding wingwalls, ft
L_r	Width of roadway prism crest, ft
L_1, L_2, L_3, L_4	Dimensions relating to tapered inlets, ft
M	Exponent in unsubmerged inlet control equation
n	Manning roughness coefficient
$\bar{n}$	Weighted Manning n value
N	Number of barrels
O	Rate of outflow from a storage basin, ft^3/s
p	Wetted perimeter, ft
p_f	Wetted perimeter of tapered inlet face, ft
p_t	Wetted perimeter of tapered inlet throat, ft
P	Length from crest of depression to face of culvert, ft
q_o	Discharge over segment of embankment, ft^3/s
Q	Discharge, ft^3/s
Q_b	Flow through culvert as opposed to flow over embankment, ft^3/s

Q_c	Discharge at critical depth, ft^3/s
Q_d	Design discharge, ft^3/s
Q_o	Discharge over total length of embankment, ft^3/s
Q_p	Peak flow rate, ft^3/s
Q_r	Routed (reduced) peak flow, ft^3/s
Q_t	Total of $Q_b + Q_o$, ft^3/s
Q_{50}	Discharge for 50-year return period (similar for other return periods), ft^3/s
R	Hydraulic radius = cross-sectional area of flow through culvert or channel divided by wetter perimeter, ft
R/o	Rainfall runoff, ft^3
R/F	Rainfall, in
RCP	Reinforced concrete pipe
s	Storage in a storage basin, ft^3
S	Slope of culvert barrel, ft/ft
S_e	Slope of embankment or face of excavation, expressed as S_e:1, horizontal:vertical, ft/ft
S_f	Slope of fall at culvert inlet, expressed as S_f:1, horizontal:vertical, ft/ft
S_n	Friction slope of full flow HGL, ft/ft
S_o	Slope of channel bed, ft/ft
t	Time, min or sec
t_i	Time of concentration for Rational equation, min
t_p	Time to peak of a runoff hydrograph, min or sec
T	Depth of depression, ft
	Rainfall duration, min
T_c	Critical storm duration, min
T_p	Top width of flow prism, ft
TAPER	Cotangent of angle of sidewalls in tapered inlet with respect to an extension of the culvert sidewalls, ft/ft.
TW	Tailwater depth measured from culvert outlet invert, ft
V	Mean velocity of flow, ft/s
V_d	Channel velocity downstream of culvert, ft/s
V_g	Velocity of flow between bars in a grate, ft/s
V_o	Velocity at outlet of culvert, ft/s
V_u	Approach velocity upstream of culvert, ft/s
w	Maximum cross-sectional width of the bars facing the flow, ft

W	Length of weir crest for slope tapered inlet with mitered face, ft
W_p	Length of weir crest of fall, excluding sides of depression, ft
WW	Wingwall of culvert entrance
x	Minimum clear spacing between bars, ft
X_1, X_2, X_3	Lengths of overflow sections along embankment, ft
y	Depth of flow, ft
y'	Change in hydraulic grade line through a junction, ft
Y	Additive term in submerged inlet control equation
y_h	Hydraulic depth = A_p/T_p
Z	The difference in elevation between the crest and face section of a slope-tapered inlet with a mitered face, ft
Θ_g	Angle of bar grate with respect to the horizontal, degrees
Θ_s	Flare angles of side walls of tapered inlet with respect to extension of culvert side wall, degrees
Θ_t	Angle of departure of the top slab from a plane parallel to the bottom slab, degrees
Θ_w	Flare angle of wingwalls with respect to extension of culvert side wall, degrees
Θ_j	Angle between outfall and lateral at a junction, degrees

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

HYDRAULIC DESIGN OF HIGHWAY CULVERTS

I. INTRODUCTION

A. General.

The purpose of this publication is to provide information for the planning and hydraulic design of highway culverts and inlet improvements for culverts. (figure I-1) Design methods are included for special shapes including long-span culverts. (figure I-2) Detailed information is provided on the routing of flow through culverts. Guidance and reference sources are furnished for environmental, safety, structural, economic, and other consideration.

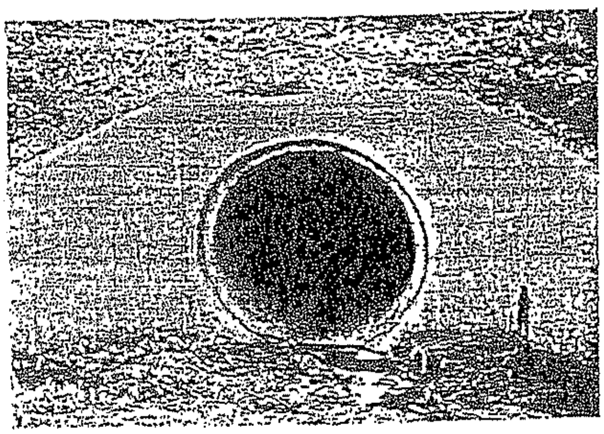


Figure I-1--Typical concrete pipe culvert.

The check lists, design charts and tables, and calculation forms of this publication should provide the designer with the necessary tools to perform culvert designs ranging from the most basic culverts to more complex improved inlet designs. Figure I-3 is a flowchart of the culvert design procedure followed in this manual.

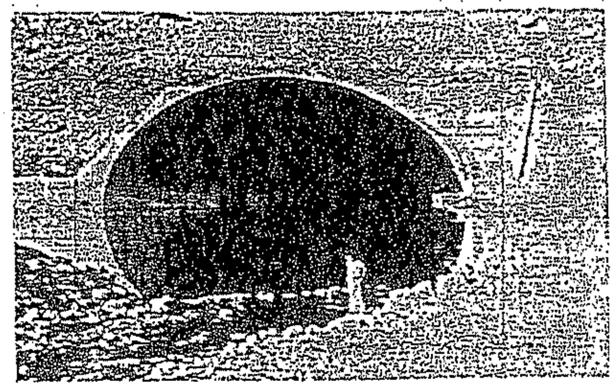


Figure I-2--Long span culvert.

The methodology of culvert design presented in this publication is in a clear, usable format. It is intended for those with a good understanding of basic hydrologic and hydraulic methods and with some experience in the design of hydraulic structures. The experienced designer is assumed to be able to understand the variety of flow conditions which are possible in these complex hydraulic structures and make appropriate adjustments. The inexperienced designer and those unfamiliar with hydraulic phenomena should use this publication with caution.

This publication combines the information and methodology contained in Hydraulic Engineering Circular (HEC Number 5, <u>Hydraulic Charts for the Selection of Highway Culverts</u>, HEC Number 10, <u>Capacity Charts for the Hydraulic Design of Highway Culverts</u>

and HEC Number 13, Hydraulic Design of Improved Inlets for Culverts with other more recent culvert information developed by governmental agencies, universities, and culvert manufacturers to produce a comprehensive culvert design publication. (1,2,3)

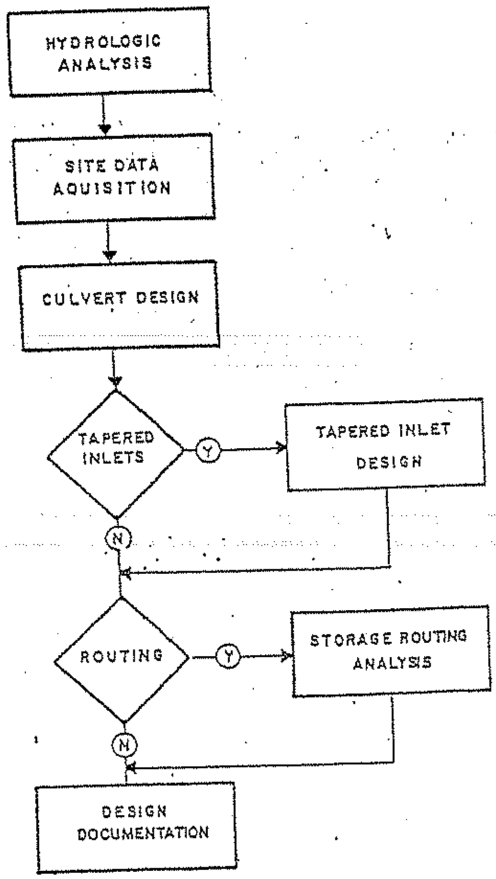


Figure I-3--Culvert design procedure flowchart.

B. Overview Of Culverts.

A culvert is a hydraulically short conduit which conveys stream flow through a roadway embankment or past some other type of flow obstruction. Culverts are constructed from a variety of materials and are available in many different shapes and configurations. Culvert selection factors include roadway profiles, channel characteristics, flood damage evaluations, construction and maintenance costs, and estimates of service life.

1. Shapes. Numerous cross-sectional shapes are available. The most commonly used shapes, depicted in figure I-4, include circular, box (rectangular), elliptical, pipe-arch, and arch. The shape selection is based on the cost of construction, the limitation on upstream water surface elevation, roadway embankment height, and hydraulic performance.

2. Materials. The selection of a culvert material may depend upon structural strength, hydraulic roughness, durability, and corrosion and abrasion resistance. The three most common culvert materials are concrete (reinforced and nonreinforced), corrugated aluminum, and corrugated steel. Culverts may also be lined with other materials to inhibit corrosion and abrasion, or to reduce hydraulic resistance. For example, corrugated metal culverts may be lined with asphaltic concrete. A concrete box culvert and a corrugated metal arch culvert are depicted in figures I-5 and I-6 respectively.

3. Inlets. A multitude of different inlet configurations are utilized on culvert barrels. These include both prefabricated and constructed-in-place installations. Commonly used inlet configurations include projecting culvert barrels, cast-in-place concrete headwalls, precast or prefabricated end sections, and culvert ends mitered to conform to the fill slope. (figure I-7) Structural stability, aesthetics, erosion control, and fill retention are considerations in the selection of various inlet configurations.

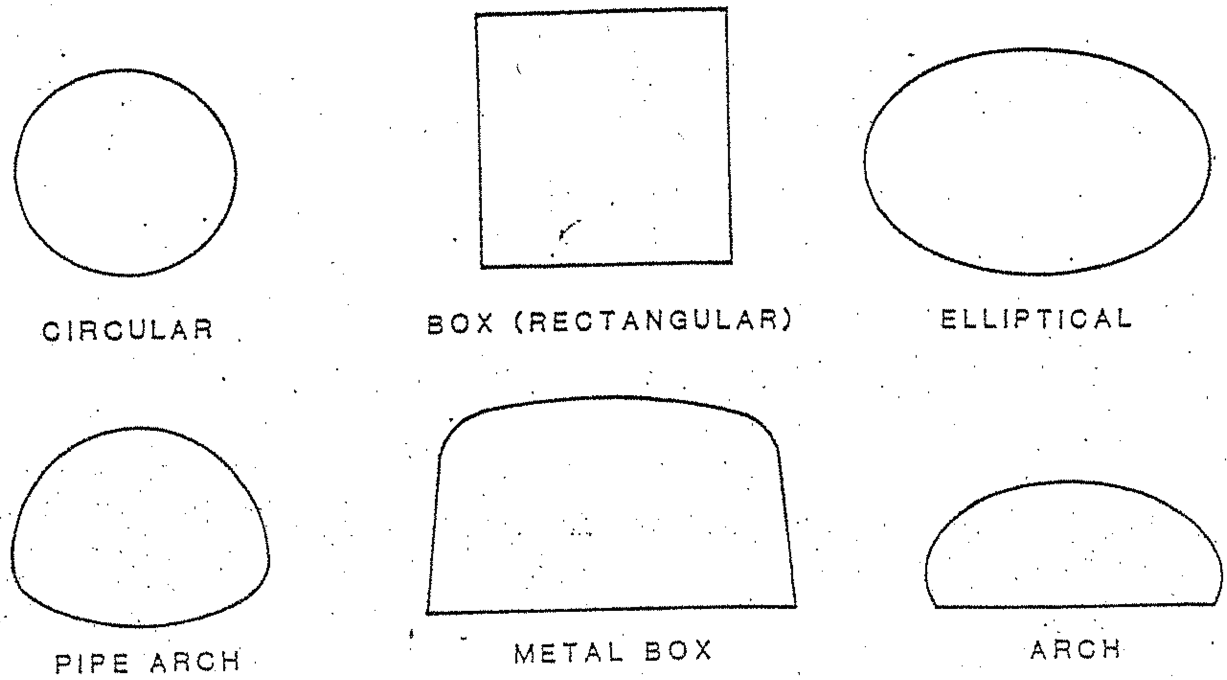


Figure I-4--Commonly used culvert shapes.

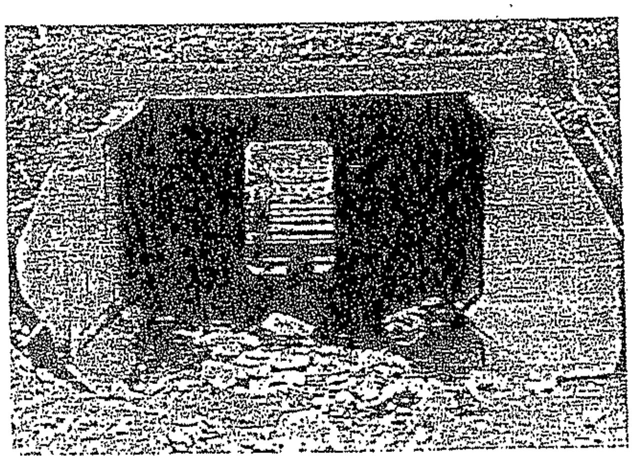


Figure I-5--Precast concrete box culvert (American Concrete Pipe Association).

The hydraulic capacity of a culvert may be improved by appropriate inlet selection. Since the natural channel is usually wider than the culvert barrel, the culvert inlet edge represents a flow contraction and may be the primary flow control. The provision of a more gradual flow transition will lessen the energy loss and thus create a more hydraulically efficient inlet condition. (figure I-8) Beveled edges are therefore more efficient than square edges. Side-tapered and slope-tapered inlets, commonly referred to as improved inlets, further reduce the flow contraction. Depressed inlets, such as slope-tapered inlets, increase the effective head on the flow control section, thereby further increasing the culvert efficiency. Figures I-9 and I-10 depict a side-tapered and a slope-tapered inlet respectively.

C. Culvert Hydraulics.

A complete theoretical analysis of the hydraulics of a particular culvert installation is time-consuming and difficult. Flow conditions vary from culvert to culvert and they also vary over time for any given culvert. The barrel of the culvert may flow full or partly full depending upon upstream and downstream conditions, barrel characteristics, and inlet geometry.

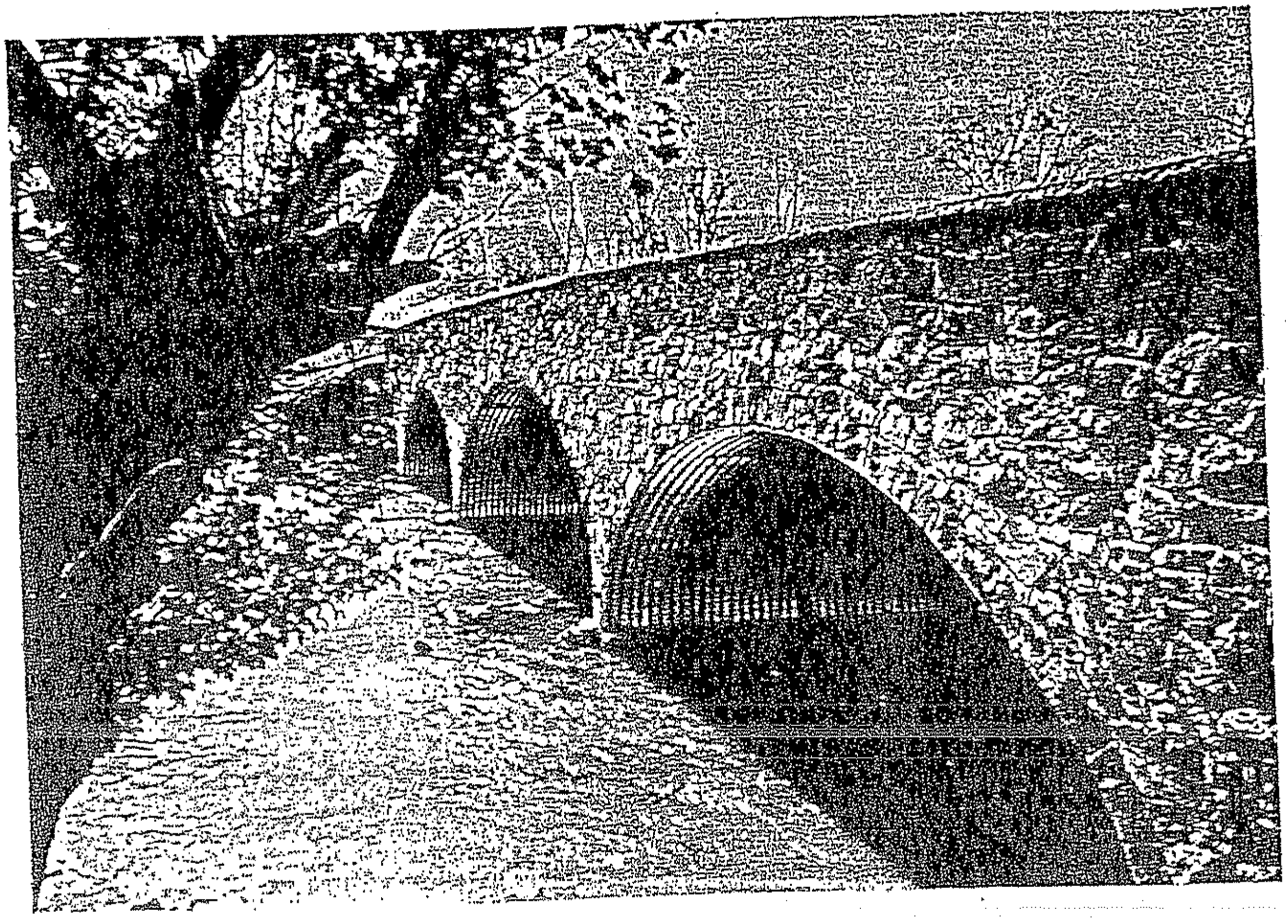


Figure I-6--Corrugated metal arch culvert (ARMCO).

Research by the National Bureau of Standards (NBS) sponsored and supported by the Federal Highway Administration (FHWA), formerly the Bureau of Public Roads (BPR), began in the early 1950's and resulted in a series of seven reports. (4 to 10) These reports provided a comprehensive analysis of culvert hydraulics under various flow conditions. These data were used by the BPR staff to develop culvert design aids, called nomographs. These nomographs are the basis of the culvert design procedures in HEC No. 5, HEC No. 13, and this publication.

The approach presented in HEC No. 5 is to analyze a culvert for various types of flow control and then design for the control which produces the minimum performance. Designing for minimum performance ignores transient conditions which might result in periods of better performance. The benefits of designing for minimum performance are ease of design and assurance of adequate performance under the least favorable hydraulic conditions.

1. Flow Conditions. A culvert barrel may flow full over all of its length or partly full. Full flow in a culvert barrel is rare. Generally, at least part of the barrel flows partly full. A water surface profile calculation is the only way to accurately determine how much of the barrel flows full.

a. Full Flow. The hydraulic condition in a culvert flowing full is called pressure flow. If the cross-sectional area of the culvert in pressure flow were increased, the flow area would expand. One condition which can create pressure flow in a culvert is the back-pressure caused by a high downstream water surface elevation. A high upstream

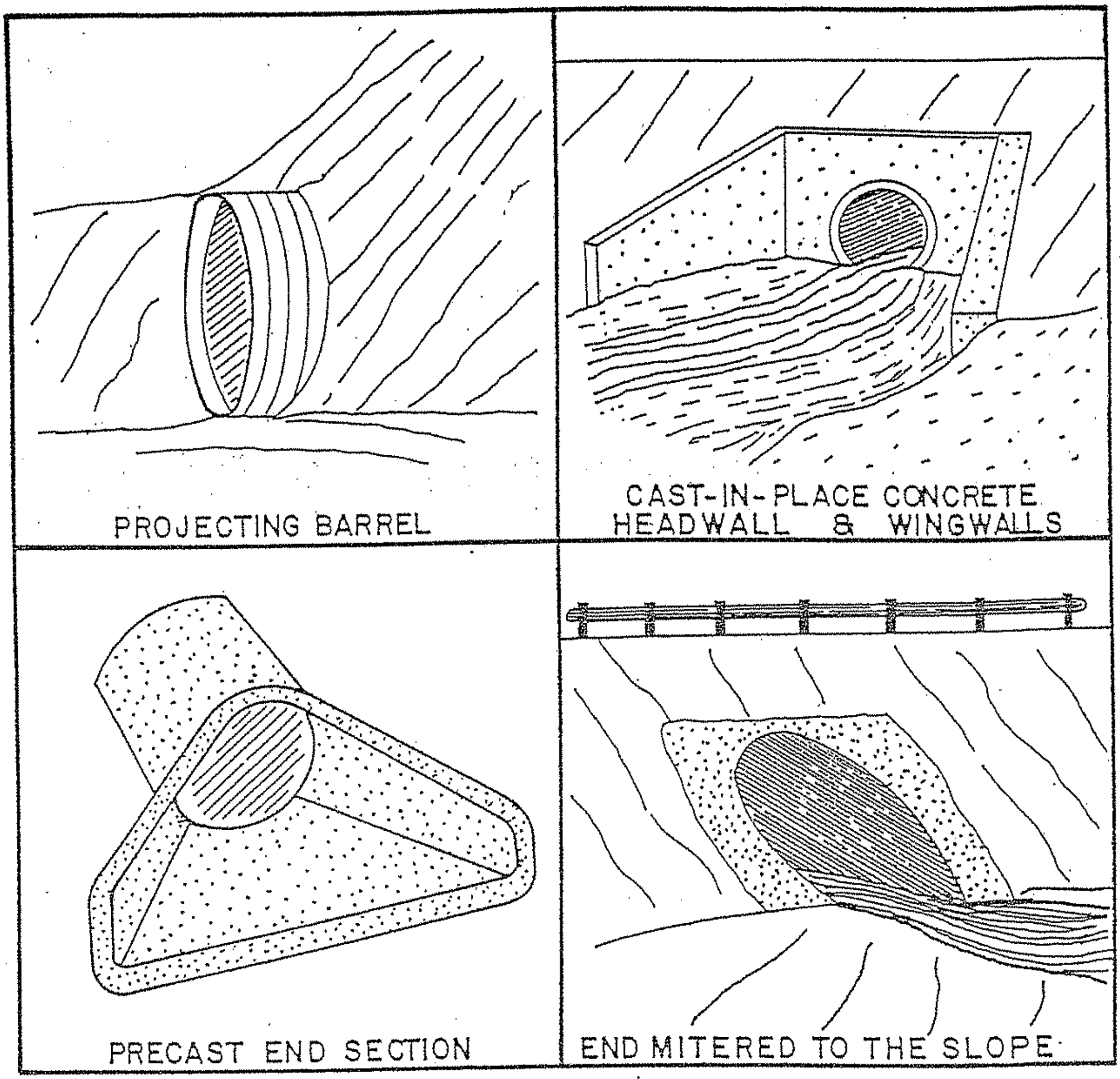


Figure I-7--Four standard inlet types (schematic).

water surface elevation may also produce full flow. (figure I-11) Regardless of the cause, the capacity of a culvert operating under pressure flow is affected by upstream and downstream conditions and by the hydraulic characteristics of the culvert.

b. Partly Full (Free Surface) Flow. Free surface flow or open channel flow may be categorized as subcritical, critical, or supercritical. A determination of the appropriate flow regime is accomplished by evaluating the dimensionless number, F_r, called the Froude number:

$$F_r = V/(gy_h)^{0.5}$$

In this equation, V is the average velocity of flow, g is the gravitational acceleration, and y_h is the hydraulic depth. The hydraulic depth is calculated by dividing the cross-sectional flow area by the width of the free water surface. When $F_r > 1.0$, the flow is supercritical and is characterized as swift. When $F_r < 1.0$, the flow is subcritical and characterized as smooth and

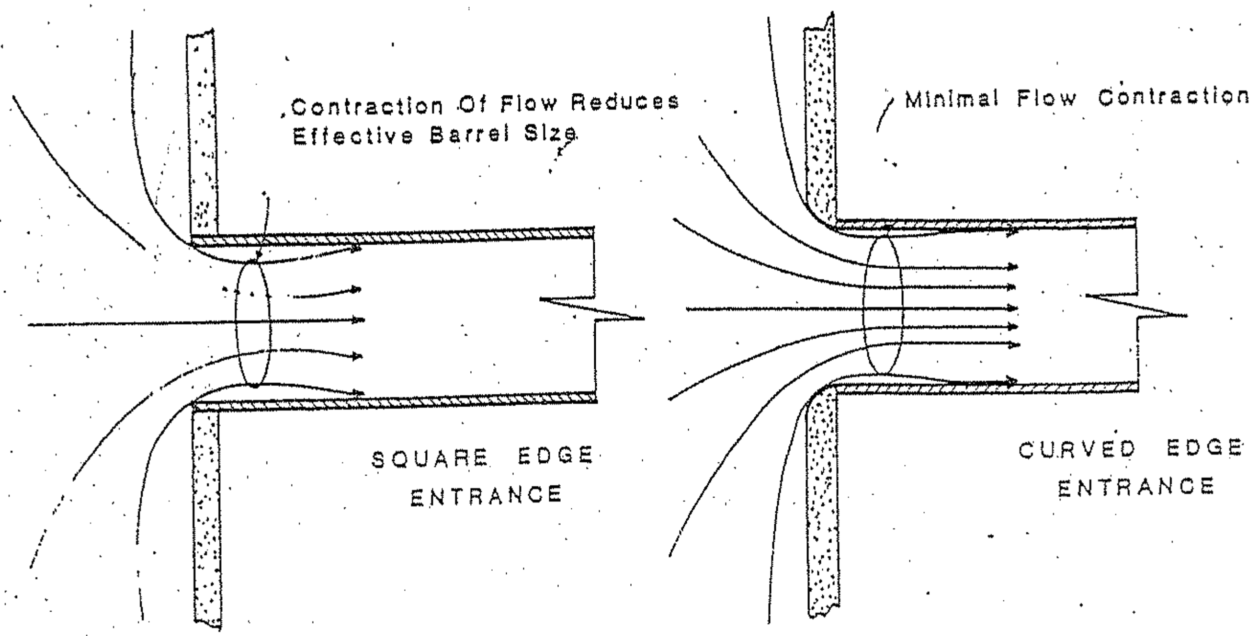


Figure I-8--Entrance contraction (schematic).

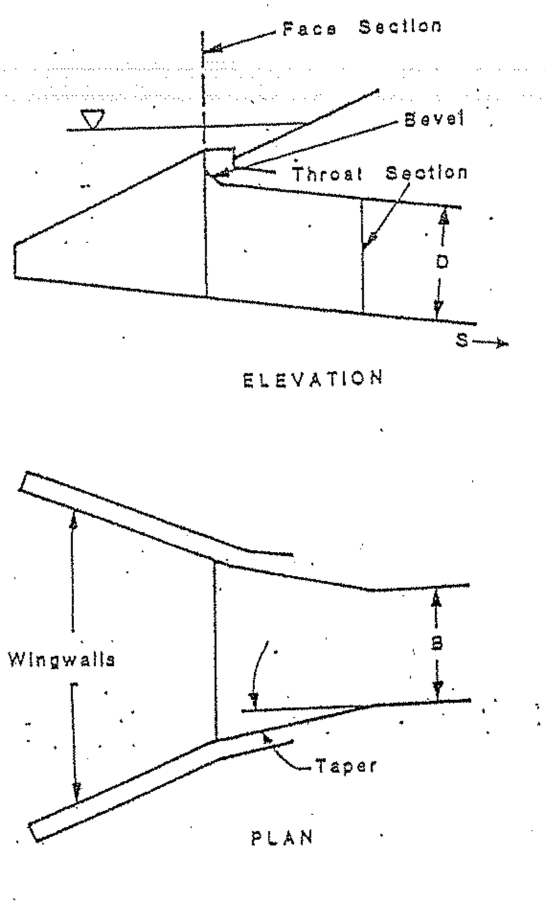


Figure I-9--Side-tapered inlet.

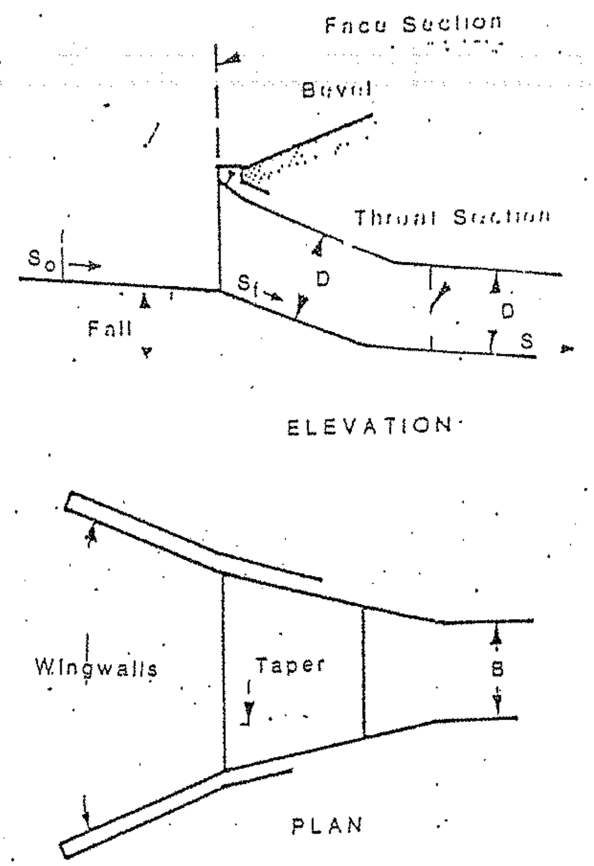


Figure I-10--Slope-tapered inlet.

Figure I-11--Culvert flowing full (no tailwater at outlet end).

tranquil. If $F_r = 1.0$, the flow is said to be critical.

The three flow regimes are illustrated in the depiction of a small dam in figure I-12. Subcritical flow occurs upstream of the dam crest where the water is deep and the velocity is low. Supercritical flow occurs downstream of the dam crest where the water is shallow and the velocity is high. Critical flow occurs at the dam crest and represents the dividing point between the subcritical and supercritical flow regimes.

To analyze free surface flow conditions, a point of known depth and flow (control section) must first be identified. A definable relationship exists between critical depth and critical flow at the dam crest, making it a convenient control section.

Identification of subcritical or supercritical flow is required to continue the analysis of free surface flow conditions. The example using the dam of figure I-12 depicts both flow regimes. Subcritical flow characteristics, such as depth and velocity, can be affected by downstream disturbances or restrictions. For example, if an obstruction is placed on the dam crest (control section), the water level upstream will rise. In the supercritical flow regime, flow characteristics are not affected by downstream disturbances. For example, an obstruction placed at the toe of the dam does not affect upstream water levels.

The same type of flow illustrated by the small dam may occur in a steep culvert flowing partly full. (figure I-13) In this situation, critical depth would occur at the culvert inlet, subcritical flow could exist in the upstream channel, and supercritical flow would exist in the culvert barrel.

A special type of free surface flow is called "just-full flow." This is a special condition where a pipe flows full with no pressure. The water surface just touches the crown of the pipe. The analysis of this type of flow is the same as for free surface flow.

2. Types of Flow Control. Inlet and outlet control are the two basic types of flow control defined in the research conducted by the NBS and the BPR. The basis for the classification system was the location of the control section. The characterization of pressure, subcritical, and supercritical flow regimes played an important role in determining the location of the control section and thus the type of control. The hydraulic capacity of a culvert depends upon a different combination of factors for each type of control.

a. <u>Inlet Control.</u> Inlet control occurs when the culvert barrel is capable of conveying more flow than the inlet will accept. The control section of a culvert operating under inlet control is located just inside the entrance. Critical depth occurs at or near this location, and the flow regime immediately downstream is supercritical. Figure I-13 shows one typical inlet control flow condition. Hydraulic characteristics downstream of the inlet control section do not affect the culvert capacity. The upstream water surface elevation and the inlet geometry represent the major flow controls. The inlet geometry includes the barrel shape, cross-sectional area, and the inlet edge. (table 1)

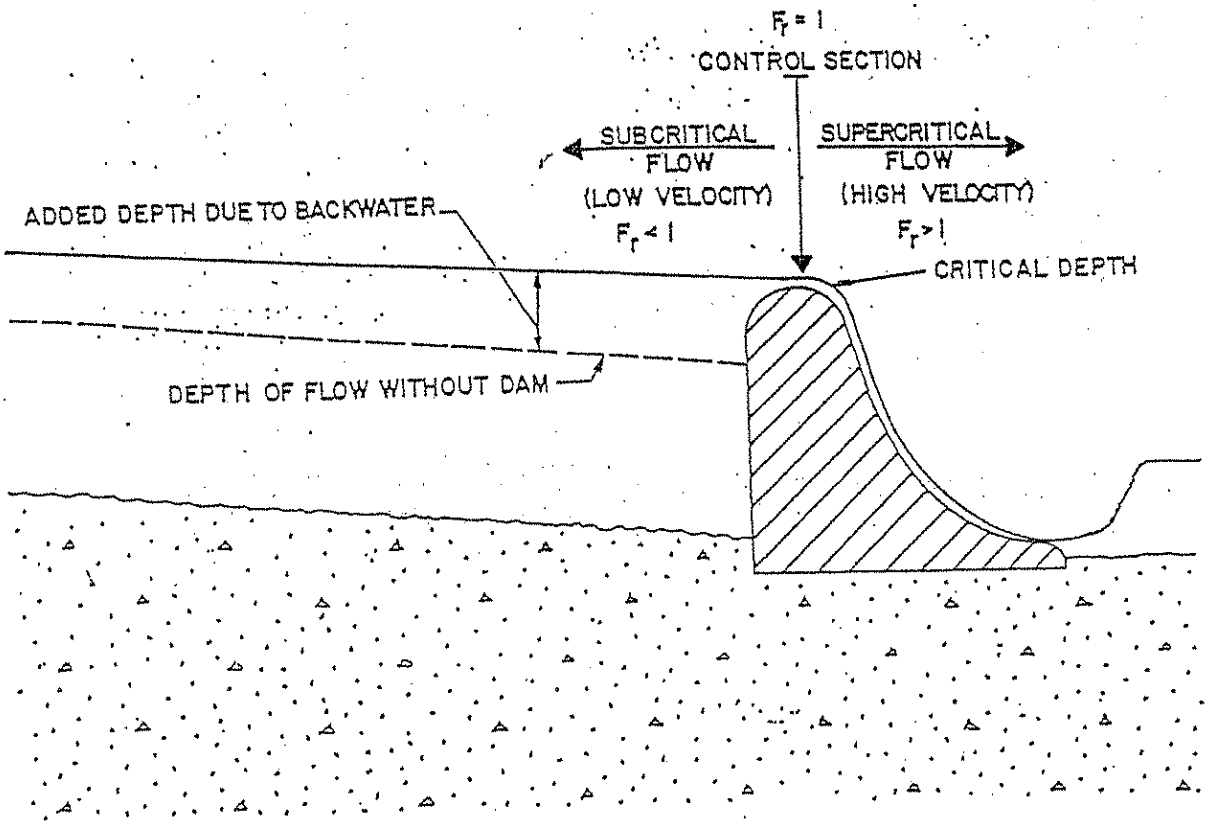


Figure I-12--Flow over a small dam (schematic).

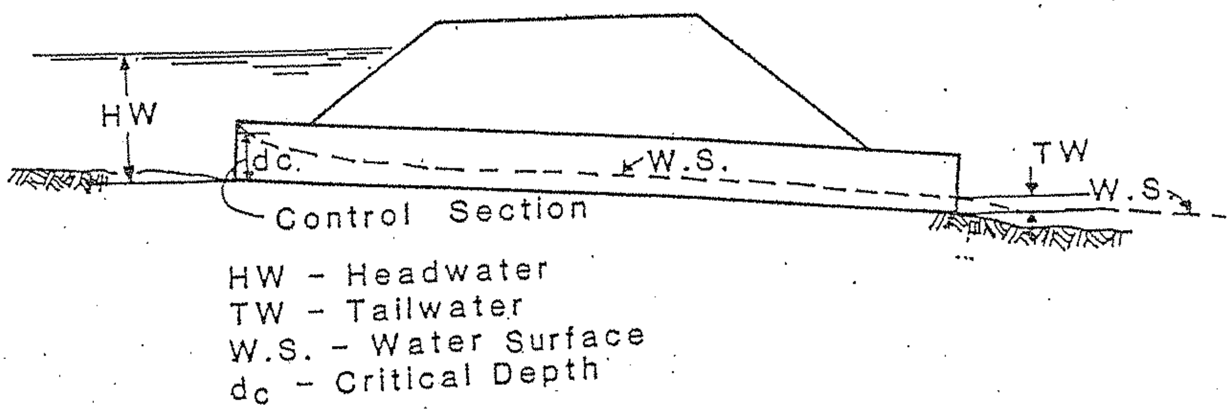


Figure I-13--Typical inlet control flow condition.

b. Outlet Control. Outlet control flow occurs when the culvert barrel is not capable of conveying as much flow as the inlet opening will accept. The control section for outlet control flow in a culvert is located at the barrel exit or further downstream. Either subcritical or pressure flow exists in the culvert barrel under these conditions. Figure I-14 shows two typical outlet control flow conditions. All of the geometric and hydraulic characteristics of the

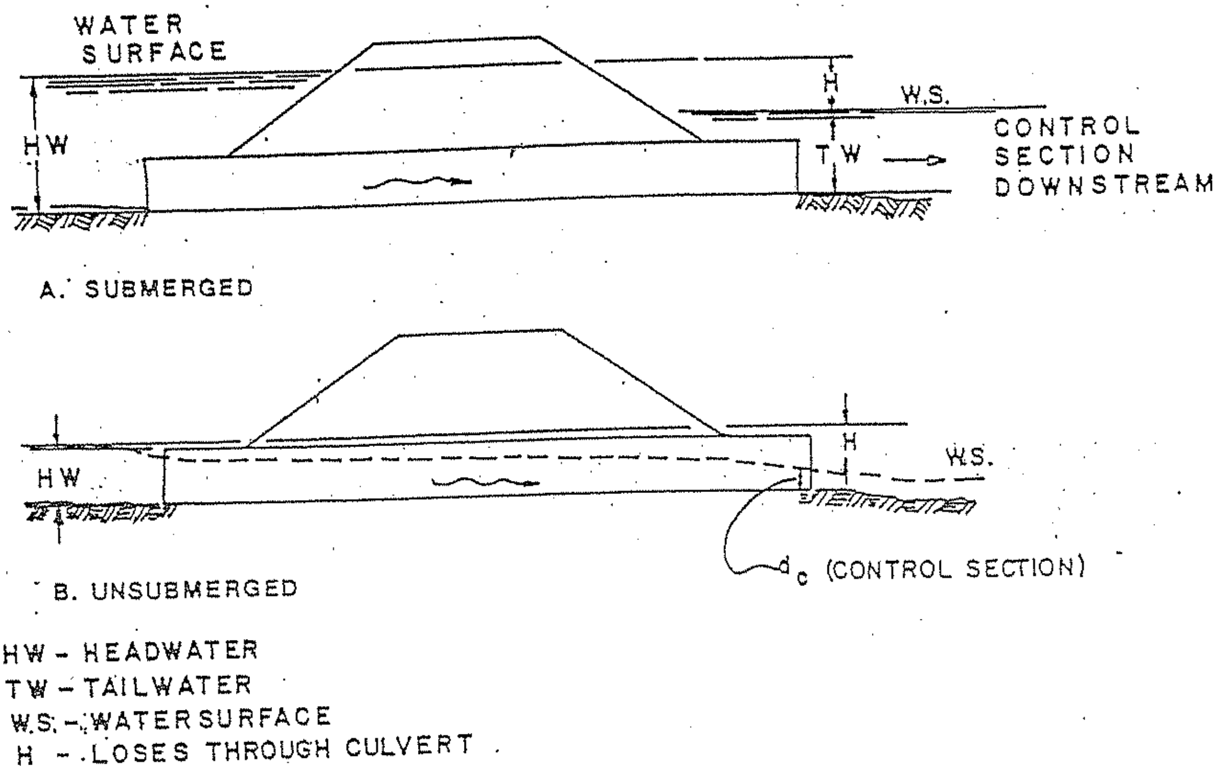


Figure I-14--Typical outlet control flow conditions.

culvert play a role in determining its capacity. These characteristics include all of the factors governing inlet control, the water surface elevation at the outlet, and the slope, length, and hydraulic roughness of the culvert barrel. (table 1)

3. Headwater. Energy is required to force flow through a culvert. This energy takes the form of an increased water surface elevation on the upstream side of the culvert. The depth of the upstream water surface measured from the invert at the culvert entrance is generally referred to as headwater depth. (figures I-13 and I-14)

A considerable volume of water may be ponded upstream of a culvert installation under high fills or in areas with flat ground slopes. The pond which is created may attenuate flood peaks under such conditions. This peak discharge attenuation may justify a reduction in the required culvert size.

4. Tailwater. Tailwater is defined as the depth of water downstream of the culvert measured from the outlet invert. (figure I-14) It is an important factor in determining culvert capacity under outlet control conditions. Tailwater may be caused by an obstruction in the downstream channel or by the hydraulic resistance of the channel. In either case, backwater calculations from the downstream control point are required to precisely define tailwater. When appropriate, normal depth approximations may be used instead of backwater calculations.

5. Outlet Velocity. Since a culvert usually constricts the available channel area, flow velocities in the culvert are likely to be higher than in the channel. These increased velocities can cause

Table 1
Factors influencing culvert performance.

Factor	Inlet Control	Outlet Control
Headwater Elevation	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Inlet Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Shape		X
Barrel Length		X
Barrel Slope	*	X
Tailwater Elevation		X

*Barrel slope affects inlet control performance to a small degree, but may be neglected.

streambed scour and bank erosion in the vicinity of the culvert outlet. Minor problems can occasionally be avoided by increasing the barrel roughness. Energy dissipators and outlet protection devices are sometimes required to avoid excessive scour at the culvert outlet. When a culvert is operating under inlet control and the culvert barrel is not operating at capacity, it is often beneficial to flatten the barrel slope or add a roughened section to reduce outlet velocities.

6. Performance Curves. A performance curve is a plot of headwater depth or elevation versus flow rate. The resulting graphical depiction of culvert operation is useful in evaluating the hydraulic capacity of a culvert for various headwaters. Among its uses, the performance curve displays the consequences of higher flow rates at the site and the benefits of inlet improvements.

In developing a culvert performance curve, both inlet and outlet control curves must be plotted. This is necessary because the dominant control at a given headwater is hard to predict. Also, control may shift from the inlet to the outlet, or vice-versa over a range of flow rates. Figure I-15 illustrates a typical culvert performance curve. At the design headwater, the culvert operates under inlet control. With inlet improvement the culvert performance can be increased to take better advantage of the culvert barrel capacity.

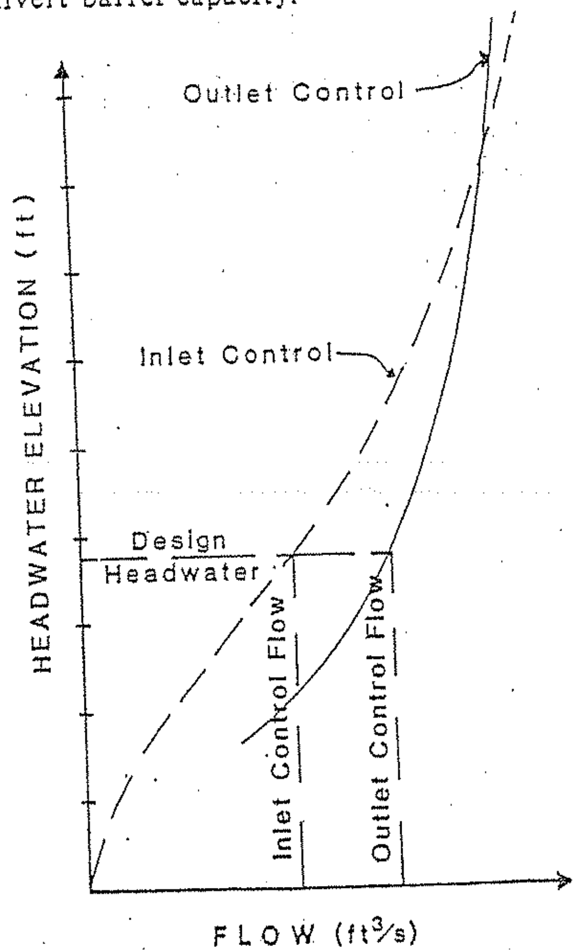


Figure I-15--Culvert performance curve.

D. Economics.

The hydraulic design of a culvert installation always includes an economic evaluation. A wide spectrum of flood flows with associated probabilities will occur at the culvert site during its service life. The benefits of constructing a large capacity culvert to accommodate all of these events with no detrimental flooding effects are normally outweighed by the initial construction costs. Thus, an economic analysis of the trade-offs is performed with varying degrees of effort and thoroughness.

1. Benefits and Costs. The purpose of a highway culvert is to convey water through a roadway embankment. The major benefits of the culvert are decreased traffic interruption time due to roadway flooding and increased driving safety. The major costs are associated with the construction of the roadway embankment and the culvert itself. Maintenance of the facility and flood damage potential must also be factored into the cost analysis.

2. Analysis. Traditional economic evaluations for minor stream crossings have been somewhat simplistic. Culvert design flows are based on the importance of the roadway being served with little attention given to other economic and site factors. A more rigorous investigation, termed a risk analysis, is sometimes performed for large culvert installations. The objective of the risk analysis is to find the optimum culvert capacity based on a comparison of benefits and costs. (figure I-16) The designer should be aware of the risk analysis process and consider using it to analyze alternatives where flood damage is large or culvert cost is significant.

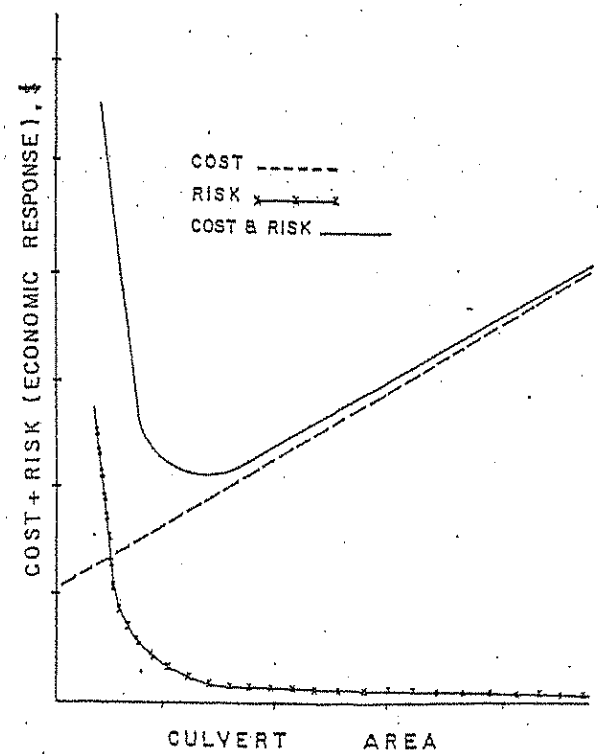


Figure I-16--Risk analysis benefit versus cost curve.

A. Hydrology.

1. General. Hydrologic analysis involves the estimation of a design flow rate based on climatological and watershed characteristics. This analysis is one of the most important aspects of culvert design. Since statistical uncertainties are inherent in hydrologic analysis, the results of the analysis are not as accurate as the results of the hydraulic analysis of a culvert. Nonetheless, both of these analyses are required, and the hydrologic study must be performed first. FHWA Hydraulic Engineering Circular (HEC) Number 19, Hydrology, is an excellent reference for gaining information and insight into most of the hydrologic methods mentioned in this publication. (11)

A statistical concept often associated with hydrologic analysis is the return period. The term return period is used when referring to the frequency of occurrence of rare events such as floods. Mathematically, the return period is the reciprocal of frequency. For example, the flood which has a 5 percent chance of occurring (frequency) in any given year also has a return period of 20 years; i.e., 1/0.05 = 20 years. In other words, this flood event will be exceeded on the average of once every 20 years over a long period of time. Hence, the 20 year flood event is likely to be exceeded five times during a 100-year period. These events will be randomly spaced over the 100 years.

Large and expensive culvert installations may warrant extensive hydrologic analysis. This increased level of effort may be necessary in order to perform risk analysis and/or storage routing calculations. Risk analysis requires the computation of flows for several different return periods. Storage routing calculations require the definition of the entire flood event or hydrograph.

Considerable study of the use of risk analysis in culvert design has occurred over the past 10 to 20 years. Risk analysis balances the culvert cost with the damages associated with inadequate culvert performance. These studies have been fruitful in relating culvert design to economic theory and in defining the monetary consequences of both over-design and under-design. The limitations of culvert design based solely on arbitrary return periods have been duly exposed in the process.

Storage routing is the attenuation of the flood flow due to the storage volume upstream of the culvert. Risk analysis studies often include storage routing as an integral part of the culvert sizing process. Consideration of storage routing in these studies often reduces the design culvert size. Hence, storage routing has been included as an optional part of the design procedure presented in this manual.

2. Peak Design Flow. As a flood wave passes a point along a stream, the flow increases to a maximum and then recedes. The maximum flow rate is called the peak flow. The peak flow has been, and continues to be, a major factor in the culvert design process.

In traditional culvert design, a structure is sized to pass a peak flow from one side of the roadway embankment to the other with an acceptable headwater elevation. The magnitude of the peak flow is dependent upon the selection of a return period. The assignment of a return period is generally based on the importance of the roadway and flood damage potential.

For gaged sites, statistical analyses can be performed on the recorded stream flow to provide an estimated peak design flow for a given return period. The

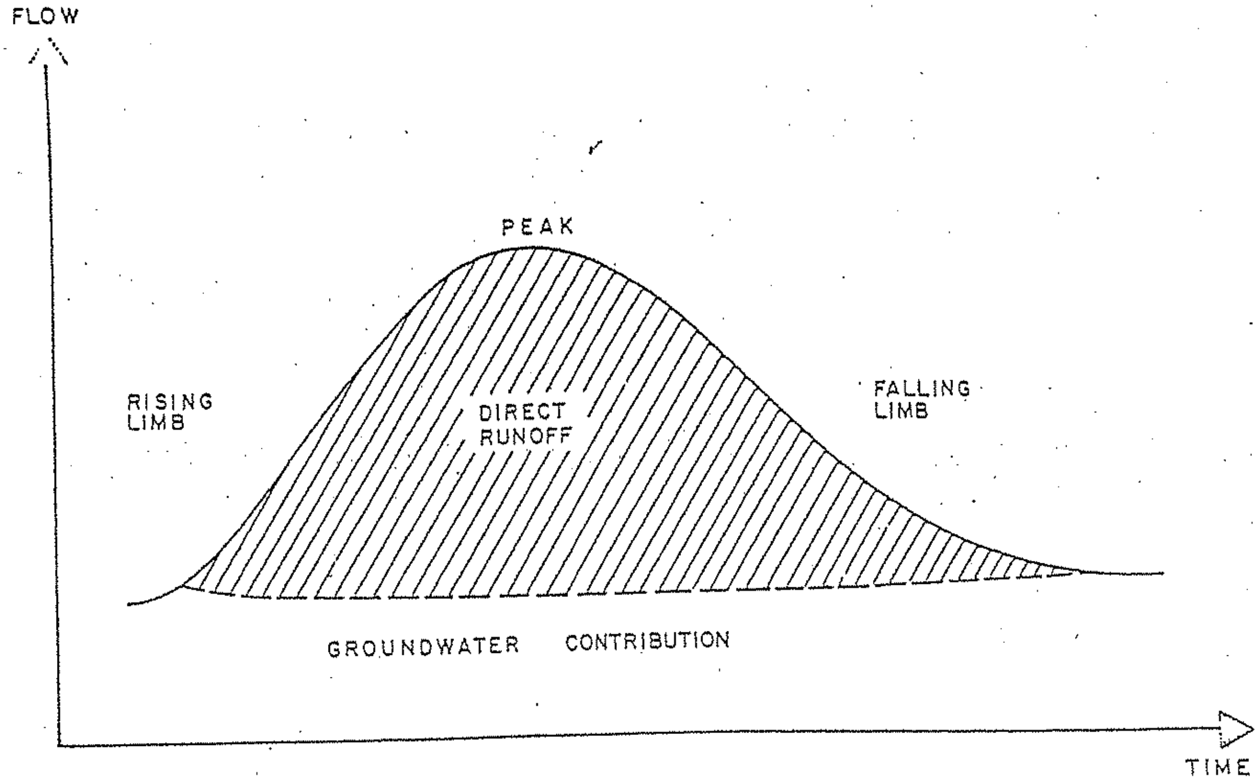


Figure II-1.--Flood hydrograph.

accuracy of the estimate improves as the length of the record increases. For culvert sites significantly removed from the gage, the peak design flow may have to be adjusted.

A typical statistical analysis for data from a gaged site proceeds as follows. First, the annual peak flows for the site are arranged in descending order. Then, the plotting position is calculated by one of several available formulas. (11) The peak floods are then plotted on a probability paper to define the frequency relationship for the gage site. If Gumbel paper (Type I extremal distribution) is used to plot the data, the mean of the data (mean annual flood) will plot at a frequency of 0.429. This equates to a return period of 2.33 years. Other return periods can be read from the frequency plot, because the return period is the inverse of the frequency.

Ungaged sites present more of a design problem. Stream gage data for particular regions have been utilized to develop statistical regression equations for most areas of the country. These equations generally require basic watershed parameters such as drainage area and average stream slope. Using the required data, peak design flows can be determined for ungaged sites within that region. Deterministic methods are also available which attempt to model the rainfall-runoff process. The key input parameter in these methods is rainfall which must be related to a return period. The amount of watershed data required is dependent upon the sophistication of the model. Table 2 lists some of the commonly employed methods of peak flow generation for gaged and ungaged sites.

Table 2--Peak determination methods.

Gaged Sites	Ungaged Sites
1) Normal Distribution	1) USGS Regression Equations
2) Log-Normal Distribution	2) FHWA Regression Equations
3) Gumbel Extreme Value Distribution	3) Regional Peak Flow Methods
4) Log-Pearson Type III Distribution	4) SCS Peak Discharge Method
	5) Rational Method

3. Check Flows. Culvert operation should be evaluated for flows other than the peak design flow because: (1) It is good design practice to check culvert performance through a range of discharges to determine acceptable operating conditions, (2) flood plain regulations may require the delineation of the 100-year flood plain, and (3) in performing flood risk analyses, estimates of the damages caused by headwater levels due to floods of various frequencies are required.

Check flows are determined in the same manner as the peak design flow. The hydrologic procedures used should be consistent unless unusual circumstances dictate otherwise. For example, a stream gage record may be long enough to estimate a 10-year peak design flow but too short to accurately generate a 100-year check flow. Under these circumstances the check flow should be evaluated by another method.

4. Hydrographs. The entire flood hydrograph at the culvert site must be defined if upstream storage is to be considered in culvert design. Passing the peak design flow through a culvert neglects the attenuating effects of upstream storage. If this storage is taken into account, the required culvert size may be substantially reduced. Since volume considerations are now involved, the flood hydrograph becomes an integral part of the design process.

A flood hydrograph is a plot of discharge versus time. Figure II-1 depicts a typical flood hydrograph showing the rise and fall of stream flow over time as the flood passes. Actual flood hydrographs can be obtained using stream gage records. These measured storm events can then be used to develop design flood hydrographs. In the absence of stream gage data, empirical or mathematical methods, such as the Snyder and SCS synthetic hydrograph methods, are used to generate a design flood hydrograph.

The unit hydrograph technique is a popular procedure for determining the response of a watershed to a specified design rainfall. A unit hydrograph represents the runoff response of a watershed to a uniform 1-inch rainfall of a given duration. A unit hydrograph may be generated from data for a gaged watershed or synthesized from rainfall and watershed parameters for an ungaged watershed. Both methods are briefly described below.

a. Unit Hydrograph Formulation - Gaged Watershed. To develop a unit hydrograph for a gaged watershed, the designer should have streamflow and rainfall records for a number of storm events. The rainfall data must be representative of the rainfall over the watershed during each storm event. In addition, the rainfall events should have relatively constant intensities over the duration of the storm.

Unit hydrograph generation involves four steps which are illustrated in figure II-2. (1) The groundwater or low flow contribution of the gaged flood hydrograph is estimated and removed from volume consideration. This groundwater or low flow contribution is generally regarded as constant and estimated to be the amount of stream flow prior to the storm event. (2) The volume of the remaining runoff hydrograph is calculated. This is termed the direct runoff volume. (3) The direct

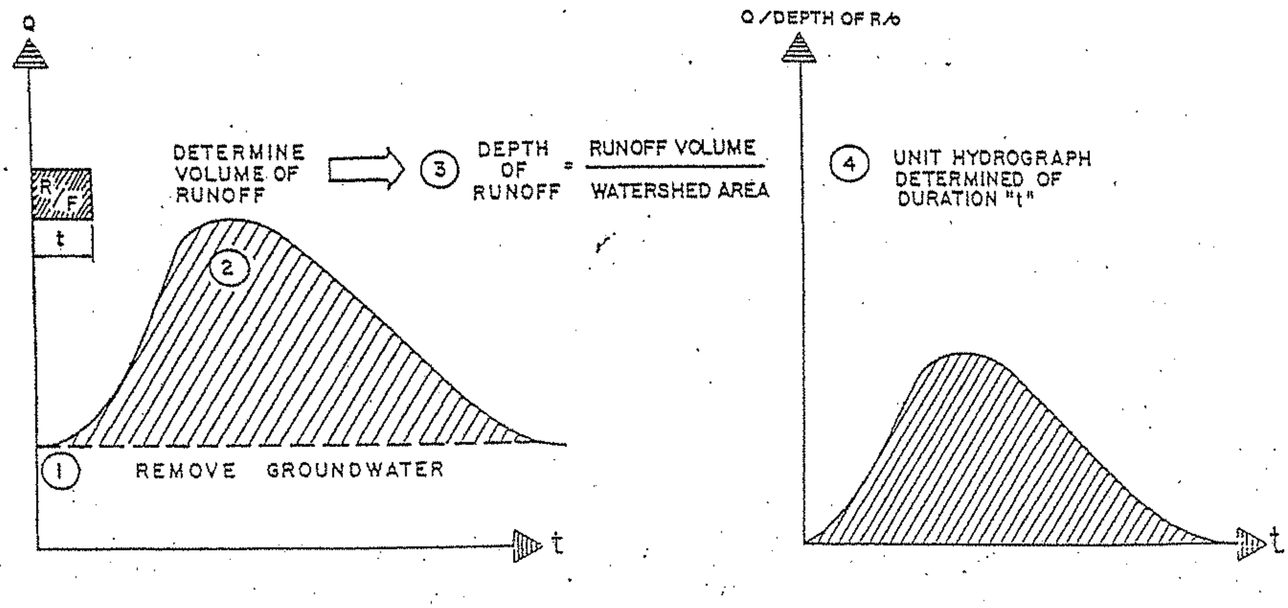


Figure II-2.--Unit hydrograph determination procedure.

runoff volume is then distributed over the entire watershed (divided by the watershed area) to determine the equivalent runoff depth. (4) The ordinates of the runoff hydrograph are divided by this runoff depth to produce the unit hydrograph for the storm duration.

The unit hydrograph can be used with the concepts of linearity and superposition to predict the watershed response to a design rainfall with a specified return period. Linearity implies that if the unit hydrograph represents a basin's response to 1-inch of runoff for a given

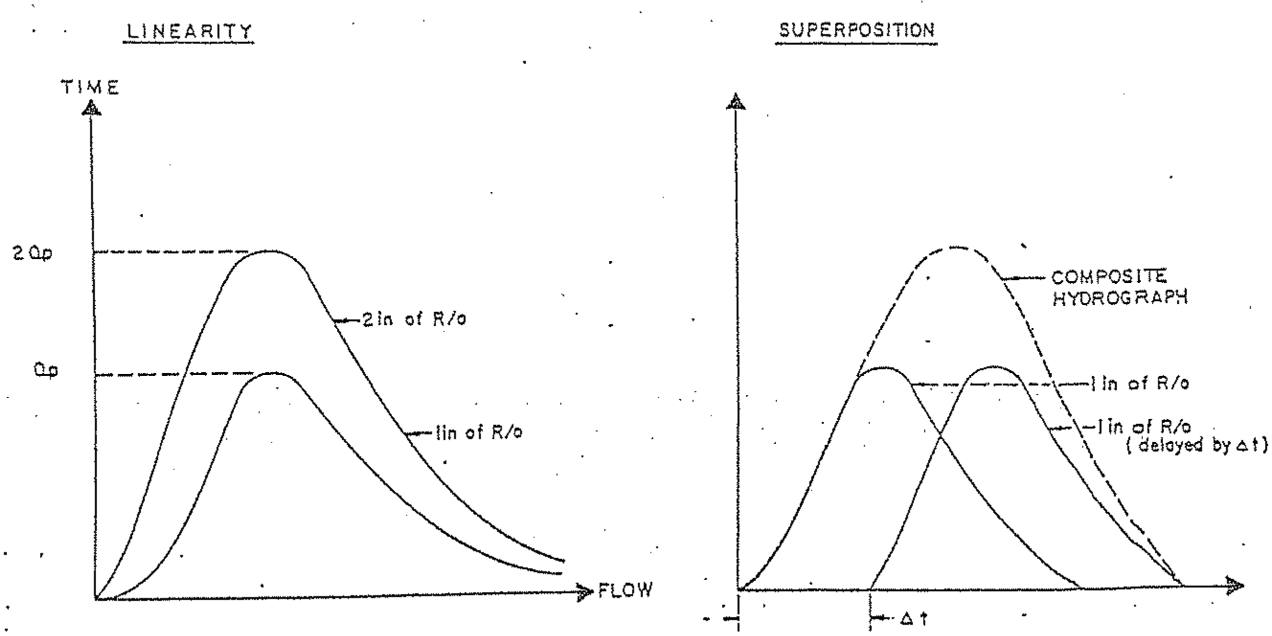


Figure II-3.--Linearity and superposition concepts.

storm duration, 2-inches of runoff over the same duration doubles the discharge at each point in time. Superposition allows for the accumulation of individual runoff responses. For example, if a storm event which generates 1-inch of runoff over a given duration is followed immediately by another 1-inch runoff storm event of the same duration, the basin response will be the accumulation of the individual effects over time. (figure II-3)

A unit hydrograph is derived for a specified storm duration. Since storm durations vary, many different unit hydrographs exist for any particular watershed. Techniques exist to vary the duration of a unit hydrograph such as the "S" Curve (Summation Curve) approach. (11) These methods are useful in matching the design unit hydrograph to the duration increment of a design rainfall. Methods are also available to formulate design rainfalls using U.S. Weather Service data. (12,13)

b. Synthetic Unit Hydrograph. A synthetic unit hydrograph may be developed in the absence of stream gage data. The methods used to develop synthetic unit hydrographs are generally empirical and depend upon various watershed parameters, such as watershed size, slope, land use, and soil type. Two synthetic procedures which have been widely used are the Snyder Method and the Soil Conservation Service (SCS) Method. The Snyder Method uses empirically defined terms and physiographic characteristics of the drainage basin as input for empirical equations which characterize the timing and shape of the unit hydrograph. The SCS method utilizes dimensionless hydrograph parameters based on the analysis of a large number of watersheds to develop a unit hydrograph. The only parameters required by the method are the peak discharge and the time to peak. A variation of the SCS synthetic unit hydrograph is the SCS synthetic triangular hydrograph.

c. Computer Models. Hydrologic computer models are becoming popular for generating flood hydrographs. Some computer models merely solve empirical hand methods more quickly. Other models are theoretical and solve the runoff cycle in its entirety using continuous simulation over short time increments. Results are obtained using mathematical equations to represent each phase of the runoff cycle such as interception, surface retention, infiltration, and overland flow.

In most simulation models, the drainage area is divided into subareas with similar hydrologic characteristics. A design rainfall is synthesized for each subarea, and abstractions, such as interception and infiltration, are removed. An overland flow routine simulates the movement of the remaining surface water. Adjacent channels receive this overland flow from the subareas. The channels of the watershed are linked together and the channel flow is routed through them to complete the basin's response to the design rainfall.

Computer models are available which simulate a single storm event or continuous runoff over a long period of time. The Stanford Watershed model was one of the earliest simulation models. It is a continuous simulation model using hourly rainfall and potential evapotranspiration as input data. The output is in the form of mean daily flows, hourly ordinates of the hydrograph, and monthly totals of the water balance. The EPA Sponsored Storm Water Management Model (SWMM) permits the simulation of a single storm event. An assumption inherent in these models is that the return period of the computed flood is the same as that of the input rainfall. All simulation models require calibration of modeling parameters using measured historical events to increase their validity. Most simulation models require a significant amount of input data and user experience to assure reliable results.

5. Basics of Storage Routing. Measurement of a flood hydrograph at a stream location is analogous to recording the

passage of a high amplitude, low frequency wave. As this wave moves downstream, its shape broadens and flattens provided there is no additional inflow along the reach of the stream. This change in shape is due to the channel storage between the upstream and downstream locations. If the wave encounters a significant amount of storage at a given location in the stream, such as a reservoir, the attenuation of the flood wave is increased. Figure II-4 depicts the effects graphically.

Storage routing is the numerical translocation of a flood wave (hydrograph). This process is applicable to reservoirs, channels, and watersheds. The effects of the routing are threefold: volume conservation, peak reduction, and time lag.

Reservoir routing is dependent only upon storage in modifying a flood wave. Channel routing is dependent upon inflow and outflow as well as storage in a stream reach. Watershed routing incorporates the runoff attenuating effects of the watershed and is of importance in some hydrograph generation methods. Reservoir routing is of special interest in culvert design, and it will be discussed further in chapter V.

B. Site Data

1. General. The hydraulic design of a culvert installation requires the evaluation of a large amount of data including culvert location, waterway data, roadway data, and the design headwater. Each of these items and its importance is discussed in the following paragraphs.

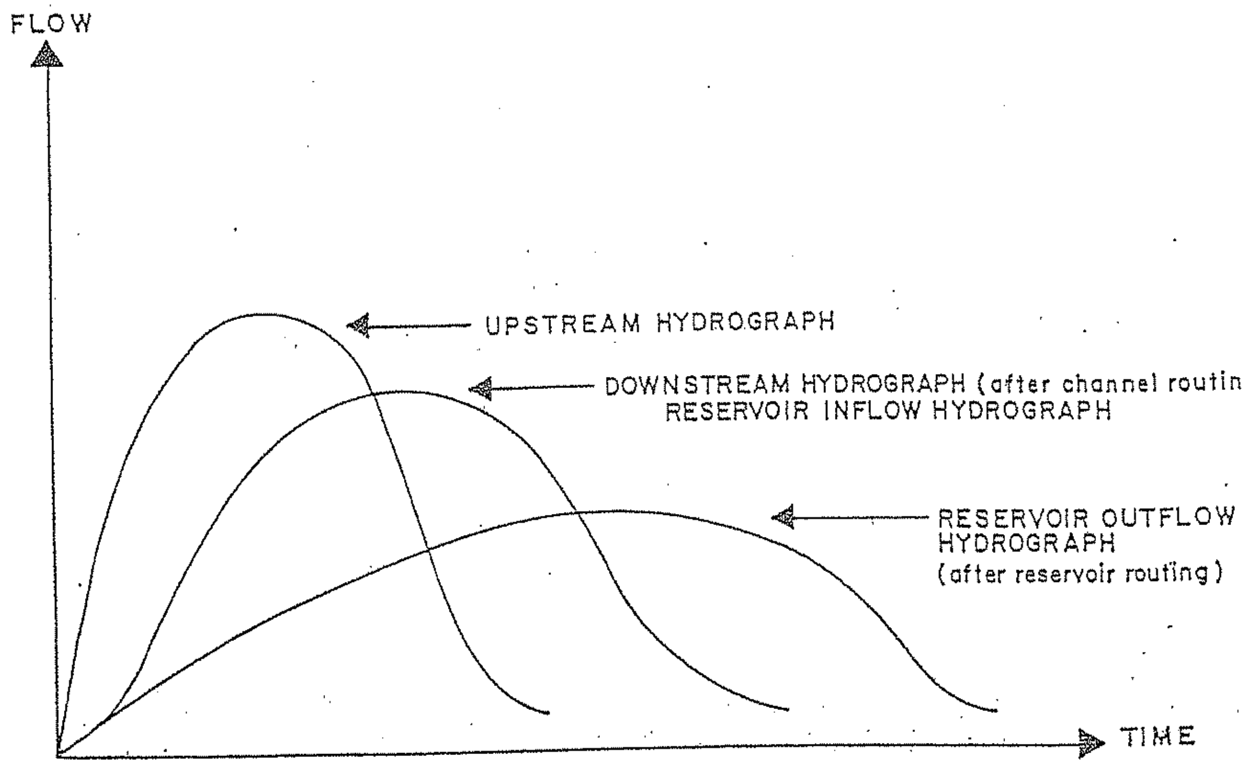


Figure II-4.--Flood hydrograph shape modification.

2. Culvert Location. A culvert should ideally be located in the existing channel bed to minimize costs associated with structural excavation and channel work. However, this is not always possible. Some streambeds are sinuous and cannot accommodate a straight culvert. In other situations, a stream channel may have to be relocated to avoid the installation of an inordinately long culvert. When relocating a stream channel, it is best to avoid abrupt stream transitions at either end of the culvert. Figure II-5 displays two examples of culvert location procedures. (14) In one case, the culvert follows the natural channel alignment. In the second case, the channel has been relocated to reduce the culvert length. Brice concluded that minor channel relocations for culvert alignments have been successful unless the natural channel was already unstable. (15)

3. Waterway Data. The installation of a culvert to convey surface water through a highway embankment significantly constricts the flood plain. To predict the consequences of this alteration, accurate preconstruction waterway data must be collected. These data include cross-sectional information, stream slope, the hydraulic resistance of the stream channel and floodplain, any condition affecting the downstream water surface elevation, and the storage capacity upstream of the culvert. Photographs of site conditions are often beneficial.

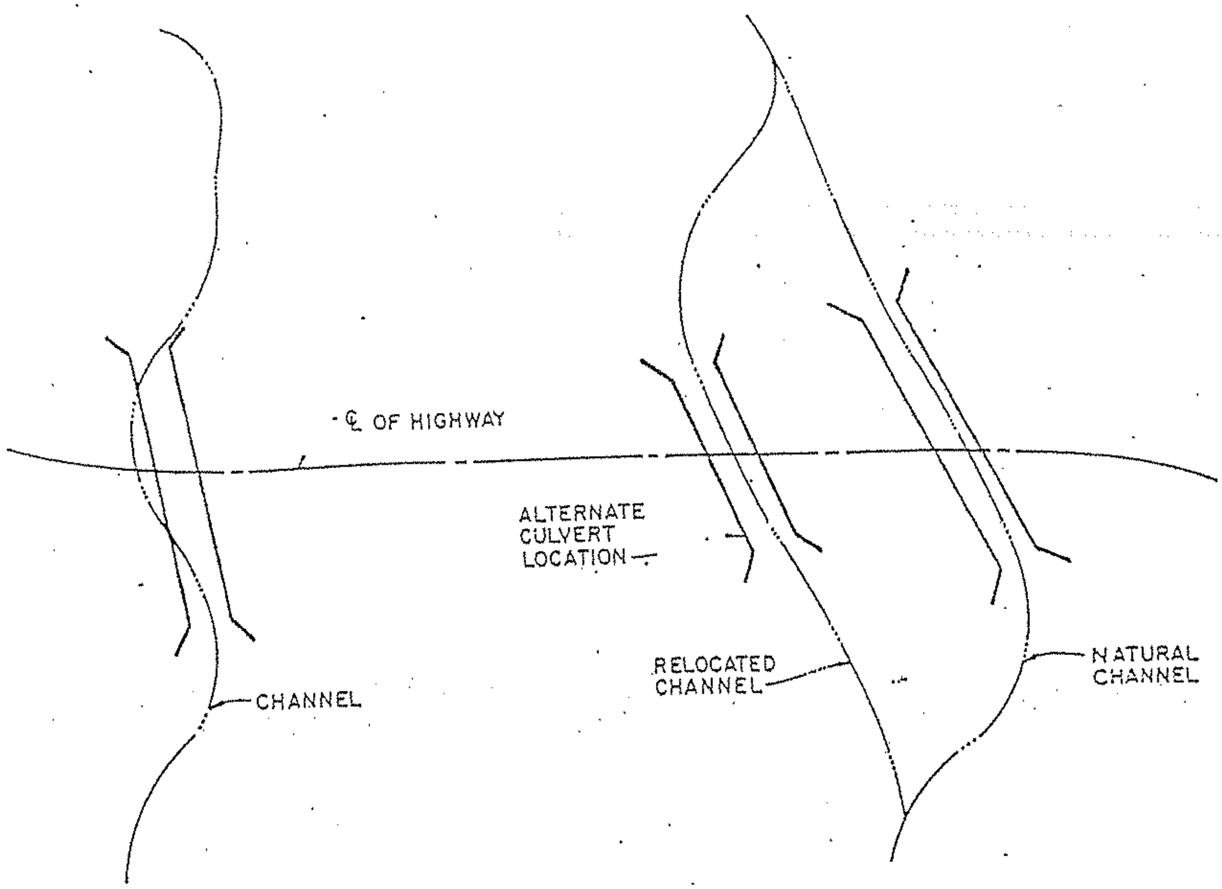


Figure II-5.--Culvert location methods.

a. Cross Sections. Stream cross sectional data acquired from a field survey at the site are highly desirable. At least three cross sections should be taken to establish the stream slope, the culvert inlet, the culvert outlet, and the configuration of the natural channel. (figure II-6) Sections should be taken (1) about 100 ft (30 m) upstream from the crossing, (2) at the centerline of the roadway, and (3) about 100 ft (30 m) downstream from the crossing. The natural streambed width and side slopes, and the floodplain width may be obtained from these cross sections. The cross-sectional data will also help to verify the accuracy of existing topographic maps. If significant ponding is likely, additional sections may be necessary to determine the storage capacity upstream of the culvert. Likewise, additional downstream sections may be necessary to establish downstream water level (tailwater) conditions.

If only one cross section of the natural channel is available, it will be used as the typical cross section. This assumption should be checked using topographic maps and aerial photos. Additional information on stream slope and upstream storage volume should also be obtained from the topographic maps.

b. Stream Slope. The longitudinal slope of the existing channel in the vicinity of the proposed culvert should be defined in order to properly position the culvert in vertical profile and to define flow characteristics in the natural stream. Often, the proposed culvert is positioned at the same longitudinal slope as the streambed. Cross sections will provide streambed elevations at the deep-

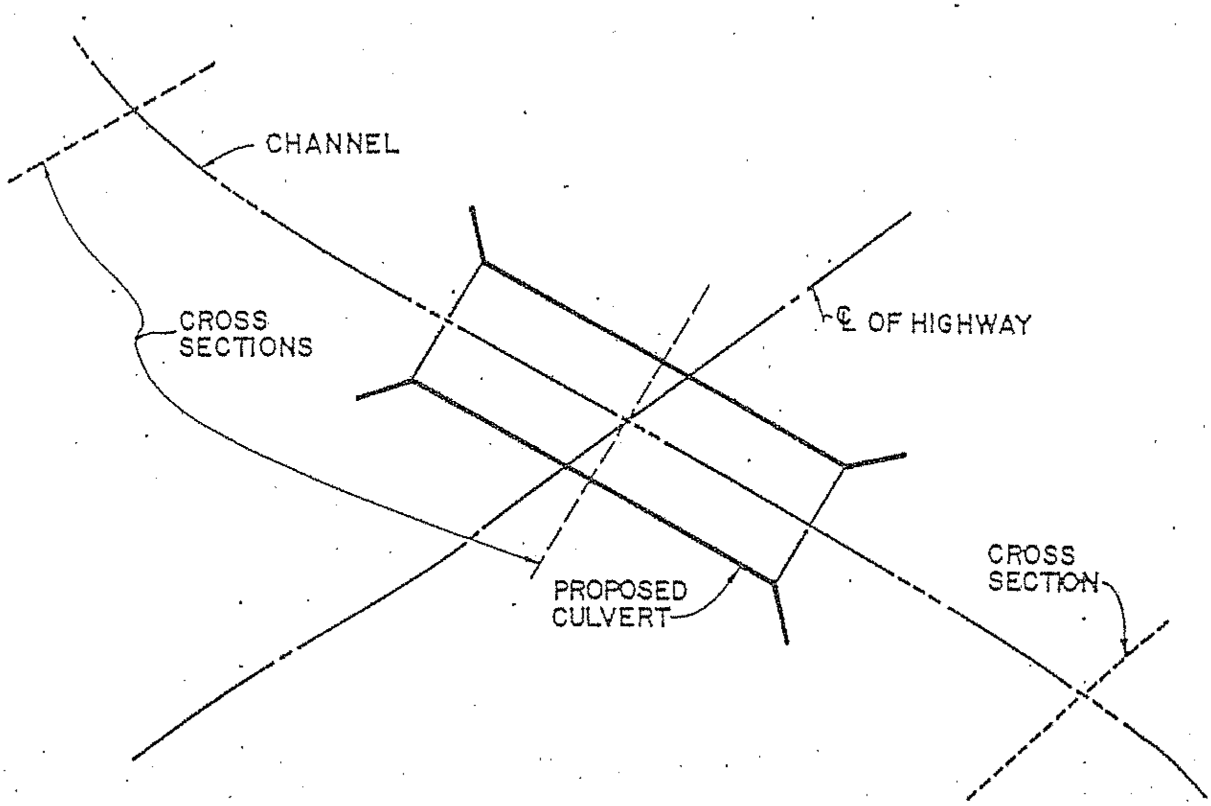


Figure II-6.--Cross section locations.

est point of the stream. From these elevations and the distances between the cross sections the stream slope may be calculated.

c. Resistance. The hydraulic resistance coefficient of the natural channel must be evaluated in order to calculate preproject flow conditions. This resistance coefficient is usually taken to be the Manning n value. Various methods are available to evaluate resistance coefficients for natural streams, including comparisons with photographs of streams with known resistance values or tabular methods based on stream characteristics (16 to 18). Table 11, appendix D, provides Manning n values for selected natural channels.

d. Tailwater. Culvert performance is likely to be affected by the downstream water surface elevation or tailwater. Therefore, conditions which might promote high tailwater elevations during flood events should be investigated. Downstream impoundments, obstructions, channel constrictions, tidal effects, and junctions with other watercourses should be investigated, based on field observations and maps, in order to evaluate their impact on the resultant tailwater elevation. Lacking these conditions, tailwater elevations should be based on water surface elevations in the natural channel. These elevations can be accurately determined from water surface elevation calculations or estimated using simplified approximations of water depth. For most culvert installations, an approximation is sufficient.

e. Upstream Storage. The storage capacity available upstream from a culvert may have an impact upon its design. Upstream storage capacity can be obtained from large scale contour maps of the upstream area, but a 2-foot (0.5m) contour interval map is desirable. If such maps are not available, a number of cross sections should be obtained upstream of the proposed culvert. These sections must be referenced horizontally as well as vertically. The length of upstream channel to be cross-sectioned will depend on the headwater expected and the stream slope. The cross sections can be used to develop contour maps or the cross sectional areas can be used to compute storage. The topographic information should extend from the channel bed upward to an elevation equal to at least the design headwater elevation in the area upstream of the culvert.

4. Roadway Data. The proposed or existing roadway affects the culvert cost, hydraulic capacity, and alignment. Roadway profile and the roadway cross section information can be obtained from preliminary roadway drawings or from standard details on roadway sections. When the culvert must be sized prior to the development of preliminary plans, a best estimate of the roadway section can be used, but the culvert design must be checked after the roadway plans are completed.

a. Cross Section. The roadway cross section normal to the centerline is typically available from highway plans. However, the cross section needed by the culvert designer is the section at the stream crossing. This section may be skewed with reference to the roadway centerline. For a proposed culvert, the roadway plan, profile, and cross-sectional data should be combined as necessary to obtain this desired section. A schematic roadway plan and section with important elevations is shown in figure II-7.

b. Culvert Length. Important dimensions and features of the culvert will become evident when the desired roadway cross section is measured or established. The dimensions are obtained by superimposing the estimated culvert barrel on the roadway cross section and the streambed profile. (figure II-7) This superposition establishes the inlet and outlet invert elevations. These elevations and the resulting culvert length are approximate since the final culvert barrel size must still be determined.

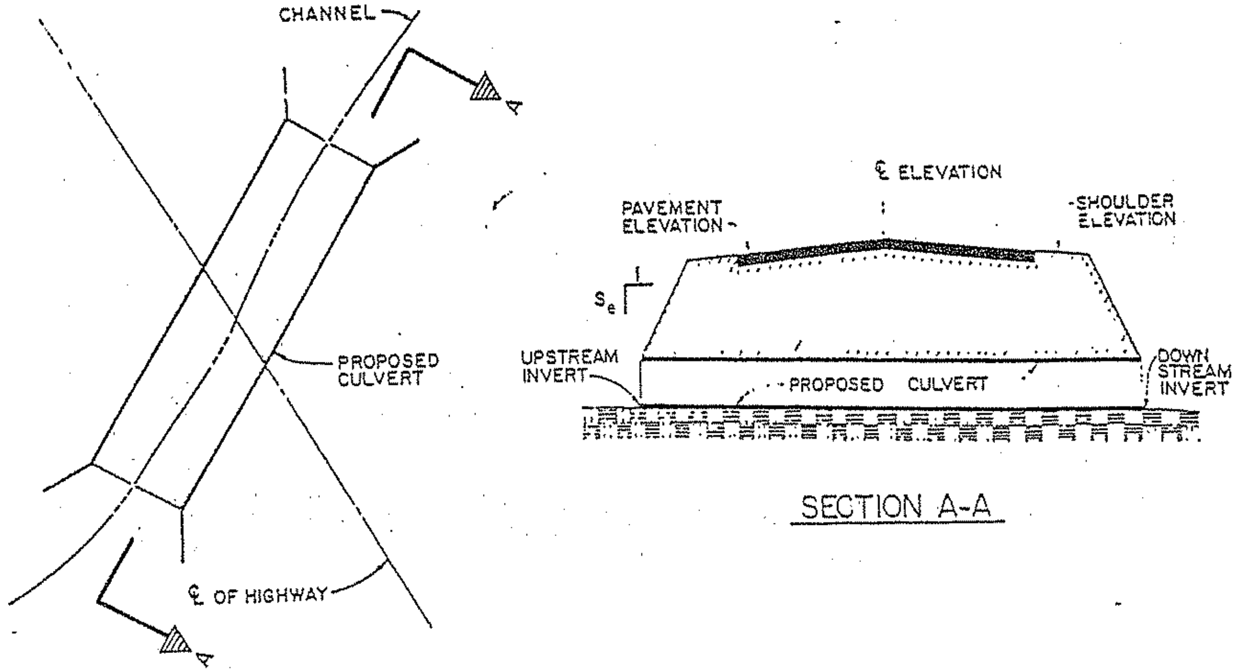


Figure II-7.--Roadway cross section and culvert length.

c. Longitudinal Roadway Profile. The roadway profile represents the obstruction encountered by the flowing stream. The embankment containing the culvert acts much like a dam. The culvert is similar to the normal release structure, and the roadway crest acts as an emergency spillway in the event that the upstream pool (headwater) attains a sufficient elevation. The location of initial overtopping is dependent upon the roadway geometry. (figure II-8)

The profile contained in highway plans generally represents the roadway centerline profile. These elevations may not represent the high point in the highway cross section. The culvert designer should extract the profile which establishes roadway flooding and roadway overflow elevations from the highway plans available. The low point of the profile is of critical importance, since this is the point at which roadway overtopping will first occur.

5. Design Headwater. The most economical culvert is one which would utilize all of the available headwater to pass the design discharge. Since the discharge capacity increases with increasing head, the available headwater elevation must be determined. This design headwater elevation generally hinges on one of three factors; economic considerations, regulatory constraints, or arbitrary constraints.

An increase in available headwater can be obtained at some sites by depressing (burying) the culvert inlet. This procedure is advantageous for steep culverts which operate under inlet control. Additional information on this procedure is contained in chapter III.

a. Economic Considerations. As ponding elevations increase upstream from a culvert, detrimental economic consequences can occur. Although for major structures it may be advantageous to perform a flood risk analysis (chapter VI), site-specific constraints are sometimes adopted in lieu of a full risk analysis. Such constraints are based on some designated elevation that is not to be exceeded within a specified return period. This elevation may correspond to some critical point on the roadway such as the roadway shoulder or the road-

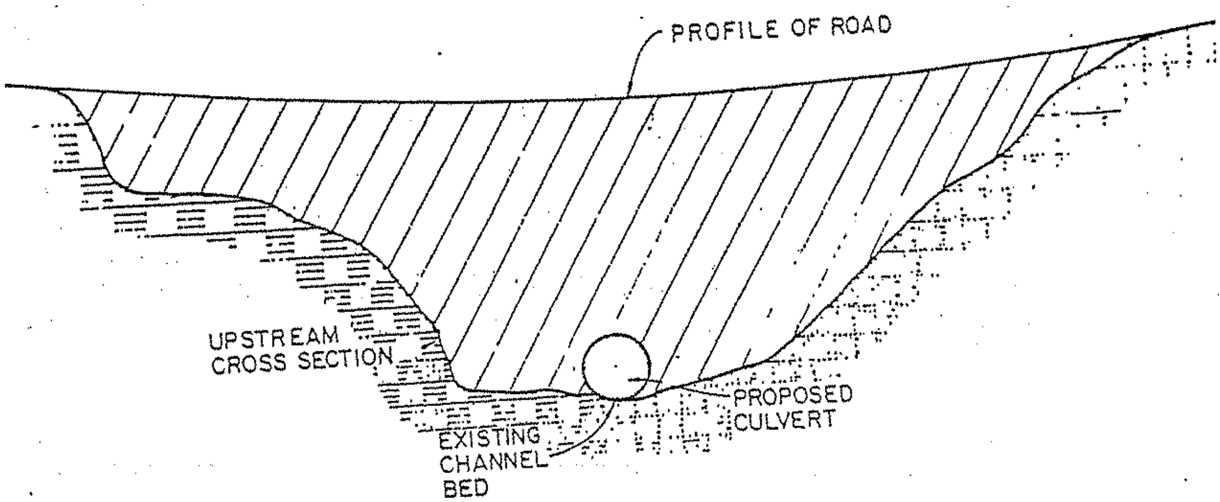


Figure II-8.--Road profile - valley section.

way overtopping elevation. Another criteria might be the flood damage elevation of an upstream building. Possible loss of life and the importance of the highway are likewise considered. While all of these factors pertain to risk analysis, a detailed risk analysis is generally not performed.

b. Regulatory Constraints. The requirements of the National Flood Insurance Program are a major consideration in culvert design. Most communities are now participating in this program. The limitation on flood plain construction as it affects the base (100-year) flood elevation is of primary importance. Depending upon the culvert location, existing floodway encroachments, and whether there is a specified floodway, the allowable water surface elevation increase varies from 0 to 1 foot (0.3m). Regardless of the return period utilized in the culvert design for the particular roadway, the 100-year return period flood must be checked to ascertain the effects of the culvert on the base flood elevation. (19)

c. Arbitrary Constraints. Some state or local agencies place arbitrary constraints on the design headwater produced by a culvert. For example, the headwater depth may not be allowed to exceed the barrel height or some multiple of the barrel height. Although these constraints will severely limit the flexibility inherent in culvert design, they must be followed unless the controlling agency can be convinced to relax the restrictions or grant an exemption.

C. Summary of Data Needs.

Table 3 summarizes the various data needed for culvert design.

Table 3--Data Requirements for Culvert Design.

DATA	SOURCE
HYDROLOGY	
Peak Flow	Stream gage analysis or calculated using Rational Formula, SCS Method, regression equations, etc.
Check Flows	Same as for peak flow
Hydrographs (if storage routing is utilized)	From stream gage information or synthetic development methods such as SCS Method, Snyder Method, or computer models
SITE DATA	
Culvert Location	Based on site characteristics including natural stream section, slope, and alignment
Waterway Data	
Cross Sections	Field survey or topographic maps
Longitudinal Slope	Field survey or topographic maps
Resistance	Observation, photographs, or calculation methods
Tailwater	Field survey, maps
Upstream storage	Field survey, maps
Roadway Data	
Cross Section	Roadway plans
Profile	Roadway plans
Culvert Length	Roadway plans
Design Headwater	
Critical points on roadway	Roadway plans
Surrounding buildings or structures	Aerial photographs, surveys, or topographic maps
Regulatory Constraints	Floodplain and flood insurance regulations for stream reach of interest
Arbitrary Constraints	State or local regulations for culvert installations

A. Culvert Flow.

1. General. An exact theoretical analysis of culvert flow is extremely complex because the flow is usually non-uniform with regions of both gradually varying and rapidly varying flow. An exact analysis involves backwater and drawdown calculations, energy and momentum balance, and application of the results of hydraulic model studies. For example, the U.S. Geological Survey has defined 18 different culvert flow types based on inlet and outlet submergence, the flow regime in the barrel, and the downstream brink depth. (20) Often, hydraulic jumps form inside or downstream of the culvert barrel. In addition, the flow types change in a given culvert as the flow rate and tailwater elevations change.

In order to systematically analyze culvert flow, the procedures of this publication have been developed, wherein the various types of flow are classified and analyzed on the basis of control section. A control section is a location where there is a unique relationship between the flow rate and the upstream water surface elevation. Many different flow conditions exist over time, but at a given time the flow is either governed by the inlet geometry (inlet control); or by a combination of the culvert inlet configuration, the characteristics of the barrel, and the tailwater (outlet control). Control may oscillate from inlet to outlet; however, in this publication, the concept of "minimum performance" applies. That is, while the culvert may operate more efficiently at times (more flow for a given headwater level), it will never operate at a lower level of performance than calculated.

The culvert design method presented in this publication is based on the use of design charts and nomographs. These charts and nomographs are, in turn, based on data from numerous hydraulic tests and on theoretical calculations. At each step of the process, some error is introduced. For example, there is scatter in the test data and the selection of a best fit design equation involves some error. Also, the correlation between the design equations and the design nomographs is not exact. Reproduction of the design charts introduces additional error. Therefore, it should be assumed that the results of the procedure are accurate to within plus or minus ten percent, in terms of head. Additional information on the precision of the design charts is provided in appendix A.

Table 1 in chapter I shows the factors which must be considered in culvert design for inlet and outlet control. In inlet control, only the inlet area, the edge configuration, and the shape influence the culvert performance for a given headwater elevation. The headwater depth is measured from the inlet invert, and the tailwater elevation has no influence on performance. In outlet control, all of the factors listed in table 1 affect culvert performance. Headwater depth is measured from the outlet invert, and the difference between headwater and tailwater elevation represents the energy which conveys the flow through the culvert.

2. Types of Control. A general description of the characteristics of inlet and outlet control flow is given below. A culvert flowing in inlet control has shallow, high velocity flow categorized as "supercritical." For supercritical flow, the control section is at the upstream end of the barrel (the inlet). Conversely, a culvert flowing in outlet control will have relatively deep, lower velocity flow termed "subcritical" flow. For subcritical flow the control is at the downstream end of the culvert (the outlet). The tailwater depth is either

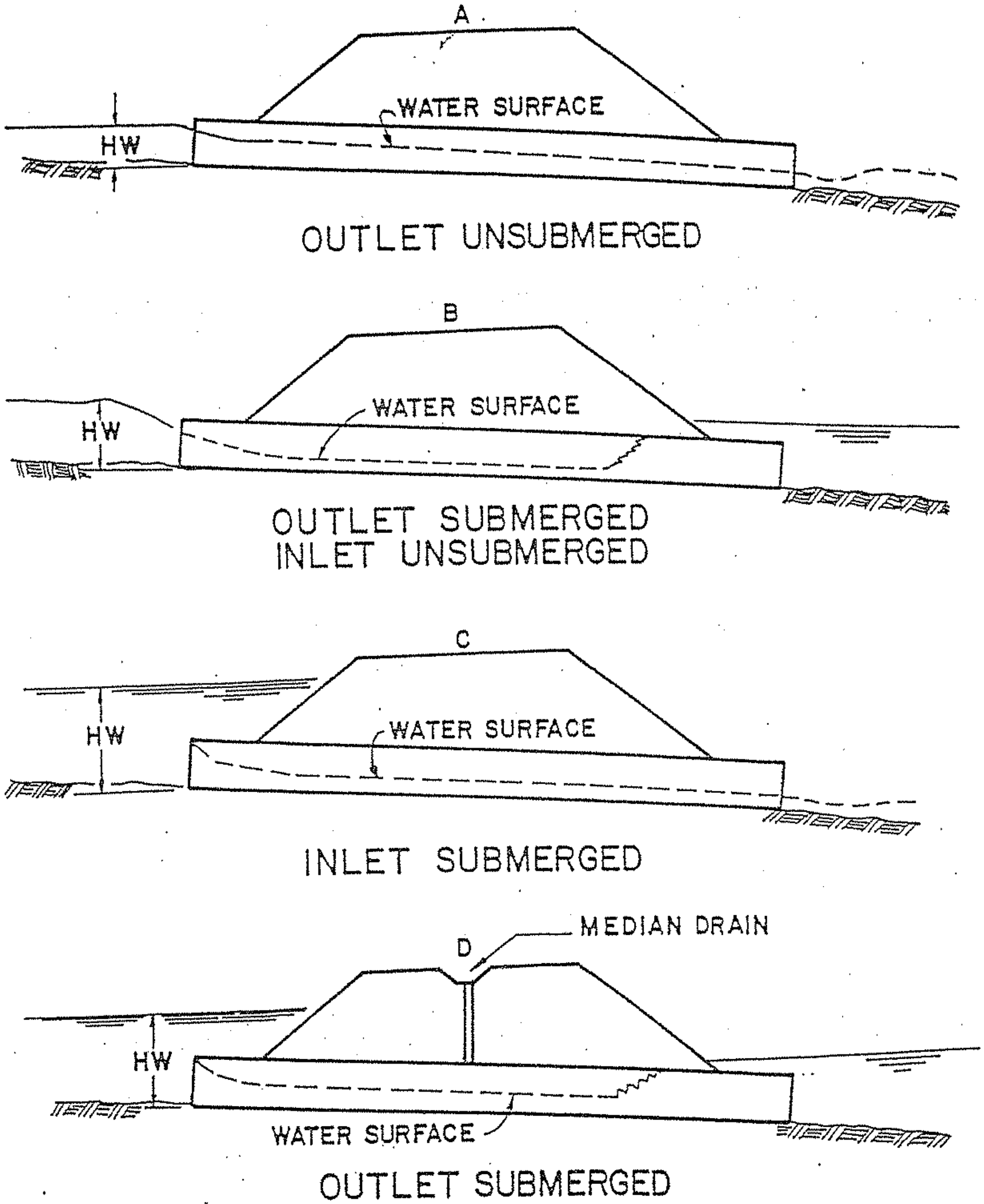


Figure III-1--Types of inlet control.

critical depth at the culvert outlet or the downstream channel depth, whichever is higher. In a given culvert, the type of flow is dependent on all of the factors listed in table 1.

a. Inlet Control.

1) Examples of Inlet Control. Figure III-1 depicts several different examples of inlet control flow. The type of flow depends on the submergence of the inlet and outlet ends of the culvert. In all of these examples, the control section is at the inlet end of the culvert. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.

Figure III-1-A depicts a condition where neither the inlet nor the outlet end of the culvert are submerged. The flow passes through critical depth just downstream of the culvert entrance and the flow in the barrel is supercritical. The barrel flows partly full over its length, and the flow approaches normal depth at the outlet end.

Figure III-1-B shows that submergence of the outlet end of the culvert does not assure outlet control. In this case, the flow just downstream of the inlet is supercritical and a hydraulic jump forms in the culvert barrel.

Figure III-1-C is a more typical design situation. The inlet end is submerged and the outlet end flows freely. Again, the flow is supercritical and the barrel flows partly full over its length. Critical depth is located just downstream of the culvert entrance, and the flow is approaching normal depth at the downstream end of the culvert.

Figure III-1-D is an unusual condition illustrating the fact that even submergence of both the inlet and the outlet ends of the culvert does not assure full flow. In this case, a hydraulic jump will form in the barrel. The median inlet provides ventilation of the culvert barrel. If the barrel were not ventilated, sub-atmospheric pressures could develop which might create an unstable condition during which the barrel would alternate between full flow and partly full flow.

2) Factors Influencing Inlet Control. Since the control is at the upstream end in inlet control, only the headwater and the inlet configuration affect the culvert performance. (table 1) The headwater depth is measured from the invert of the inlet control section to the surface of the upstream pool. The inlet area is the cross-sectional area of the face of the culvert. Generally, the inlet face area is the same as the barrel area, but for tapered inlets the face area is enlarged, and the control section is at the throat. The inlet

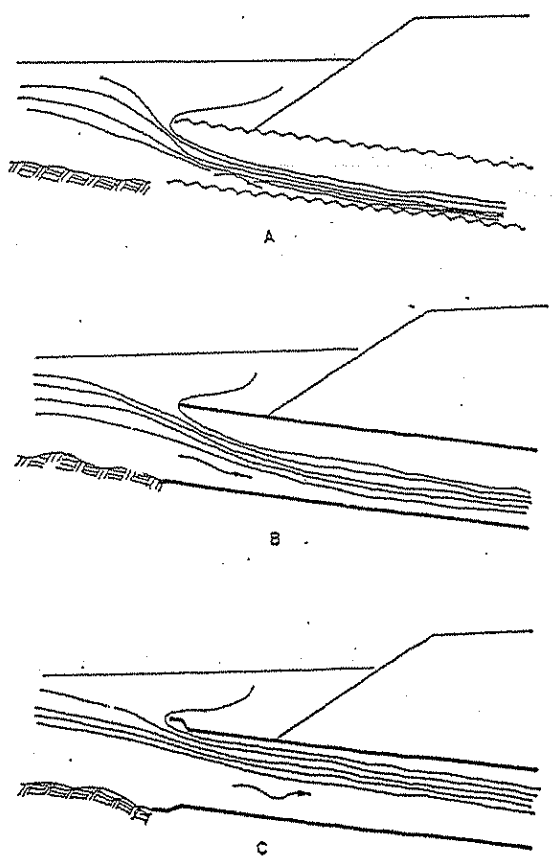


Figure III-2-- Flow contractions for various culvert inlets.

edge configuration describes the entrance type. Some typical inlet edge configurations are thin edge projecting, mitered, square edges in a headwall, and beveled edge. The inlet shape is usually the same as the shape of the culvert barrel; however, it may be enlarged as in the case of a tapered inlet. Typical shapes are rectangular, circular, and elliptical. Whenever the inlet face is a different size or shape than the culvert barrel, the possibility of an additional control section within the barrel exists.

An additional factor which influences inlet control performance is the barrel slope. The effect is small, however, and it can be ignored or a small slope correction factor can be inserted in the inlet control equations. (appendix A)

The inlet edge configuration is a major factor in inlet control performance, and it can be modified to improve performance. Various inlet edges are shown in figure III-2. Figure III-2-A is a thin edge projecting inlet typical of metal pipe, figure III-2-B is a projecting thick-walled inlet (about the same performance as a square edge in a headwall) which is typical of concrete pipe without a groove end, and figure III-2-C is a groove end or socket inlet which is typical of a concrete pipe joint. Note that as the inlet edge condition improves (from figure III-2-A to III-2-C), the flow contraction at the inlet decreases. This reduced flow contraction indicates increased inlet performance and more flow through the barrel for the same headwater.

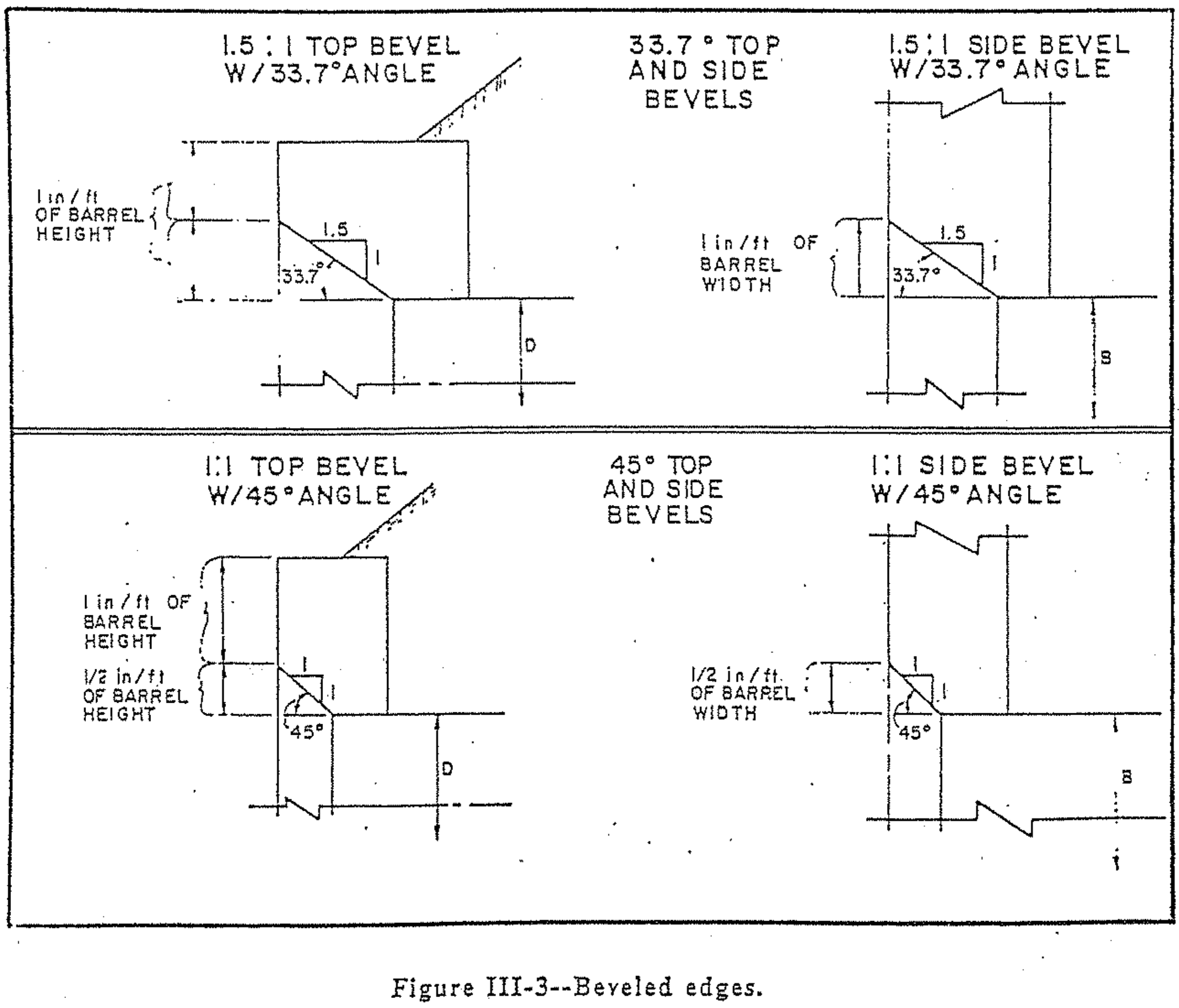


Figure III-3--Beveled edges.

A method of increasing inlet performance is the use of beveled edges at the entrance of the culvert. Beveled edges reduce the contraction of the flow by effectively enlarging the face of the culvert. Although any beveling will help the hydraulics, design charts are available for two bevel angles, 45 degrees and 33.7 degrees, as shown in figure III-3.

The larger, 33.7-degree bevels require some structural modification, but they provide slightly better inlet performance than the 45-degree bevels. The smaller, 45-degree bevels require very minor structural modification of the culvert headwall and increase both inlet and outlet control performances. Therefore, the use of 45 degree bevels is recommended on all culverts, whether in inlet or outlet control, unless the culvert has a groove end. (The groove end provides about the same performance as a beveled edge.)

3) Hydraulics of Inlet Control. Inlet control performance is defined by the three regions of flow shown in Figure III-4: unsubmerged, transition and submerged. For low headwater conditions, as shown in figures III-1-A and III-1-B, the entrance of the culvert operates as a weir. A weir is an unsubmerged flow control section where the upstream water surface elevation can be predicted for a given flow rate. The relationship between flow and water surface elevation must be determined by model tests of the weir geometry or by measuring prototype discharges. These tests or measurements are then used to develop equations for unsubmerged inlet control flow. Appendix A contains the equations which were developed from the NBS model test data.

For headwaters submerging the culvert entrance, as are shown in figures III-1-C and III-1-D, the entrance of the culvert operates as an orifice. An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section. The relationship between flow and headwater can be defined based on results from model tests. Appendix A contains the submerged flow equations which were developed from the NBS test data.

The flow transition zone between the low headwater (weir control) and the high headwater flow conditions (orifice control) is poorly defined. This zone is approximated by plotting the unsubmerged and submerged flow equations and connecting them with a line tangent to both curves, as shown in figure III-4.

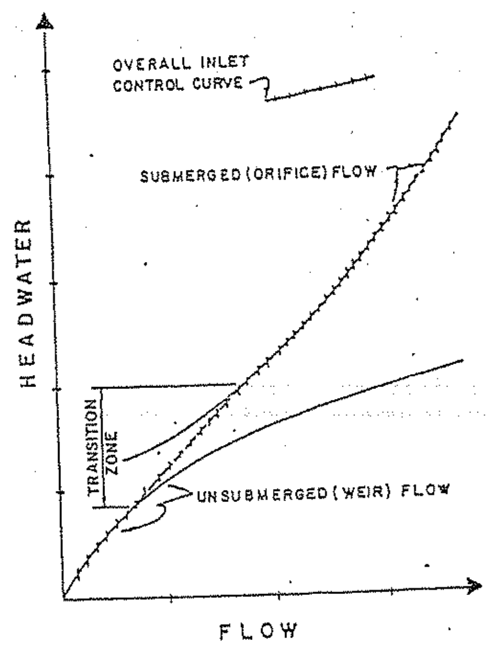


Figure III-4--Inlet flow control curves.

The inlet control flow versus headwater curves which are established using the above procedure are the basis for constructing the inlet control design nomographs. Note that the approach velocity head can be included as a part of the available headwater in the inlet control relationships.

4) Inlet Depressions. The inlet control equations or nomographs provide the depth of headwater above the inlet

invert required to convey a given discharge through the inlet. This relationship remains constant regardless of the elevation of the inlet invert. If the entrance end of the culvert is depressed below the stream bed, more head can be exerted on the inlet for the same headwater elevation.

Two methods of depressing the entrance ends of culverts are shown in figures III-5 and III-6. Figure III-5 depicts the use of a depressed approach apron with the fill retained by wingwalls. Paving the apron is desirable. Figure III-6 shows a sump constructed upstream of the culvert face. Usually the sump

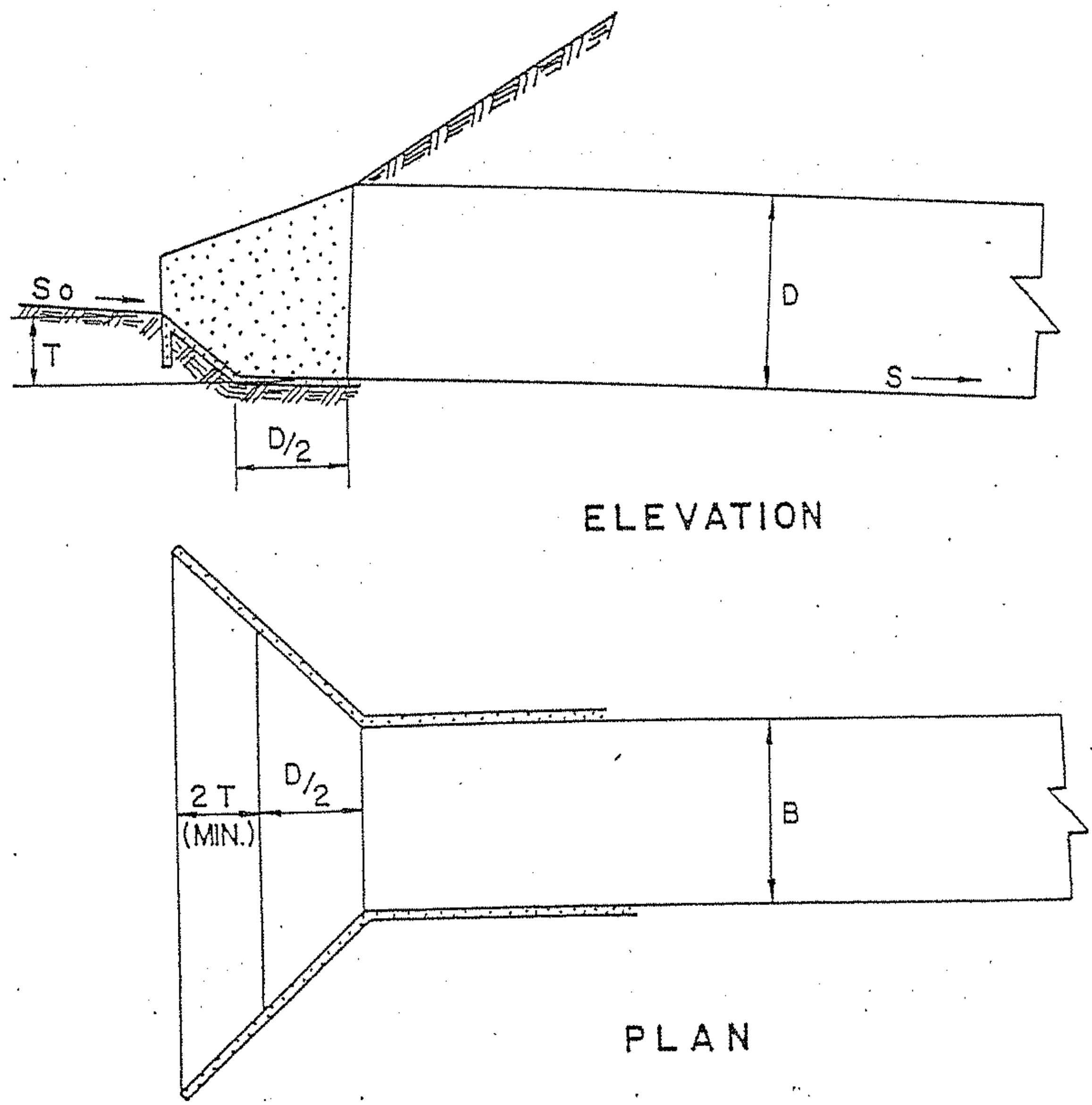


Figure III-5--Culvert with depressed apron and wingwalls.

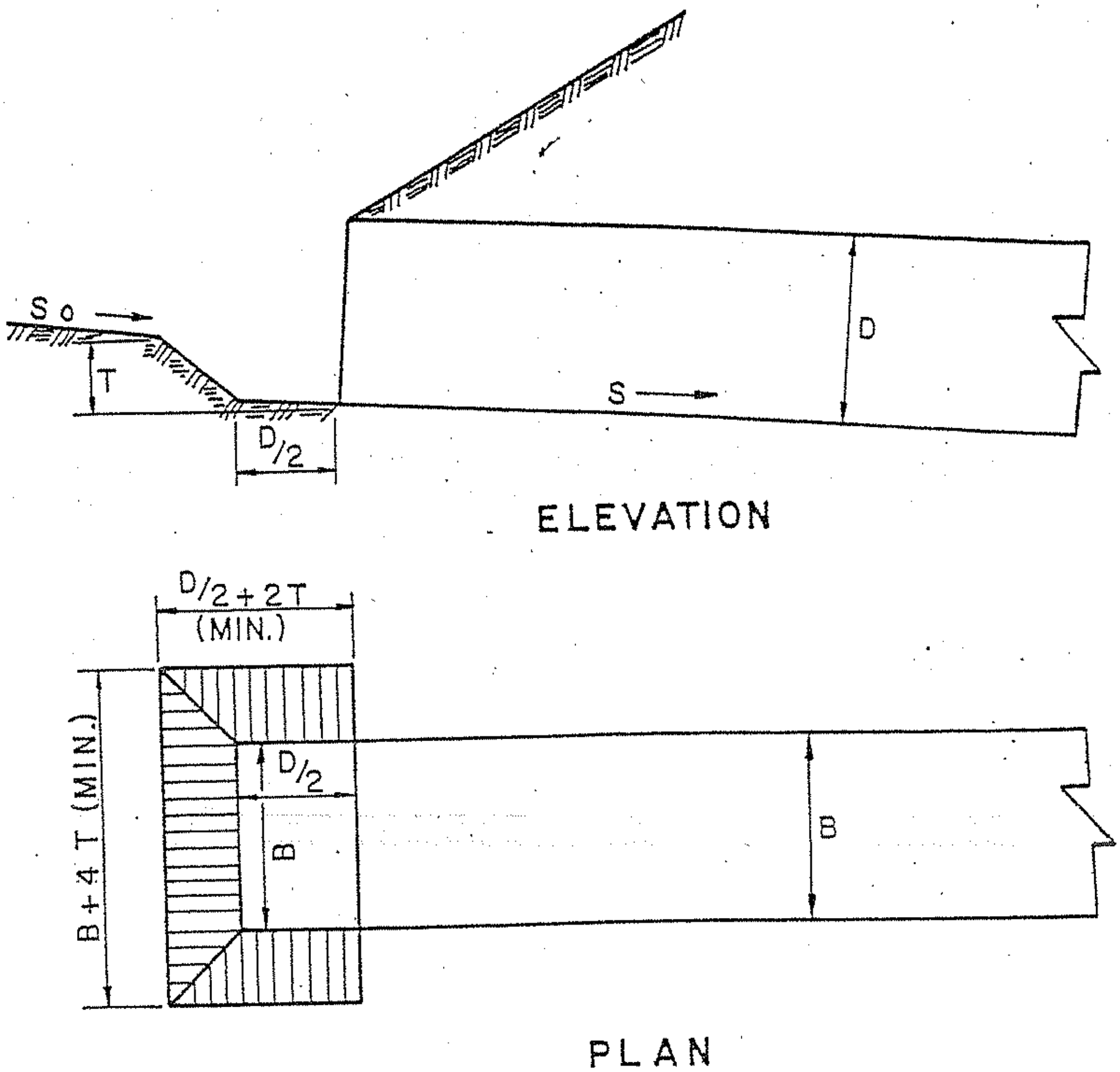


Figure III-6--Culvert with inlet sump.

is paved, but for small depressions, an unpaved excavation may be adequate.

When a culvert is depressed below the stream bed at the inlet, the depression is called the FALL. For culverts without tapered inlets, the FALL is defined as the depth from the natural stream bed at the face to the inlet invert. For culverts with tapered inlets, the FALL is defined as the depth from the natural stream bed at the face to the throat invert. Tapered inlets will be discussed further in chapter IV.

b. Outlet Control

1) Examples of Outlet Control. Figure III-7 illustrates various outlet control flow conditions. In all cases, the control section is at the outlet end of the culvert or further downstream.

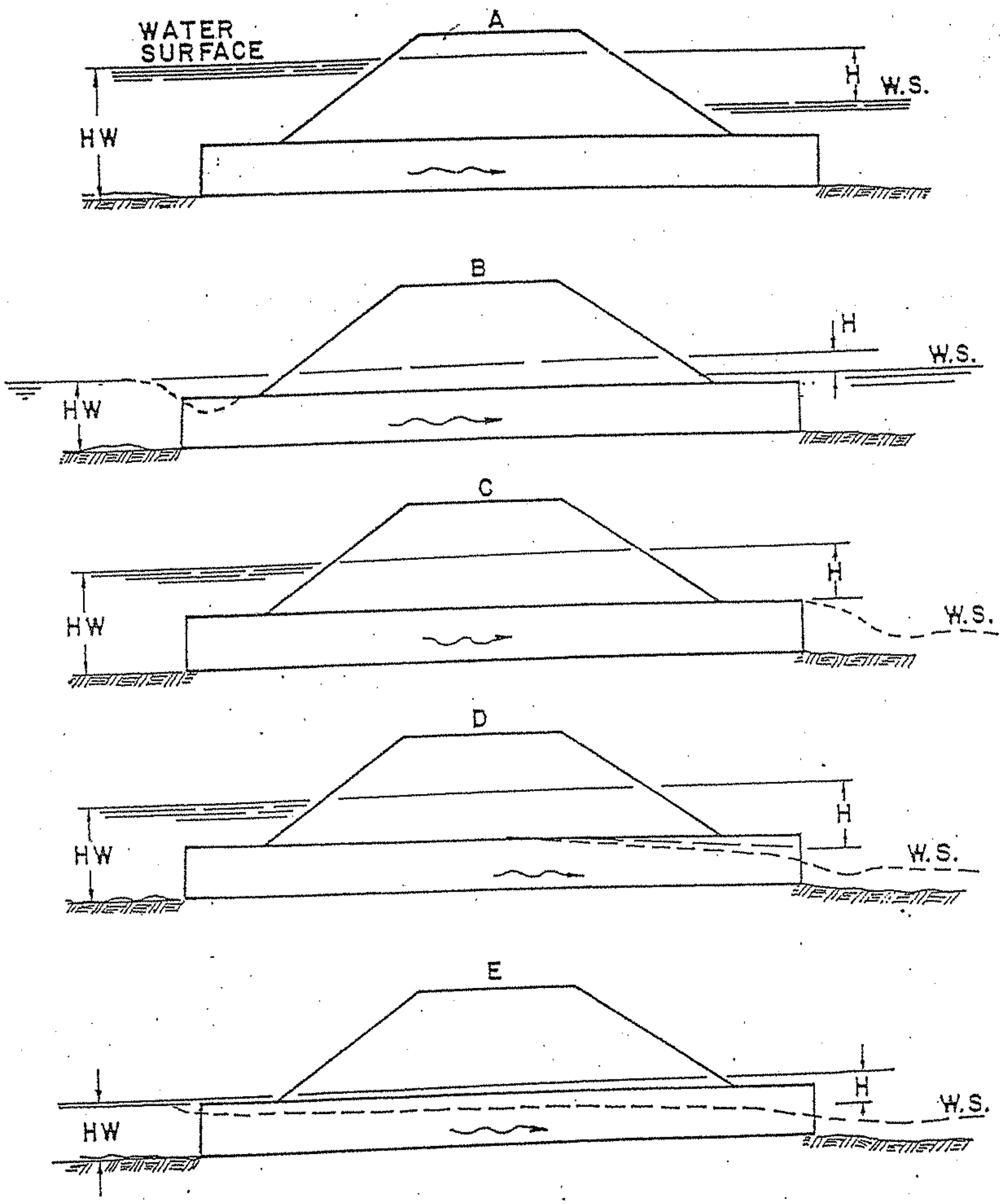


Figure III-7-- Types of outlet control.

For the partly full flow situations, the flow in the barrel is subcritical.

Condition III-7-A represents the classic full flow condition, with both inlet and outlet submerged. The barrel is in pressure flow throughout its length. This condition is often assumed in calculations, but seldom actually exists.

Condition III-7-B depicts the outlet submerged with the inlet unsubmerged. For this case, the headwater is shallow so that the inlet crown is exposed as the flow contracts into the culvert.

Condition III-7-C shows the entrance submerged to such a degree that the culvert flows full throughout its entire length while the exit is unsubmerged. This is a rare condition. It requires an extremely high headwater to maintain the full barrel flow with no tailwater. The outlet velocities are usually high under this condition.

Condition III-7-D is more typical. The culvert entrance is submerged by the headwater and the outlet end flows freely with a low tailwater. For this condition, the barrel flows partly full over at least part of its length (subcritical flow) and the flow passes through critical depth just upstream of the outlet.

Condition III-7-E is also typical, with neither the inlet nor the outlet end of the culvert submerged. The barrel flows partly full over its entire length, and the flow profile is subcritical.

2) Factors Influencing Outlet Control. All of the factors influencing the performance of a culvert in inlet control also influence culverts in outlet control. In addition, the barrel characteristics (roughness, area, shape, length, and slope) and the tailwater elevation affect culvert performance in outlet control. (table 1)

The barrel roughness is a function of the material used to fabricate the barrel. Typical materials include concrete and corrugated metal. The roughness is represented by a hydraulic resistance coefficient such as the Manning n value. Typical Manning n values for culverts are presented in table 4. Additional discussion on the sources and derivations of the Manning n values are contained in appendix B.

The barrel area and barrel shape are self explanatory.

The barrel length is the total culvert length from the entrance to the exit of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is usually necessary to begin the design process.

The barrel slope is the actual slope of the culvert barrel. The barrel slope is often the same as the natural stream slope. However, when the culvert inlet is raised or lowered, the barrel slope is different from the stream slope.

The tailwater elevation is based on the downstream water surface elevation. Backwater calculations from a downstream control, a normal depth approximation, or field observations are used to define the tailwater elevation.

3) Hydraulics of Outlet Control. Full flow in the culvert barrel, as depicted in figure III-7-A, is the best type of flow for describing outlet control hydraulics.

Outlet control flow conditions can be calculated based on energy balance. The total energy (H_L) required to pass the flow through the culvert barrel is made up of the entrance loss (H_e), the friction losses through the barrel (H_f), and the exit loss (H_o). Other losses, including bend losses (H_b), losses at junctions (H_j), and loses at grates (H_g) should be included as appropriate. These losses are discussed in chapter VI.

$$H_L = H_e + H_f + H_o + H_b + H_j + H_g \quad (1)$$

Table 4. Manning n values for culverts.

Type of Conduit	Wall & Joint Description	Manning n
Concrete Pipe	Good joints, smooth walls	0.011-0.013
	Good joints, rough walls	0.014-0.016
	Poor joints, rough walls	0.016-0.017
Concrete Box	Good joints, smooth finished walls	0.012-0.015
	Poor joints, rough, unfinished walls	0.014-0.018
Corrugated Metal Pipes and Boxes, Annular Corrugations (Manning n varies with barrel size)	2-2/3 by 1/2 in corrugations	0.027-0.022
	6 by 1 inch corrugations	0.025-0.022
	5 by 1 inch corrugations	0.026-0.025
	3 by 1 inch corrugations	0.028-0.027
	6 by 2 inch structural plate corrugations	0.035-0.033
	9 by 2 1/2 inch structural plate corrugations	0.037-0.033
Corrugated Metal Pipes, Helical Corrugations, Full Circular Flow	2-2/3 by 1/2 inch corrugations, 24 inch plate width	0.012-0.024
Spiral Rib Metal Pipe	3/4 by 3/4 in recesses at 12 inch spacing, good joints	0.012-0.013

The barrel velocity is calculated as follows:

$$V = \frac{Q}{A} \qquad (2)$$

V is the average velocity in the culvert barrel, ft/s (m/s)

Q is the flow rate, ft^3/s (m^3/s)

A is the full cross sectional area of the flow, ft^2 (m^2)

The velocity head is:

$$H_v = \frac{V^2}{2g} \qquad (3)$$

g is the acceleration due to gravity, 32.2 ft/s/s (9.8 m/s/s)

The entrance loss is a function of the velocity head in the barrel, and can be expressed as a coefficient times the velocity head.

$$H_e = k_e \left(\frac{V^2}{2g} \right) \qquad (4a)$$

Values of k_e based on various inlet configurations are given in table 12, appendix D.

The friction loss in the barrel is also a function of the velocity head. Based on the Manning equation, the friction loss is:

$$H_f = \left[\frac{29\, n^2\, L}{R^{1.33}} \right] \frac{V^2}{2g} \qquad (4b)$$

n is the Manning roughness coefficient (table 4)

L is the length of the culvert barrel, ft (m)

R is the hydraulic radius of the full culvert barrel = A/p, ft (m)

A is the cross-sectional area of the barrel, ft^2 (m^2)

p is the perimeter of the barrel, ft (m)

V is the velocity in the barrel, ft/s (m/s)

The exit loss is a function of the change in velocity at the outlet of the culvert barrel. For a sudden expansion such as an endwall, the exit loss is:

$$H_o = 1.0 \left[\frac{V^2}{2g} - \frac{V_d^2}{2g} \right] \qquad (4c)$$

V_d is the channel velocity downstream of the culvert, ft/s (m/s)

Equation (4c) may overestimate exit losses, and a multiplier of less than 1.0 can be used. (40) The downstream velocity is usually neglected, in which case the exit loss is equal to the full flow velocity head in the barrel, as shown in equation (4d).

$$H_o = H_v = \frac{V^2}{2g} \qquad (4d)$$

Bend losses, junction losses, grate losses and other losses are discussed in chapter VI. These other losses are added to the total losses using equation (1).

Inserting the above relationships for entrance loss, friction loss, and exit loss (equation 4d) into equation (1), the following equation for loss is obtained:

$$H = \left[1 + k_e + \frac{29\, n^2\, L}{R^{1.33}} \right] \frac{V^2}{2g} \qquad (5)$$

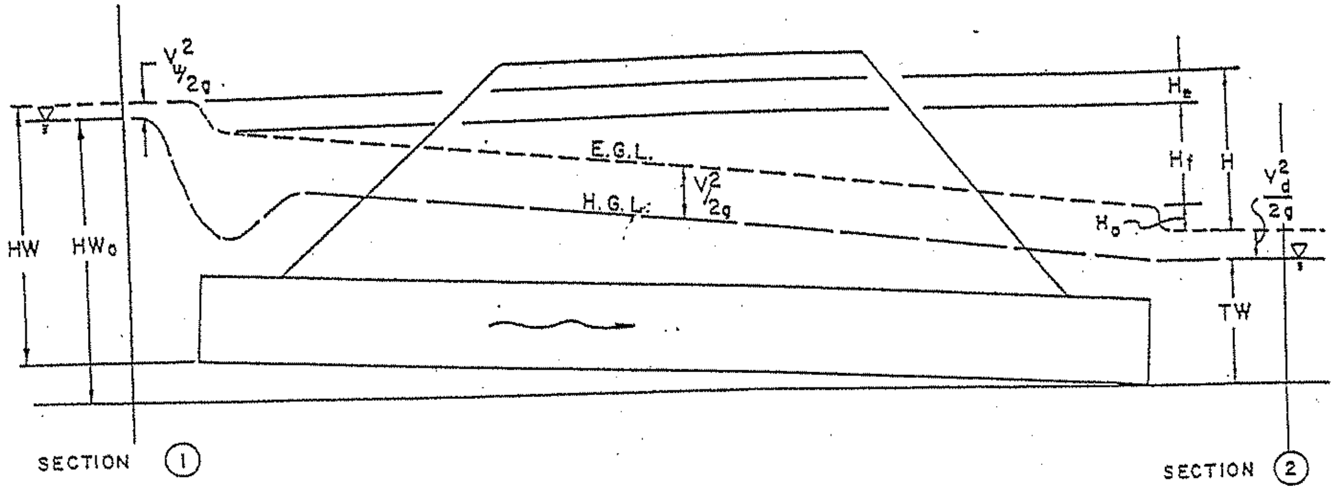


Figure III-8--Full flow energy and hydraulic grade lines.

Figure III-8 depicts the energy grade line and the hydraulic grade line for full flow in a culvert barrel. The energy grade line represents the total energy at any point along the culvert barrel. HW is the depth from the inlet invert to the energy gradė line.The hydraulic grade line is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel straight lines separated by the velocity head lines except in the vicinity of the inlet where the flow passes through a contraction.

The headwater and tailwater conditions as well as the entrance, friction, and exit losses are also shown in figure III-8. Equating the total energy at sections 1 and 2, upstream and downstream of the culvert barrel in figure III-8, the following relationship results:

$$HW_o + \frac{V_u^2}{2g} = TW + \frac{V_d^2}{2g} + H_L \qquad (6)$$

HW_o is the headwater depth above the outlet invert, ft (m)

V_u is the approach velocity, ft/s (m/s)

TW is the tailwater depth above the outlet invert, ft (m)

V_d is the downstream velocity, ft/s (m/s)

H_L is the sum of all losses including entrance (H_e), friction (H_f), exit (H_o) and other losses, (H_b), (H_j), etc., ft (m)

Note that the total available upstream energy (HW) includes the depth of the upstream water surface above the outlet invert and the approach velocity head. In most instances, the approach velocity is low, and the approach velocity head is neglected. However, it can be considered to be a part of the available headwater and used to convey the flow through the culvert.

Likewise, the velocity downstream of the culvert (V_d) is usually neglected. When both approach and downstream velocities are neglected, equation (6) becomes:

$$HW_o = TW + H_L \qquad (7)$$

In this case, H_L is the difference in elevation between the water surface elevation at the outlet (tailwater elevation) and the water surface elevation at the inlet (headwater elevation). If it is desired to include the approach and/or downstream velocities, use equation (4c) for exit losses and equation (6) instead of equation (7) to calculate the headwater.

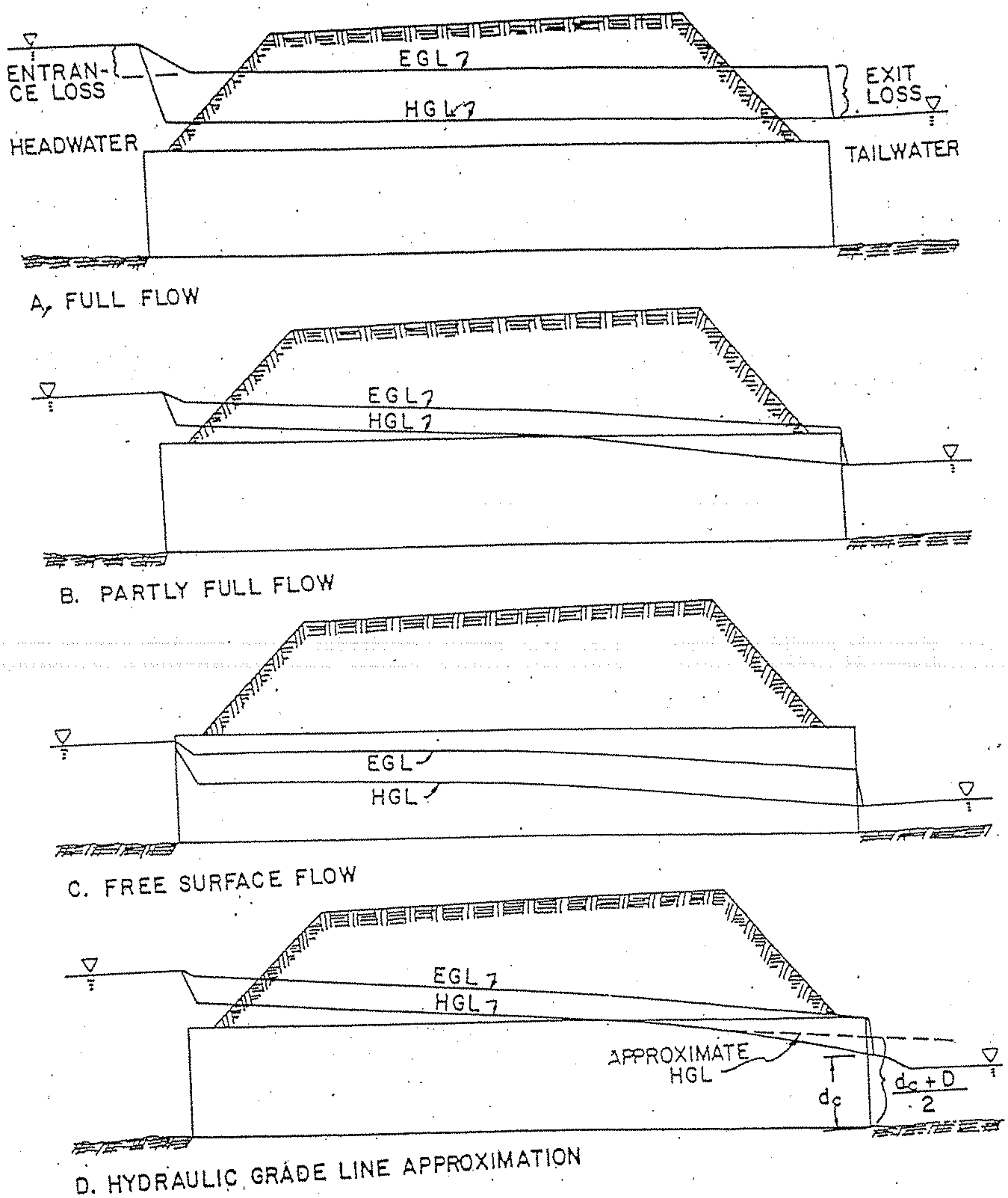


Figure III-9--Outlet control energy and hydraulic grade lines.

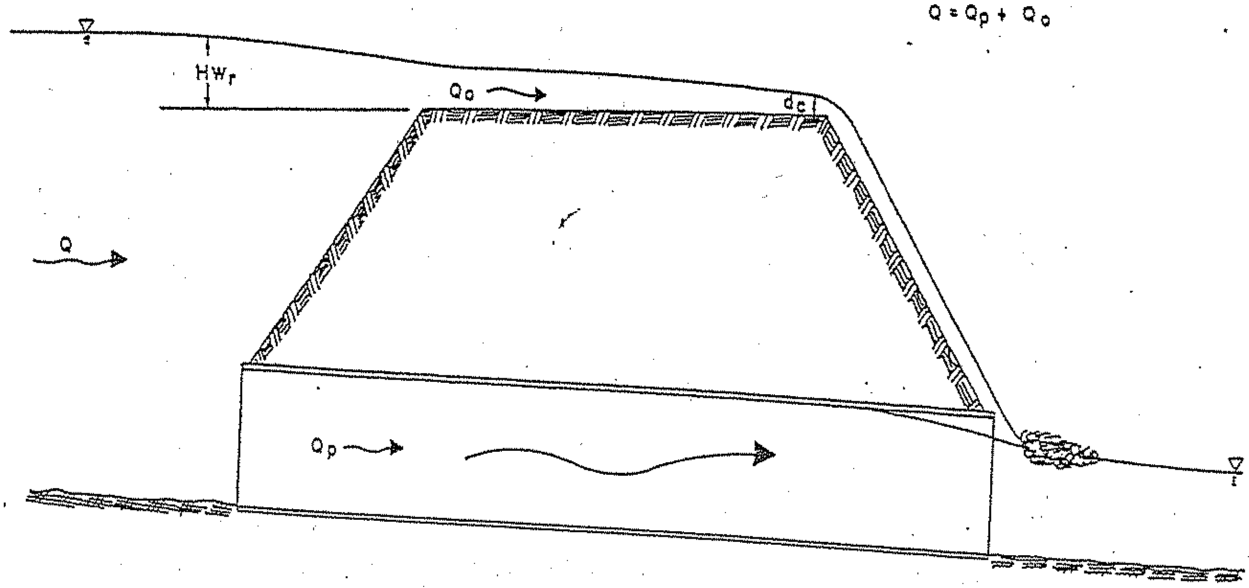


Figure III-10--Roadway overtopping.

Equations (1) through (7) were developed for full barrel flow, shown in figure III-7-A. The equations also apply to the flow situations shown in figures III-7-B and C, which are effectively full flow conditions. Backwater calculations may be required for the partly full flow conditions shown in figures III-7-D and E. These calculations begin at the water surface at the downstream end of the culvert and proceed upstream to the entrance of the culvert. The downstream water surface is based on critical depth at the culvert outlet or on the tailwater depth, whichever is higher. If the calculated backwater profile intersects the top of the barrel, as in figure III-7-D, a straight, full flow hydraulic grade line extends from that point upstream to the culvert entrance. From equation (4b), the full flow friction slope is:

$$S_n = \frac{H_f}{L} = \frac{29\ n^2}{R^{1.33}} \quad \frac{V^2}{2g}$$

In order to avoid tedious backwater calculations, approximate methods have been developed to analyze partly full flow conditions. Based on numerous backwater calculations performed by the FHWA staff, it was found that a downstream extension of the full flow hydraulic grade line for the flow condition shown in figure III-9-B pierces the plane of the culvert outlet at a point one-half way between critical depth and the top of the barrel. Therefore, it is possible to begin the hydraulic grade line at a depth of $(d_c + D)/2$ above the outlet invert and extend the straight, full flow hydraulic grade line upstream to the inlet of the culvert at a slope of S_n. (figure III-9-D) If the tailwater exceeds $(d_c + D)/2$, the tailwater is used to set the downstream end of the extended full flow hydraulic grade line. The inlet losses and the velocity head are added to the elevation of the hydraulic grade line at the inlet to obtain the headwater elevation.

This approximate method works best when the barrel flows full over at least part of its length. (figure III-9-B) When the barrel is partly full over its entire length (figure III-9-C), the method becomes increasingly inaccurate as the headwater falls further below the top of the barrel at the inlet. Adequate results are obtained down to a headwater of 0.75D. For lower headwaters, backwater calculations are required to obtain accurate headwater elevations.

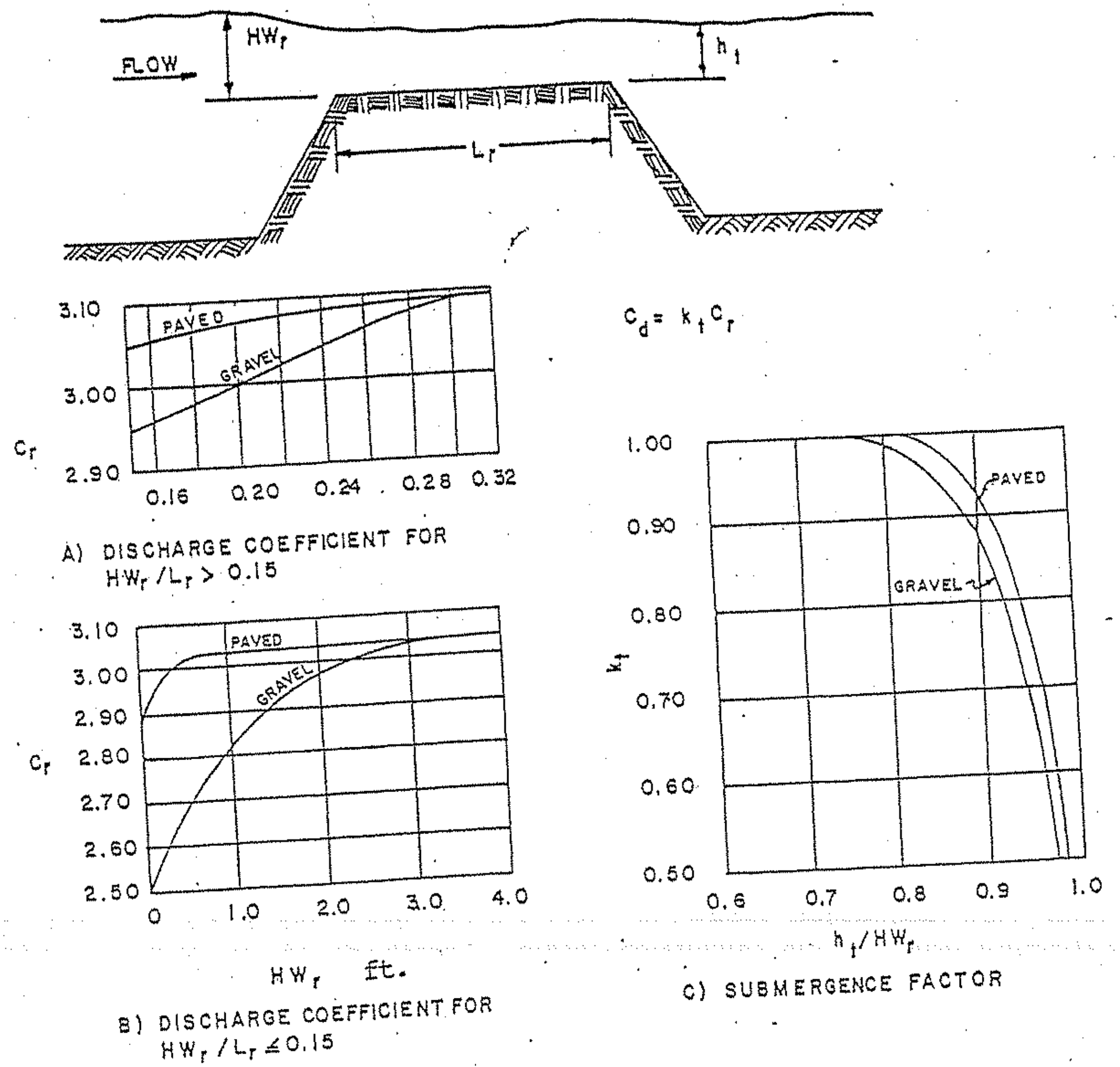


Figure III-11--Discharge coefficients for roadway overtopping.

The outlet control nomographs in appendix D provide solutions for equation (5) for entrance, friction, and exit losses in full barrel flow. Using the approximate backwater method, the losses (H) obtained from the nomographs can be applied for the partly full flow conditions shown in figures III-7 and III-9. The losses are added to the elevation of the extended full flow hydraulic grade line at the barrel outlet in order to obtain the headwater elevation. The extended hydraulic grade line is set at the higher of $(d_c + D)/2$ or the tailwater elevation at the culvert outlet. Again, the approximation works best when the barrel flows full over at least part of its length.

3. Roadway Overtopping. Overtopping will begin when the headwater rises to the elevation of the roadway. (figure III-10) The overtopping will usually occur at the low point of a sag vertical curve on the roadway. The flow will be similar to flow over a broad crested weir. Flow coefficients for flow overtopping roadway embankments are found in HDS No. 1, Hydraulics of Bridge Waterways (21), as well as in the documentation of HY-7, the Bridge Waterways Analysis Model (22). Curves from reference (22) are shown in figure III-11. Figure III-11-A is for deep overtopping, figure III-11-B is for shallow overtopping, and figure III-11-C is a correction factor for down-

stream submergence. Equation (8) defines the flow across the roadway.

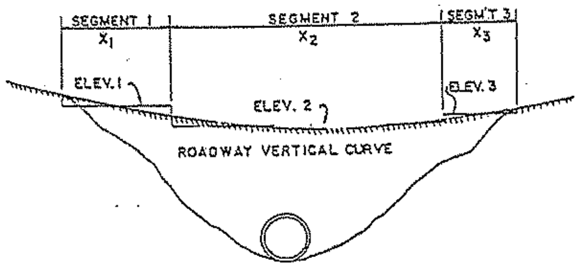
$$Q_o = C_d \; L \; HW_r^{1.5} \qquad (8)$$

Q_o is the overtopping flow rate in ft^3/s (m^3/s)

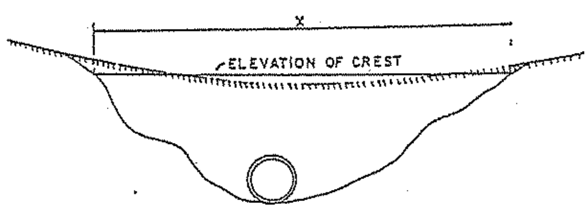
C_d is the overtopping discharge coefficient

L is the length of the roadway crest, ft (m)

HW_r is the upstream depth, measured from the roadway crest to the water surface upstream of the weir draw-down, ft (m)



A. METHOD 1 - SUBDIVISION INTO SEGMENTS



B. METHOD 2 - USE OF A SINGLE SEGMENT

Figure III-12--Weir crest length determinations for roadway overtopping.

The length and elevation of the roadway crest are difficult to determine when the crest is defined by a roadway sag vertical curve. The sag vertical curve can be broken into a series of horizontal segments as shown in figure III-12-A. Using equation (8), the flow over each segment is calculated for a given head-water. Then, the incremental flows for each segment are added together, resulting in the total flow across the roadway.

Representing the sag vertical curve by a single horizontal line (one segment) is often adequate for culvert design. (figure III-12-B) The length of the weir can be taken as the horizontal length of this segment or it can be based on the roadway profile and an acceptable variation above and below the horizontal line. In effect, this method utilizes an average depth of the upstream pool above the roadway crest for the flow calculation.

It is a simple matter to calculate the flow across the roadway for a given upstream water surface elevation using equation (8). The problem is that the roadway overflow plus the culvert flow must equal the total design flow. A trial and error process is necessary to determine the amount of the total flow passing through the culvert and the amount flowing across the roadway. Performance curves may also be superimposed for the culvert flow and the road overflow to yield an overall solution as is discussed later in this chapter.

4. Outlet Velocity. Culvert outlet velocities should be calculated to determine the need for erosion protection at the culvert exit. Culverts usually result in outlet velocities which are higher than the natural stream velocities. These outlet velocities may require flow readjustment or energy dissipation to prevent downstream erosion.

In inlet control, backwater (also called drawdown) calculations may be necessary to determine the outlet velocity. These calculations begin at the culvert entrance and proceed downstream to the exit. The flow velocity is obtained from the flow and the cross-sectional area at the exit. (equation (2))

An approximation may be used to avoid backwater calculations in determining the outlet velocity for culverts operating in inlet control. The water surface

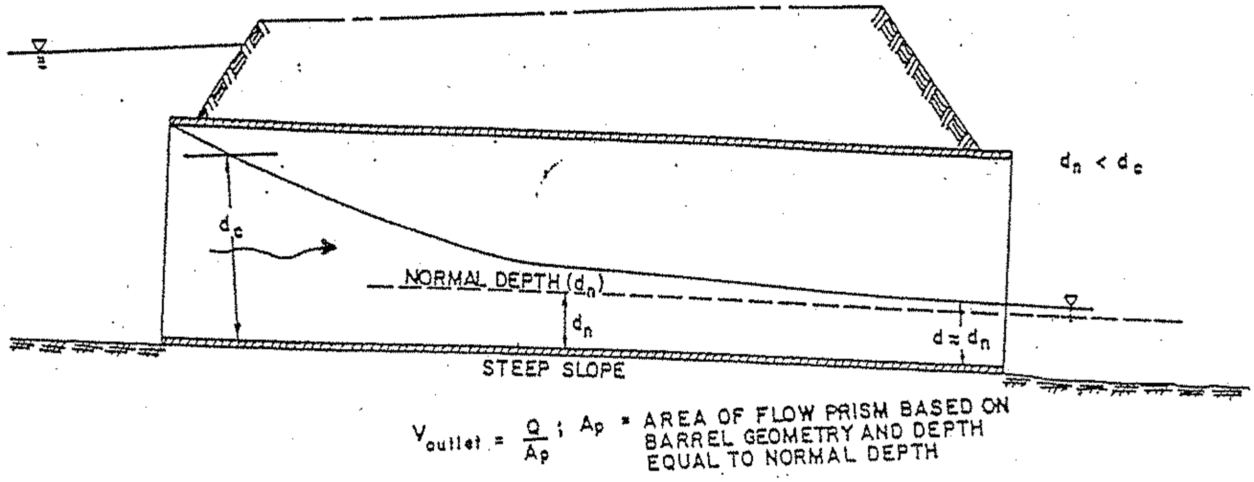


Figure III-13--Outlet velocity - inlet control.

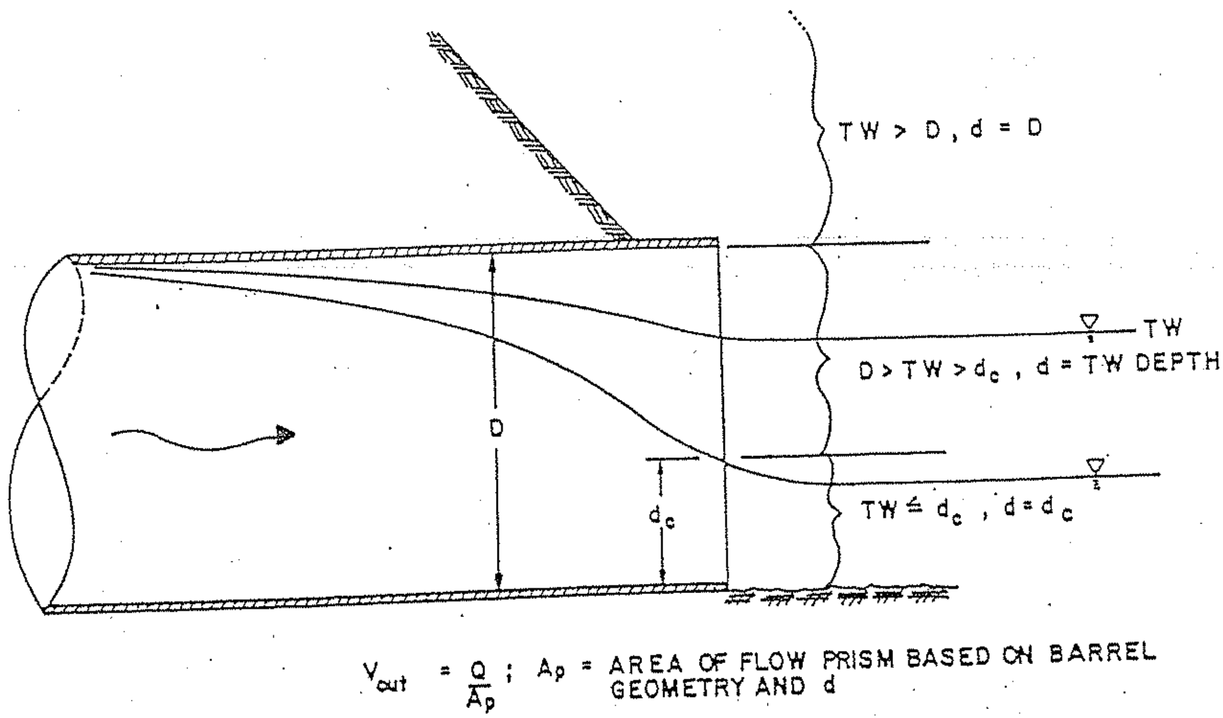


Figure III-14--Outlet velocity - outlet control.

profile converges toward normal depth as calculations proceed down the culvert barrel. Therefore, if the culvert is of adequate length, normal depth will exist at the culvert outlet. Even in short culverts, normal depth can be assumed and used to define the area of flow at the outlet and obtain the outlet velocity. (figure III-13) The velocity calculated in this manner may be slightly higher than the actual velocity at the outlet. Normal depth in common culvert shapes may be calculated using a trial and error solution of the Manning equation. The known inputs are flow rate, barrel resistance, slope and geometry. Normal depths may also be obtained from design aids in publications such as HDS No. 3. (23)

In outlet control, the cross sectional area of the flow is defined by the geometry of the outlet and either critical depth, tailwater depth, or the height of the conduit. (figure III-14)

Critical depth is used when the tailwater is less than critical depth and the tailwater depth is used when tailwater is greater than critical depth but below the top of the barrel. The total barrel area is used when the tailwater exceeds the top of the barrel.

B. Performance Curves.

Performance curves are representations of flow rate versus headwater depth or elevation for a given flow control device, such as a weir, an orifice, or a culvert. A weir constricts open channel flow so that the flow passes through critical depth just upstream of the weir. An orifice is a flow control device, fully submerged on the upstream side, through which the flow passes. Performance curves and equations for these two basic types of flow control devices are shown in figure III-15.

When a tailwater exists, the control device may be submerged so that more than one flow-versus-elevation relationship exists. Then, the performance curve is dependent on the variation of both tailwater and headwater. In the case of a weir or orifice, the device is called a submerged weir or a submerged orifice, respectively. For some cases, submergence effects have been analyzed and correction factors have been developed. (21,22,24)

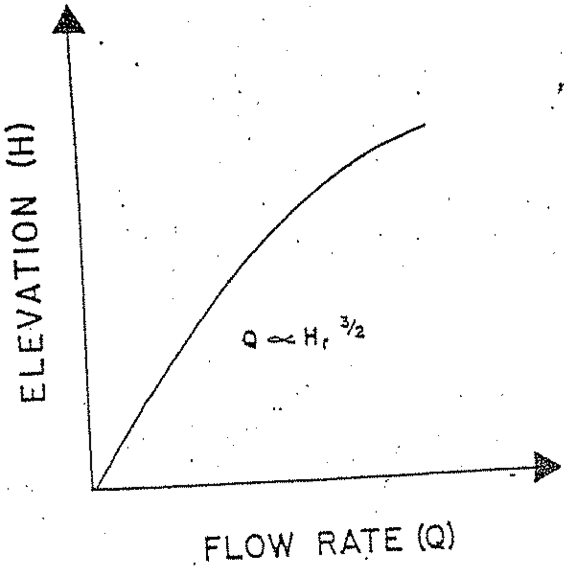
Culvert performance curves are similar to weir and/or orifice performance curves. In fact, culverts often behave as weirs or orifices. However, due to the fact that a culvert has several possible control sections (inlet, outlet, throat), a given installation will have a performance curve for each control section and one for roadway overtopping. The overall culvert performance curve is made up of the controlling portions of the individual performance curves for each control section.

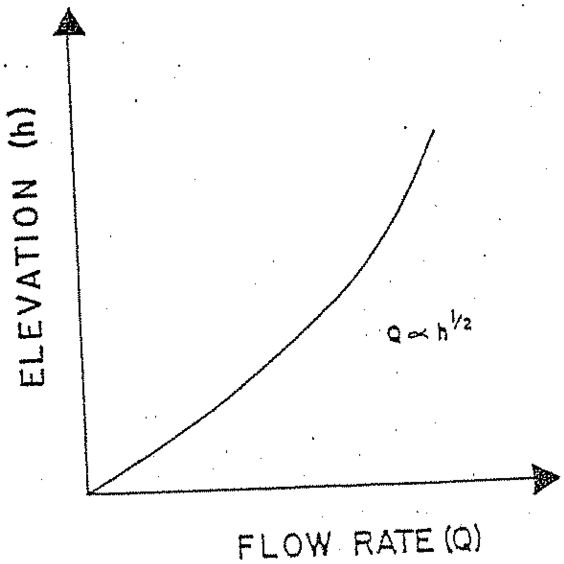
1. Inlet Control. The inlet control performance curves are developed using either the inlet control equations of appendix A or the inlet control nomographs of appendix D. If the equations of appendix A are used, both unsubmerged (weir) and submerged (orifice) flow headwaters must be calculated for a series of flow rates bracketing the design flow. The resultant curves are then connected with a line tangent to both curves (the transition zone). If the inlet control nomographs are used, the headwaters corresponding to the series of flow rates are determined and then plotted. The transition zone is inherent in the nomographs.

2. Outlet Control. The outlet control performance curves are developed using equations (1) through (7) of this chapter, the outlet control nomographs of appendix D, or backwater calculations. Flows bracketing the design flow are selected. For these flows, the total losses through the barrel are calculated or read from the outlet control nomographs. The losses are added to the elevation of the hydraulic grade line at the culvert outlet to obtain the headwater.

If backwater calculations are performed beginning at the downstream end of the culvert, friction losses are accounted for in the calculations. Adding the inlet loss to the energy grade line in the barrel at the inlet results in the headwater elevation for each flow rate.

3. Roadway Overtopping. A performance curve showing the culvert flow as well as the flow across the roadway is a useful analysis tool. Rather than using





RECTANGULAR WEIR

Equation: $Q = C_d L (HW_r)^{3/2}$

Q = flow rate, ft^3/s (m^3/s)
C_d = weir coefficient
L = length of weir, ft (m)
HW_r = driving head above weir crest, ft (m)

ORIFICE

Equation: $Q = kah^{1/2}$

Q = flow rate, ft^3/s (m^3/s)
k = coefficient
a = area of orifice, ft^2 (m^2)
h = driving head above center of orifice, ft (m)

Figure III-15--Performance curves and equations for weirs and orifices.

a trial and error procedure to determine the flow division between the overtopping flow and the culvert flow, an overall performance curve can be developed. The performance curve depicts the sum of the flow through the culvert and the flow across the roadway.

The overall performance curve can be determined by performing the following steps.

1. Select a range of flow rates and determine the corresponding headwater elevations for the culvert flow alone. These flow rates should fall above and below the design discharge and cover the entire flow range of interest. Both inlet and outlet control headwaters should be calculated.

2. Combine the inlet and outlet control performance curves to define a single performance curve for the culvert.

3. When the culvert headwater elevations exceed the roadway crest elevation, overtopping will begin. Calculate the equivalent upstream water surface depth above the roadway (crest of weir)

for each selected flow rate. Use these water surface depths and equation (8) to calculate flow rates across the roadway.

4. Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve.

Using the combined culvert performance curve, it is an easy matter to determine the headwater elevation for any flow rate, or to visualize the performance of the culvert installation over a range of flow rates. When roadway overtopping begins, the rate of headwater increase will flatten severely. The headwater will rise very slowly from that point on. Figure III-16 depicts an overall culvert performance curve with roadway overtopping. Example problem III-4 illustrates the development of an overall culvert performance curve.

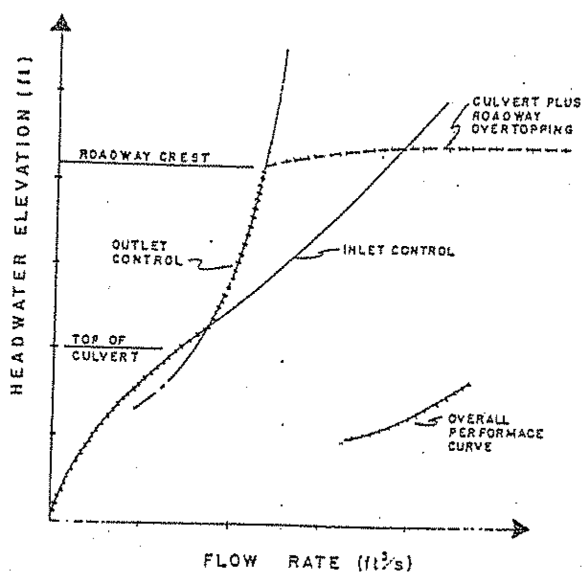


Figure III-16--Culvert performance curve with roadway overtopping.

C. Culvert Design Method.

The culvert design method provides a convenient and organized procedure for designing culverts, considering inlet and outlet control. While it is possible to follow the design method without an understanding of culvert hydraulics, this is not recommended. The result could be an inadequate and possibly unsafe structure.

1. Culvert Design Form. The Culvert Design Form, shown in figure III-17, has been formulated to guide the user through the design process. Summary blocks are provided at the top of the form for the project description, and the designer's identification. Summaries of hydrologic data of the form are also included. At the top right is a small sketch of the culvert with blanks for inserting important dimensions and elevations.

The central portion of the design form contains lines for inserting the trial culvert description and calculating the inlet control and outlet control headwater elevations. Space is provided at the lower center for comments and at the lower right for a description of the culvert barrel selected.

The first step in the design process is to summarize all known data for the culvert at the top of the Culvert Design Form. This information will have been collected or calculated prior to performing the actual culvert design. The next step is to select a preliminary culvert material, shape, size, and entrance type. The user then enters the design flow rate and proceeds with the inlet control calculations.

2. Inlet Control. The inlet control calculations determine the headwater elevation required to pass the design flow through the selected culvert configuration in inlet control. The approach velocity head may be included as part of the headwater, if desired. The inlet control nomographs of appendix D are used in the design process. For the following discussion, refer to the schematic inlet control nomograph shown in figure III-18.

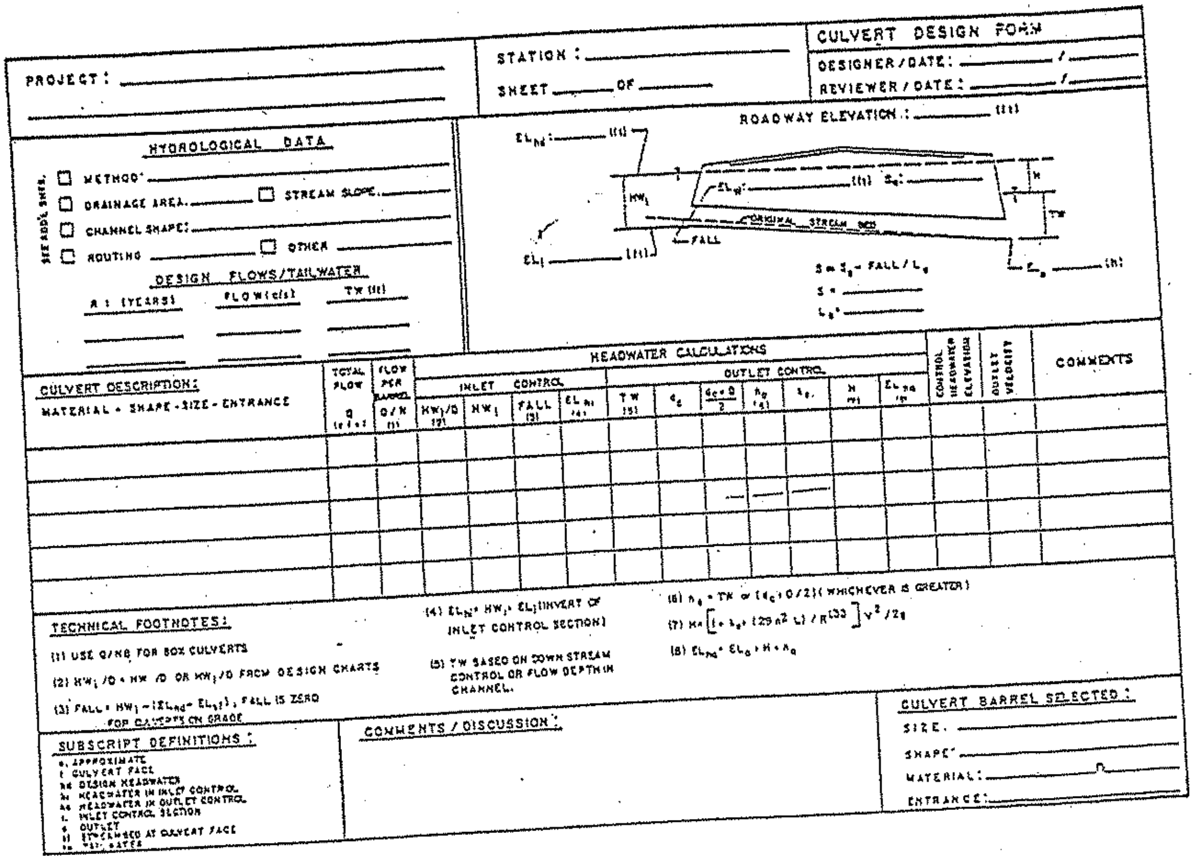


Figure III-17--Culvert design form.

a. Locate the selected culvert size (point 1) and flow rate (point 2) on the appropriate scales of the inlet control nomograph. (Note that for box culverts, the flow rate per foot of barrel width is used.)

b. Using a straightedge, carefully extend a straight line from the culvert size (point 1) through the flow rate (point 2) and mark a point on the first headwater/culvert height (HW/D) scale (point 3). The first HW/D scale is also a turning line.

(NOTE: If the nomographs are put into a notebook, a clean plastic sheet with a matte finish can be used to mark on so that the nomographs can be preserved.)

c. If another HW/D scale is required, extend a horizontal line from the first HW/D scale (the turning line) to the desired scale and read the result.

d. Multiply HW/D by the culvert height, D, to obtain the required headwater (HW) from the invert of the control section to the energy grade line. If the approach velocity is neglected, HW equals the required headwater depth (HW_i). If the approach velocity is included in the calculations, deduct the approach velocity head from HW to determine HW_i.

e. Calculate the required depression (FALL) of the inlet control section below the stream bed as follows:

$$HW_d = EL_{hd} - EL_{sf}$$

$$FALL = HW_i - HW_d$$

HW_d is the design headwater depth, ft (m)

EL_{hd} is the design headwater elevation, ft (m)

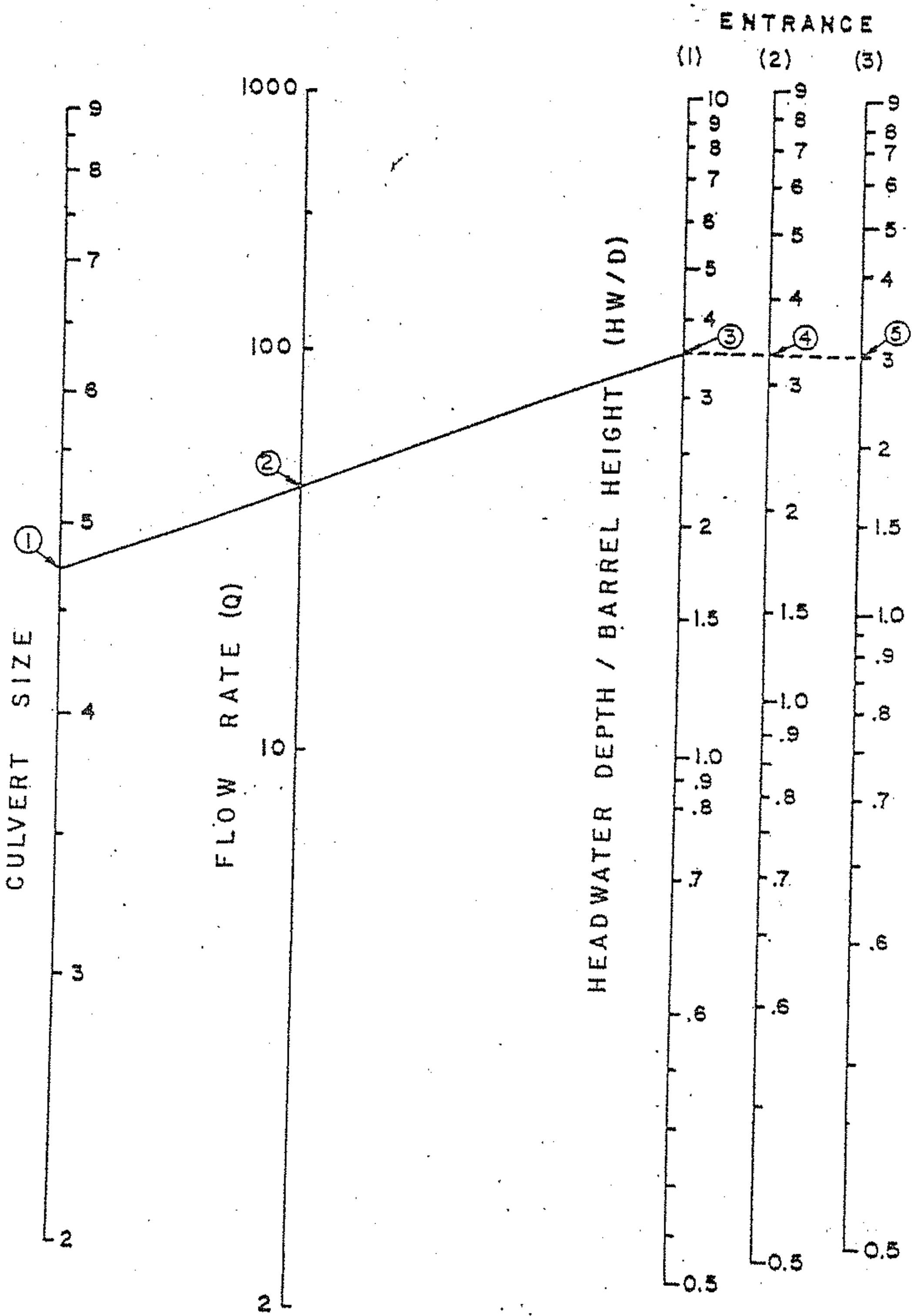


Figure III-18--Inlet control nomograph (schematic).

EL_{sf} is the elevation of the streambed at the face, ft (m)

HW_i is the required headwater depth, ft (m)

Possible results and consequences of this calculation are:

1) If the FALL is negative or zero, set FALL equal to zero and proceed to step f.

2) If the FALL is positive, the inlet control section invert must be depressed below the streambed at the face by that amount. If the FALL is acceptable, proceed to step f.

3) If the FALL is positive and greater than is judged to be acceptable, select another culvert configuration and begin again at step a.

f. Calculate the inlet control section invert elevation as follows:

$$EL_i = EL_{sf} - FALL$$

where EL_i is the invert elevation at the face of a culvert (EL_f) or at the throat of a culvert with a tapered inlet (EL_t).

3. Outlet Control. The outlet control calculations result in the headwater elevation required to convey the design discharge through the selected culvert in outlet control. The approach and downstream velocities may be included in the design process, if desired. The critical depth charts and outlet control nomographs of appendix D are used in the design process. For illustration, refer to the schematic critical depth chart and outlet control nomograph shown in figures III-19 and III-20, respectively.

a. Determine the tailwater depth above the outlet invert (TW) at the design flow rate. This is obtained from backwater or normal depth calculations, or from field observations.

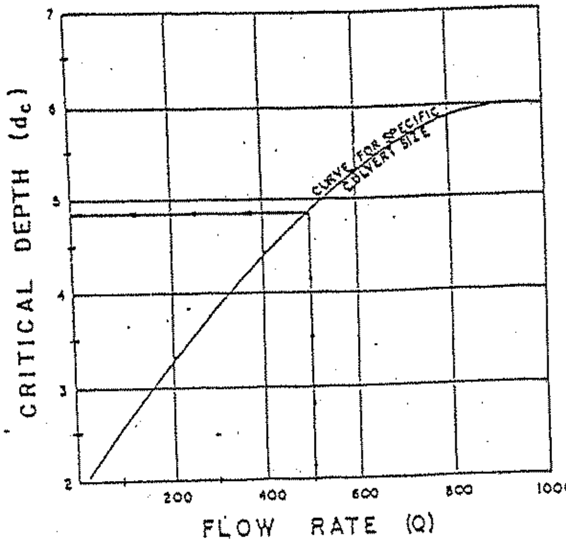


Figure III-19--Critical depth chart (schematic).

b. Enter the appropriate critical depth chart (figure III-19) with the flow rate and read the critical depth (d_c). d_c cannot exceed D!

(Note: The d_c curves are truncated for convenience when they converge. If an accurate d_c is required for $d_c > .9D$ consult the Handbook of Hydraulics or other hydraulic references. (24))

c. Calculate $(d_c + D)/2$

d. Determine the depth from the culvert outlet invert to the hydraulic grade line (h_o).

h_o = TW or $(d_c + D/2)$, whichever is larger.

e. From table 12, appendix D, obtain the appropriate entrance loss coefficient, k_e, for the culvert inlet configuration.

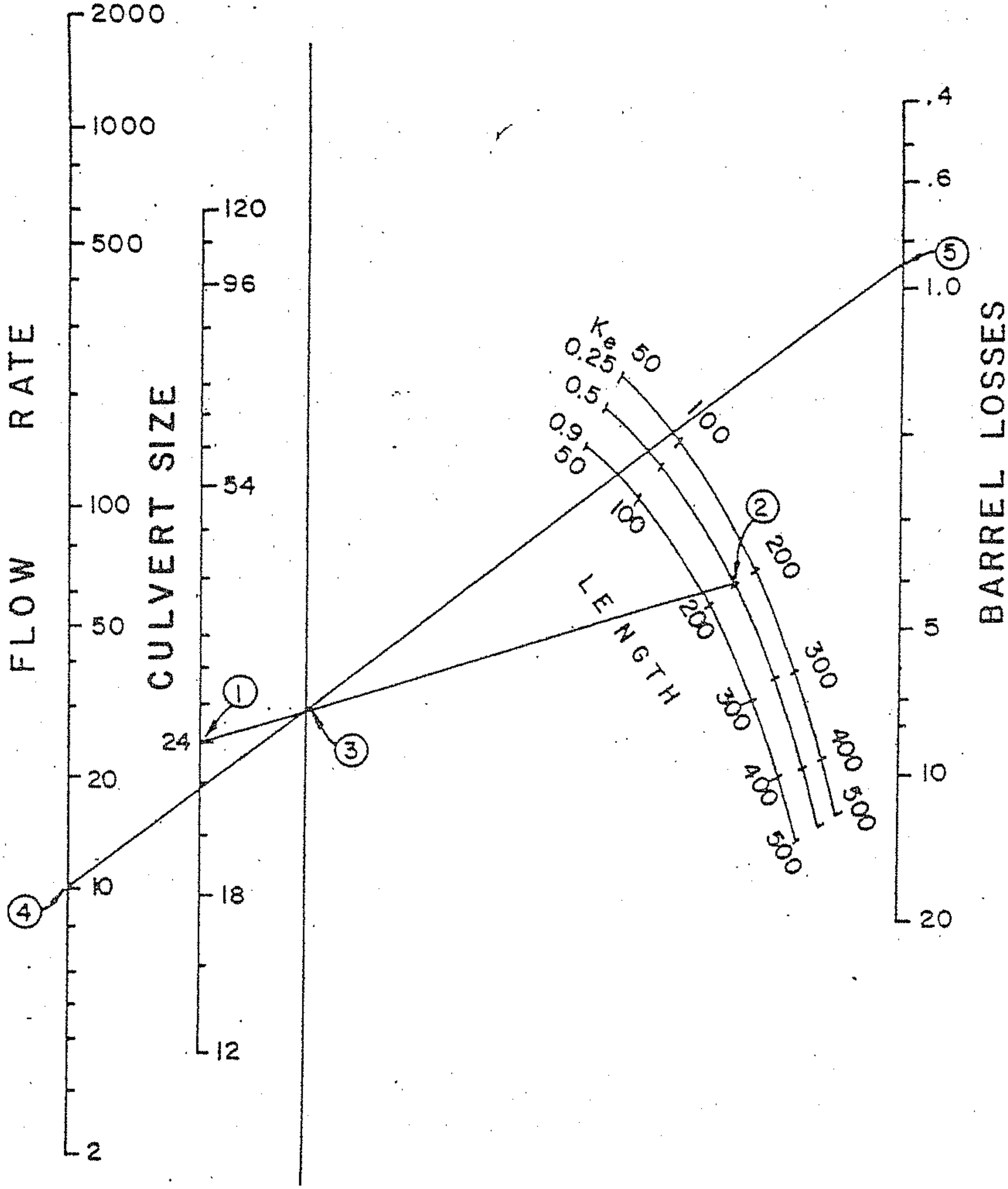


Figure III-20--Outlet control nomograph (schematic).

f. Determine the losses through the culvert barrel, H, using the outlet control nomograph (figure III-20) or equation (5) or (6) if outside the range of the nomograph.

1) If the Manning n value given in the outlet control nomograph is different than the Manning n for the culvert, adjust the culvert length using the formula:

$$L_1 = L \left(\frac{n_1}{n} \right)^2 \qquad (9)$$

L_1 is the adjusted culvert length, ft (m)
L is the actual culvert length, ft (m)
n_1 is the desired Manning n value
n is the Manning n value from the outlet control chart.

Then, use L_1 rather than the actual culvert length when using the outlet control nomograph.

2) Using a straightedge, connect the culvert size (point 1) with the culvert length on the appropriate k_e scale (point 2). This defines a point on the turning line (point 3).

3) Again using the straightedge, extend a line from the discharge (point 4) through the point on the turning line (point 3) to the Head Loss (H) scale. Read H. H is the energy loss through the culvert, including entrance, friction, and outlet losses.

Note: Careful alignment of the straightedge in necessary to obtain good results from the outlet control nomograph.

g. Calculate the required outlet control headwater elevation.

$$EL_{ho} = EL_o + H + h_o \qquad (10)$$

where EL_o is the invert elevation at the outlet. (If it is desired to include the approach and downstream velocities in the calculations, add the downstream velocity head and subtract the approach velocity head from the right side of equation (10). Also, use equation (4c) instead of equation (4d) to calculate the exit losses and equation (1) to calculate total losses.)

h. If the outlet control headwater elevation exceeds the design headwater elevation, a new culvert configuration must be selected and the process repeated. Generally, an enlarged barrel will be necessary since inlet improvements are of limited benefit in outlet control.

4. Evaluation of Results. Compare the headwater elevations calculated for inlet and outlet control. The higher of the two is designated the controlling headwater elevation. The culvert can be expected to operate with that higher headwater for at least part of the time.

The outlet velocity is calculated as follows:

a. If the controlling headwater is based on inlet control, determine the normal depth and velocity in the culvert barrel. The velocity at normal depth is assumed to be the outlet velocity.

b. If the controlling headwater is in outlet control, determine the area of flow at the outlet based on the barrel geometry and the following:

1) Critical depth if the tailwater is below critical depth.

2) The tailwater depth if the tailwater is between critical depth and the top of the barrel.

3) The height of the barrel if the tailwater is above the top of the barrel.

Repeat the design process until an acceptable culvert configuration is determined. Once the barrel is selected it must be fitted into the roadway cross section. The culvert barrel must have adequate cover, the length should be close to the approximate length, and the headwalls and wingwalls must be dimensioned.

If outlet control governs and the headwater depth (referenced to the inlet invert) is less than 1.2D, it is possible that the barrel flows partly full though its entire length. In this case, caution should be used in applying the approximate method of setting the downstream elevation based on the greater of tailwater or $(d_c + D)/2$. If an accurate headwater is necessary, backwater calculations should be used to check the result from the approximate method. If the headwater depth falls below 0.75D, the approximate method should not be used.

If the selected culvert will not fit the site, return to the culvert design process and select another culvert. If neither tapered inlets nor flow routing are to be applied, document the design. An acceptable design should always be accompanied by a performance curve which displays culvert behavior over a range of discharges. If tapered inlets are to be investigated, proceed to chapter IV. If storage routing will be utilized, proceed to chapter V.

Special culvert installations, such as culverts with safety grates, junctions, or bends are discussed in chapter VI. Unusual culvert configurations such as "broken-back" culverts, siphons, and low head installations are also discussed.

5. Example Problems. The following example problems illustrate the use of the design methods and charts for selected culvert configurations and hydraulic conditions. The problems cover the following situations:

Problem No. 1: Circular pipe culvert, standard 2-2/3 by 1/2 in (6.8 by 1.3 cm) CMP with beveled edge and reinforced concrete pipe with groove end. No FALL.

Problem No. 2: Reinforced cast-in-place concrete box culvert with square edges and with bevels. No FALL.

Problem No. 3: Elliptical pipe culvert with groove end and a FALL.

Problem No. 4: Analysis of an existing reinforced concrete box culvert with square edges.

Example Problem No. 1

A culvert at a new roadway crossing must be designed to pass the 25-year flood. Hydrologic analysis indicates a peak flow rate of 200 ft^3/s. Use the following site information:

Elevation at Culvert Face: 100 ft

Natural Stream Bed Slope: 1 percent = 0.01 ft/ft

Tailwater for 25-Year Flood: 3.5 ft

Approximate Culvert Length: 200 ft

Shoulder Elevation: 110 ft

Design a circular pipe culvert for this site. Consider the use of a corrugated metal pipe with standard 2-2/3 by 1/2 in corrugations and beveled edges and concrete pipe with a groove end. Base the design headwater on the shoulder elevation with a two ft freeboard (elevation 108.0 ft). Set the inlet invert at the natural streambed elevation (no FALL).

Note: Design charts used in this example are reproduced on the following pages.

CULVERT DESIGN FORM

PROJECT: EXAMPLE PROBLEM No. 1
CHAPTER III, HDS No. 5

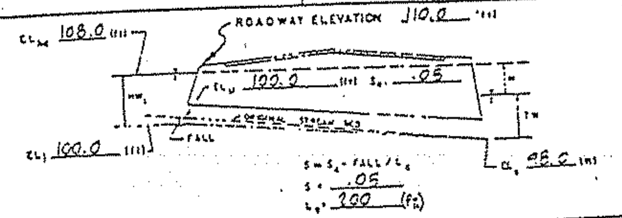
STATION: 1+00
SHEET 1 OF 1

DESIGNER/DATE: WJJ / 7/18
REVIEWER/DATE: JMN / 7/19

HYDROLOGICAL DATA
- METHOD: RATIONAL
- DRAINAGE AREA: 175 AC. STREAM SLOPE: 1.0%
- CHANNEL SHAPE: TRAPEZOIDAL
- ROUTING: N/A OTHER:

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
25	200	3.5



$S = S_o - FALL/L_a$
S = .05
L_a = 200 (ft)

HEADWATER CALCULATIONS

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CMP - CIRC. - 72 IN. - BEVEL 45° IN HEADWALL	200	200	.96	5.8	—	105.8	3.5	3.8	4.9	4.9	.002	2.6	105.5	105.8	8.0	TRY 60" CMP.
" " - 60 IN. - " 45°	|	|	1.43	7.15	—	107.2	|	4.1	4.6	4.6	|	6.3	108.9	108.9	12.0	TRY 60" CONC.
CONC. " - 60 IN. - GROOVE END	|	|	1.36	6.8	—	106.8	|	|	4.6	4.6	|	2.9	105.5	106.8	16.0	TRY 54" CONC.
" " - 54 IN. - "	↓	↓	1.77	7.97	—	108.0	↓	↓	4.3	4.3	↓	4.7	107.0	108.0	13.5	OK

TECHNICAL FOOTNOTES:

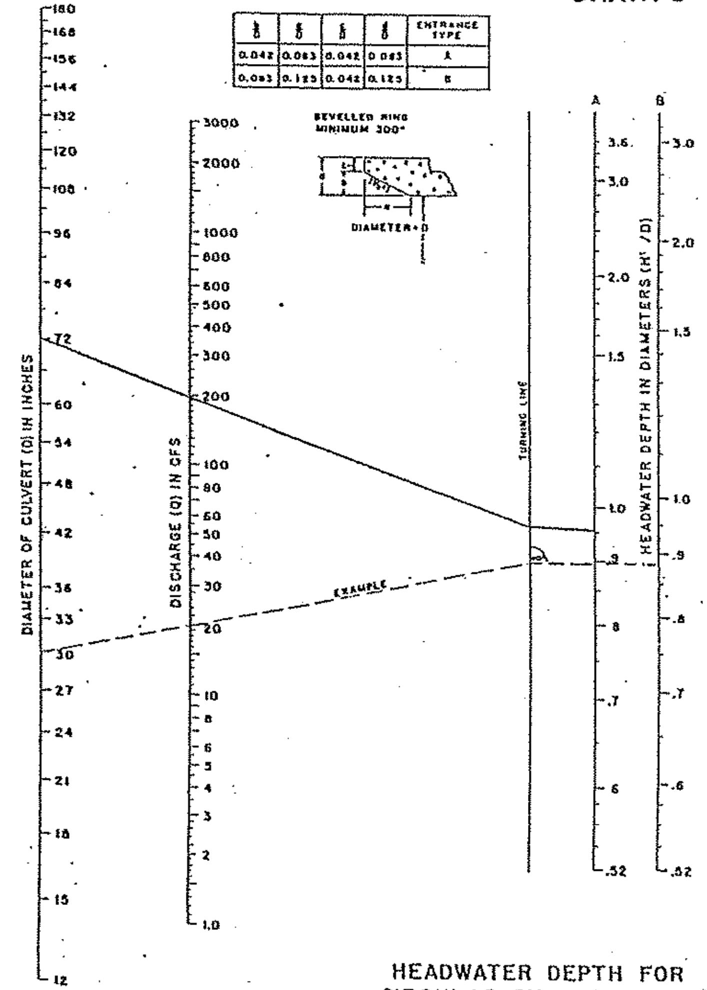
(1) USE Q/NB FOR BOX CULVERTS
(2) $HW_i/D = HW_i/D$ OR HW_i/D FROM DESIGN CHARTS
(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE
(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)
(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.
(6) $h_o = TW$ or $(d_c + D/2)$ (WHICHEVER IS GREATER)
(7) $H = [1 + k_e + (29 n^2 L)/R^{1.33}] V^2/2g$
(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:
a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:
HIGH OUTLET VELOCITY - OUTLET PROTECTION OR LARGER CONDUIT MAY BE NECESSARY

CULVERT BARREL SELECTED:
SIZE: 54 IN.
SHAPE: CIRCULAR
MATERIAL: CONC. n .012
ENTRANCE: GROOVE END

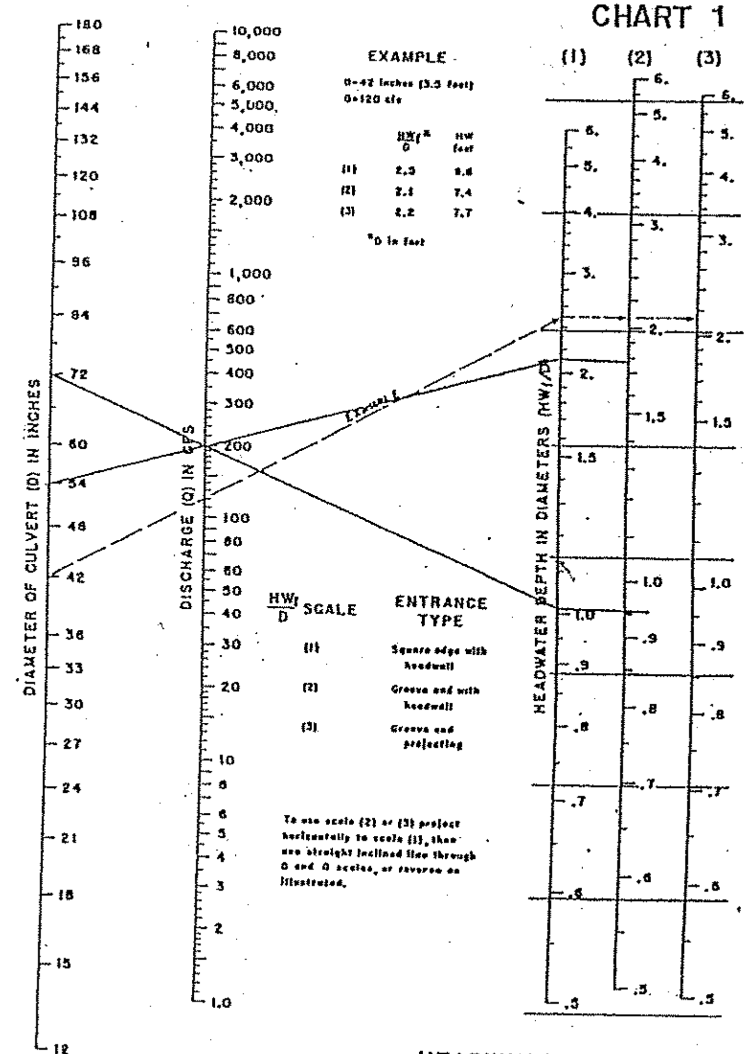
CHART 3



HEADWATER DEPTH FOR CIRCULAR PIPE CULVERTS WITH BEVELED RING INLET CONTROL

(F)ERAL HIGHWAY ADMINISTRATION
MAY 1973

CHART 1



HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

HEADWATER SCALES 2&3
REVISED MAY 1964

BUREAU OF PUBLIC ROADS JAN. 1963

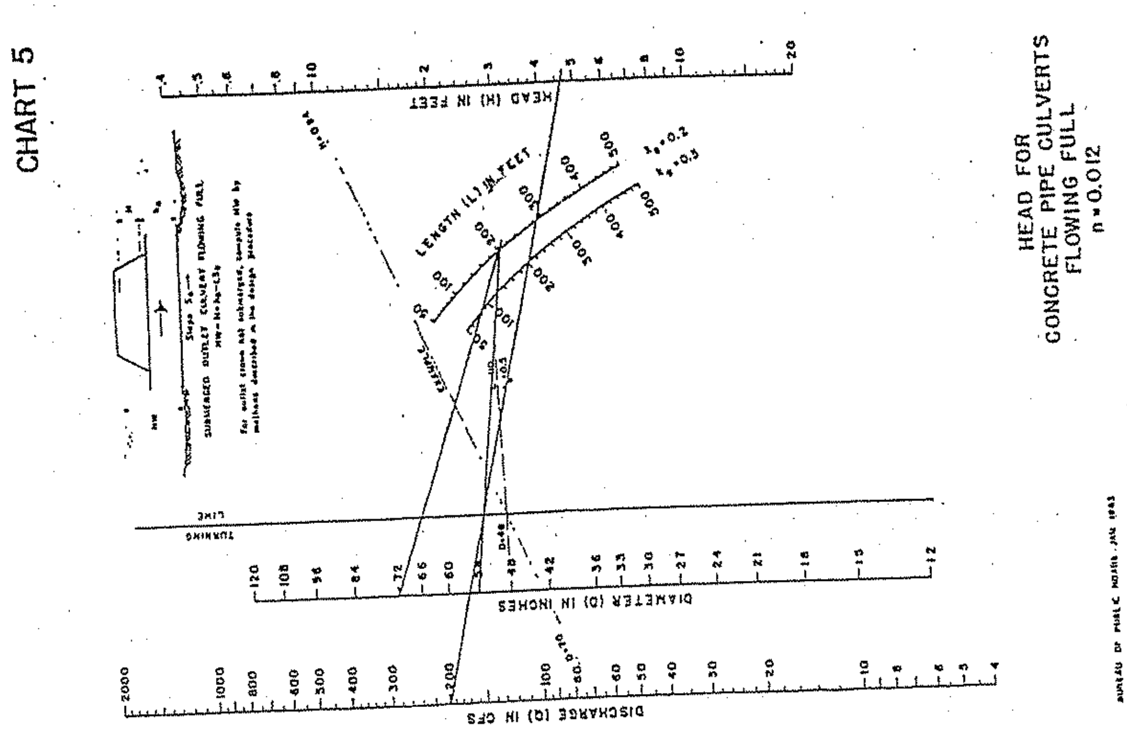


CHART 5
HEAD FOR
CONCRETE PIPE CULVERTS
FLOWING FULL
n = 0.012
HEAD (H) IN FEET
LENGTH (L) IN FEET
TURNING LINE
DIAMETER (D) IN INCHES
DISCHARGE (Q) IN CFS
SUBMERGED OUTLET CULVERT FLOWING FULL
BUREAU OF PUBLIC ROADS JAN. 1963

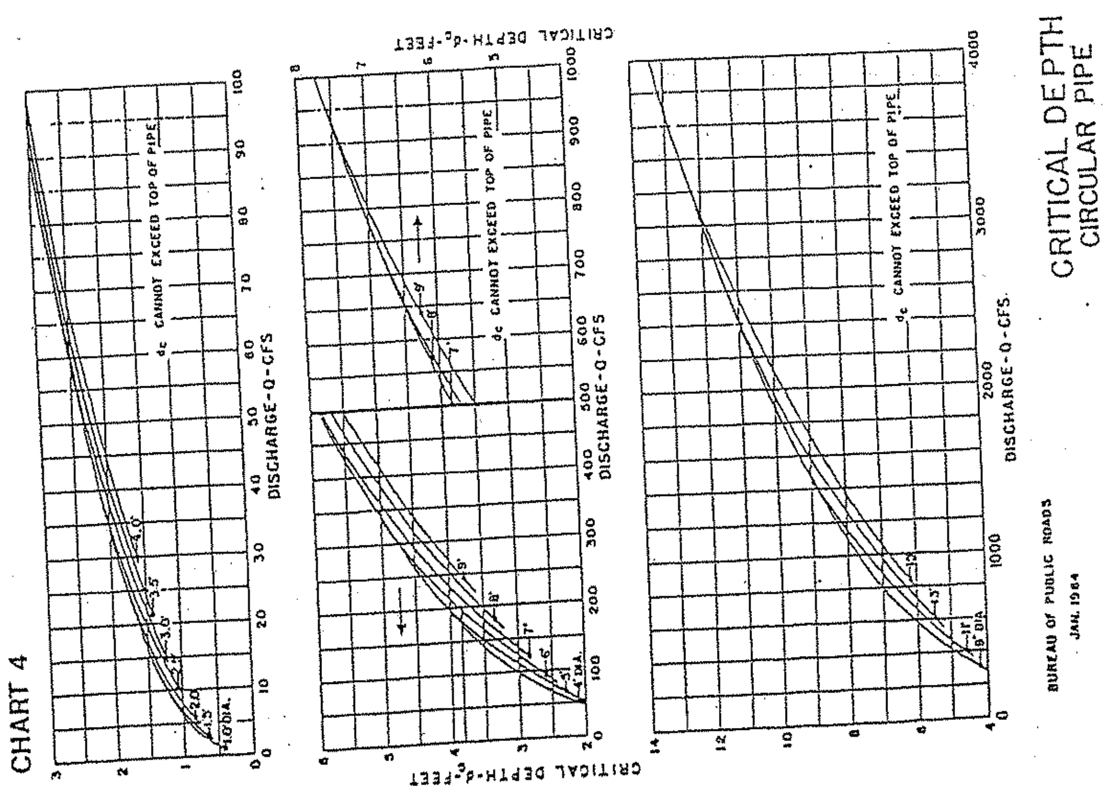
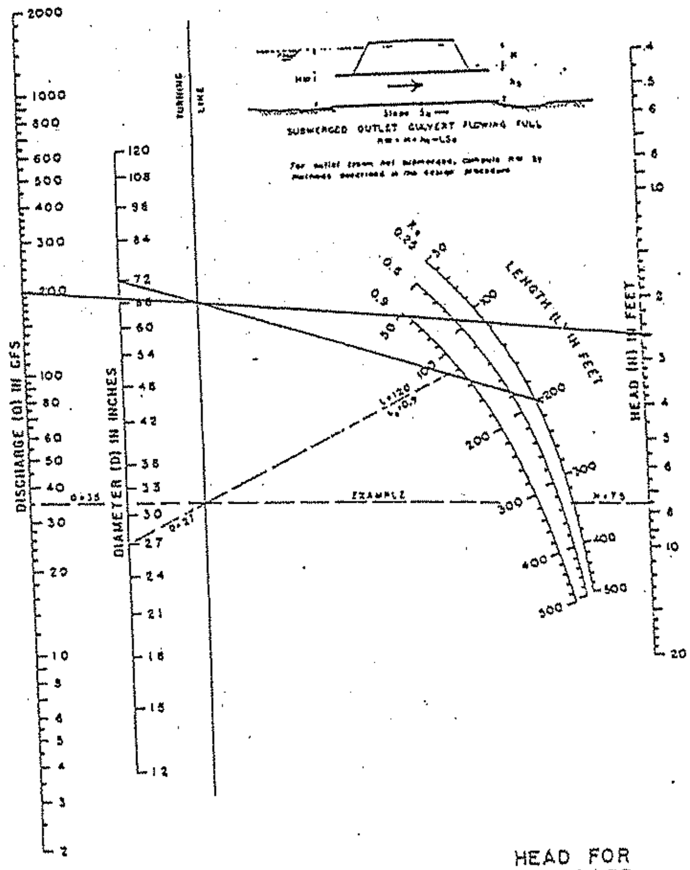


CHART 4
CRITICAL DEPTH
CIRCULAR PIPE
CRITICAL DEPTH-d_c-FEET
DISCHARGE-Q-CFS
d_c CANNOT EXCEED TOP OF PIPE
BUREAU OF PUBLIC ROADS
JAN. 1964

CHART 6



HEAD FOR
STANDARD
C. M. PIPE CULVERTS
FLOWING FULL
n = 0.024

BUREAU OF PUBLIC ROADS JAN 1963

Example Problem No. 2

A new culvert at a roadway crossing is required to pass a 50-year flow rate of 300 ft^3/s. Use the following site conditions:

EL_{hd} : 110 ft based on adjacent structures

Shoulder Elev: 113.5 ft

Elevation of Stream Bed at Culvert Face: 100.0 ft

Natural Stream Slope: 2 percent

Tailwater Depth: 4.0 ft

Approximate Culvert Length: 250 ft

Design a reinforced concrete box culvert for this installation. Try both square edges and 45-degree beveled edges in a headwall. Do not depress the inlet (no FALL).

Note: Design charts 8, 10, 14, and 15 are used in this solution.

CULVERT DESIGN FORM

PROJECT: EXAMPLE PROBLEM No. 2, CHAPTER III, HDS No. 5

STATION: 1+00

SHEET 1 OF 1

DESIGNER/DATE: WJJ / 7/18

REVIEWER/DATE: JNN / 7/19

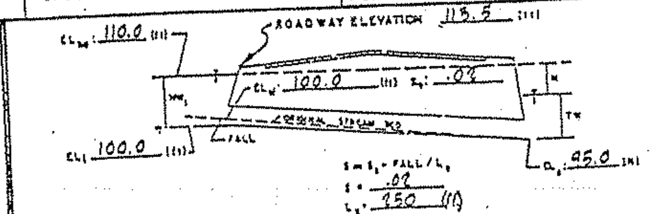
HYDROLOGICAL DATA

- ☐ METHOD: SCS
- ☐ DRAINAGE AREA: 200 AC ☐ STREAM SLOPE: 2.0 %
- ☐ CHANNEL SHAPE: TRAPEZOIDAL
- ☐ ROUTING: N/A ☐ OTHER

SEE ADD. SHTS.

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
50	300	4.0



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONCRETE - BOX - 6'x5' - SQ EDGE	300	50	1.57	7.9	–	107.9	4.0	4.2	4.6	4.6	0.5	3.55	103.2	107.9	21.7	OK TRY SM. BOX
" " - 5'x5' - "	300	60	1.91	9.0	–	109.6	4.0	4.8	4.9	4.9	0.5	5.2	105.1	109.6	20.8	CHECK BEVELS
" " - 5'x5' - 45° BEVEL	300	60	1.71	8.55	–	108.6	4.0	4.8	4.9	4.9	0.2	4.6	104.5	108.6	20.8	OK

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS.

(2) $HW_i/D = HW_i/D$ OR HW_i/D FROM DESIGN CHARTS

(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE.

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) h_o = TW or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L) / R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:

5' x 5' BOX WILL WORK WITH OR WITHOUT BEVELS. BEVELS PROVIDE ADDITIONAL FLOW CAPACITY

CULVERT BARREL SELECTED:

SIZE: 5 FT. x 5 FT.

SHAPE: RECTANGULAR

MATERIAL: CONC. n: .012

ENTRANCE: 90 EDGE - 90° HEADWALL

Example Problem No. 3

Design a culvert to pass a 25-year flow of 220 ft³/s. Minimum depth of cover for this culvert is 2 ft.

EL_{hd}: 105 ft based on adjacent structures

Shoulder Elev.: 105.5 ft

Elevation of Stream Bed
at Culvert Face (EL_{sf}): 100 ft

Original Stream Slope: 5 percent

Tailwater Depth: 4 ft

Approximate Culvert Length: 150 ft

Due to the low available cover the conduit, use an elliptical co pipe. Use of a small depression (F of about 1 ft at the inlet is a able.

NOTE: Charts 29, 31, and 33 are u this solution.

PROJECT: EXAMPLE PROBLEM No. 3
CHAPTER III, HDS No. 5

STATION: 2+00
SHEET 1 OF 1

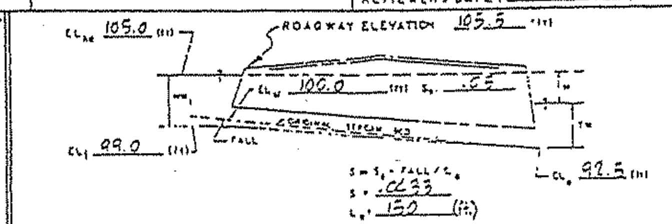
CULVERT DESIGN FORM
DESIGNER/DATE: WJJ / 7/18
REVIEWER/DATE: JMN / 7/19

HYDROLOGICAL DATA
- ☐ METHOD: RATIONAL
- ☐ DRAINAGE AREA: 110 AC. ☐ STREAM SLOPE: 5.0%
- ☐ CHANNEL SHAPE: SEMI-CIRCULAR
- ☑ ROUTING: 60CFS RED. FROM PEAK ☐ OTHER: DEPTH OF COVER 2' MIN

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
25	160*	4.0

* APPROX. ROUTED FLOW RATE



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONC. - HORIZ. ELLIPSE - 68"x43" - SQ. EDGE	180	–	1.98	7.1	–	107.1	4.0	3.2	3.4	4.0	0.5	3.7	100.2	107.1	–	TRY GROOVE END W/HEADWALL
" - " - " x " - GROOVE END	180	–	1.63	5.8	–	105.8	4.0	3.2	3.4	4.0	0.2	3.2	99.7	105.8	–	EL_{hi} TOO HIGH USE FALL
" - " - " x " - "	180	–	1.63	5.8	1.0	104.8	4.0	3.2	3.4	4.0	0.2	3.2	99.7	104.8	14.9	OK - DEPTH OF COVER OK ALSO

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW_i/D$ OR HW_i/D FROM DESIGN CHARTS

(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) $h_o = TW$ or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L)/R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:
- a. APPROXIMATE
- f. CULVERT FACE
- hd. DESIGN HEADWATER
- hi. HEADWATER IN INLET CONTROL
- ho. HEADWATER IN OUTLET CONTROL
- i. INLET CONTROL SECTION
- o. OUTLET
- sf. STREAMBED AT CULVERT FACE
- tw. TAILWATER

COMMENTS / DISCUSSION:
HIGH OUTLET VELOCITY - CHECK STREAM BED STABILITY

CULVERT BARREL SELECTED:
- SIZE: 68"x 43"
- SHAPE: HORIZONTAL ELLIPSE
- MATERIAL: CONC. n .012
- ENTRANCE: GROOVE END

Example Problem No. 4

An existing 7 ft by 7 ft concrete box culvert was designed for a 50-year flood of 600 ft^3/s and a design headwater elevation of 114 ft. Upstream development has increased the 50-year runoff to 1,000 ft^3/s. The roadway is gravel with a width of 40 ft. The roadway profile may be approximated as a broad crested weir 200 ft long. Use figure III-11 to calculate overtopping flows, and the following site data:

Inlet Invert Elevation: 100 ft

Entrance Condition: Square Edges

Slope: 5 percent

Roadway Centerline Elevation: 116 ft

Culvert Length: 200 ft

Tailwater Information

Flow, ft^3/s	TW, ft
400	2.6
600	3.1
800	3.8
1000	4.1

Prepare a performance curve for this installation, including any roadway overtopping, up to a flow rate of 1,200 ft^3/s.

NOTE: Charts 8, 14, and 15, and figure III-11 are used in this solution.

PROJECT: EXAMPLE PROBLEM No. 4
CHAPTER III, HDS No. 5

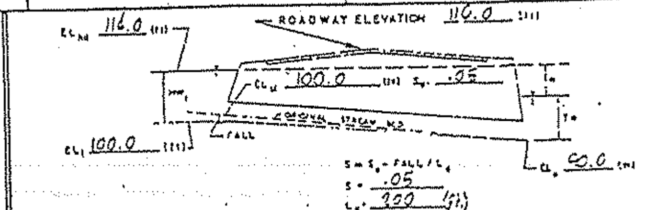
STATION: 4+50
SHEET 1 OF 3

CULVERT DESIGN FORM
DESIGNER/DATE: WJJ / 7/15
REVIEWER/DATE: JNN / 7/10

HYDROLOGICAL DATA
- METHOD: SCS
- DRAINAGE AREA: 400 Ac.   STREAM SLOPE: 5.0%
- CHANNEL SHAPE: TRAPEZOIDAL
- ROUTING: N/A   OTHER:

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
50 (OLD)	600	3.1
50 (NEW)	1000	4.1



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/B (1)	INLET CONTROL HWi/D (2)	HWi	FALL (3)	ELhi (4)	OUTLET CONTROL TW (5)	dc	(dc+D)/2	ho (6)	ke	H (7)	ELho (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONC. - BOX - 7'x 7' - SQ. EDGE	400	57.1	1.15	8.1	—	108.1	2.0	4.6	5.8	5.8	0.5	1.95	97.8	108.1	—	—
	600	85.7	1.65	11.6	—	111.6	3.1	6.1	6.6	6.6		4.4	101.0	111.6	—	—
	700	100.0	1.95	13.7	—	113.7	3.5	6.8	6.9	6.9		6.0	102.9	113.7	—	—
	800	116.3	2.35	16.5	—	116.5	3.8	7	7.0	7.0		7.9	104.9	116.5	—	—
	850	121.9	2.55	17.9	—	117.9	3.9		"	"		9.0	106.0	117.5	—	—

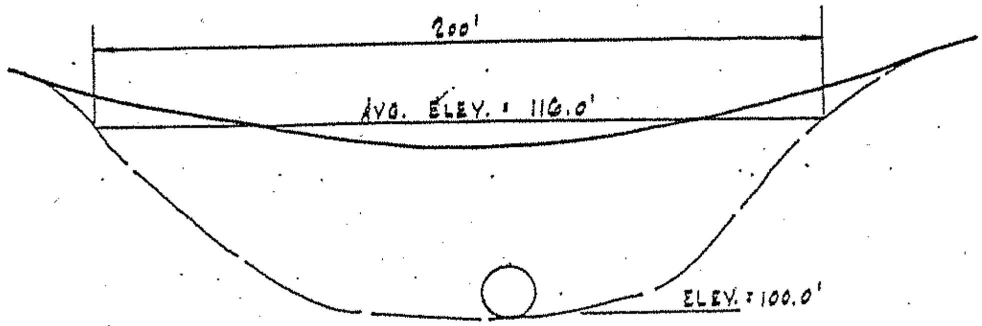
TECHNICAL FOOTNOTES:
(1) USE Q/NB FOR BOX CULVERTS
(2) $HW_i/D = HW_i/D$ OR HW_f/D FROM DESIGN CHARTS
(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE
(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)
(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.
(6) h_o = TW or $(d_c + D/2)$ (WHICHEVER IS GREATER)
(7) $H = [1 + k_e + (29 n^2 L)/R^{1.33}] v^2/2g$
(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:
a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:
NEW Q_{50} RESULTS IN ROADWAY OVERTOPPING: 2.5' ABOVE EL_{hd}

CULVERT BARREL SELECTED:
SIZE: 7' x 7'
SHAPE: RECTANGULAR
MATERIAL: CONC. n .012
ENTRANCE: SQ. EDGE W/HEADWALL

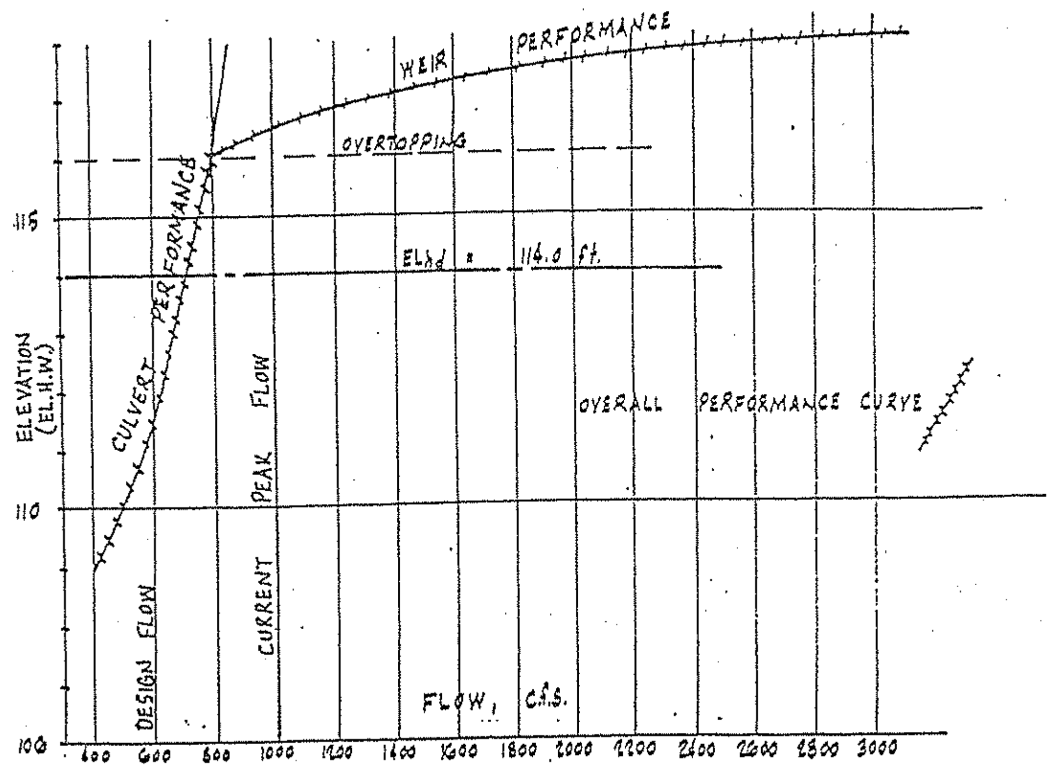
CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/B (1)	INLET CONTROL HWi/D (2)	HWi	FALL (3)	ELhi (4)	OUTLET CONTROL TW (5)	dc	(dc+D)/2	ho (6)	ke	H (7)	ELho (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
															—	—
CONC. - BOX - 7'x 7' - SQ. EDGE	1000	142.9	3.21	22.5	—	122.5	4.1	7	7.0	7.0	0.5	1.20	109.6	122.5		



Q_c CULVERT FLOW	EL_h	H_o	Q_o OVERTOPPING FLOW	Q TOTAL FLOW
400	108.1	–	–	400
600	111.6	–	–	600
700	113.7	–	–	700
800	116.5	0.5	191	991
850	117.5	1.5	1073	1923
1000	122.5	6.0	–	–

FROM FIGURE III-11-B: $C_d = 2.70$ @ $HW_r = .5$; $C_d = 2.92$ @ $HW_r = 1.5$ } $K_t = 1$

$Q = C_d L HW_r^{1.5}$



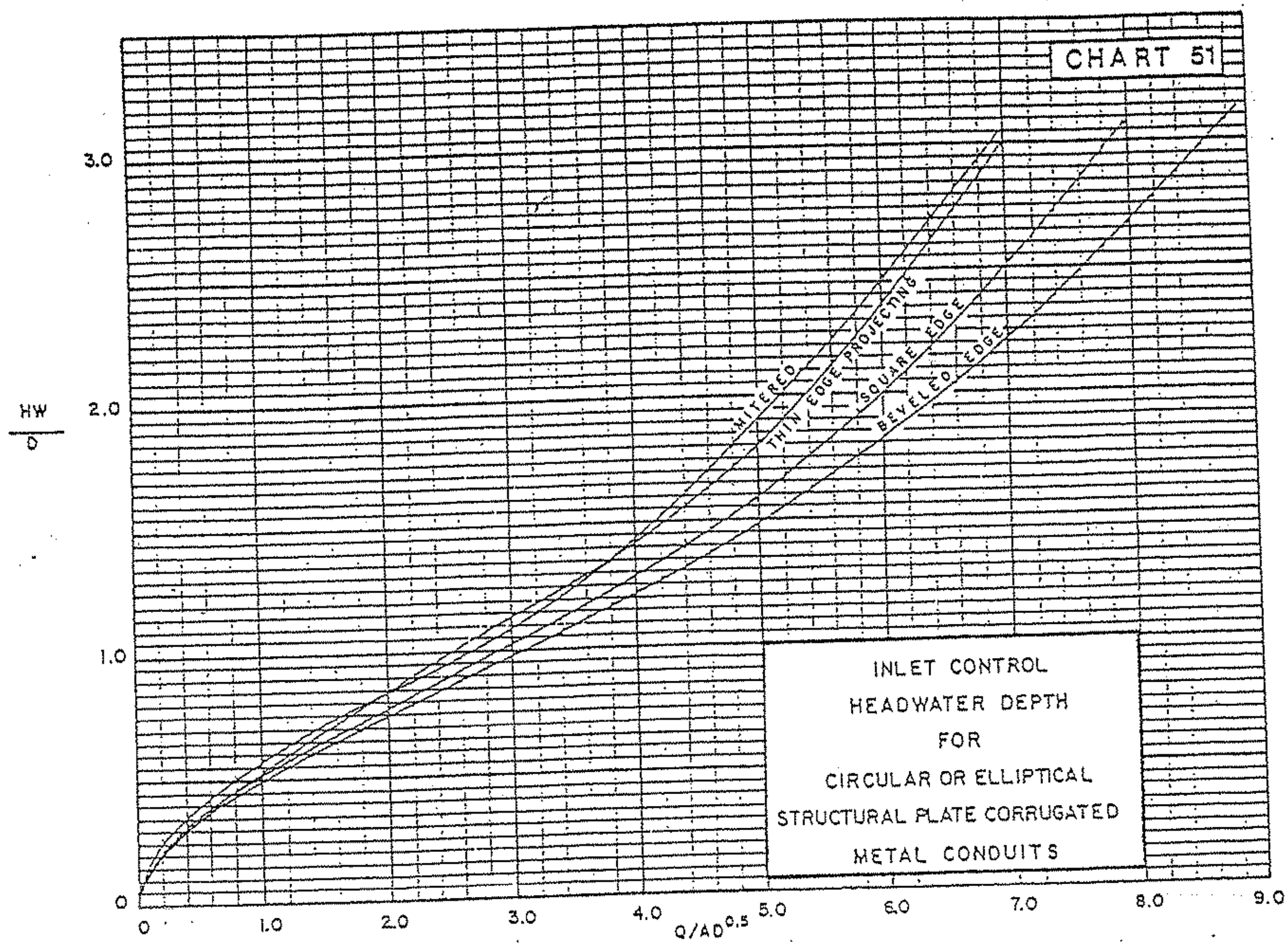


Figure III-21--Inlet control curves - circular or elliptical structural plate corrugated metal conduits.

D. Design Methods for Culverts Without Standard Design Charts.

Some culvert sizes, shapes, and materials do not have design nomographs and critical depth charts. For example, long span, structural plate, corrugated metal conduits do not have standard design charts. Developing design charts for all possible conduit shapes and sizes is not practical because they are so numerous and new shapes are constantly being produced. Also, the large size conduits tend to fall outside the nomograph scales. With some modification, usual culvert hydraulic techniques can be used to analyze these culverts.

For outlet control, the analysis includes pressure flow and backwater calculations to determine the headwater. Since the inlet has not been modeled, the inlet control equations are necessarily based on hydraulic test results from similar tested conduit shapes. Appendix A contains approximate inlet control equations for nonrectangular conduits with a variety of edge conditions.

1. Inlet Control. In order to facilitate the design process, the appropriate inlet control equations of appendix A have been used to develop dimensionless inlet control design curves for selected conduit shapes and edge configurations. The curves of figures III-21 and III-22 are for nonrectangular, structural plate corrugated metal conduits of two basic shapes and four inlet edge conditions. Figure III-21 is for circular or ellipti-

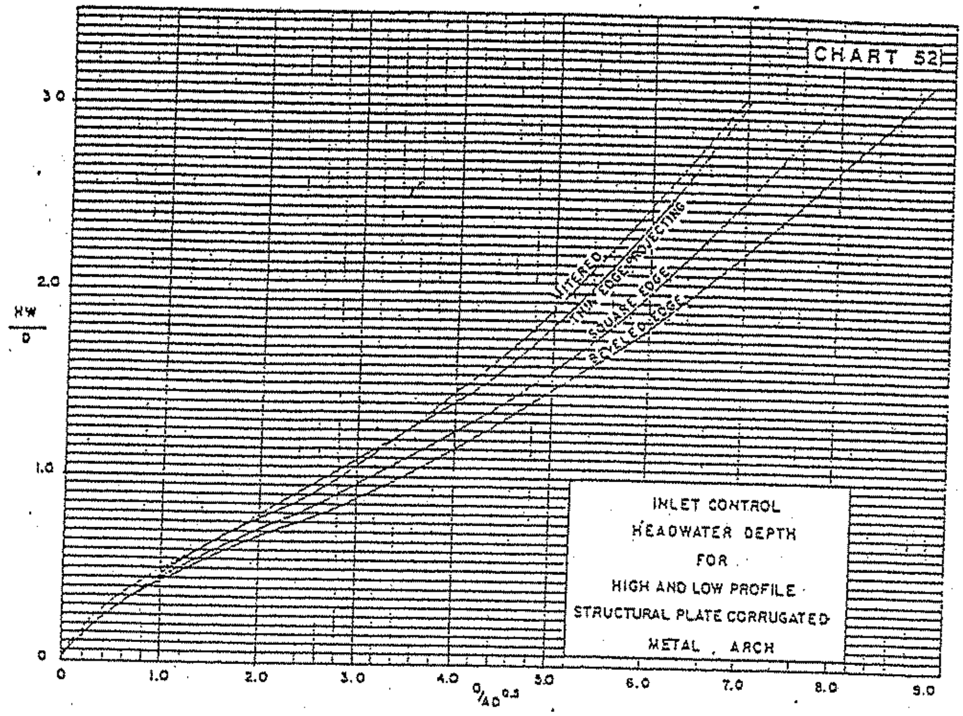


Figure III-22--Inlet control curves - high and low profile structural plate arches.

cal conduits with the long horizontal axis at the mid-point of the barrel. Figure III-22 is used for high and low profile structural plate arches.

The curves in these figures are for four different inlet edge conditions: thin edge projecting, mitered, square-edge, and 45-degree bevels. The horizontal axis of the chart is flow rate divided by the area times the square root of barrel height ($Q/AD^{0.5}$) and the vertical axis is headwater depth divided by barrel height (HW/D). Figure III-21 will provide adequate results for any conduit with curved surfaces, including pipe-arches and underpasses. Figure III-22 is used for conduits similar to arches with flat bottoms.

To use the figures, perform the following steps:

a. From manufacturers' information, select a barrel size, shape and inlet edge configuration. Obtain the area, A, and the interior height, D, for the selected barrel.

b. Calculate $AD^{0.5}$.

c. Divide the design flow rate, Q, by $AD^{0.5}$.

d. Enter the appropriate design chart with $Q/AD^{0.5}$, and for the selected edge condition, read HW/D.

e. Multiply HW/D by D to obtain the face control headwater, HW.

f. If it is desired to take credit for the approach velocity (V_u) in the calculations, deduct the approach velocity head ($V_u^2/2g$) from HW to obtain the face control headwater, HW_f. If V_u is neglected, set HW_f equal to HW.

g. If the inlet control headwater is higher than the design headwater, or if the conduit is oversized, select another conduit size and/or inlet edge condition and return to step a.

2. Outlet Control.

a. Partly Full Flow. Large conduits, such as long span culverts, usually flow partly full throughout their lengths. In addition, the invert of the culvert is often unlined. In these situations it is advisable to perform backwater calculations to determine the headwater elevation.

The backwater calculations begin at the tailwater level or at critical depth at the culvert exit, whichever is higher. Hydraulic resistance values for the backwater calculations are contained in Hydraulic Flow Resistance Factors for Corrugated Metal Conduit. (25) Data from that reference are included in appendix B. Selected resistance values for natural channels are found in table 11 of appendix D. Note that when the perimeter of the conduit is constructed of two or more materials, a composite resistance value should be used. Methods of calculating composite resistance values are discussed in appendix B.

b. Full Flow. If the conduit flows full or nearly full throughout its length, equation (7) may be used to calculate the outlet control headwater depth.

$$HW_o = TW + H_L \quad (7)$$

H is the total loss through the culvert barrel which is calculated using equation (1) or equation (5). TW is either the tailwater depth or $(d_c + D)/2$, whichever is larger. Values of critical depth for most conduits are provided in the manufacturers' information. In equation (5), the hydraulic radius and velocity are full flow values. The Manning n value is a composite value when more than one material is used in the perimeter of the conduit.

3. Discussion of Results.

The inlet control headwater obtained from figure III-21 or figure III-22 includes the approach velocity head. Therefore, credit may be taken for the approach velocity head in determining the required headwater pool depth.

In outlet control, the same limitations on use of the approximate backwater method apply as for culverts with design charts. That is, if the headwater (referenced to the inlet invert) falls between 1.2D and 0.75D, use the results with caution. For large, expensive installations, check the results using backwater calculations. If the headwater falls below 0.75D do not use the approximate method. Perform backwater calculations as illustrated in the following example problem.

4. Example Problem.

Problem No. 5: Design of a long span structural plate corrugated metal elliptical culvert.

Use a long span culvert to pass the 25-year flood of 5,500 ft^3/s under a high roadway fill. The design flow should be below the crown of the conduit at the inlet, but the check flow (100-year flow) of 7,500 ft^3/s may exceed the crown by not more than 5 feet. Use the following site conditions:

EL_{hd}: 240 ft

Elevation of Stream Bed at Culvert Face (EL_{sf}): 220 ft

Shoulder Elevation: 260 ft

Stream Slope (S_o): 1.0 percent

Approximate Culvert Length: 200 ft

Tailwater Depth: 16 ft for Q = 550 ft^3/s, 19 ft for Q = 7500 ft^3/s

Design an elliptical structural plate corrugated metal conduit for this site. Use a headwall to provide a square edge condition. Corrugations are 6-in by 2-in.

Try a 30 foot (span) by a 20 foot (rise) elliptical structural plate conduit for this site. From manufacturer's information, $A = 487.5\ ft^2$ and $D = 20$ ft. Neglect the approach velocity.

INLET CONTROL:

$AD^{0.5} = (487.5)(20)^{0.5} = 2{,}180$

$Q/AD^{0.5} = 2.52$

Based on chart 51, HW/D = 0.90, therefore:

$HW = HW_f = (0.90)(20) = 18$ ft
$EL_{hi} = 220 + 18 = 238.0$ ft

For the check flow:

$Q/AD^{0.5} = 3.44$

Based on figure III-21, HW/D = 1.13, therefore:

$HW = HW_f = (1.13)(20) = 22.6$ ft
$EL_{hi} = 220 + 22.6 = 242.6$ ft

OUTLET CONTROL:

Backwater calculations will be necessary to check Outlet Control.

Backwater Calculations

From hydraulic tables for elliptical conduits (60):

for $Q = 5{,}500\ ft^3/s$, $d_c = 12.4$ ft
for $Q = 7{,}500\ ft^3/s$, $d_c = 14.6$ ft

Since $TW > d_c$, start backwater calculations at TW depth.

Determine normal depths (d_n) using hydraulic tables.

for $Q = 5{,}500\ ft^3/s$, $n = 0.034$;
$d_n = 13.1$ ft

for $Q = 7{,}500\ ft^3/s$, $n = 0.034$;
$d_n = 16.7$ ft

since $d_n > d_c$, flow is subcritical

since $TW > d_n$, water surface has an M-1 profile

Plot Area and Hydraulic Radius vs. depth from data obtained from tables.

d/D	d	A/BD	A	R/D	R
0.65	13.0	0.5537	332.2	0.3642	7.28
0.70	14.0	0.6013	360.8	0.3781	7.56
0.75	15.0	0.6472	388.3	0.3886	7.77
0.80	16.0	0.6908	414.5	0.3950	7.90
0.85	17.0	0.7313	438.8	0.3959	7.92
0.90	18.0	0.7671	460.3	0.3870	7.74
0.95	19.0	0.7953	477.2	0.3649	7.30
1.00	20.0	0.8108	486.5	0.3060	6.12

Complete Water Surface Computations (see attached calculation sheet, p 64).

$HW = \text{specific head } (H) + k_e (V^2/2g)$

Neglecting approach velocity head :

for $Q = 5{,}500\ ft^3/s$:
$HW = 18.004 + (0.5)(3.208)$
$= 19.6$ ft
$EL_{ho} = 220 + 19.6 = 239.6$ ft

for $Q = 7{,}500\ ft^3/s$:
$HW_f = 22.627 + (0.5)(3.89)$
$= 24.6$ ft
$EL_{ho} = 220 + 24.6 = 244.6$ ft

SUMMARY:

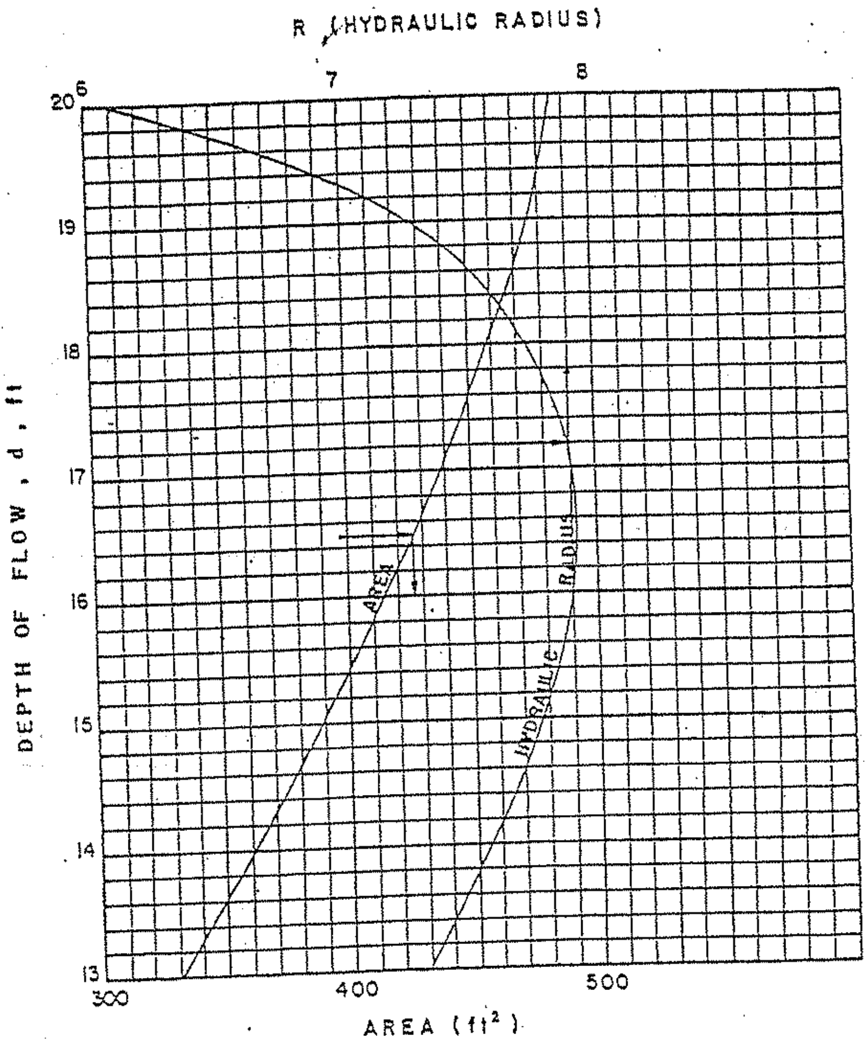
DESIGN Q:

EL_{hd}	EL_{hi}	EL_{ho}
240.0	238.0	239.6

CHECK Q:

EL_{ha}	EL_{hi}	EL_{ho}
245.0	242.6	244.6

This culvert design meets the requirements stated in the problem.



R (HYDRAULIC RADIUS)
6
7
8
20
19
18
17
16
15
14
13
DEPTH OF FLOW, d, ft
AREA
HYDRAULIC RADIUS
300
400
500
AREA (ft²)

WATER SURFACE PROFILE COMPUTATIONS

Identification: *Example Problem No. 5, HDS No. 5* By: *JMN* Date: *3/14*

Channel Shape: *Elliptical C.M.P., B = 30 ft, D = 20 ft, d_n = 13.1 ft, TW = 16 ft, S_o = 0.01*
M_1 Profile, Barrel Length = 20 ft, Start at TW = 16 ft

Manning n = *0.034*
Q = *5500 c.f.s.*

d	A	R	V = Q/A	$V^2/2g$	H = d + $V^2/2g$	ΔH (1)	$R^{2/3}$	$AR^{2/3}$	(2) $S_f = (K_n/AR^{2/3})^2$	$\bar{S}_f = (S_{f1}+S_{f2})/2$	$S_o-\bar{S}_f$	(3) $\Delta L = \frac{\Delta H}{S_o-\bar{S}_f}$	L = ΣΔL
16	414.5	7.90	13.27	2.73	18.734		3.969	1445.3	0.00582				0.0
15.5	401.6	7.85	13.70	2.91	18.412	0.322	3.953	1587.35	.00620	0.00601	0.00399	80.7	80.7
15.0	388.3	7.77	14.16	3.115	18.115	0.297	3.926	1524.33	.00678	.00648	.00352	84.4	165.1
14.8	382.9	7.34	14.36	3.308	18.004	0.111	3.779	1447.12	.00752	.00714	.00286	38.8	203.9
													OK

(1) SUBTRACT SECOND H FROM FIRST H VALUE
(2) $K_n = \frac{Qn}{1.49} = \frac{(5500)(.034)}{1.49} = 125.50$
(3) IF ΔL IS +, PROFILE IS PROGRESSING UPSTREAM.
−ΔL DENOTES DOWNSTREAM PROGRESSION.

WATER SURFACE PROFILE COMPUTATIONS

Identification: *Example Problem No. 5, HDS No. 5* By: *WJJ* Date: *3/14*

Channel Shape: *Elliptical CMP, B = 30 ft, D = 20 ft, d_n = 16.7 ft, TW = 19.0 ft, S_o = 0.01*
M_1 Profile, Barrel Length = 200 ft, Start at TW = 19.0 ft

Manning n = *0.034*
Q = *7500 ft³/s*

d	A	R	V = Q/A	$V^2/2g$	H = d + $V^2/2g$	ΔH (1)	$R^{2/3}$	$AR^{2/3}$	(2) $S_f = (K_n/AR^{2/3})^2$	$\bar{S}_f = (S_{f1}+S_{f2})/2$	$S_o-\bar{S}_f$	(3) $\Delta L = \frac{\Delta H}{S_o-\bar{S}_f}$	L = ΣΔL
19.0	477.30	7.30	15.72	3.836	22.835		3.765	1796.6	0.00907				0.0
18.8	474.34	7.108	15.81	3.833	22.684	0.151	3.803	1803.4	.00901	0.00904	0.00096	157.6	157.6
18.7	472.65	7.457	15.88	3.9098	22.610	.074	3.820	1805.3	.00899	.00900	.00100	74.1	Too Much 231.7
18.75	473.80	7.440	15.83	3.8911	22.627	.057	3.814	1806.9	.00897	.00899	.00101	56.46	214.1
													OK

(1) SUBTRACT SECOND H FROM FIRST H VALUE
(2) $K_n = \frac{Qn}{1.49} = \frac{(7500)(0.034)}{1.49} = 171.14$
(3) IF ΔL IS +, PROFILE IS PROGRESSING UPSTREAM.
−ΔL DENOTES DOWNSTREAM PROGRESSION.

A. Introduction.

A tapered inlet is a flared culvert inlet with an enlarged face section and a hydraulically efficient throat section. A tapered inlet may have a depression, or FALL, incorporated into the inlet structure or located upstream of the inlet. The depression is used to exert more head on the throat section for a given headwater elevation. Therefore, tapered inlets improve culvert performance by providing a more efficient control section (the throat). Tapered inlets with FALLs also improve performance by increasing the head on the throat.

Inlet edge configuration is one of the prime factors influencing the performance of a culvert operating in inlet control. Inlet edges can cause a severe contraction of the flow, as in the case of a thin edge projecting inlet. In a flow contraction, the effective cross-sectional area of the barrel may be reduced to about one half of the actual available barrel area. As the inlet edge configuration is improved, the flow contraction is reduced, thus improving the performance of the culvert. As an example, inlet edge improvement can be achieved by the installation of a concrete headwall with a square edged entrance on a thin edge projecting inlet. Additional performance increases are possible by the installation of beveled edges or by retaining the groove end on a concrete pipe culvert.

In outlet control, the inlet edge configuration is just one of many factors affecting culvert performance. Improved edge conditions reduce the inlet loss coefficient, k_e, which is multiplied by the velocity head to determine the energy losses at the culvert inlet as shown in equation (4a).

Values of k_e vary from 0.9 for thin edge projecting entrances to 0.2 for beveled edges or groove ends. Still lower k_e values can be obtained by using specially designed inlets with rounded edges. Unfortunately, the construction difficulties for these inlets often outweigh the hydraulic benefits.

The entrance of any culvert operating in inlet control can be depressed to obtain better performance, regardless of the inlet configuration. However, edge conditions are normally improved first and then an inlet depression is applied. The purpose is to provide more head on the inlet control section for a given headwater elevation. This design technique utilizes part of the available elevation head to force the flow into the culvert entrance. Otherwise, the head is expended in accelerating the flow down the steep culvert barrel, possibly causing erosion at the downstream end of the culvert.

Tapered inlets improve culvert performance primarily by reducing the contraction at the inlet control section which is located at the throat. Secondarily, some tapered inlet configurations also depress the inlet control section below the stream bed. The hydraulic performance of tapered inlets is better than the performance of beveled edges for culverts operating in inlet control. In outlet control the performance of tapered inlets is effectively the same as for inlets with beveled edges. An entrance loss coefficient (k_e) of 0.2 is used for both tapered inlets and beveled edges. Tapered inlets are not recommended for use on culverts flowing in outlet control because the simple beveled edge is of equal benefit.

Design criteria and methods have been developed for two basic tapered inlet designs: the side-tapered inlet and the slope-tapered inlet. Tapered inlet design charts are available for rectangular box culverts and circular pipe culverts. The same principles apply to other culvert barrel shapes, but no design charts are presently available for other shapes. The side-tapered inlet can be installed with or without a depression upstream of the face. There are two configurations of the slope-tapered inlet, one with a vertical face and one with its face mitered to the fill slope.

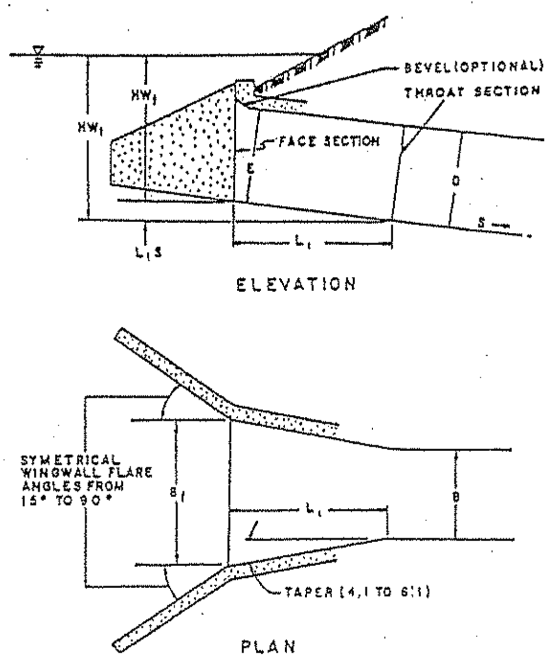


Figure IV-1--Side-tapered inlet.

The inlet configurations presented in this manual are based on research conducted at the National Bureau of Standards (NBS) under the sponsorship of the Bureau of Public Roads. (7, 9, 10) Many improved inlet configurations were tested; however, only those determined to best satisfy the criteria of hydraulic efficiency, economy of materials, simplicity of construction, and minimization of maintenance problems were selected. For example, while the use of curved surfaces rather than plane surfaces might result in slightly improved hydraulic efficiency at times, the advantages are outweighed by the construction difficulties. Therefore, only plane surfaces are utilized in the recommended designs.

B. Descriptions of Tapered Inlets.

1. Side-tapered. The side-tapered inlet has an enlarged face section with the transition to the culvert barrel accomplished by tapering the side walls. (figure IV-1) The face section is about the same height as the barrel height and the inlet floor is an extension of the barrel floor. The inlet roof may slope upward slightly, provided that the face height does not exceed the barrel height by more than 10 percent (1.1D). The intersection of the tapered sidewalls and the barrel is defined as the throat section.

There are two possible control sections, the face and the throat. HW_f, shown in figure IV-1, is the headwater depth measured from the face section invert and HW_t is the headwater depth measured from the throat section invert.

The throat of a side-tapered inlet is a very efficient control section. The flow contraction is nearly eliminated at the throat. In addition, the throat is always slightly lower than the face so that more head is exerted on the throat for a given headwater elevation.

The beneficial effect of depressing the throat section below the stream bed can be increased by installing a depression upstream of the side-tapered inlet. Figures IV-2 and IV-3 show two methods of constructing the depression. Figure IV-2 depicts a side-tapered inlet with the depression contained between wingwalls. For this type of depression, the floor of the barrel should extend upstream from the face a minimum distance of D/2 before sloping upward more steeply. Figure IV-3 shows a side-tapered inlet with a sump upstream of the face. Dimensional limitations for the designs are shown. In both cases, the length of the resultant upstream crest where the slope of the depression meets the stream bed should be checked to assure that the crest will not control the flow at the

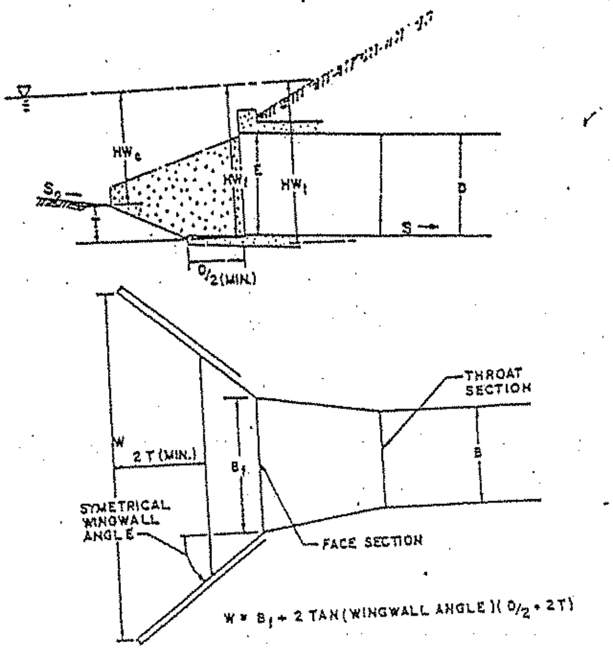


Figure IV-2--Side-tapered inlet with upstream depression contained between wingwalls.

design flow and headwater. If the crest length is too short, the crest may act as a weir control section. For depressed side-tapered inlets, both the face section and the throat section have more head exerted on them for a given headwater elevation. The increased head results in a smaller required throat section. Likewise, the required size of the face is reduced by the increased head. Beveled edges or other favorable edge conditions also reduce the required size of the face.

2. Slope-tapered. The slope-tapered inlet, like the side tapered inlet, has an enlarged face section with tapered sidewalls meeting the culvert barrel walls at the throat section. (figure IV-4) In addition, a vertical FALL is incorporated into the inlet between the face and throat sections. This FALL concentrates more head on the throat section. At the location where the steeper slope of the inlet intersects the flatter slope of the barrel, a third section, designated the bend section, is formed.

A slope-tapered inlet has three possible control sections, the face, the bend, and the throat. Of these, only the dimensions of the face and the throat section are determined by the design procedures of this manual. The size of the bend section is established by locating it a minimum distance upstream from the throat.

The slope-tapered inlet combines an efficient throat section with additional head on the throat. The face section does not benefit from the FALL between

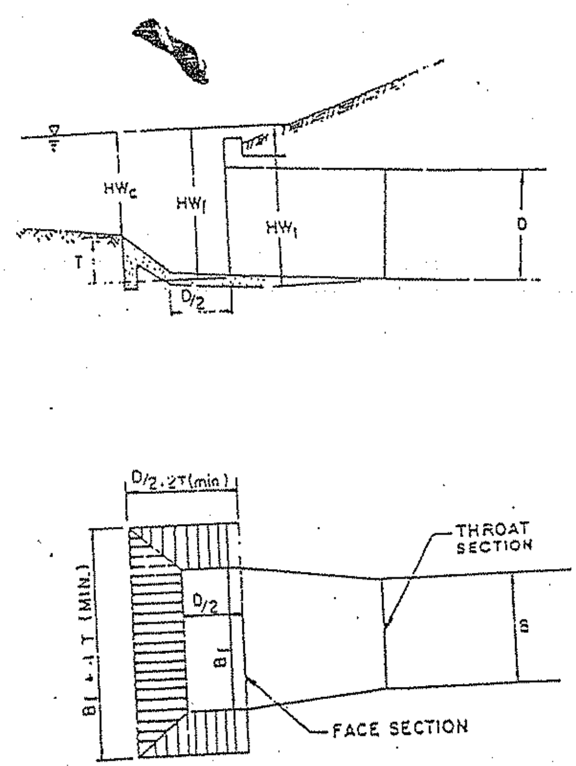


Figure IV-3--Side-tapered inlet with upstream sump.

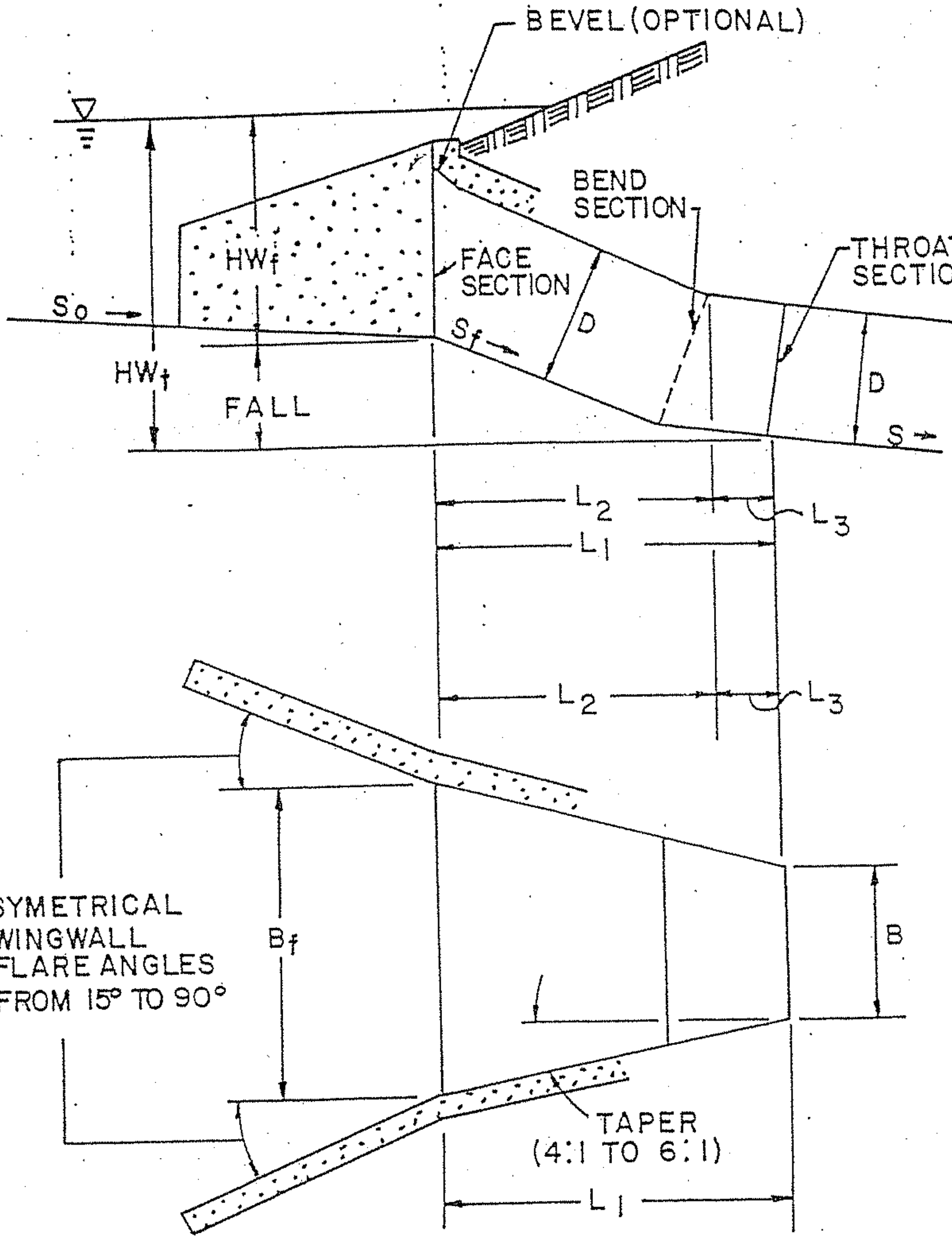


Figure IV-4--Slope-tapered inlet with vertical face.

the face and throat; therefore, the face sections of these inlets are larger than the face sections of equivalent depressed side-tapered inlets. The required face size can be reduced by the use of bevels or other favorable edge configura-

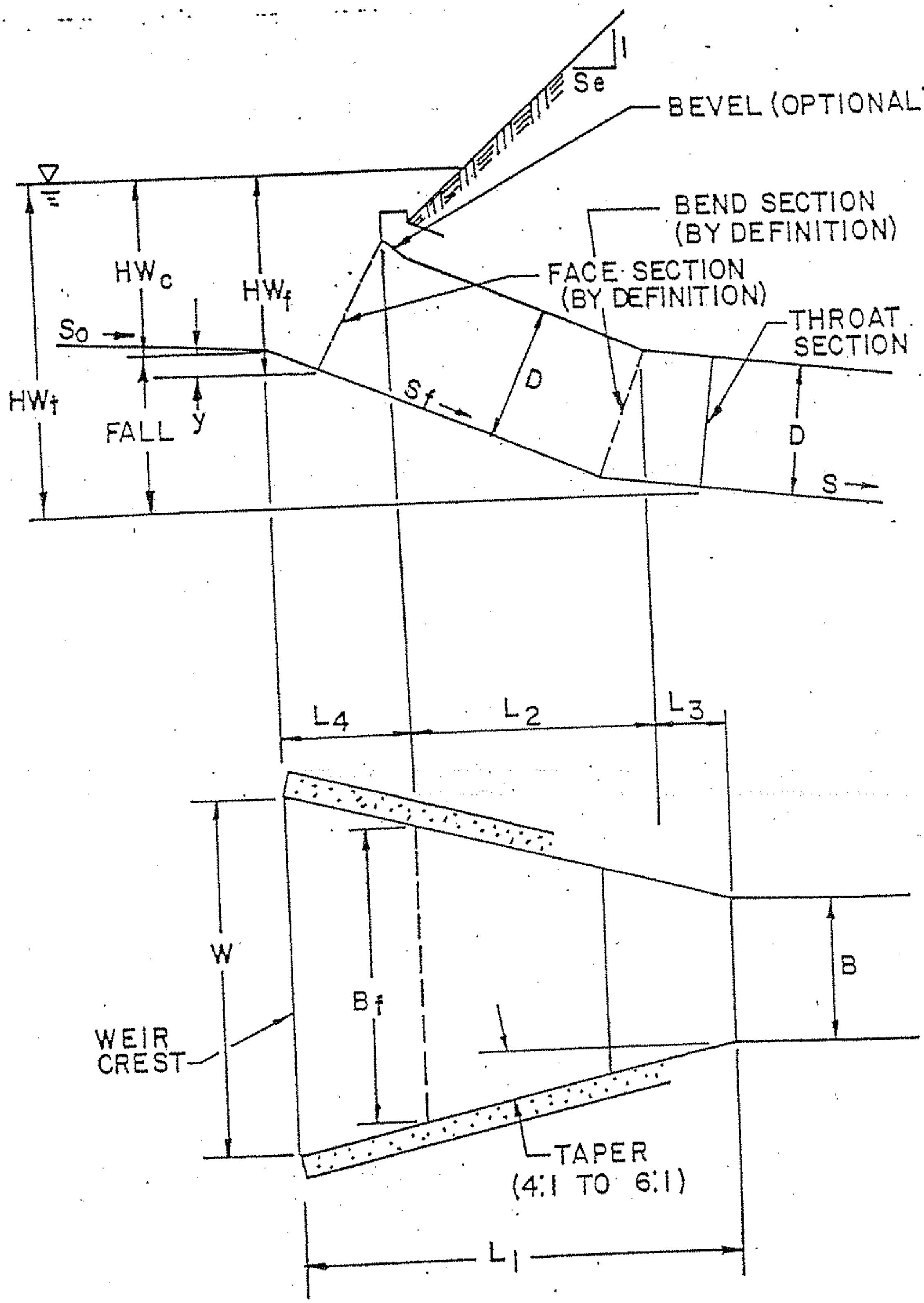


Figure IV-5--Slope-tapered inlet with mitered face.

tions. The vertical face slope-tapered inlet design is shown in figure IV-4 and the mitered face design is shown in figure IV-5.

The mitered face slope-tapered inlet design is more complicated than the vertical face design. A hypothetical face section is located downstream of the weir crest formed where the extension of the fill slope meets the stream bed. The face section is defined by a perpendicular line extending to the FALL slope from the top edge of the inlet, neglecting bevels.

The slope-tapered inlet is the most complex inlet improvement recommended in this manual. Construction difficulties are inherent, but the benefits in increased performance can be great. With proper design, a slope-tapered inlet passes more flow at a given headwater elevation than any other configuration.

Slope-tapered inlets can be applied to both box culverts and circular pipe culverts. For the latter application, a square to round transition is normally used to connect the rectangular slope-tapered inlet to the circular pipe.

C. <u>Hydraulics</u>.

1. Inlet Control. Tapered inlets have several possible control sections including the face, the bend (for slope-tapered inlets), and the throat. In addition, a depressed side-tapered inlet has a possible control section at the crest upstream of the depression. Each of these inlet control sections has an individual performance curve. The headwater depth for each control section is referenced to the invert of the section. One method of determining the overall inlet control performance curve is to calculate performance curves for each potential control section, and then select the segment of each curve which defines the minimum overall culvert performance. (figure IV-6)

If the dimensional criteria of this publication are followed, the crest and the bend sections will not function as control sections over the normal range of headwaters and discharges. The crest of the depression may function as a control section for very low flows and headwaters but this is generally not of importance in design. Figure IV-6 depicts performance curves for each of the potential inlet control sections and the overall inlet control performance curves.

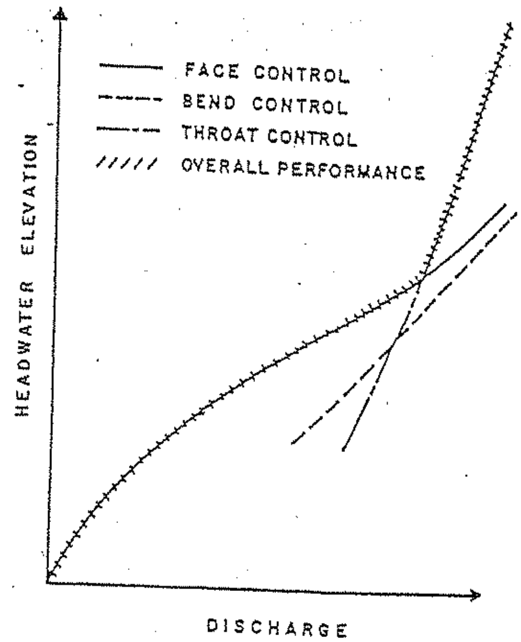


Figure IV-6--Inlet control performance curves (schematic).

The design procedures for tapered inlets include checks on crest lengths for both depressed side-tapered inlets and slope-tapered inlets with mitered faces. As long as the actual crest length exceeds a certain minimum value, there is no need to construct a crest performance curve. Also, if the bend section is located a minimum distance of D/2 upstream of the throat section, the bend will not control and the bend section performance curve does not need to be calculated.

The inlet control equations for tapered inlets are given in appendix A. The coefficients and exponents for each control section were developed based on the NBS section were developed based on the NBS hydraulic tests. All of the previously described control sections function in a manner similar to weirs for unsubmerged flow conditions, and in a manner similar to orifices for submerged flow conditions. For each section, there is a transition zone defined by an empirical curve connecting the unsubmerged and submerged curves.

a. Side-tapered Inlet. The side-tapered inlet throat should be designed to be the primary control section for the design range of flows and headwaters. Since the throat is only slightly lower than the face, it is likely that the face section will function as a weir or an orifice with downstream submergence within the design range. At lower flow rates and headwaters, the face will usually control the flow.

b. Slope-tapered Inlet. The slope-tapered inlet throat can be the primary control section with the face section submerged or unsubmerged. If the face is submerged, the face acts as an orifice with downstream submergence. If the face is unsubmerged, the face acts as a weir, with the flow plunging into the pool formed between the face and the throat. As previously noted, the bend section will not act as the control section if the dimensional criteria of this publication are followed. However, the bend will contribute to the inlet losses which are included in the inlet loss coefficient, k_e.

2. Outlet Control. When a culvert with a tapered inlet performs in outlet control, the hydraulics are the same as described in chapter III for all culverts. The factors influencing flow in outlet control are shown in table 1. (chapter 1) The inlet area is the area of the face section, the inlet edge configuration describes the type of tapered inlet as well as the face edge conditions, and the shape is either circular or rectangular. The barrel characteristics refer to the barrel portion of the culvert, downstream of the throat section, except that the barrel length includes the length of the tapered inlet, and the barrel slope may be flatter than the natural stream bed slope.

Equation (5) in chapter III describes the losses in outlet control. The tapered inlet entrance loss coefficient (k_e) is 0.2 for both side-tapered and slope-tapered inlets. This loss coefficient includes contraction and expansion losses at the face, increased friction losses between the face and the throat, and the minor expansion and contraction losses at the throat.

The headwater depth in outlet control is measured from the invert of the culvert exit. Equation (5) or the outlet control nomograph for the appropriate barrel size is used to determine the total losses through the culvert. Equation (7) is then used to calculate the headwater depth, where the tailwater (TW) is taken to be either $(d_c + D)/2$ or the downstream channel depth, whichever is larger.

3. Outlet Velocity. Outlet velocities for culverts with tapered inlets are determined in the same manner as described in chapter III. Note that when a FALL is used at the inlet, the barrel slope is flatter than the stream slope and is calculated as follows.

$$S = \frac{EL_t - EL_o}{L_a - L_1} \qquad (11)$$

- S is the approximate barrel slope, ft/ft (m/m)
- EL_t is the invert elevation at the throat, ft (m)
- EL_o is the invert elevation at the outlet, ft (m)
- L_a is the approximate length of the culvert, ft (m)
- L_1 is the overall length of the tapered-inlet, ft (m)

D. Performance Curves.

Performance curves are of utmost importance in understanding the operation of a culvert with a tapered inlet. Each potential control section (face, throat, and outlet) has a performance curve, based on the assumption that that particular section controls the flow. Calculating and plotting the various performance curves results in a graph similar to figure IV-7, containing the face control, throat control and outlet control curves. The overall culvert performance curve is represented by the hatched line. In the range of lower discharges face control governs; in the intermediate range, throat control governs; and in the higher discharge range, outlet control governs. The crest and bend performance curves are not calculated since they do not govern in the design range.

Constructing performance curves for culverts with tapered inlets helps to assure that the designer is aware of how the culvert will perform over a range of discharges. For high discharges, the outlet control curve may have a very steep slope which means that the headwater will increase rapidly with increasing discharge. Since there is a probability that the design discharge will be exceeded over the life of the culvert, the consequences of that event should be considered. This will help to evaluate the potential for damage to the roadway and to adjacent properties.

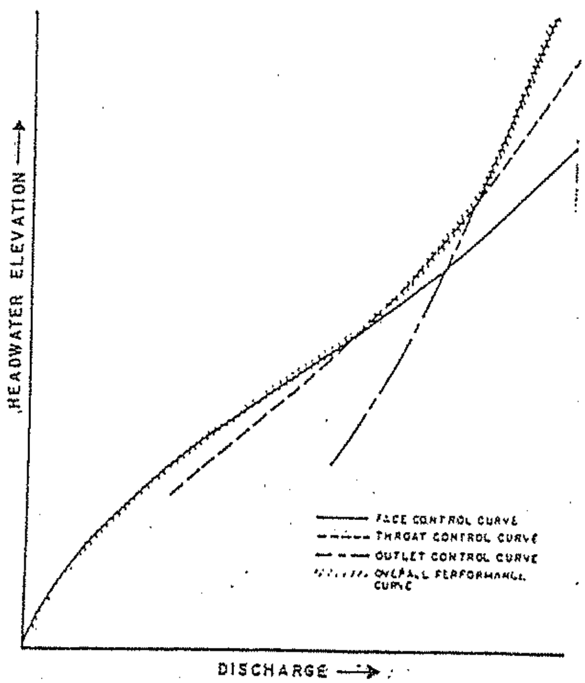


Figure IV-7--Culvert performance curve (schematic).

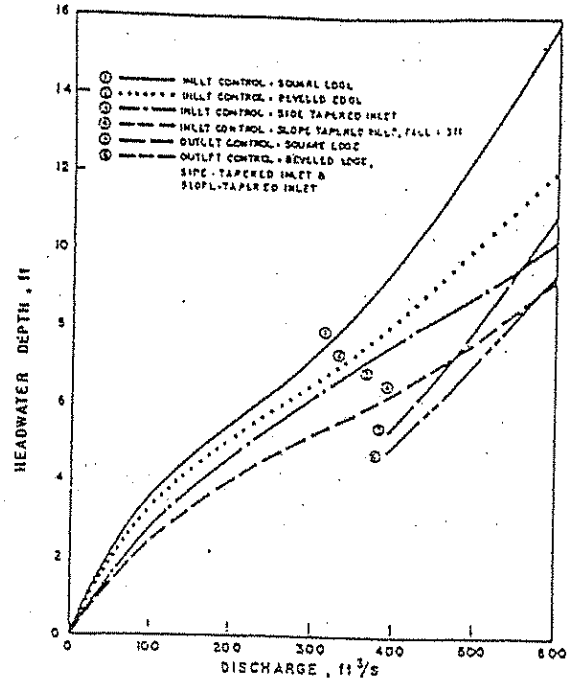
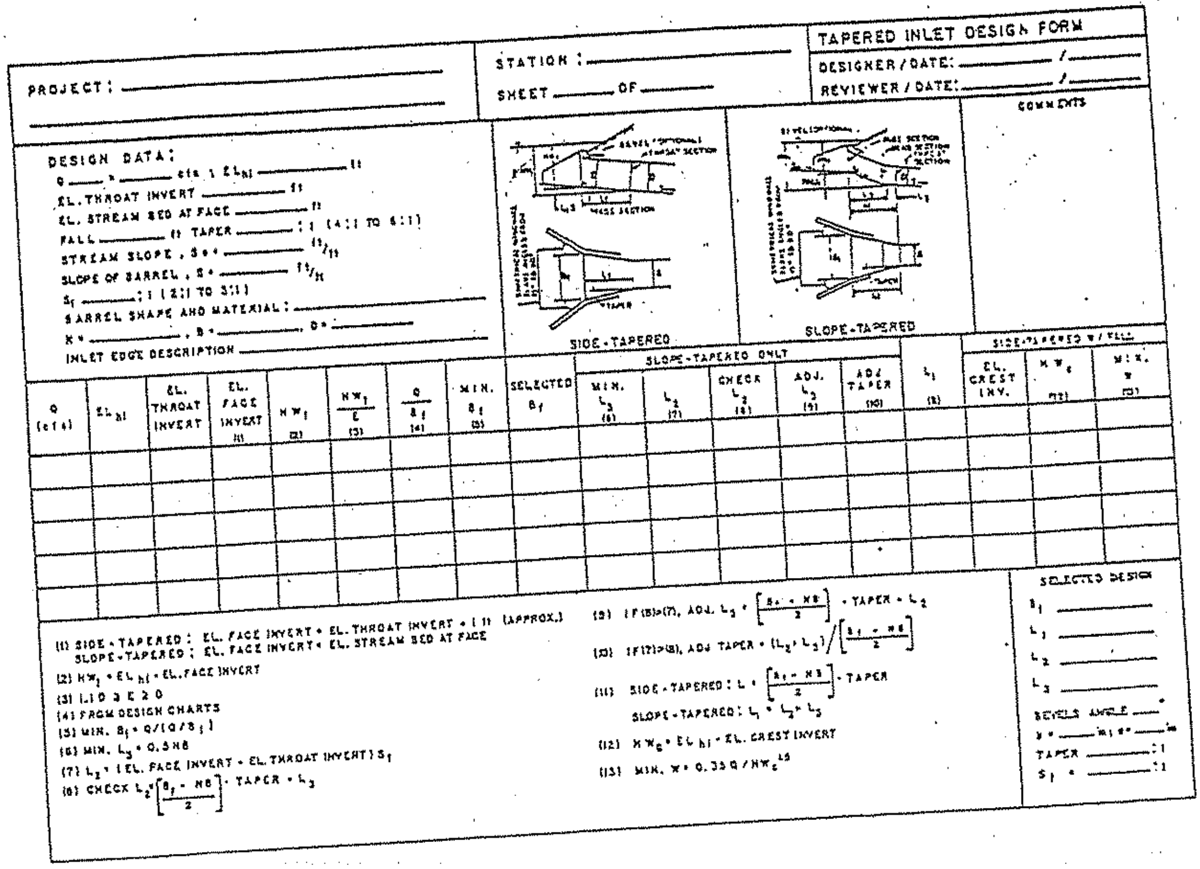


Figure IV-8--Performance curves for 6 ft by 6 ft box culvert with 90-degree wingwall.

Performance curves provide a basis for the selection of the most appropriate culvert design. For example, culvert designs with and without tapered inlets can be compared and evaluated using performance curves. (figure IV-8)

Performance curves are useful in optimizing the performance of a culvert. By manipulating the depressions of the face and throat sections, it is often possible to achieve a higher flow rate for a given


TAPERED INLET DESIGN FORM
DESIGNER / DATE: ________ / ________
REVIEWER / DATE: ________ / ________

PROJECT: ________

STATION: ________
SHEET ____ OF ____

DESIGN DATA:
Q ____ = ____ cfs ; EL$_{hi}$ ________ ft
EL. THROAT INVERT ________ ft
EL. STREAM BED AT FACE ________ ft
FALL ________ ft TAPER ________ : 1 (4:1 TO 6:1)
STREAM SLOPE, So = ________ ft/ft
SLOPE OF BARREL, S = ________ ft/ft
S_f ________ : 1 (2:1 TO 3:1)
BARREL SHAPE AND MATERIAL: ________
N = ________ , B = ________ , D = ________
INLET EDGE DESCRIPTION ________

Q (cfs)	EL$_{hi}$	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f/E (3)	Q/B_f (4)	MIN. B_f (5)	SELECTED B_f	SLOPE-TAPERED ONLY: MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	SIDE-TAPERED W/ FALL: EL. CREST INV.	HW_c (12)	MIN. W (13)

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE
(2) HW_f = EL$_{hi}$ − EL. FACE INVERT
(3) 1.1 D ≥ E ≥ 2 D
(4) FROM DESIGN CHARTS
(5) MIN. B_f = Q/(Q/B_f)
(6) MIN. L_3 = 0.5 NB
(7) L_2 = (EL. FACE INVERT − EL. THROAT INVERT) S_f
(8) CHECK L_2 = $\left[\frac{B_f - NB}{2}\right]$ · TAPER − L_3
(9) IF (8)>(7), ADJ. L_3 = $\left[\frac{B_f - NB}{2}\right]$ · TAPER − L_2
(10) IF (7)>(8), ADJ. TAPER = $(L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$
(11) SIDE-TAPERED: L = $\left[\frac{B_f - NB}{2}\right]$ · TAPER
SLOPE-TAPERED: $L_1 = L_2 + L_3$
(12) HW_c = EL$_{hi}$ − EL. CREST INVERT
(13) MIN. W = $0.35\,Q / HW_c^{1.5}$

SELECTED DESIGN
B_f ________
L_1 ________
L_2 ________
L_3 ________
BEVELS ANGLE ________
b = ____ in; d = ____ in
TAPER ________ : 1
S_f = ________ : 1

Figure IV-9--Tapered inlet design form.

headwater elevation, or to pass the same flow at a lower headwater. A more detailed description of the use of performance curves in improved inlet design is presented in appendix C.

E. Design Methods.

Tapered inlet design begins with the selection of the culvert barrel size, shape, and material. These calculations are performed using the Culvert Design Form shown in figure III-17. The tapered-inlet design calculation forms and the design nomographs contained in appendix D are used to design the tapered inlet. The result will be one or more culvert designs, with and without tapered inlets, all of which meet the site design criteria. The designer must select the best design for the site under consideration.

In the design of tapered inlets, the goal is to maintain control at the efficient throat section in the design range of headwater and discharge. This is because the throat section has the same geometry as the barrel, and the barrel is the most costly part of the culvert. The inlet face is then sized large enough to pass the design flow without acting as a control section in the design discharge range. Some slight oversizing of the face is beneficial because the cost of constructing the tapered inlet is usually minor compared with the cost of the barrel.

The required size of the face can be reduced by use of favorable edge configurations, such as beveled edges, on the face section. Design nomographs are provided for favorable and less favorable edge conditions.

The following steps outline the design process for culverts with tapered inlets. Steps 1 and 2 are the same for all culverts, with and without tapered inlets.

1. **Preliminary Culvert Sizing.** Estimate the culvert barrel size to begin calculations.

2. **Culvert Barrel Design.** Complete the Culvert Design Form. (figure III-17) These calculations yield the required FALL at the culvert entrance. For the inlet control calculations, the appropriate inlet control nomograph is used for the tapered inlet throat. The required FALL is upstream of the inlet face section for side-tapered inlets and is between the face section and throat section for slope tapered inlets. The Culvert Design Form should be completed for all barrels of interest. Plot outlet control performance curves for the barrels of interest and inlet control performance curves for the faces of culverts with nonenlarged inlets and for the throats of tapered inlets.

3. **Tapered Inlet Design.** Use the Tapered Inlet Design Form (figure IV-9) for selecting the type of tapered inlet to be used and determining its dimensions. If a slope-tapered inlet with mitered face is selected, use the special design form shown in figure IV-10. A separate form is provided for the mitered inlet because of its dimensional complexity.

To use the Tapered Inlet Design Form (figure IV-9) or the design form for a slope-tapered inlet with mitered face (figure IV-10), perform the following steps:

PROJECT: ______ STATION: ______ SHEET ____ OF ____

MITERED INLET DESIGN FORM

DESIGNER / DATE: ______ / ______
REVIEWER / DATE: ______ / ______

DESIGN DATA: N ____ ; B ____ ; D ____

Q ____ = ____ cfs ; EL_{hi} ____ ft

EL. THROAT INVERT ____ ft EL. STREAM BED AT CREST ____ ft

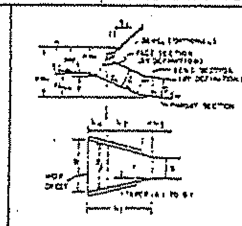
FALL ____ ft ; TAPER ____ : (4:1 TO 6:1)

STREAM SLOPE, S_o ____ ft/ft ; BARREL SLOPE, S = ____ ft/ft

SLOPE OF THE EMBANKMENT S_e = ____ : 1 ; S_f ____ : 1 (2:1 TO 3:1)

BARREL SHAPE AND MATERIAL: ______

INLET EDGE DESCRIPTION: ______



SLOPE-TAPERED INLET/MITERED FACE

COMMENTS

Q (cfs)	EL_{hi}	EL. THROAT INVERT	y (1)	EL. FACE INVERT (2)	HW_f (3)	HW_f/E (4)	Q/B_f (5)	MIN. B_f (6)	SELECTED B_f	MIN. L_3 (7)	L_4 (8)	L_2 (9)	CHECK L_2 (10)	ADJ. L_3 (11)	ADJ. TAPER (12)	L_1 (13)	EL. CREST INV.	HW_c (14)	MIN. W (15)	W (16)

(1) $y = \left[\frac{(S_e \cdot S_f) - 1}{(S_e + S_f)(S_f^2 + 1)^{0.5}}\right] \cdot D$

(2) EL. FACE INVERT = EL. STREAM BED AT CREST − y

(3) HW_f = EL_{hi} − EL. FACE INVERT

(4) $1.1 D \geq E \geq D$

(5) FROM DESIGN CHARTS

(6) MIN. $B_f = Q/(Q/B_f)$

(7) MIN. $L_3 = 0.5\,NB$

(8) $L_4 = S_f y + D/S_f$

(9) L_2 = (EL. CREST INVERT − EL. THROAT INVERT) $S_f - L_4$

*** IF L_2 IS NEGATIVE DO NOT USE THIS INLET

(10) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right]$ TAPER − L_3

(11) IF (10)>(9), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right]$ TAPER − L_2

(12) IF (9)>(10), ADJ. TAPER = $(L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$

(13) $L_1 = L_2 + L_3 + L_4$

(14) $HW_c = EL_{hi}$ − EL. CREST INVERT

(15) MIN. $W = 0.35\,Q / (HW_c)^{1.5}$

(16) $W = NB + 2\left[\frac{L_1}{TAPER}\right]$

IF W<MIN. W, ADJUST TAPER

SELECTED DESIGN

B_f ______
L_1 ______
L_2 ______
L_3 ______
L_4 ______
BEVELS ANGLE ____°
b = ____ in ; d = ____ in
TAPER ____ : 1
S_f ____ : 1

Figure IV-10--Design Form - Slope-tapered inlet with mitered face.

a. Complete Design Data. Fill in the required design data on the top of the form.

1) Flow, Q, is the selected design flow rate, from the Culvert Design Form, figure III-17.

2) EL_{hi} is the inlet control headwater elevation.

3) The elevation of the throat invert (EL_t) is the inlet invert elevation (EL_i) from figure III-17.

4) The elevation of the stream bed at the face (EL_{sf}), the stream slope (S_o), and the slope of the barrel (S) are from figure III-17. (For the slope-tapered inlet with mitered face, estimate the elevation of the stream bed at the crest. This point is located upstream of the face section).

5) The FALL is the difference between the stream bed elevation at the face and the throat invert elevation.

6) Select a side taper (TAPER) between 4:1 and 6:1 and a fall slope (S_f) between 2:1 and 3:1. The TAPER may be modified during the calculations.

7) Enter the barrel shape and material, the size, and the inlet edge configuration from figure III-17. Note that for tapered inlets, the inlet edge configuration is designated the "tapered inlet throat."

b. Calculate the Face Width.

1) Enter the flow rate, the inlet control headwater elevation (EL_{hi}), and the throat invert elevation on the design forms. (For the slope-tapered inlet with mitered face, the face section is downstream of the crest. Calculate the vertical difference between the stream bed at the crest and the face invert (y). y includes part of the total inlet FALL.)

2) Perform the calculations resulting in the face width (B_f). Face control design nomographs are contained in appendix D.

c. Calculate Tapered-Inlet Dimensions. If the FALL is less than D/4 (D/2 for a slope-tapered inlet with a mitered face), a side-tapered inlet must be used. Otherwise, either a side-tapered inlet with a depression upstream of the face or a slope-tapered inlet may be used.

1) For a slope-tapered inlet with a vertical face, calculate L_2, L_3, and the TAPER. (For the slope-tapered inlet with a mitered face, calculate the horizontal distance between the crest and the face section invert L_4. These dimensions are shown on the small sketches in the top center of the forms.)

2) Calculate the overall tapered inlet length, L_1.

3) For a side-tapered inlet, check to assure that the FALL between the face section and the throat section is one foot or less. If not, return to step b. with a revised face invert elevation.

d. Calculate the Minimum Crest Width. For a side-tapered inlet with FALL upstream of the face or for a slope-tapered inlet with a mitered face, calculate the minimum crest width and check it against the proposed crest width. In order to obtain the necessary crest length for a depressed side-tapered inlet, it may be necessary to increase the flare angle of the wingwalls for the type of depression shown in figure IV-2, or to increase the length of crest on the sump for the design shown in figure IV-3. For a slope-tapered inlet with a mitered face, reduce the TAPER to increase crest width. Note that the TAPER must be greater than 4:1.

e. Fit the Design into the Embankment Section. Using a sketch based on the derived dimensions, and a sketch of the roadway section to the same scale, assure that the culvert design fits the site. Adjust inlet dimensions as necessary but do not reduce dimensions below the minimum dimensions on the design form.

f. Prepare Performance Curves. Using additional flow rate values and the appropriate nomographs, calculate a performance curve for the selected face section. Do not adjust inlet dimensions at this step in the design process. Plot the face control performance curve on the same sheet as the throat control and the outlet control performance curves.

g. Enter Design Dimensions. If the design is satisfactory, enter the dimensions at the lower right of the Design Form. Otherwise, calculate another alternative design by returning to step 3a.

4. Dimensional Limitations. The following dimensional limitations must be observed when designing tapered inlets using the design charts of this publication.

a. Side-Tapered Inlets.

1) 4:1 ≤ TAPER ≤ 6:1

Tapers less divergent than 6:1 may be used but performance will be underestimated. (9,10)

2) Wingwall flare angle range from 15- degrees to 26-degrees with top edge beveled or from 26-degrees to 90-degrees with or without bevels. (figure IV-11)

3) If a FALL is used upstream of the face, extend the barrel invert slope upstream from the face a distance of D/2 before sloping upward more steeply. The maximum vertical slope of the apron is 2 (horizontal):1 (vertical).

4) D ≤ E ≤ 1.1D

b. Slope-tapered Inlets.

1) 4:1 ≤ TAPER ≤ 6:1

(Tapers > 6:1 may be used, but performance will be underestimated.)

2) 3:1 ≥ S_f ≥ 2.1

If S_f > 3:1, use side-tapered design.

3) Minimum $L_3 = 0.5B$

4) D/4 ≤ FALL ≤ 1.5D

i. For FALL < D/4, use side-tapered design

ii. For FALL < D/2, do not use the slope-tapered inlet with mitered face

iii. For FALL > 1.5D, estimate friction losses between the face and the throat by using equation (12) and add the additional losses to HW_t.

$$H_1 = \left[\frac{29\, n^2 L_1}{R^{1.33}}\right] \frac{Q^2}{2gA^2} \qquad (12)$$

where H_1 is the friction head loss in the tapered inlet, ft (m)
n is the Manning n for the tapered inlet material
L_1 is the length of the tapered inlet, ft (m)
R is the average hydraulic radius of the tapered inlet $= (A_f + A_t)/(P_f + P_t)$, ft (m)
Q is the flow rate, ft^3/s (m^3/s)
g is the gravitational acceleration, ft/s/s (m/s/s)
A is the average cross sectional area of the tapered inlet $= (A_f + A_t)/2$, ft^2 (m^2).

5) Wingwall flare angles range from 15- degrees to 26-degrees with top edge beveled or from 26-degrees to 90-degrees with or without bevels. (figure IV-11)

F. Rectangular (Box) Culverts.

1. Design Procedures. This section supplements the general design procedures described previously with information specifically related to rectangular

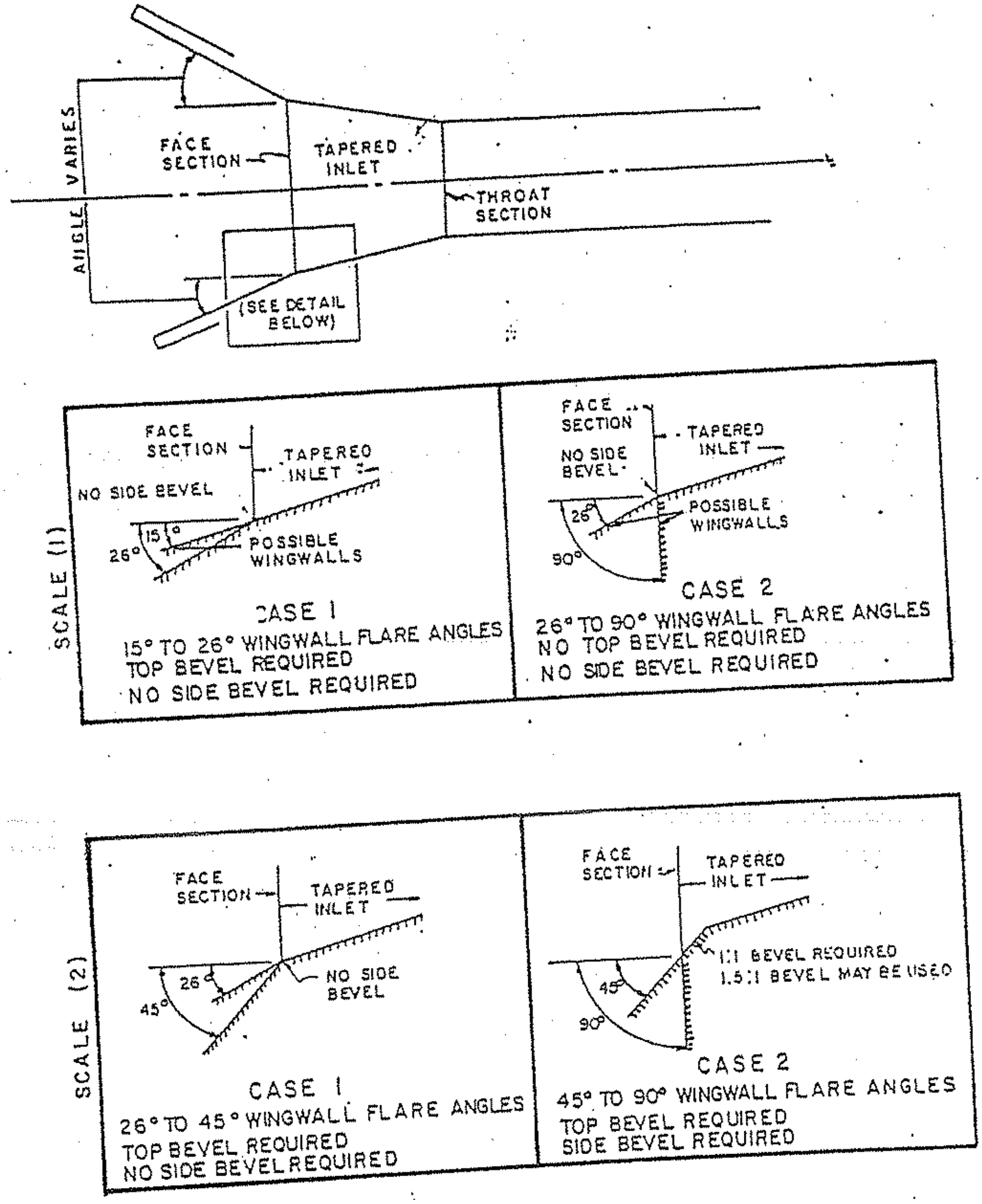


Figure IV-11--Inlet edge conditions, face section, rectangular tapered inlets.

box culverts. The design charts for throat and face control for tapered inlets are contained in appendix D. There is a single throat control nomograph for side- or slope-tapered rectangular inlets.

For determining the required face width, there are two nomographs in appendix D, one for side-tapered inlets and one for slope-tapered inlets. Each nomograph has two scales, and each scale refers to a specific inlet edge condition. The edge conditions are depicted in figure IV-11. Both the inlet edge condition and the wingwall flare angle affect the performance of the face section for box culverts.

Scale 1 on the design nomographs refers to the less favorable edge conditions, defined as follows:

a. wingwall flares of 15-degrees to 26-degrees and a 1:1 top edge bevel, or

b. wingwall flares of 26-degrees to 90-degrees and square edges (no bevels). A 90-degree wingwall flare is a straight headwall.

Scale 2 applies to the more favorable edge conditions, defined as follows:

a. wingwall flares of 26-degrees to 45-degrees with 1:1 top edge bevel, or

b. wingwall flares of 45-degrees to 90-degrees with a 1:1 bevel on the side and top edges.

Note that undesirable design features, such as wingwall flare angles less than 15-degrees, or 26-degrees without a top bevel, are not covered by the charts. Although the large 33.7 degree bevels can be used, the smaller 45 degree bevels are preferred due to structural considerations.

2. Multiple Barrel Designs. When designing side- or slope-tapered inlets for box culverts with double barrels, the required face width derived from the design procedures is the total clear width of the face. The thickness of the center wall must be added to this clear width to obtain the total face width. No design procedures are available for tapered inlets on box culverts with more than two barrels.

3. Example Problems.

a. <u>Problem No. 1</u>. The 50-year flood at the design site has a peak flow of 400 ft^3/s. The EL_{hd} of 195 ft is selected so that overtopping of the roadway will not occur for the design discharge.

<u>Given</u>:

Elevation of Outlet Invert: 172.5 ft

Elevation of Shoulder: 196 ft

Stream Bed Slope: 5 percent

Approximate Culvert Length: 300 ft

The tailwater variation is as follows:

Flow (ft^3/s)	T.W. (ft)
300	4.4
400	4.9
500	5.3

<u>Requirements</u>: Design the smallest possible barrel to pass the peak flow rate without exceeding the EL_{hd}. The culvert will be located in a rural area with a low risk of damage. Underground utilities limit the available FALL to 2.5 ft below the standard stream bed elevation at the inlet. Use a reinforced concrete box culvert with n = 0.012.

<u>NOTE:</u> Charts 14, 15, 57, 58, and 59 are used in this solution.

CULVERT DESIGN FORM

PROJECT: EXAMPLE PROBLEM No. 1
CHAPTER IV, HDS No. 5

STATION: 5+00
SHEET 1 OF 2

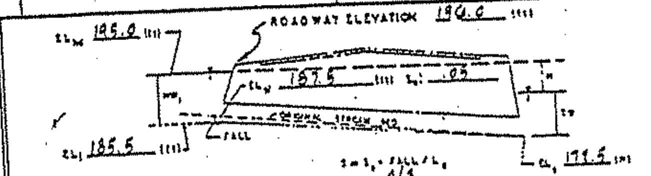
DESIGNER/DATE: WJJ / 7/16
REVIEWER/DATE: JMN / 7/17

HYDROLOGICAL DATA

- ☐ METHOD: RATIONAL
- ☐ DRAINAGE AREA: 150 AC. ☐ STREAM SLOPE: 5.0 %
- ☐ CHANNEL SHAPE: TRAPEZOIDAL
- ☐ ROUTING: N/A ☐ OTHER: —

DESIGN FLOWS/TAILWATER

R.I (YEARS)	FLOW (cfs)	TW (ft)
50	600	6.9



$S = S_o - FALL/L_a$
$S =$ .043
$L_a =$ 300 (ft)

HEADWATER CALCULATIONS

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONC. - BOX - 5'x5' - 45° BEVEL	600	80	2.4	12.0	4.5	195.0	4.5	2.5	5.0	5.0	0.2	8.9	186.4	195.0	—	EXCESSIVE FILL REQ'D.
" - " - 5'x5' - TAPERED INLET THROAT	600	80	1.9	9.5	2.0	195.0	"	"	"	5.0		"	"	195.0	29.1	INLET AND FALL OK.
" - " - " - "	300	60	1.48	7.6	↓	192.9	6.6	6.8	6.9	6.9		5.0	182.6	192.9	—	PERFORM
" - " - " - "	500	100	2.6	12.0	↓	197.5	5.3	2.5	5.0	5.0	↓	16.1	191.0	197.5	—	CURVE DATA

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS
(2) $HW_i/D = HW_i/D$ OR HW_i/D FROM DESIGN CHARTS
(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE
(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)
(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.
(6) h_o = TW or $(d_c + D/2)$ (WHICHEVER IS GREATER)
(7) $H = \left[1 + k_e + (29 n^2 L)/R^{1.33}\right] V^2/2g$
(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS/DISCUSSION:

USE 5'x5' CONCRETE BOX WITH TAPERED INLET. CHECK SIDE - & - SLOPE - TAPERED ENTRANCES.

CULVERT BARREL SELECTED:

SIZE: 5'x5'
SHAPE: RECTANGULAR
MATERIAL: CONC. n .012
ENTRANCE: TAPERED INLET

TAPERED INLET DESIGN FORM

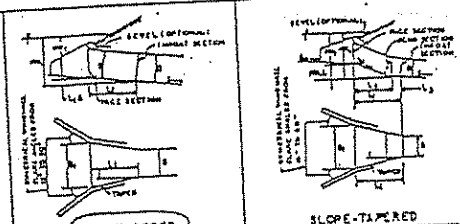
PROJECT: EXAMPLE PROBLEM No. 1
CHAPTER IV, HDS No. 5

STATION: 5+00
SHEET 2 OF 2

DESIGNER/DATE: WJJ / 7/16
REVIEWER/DATE: JMN / 7/17

DESIGN DATA:

Q_{50} = 600 cfs; EL_{hd} = 195.0 ft
EL. THROAT INVERT 185.5 ft
EL. STREAM BED AT FACE 187.5 ft
FALL 2.0 ft TAPER 4 :1 (4:1 TO 6:1)
STREAM SLOPE, S_o = .05 ft/ft
SLOPE OF BARREL, S = .043 ft/ft
S_f — :1 (2:1 TO 3:1)
BARREL SHAPE AND MATERIAL: BOX - CONC.
N = 1, B = 5 FT, D = 5 FT
INLET EDGE DESCRIPTION: TAPERED INLET THROAT



COMMENTS: USE 20° TO 90° WINGWALLS WITH NO BEVELS ON A SIDE TAPERED INLET.

Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f/E (3)	Q/B_f (4)	MIN. B_f (5)	SELECTED B_f	SLOPE-TAPERED ONLY: MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (ft)	SIDE-TAPERED W/ FALL: EL. CREST INV.	HW_c (12)	MIN. W (13)
600	195.0	185.5	186.5	8.5	1.7	67	8.51	9.0	/	/	/	/	/	8.0	188.5	6.5	6.5
600	193.8	↓	*185.8	7.95	1.59	66	—	9.0	FACE CONTROL PERFORMANCE DATA								
300	192.1	↓	↓	6.25	1.25	33	—	9.0									
500	190.0	↓	↓	10.2	2.04	56	—	9.0									

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT − 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE
(2) $HW_f = EL_{hi} - $ EL. FACE INVERT
(3) $1.1 D \geq E \geq D$
(4) FROM DESIGN CHARTS
(5) MIN. $B_f = Q/(Q/B_f)$
(6) MIN. $L_3 = 0.5 NB$
(7) L_2 = (EL. FACE INVERT − EL. THROAT INVERT) S_f
(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER $- L_3$
(9) IF (8)>(7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER $- L_2$
(10) IF (7)>(8), ADJ. TAPER $= (L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$
(11) SIDE-TAPERED: $L = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER
SLOPE-TAPERED: $L_1 = L_2 + L_3$
(12) $HW_c = EL_{hi} - $ EL. CREST INVERT
(13) MIN. $W = 0.35 Q / HW_c^{1.5}$

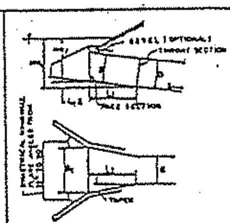
SELECTED DESIGN:

B_f 8.5
L_1 8.0
L_2 ____
L_3 ____
BEVELS ANGLE 0°
b = 0 in, d = 0 in
TAPER 4 :1
S_f = — :1

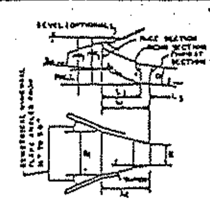
*ACTUAL EL. FACE INVERT = $EL_t + L_1 S$ = 185.5 + (8.0)(.043) = 185.8 ft.

PROJECT: EXAMPLE PROBLEM No. 1 CHAPTER IV HDS No. 5	STATION: 5+00 SHEET 3 OF 4	**TAPERED INLET DESIGN FORM** DESIGNER/DATE: WJJ / 7/16 REVIEWER/DATE: JMN / 7/17

DESIGN DATA:
Q 50 - 400 cfs ; EL_{hi} 195.0 ft
EL. THROAT INVERT 185.5 ft
EL. STREAM BED AT FACE 187.5 ft
FALL 2.0 ft TAPER 4 : 1 (4:1 TO 6:1)
STREAM SLOPE, S_o = .05 ft/ft
SLOPE OF BARREL, S = .066 ft/ft
S_f 2 : 1 (2:1 TO 3:1)
BARREL SHAPE AND MATERIAL: BOX - CONC.
N = 1, B = 5 FT., D = 5 FT.
INLET EDGE DESCRIPTION TAPERED INLET THROAT



SIDE-TAPERED



SLOPE-TAPERED

COMMENTS

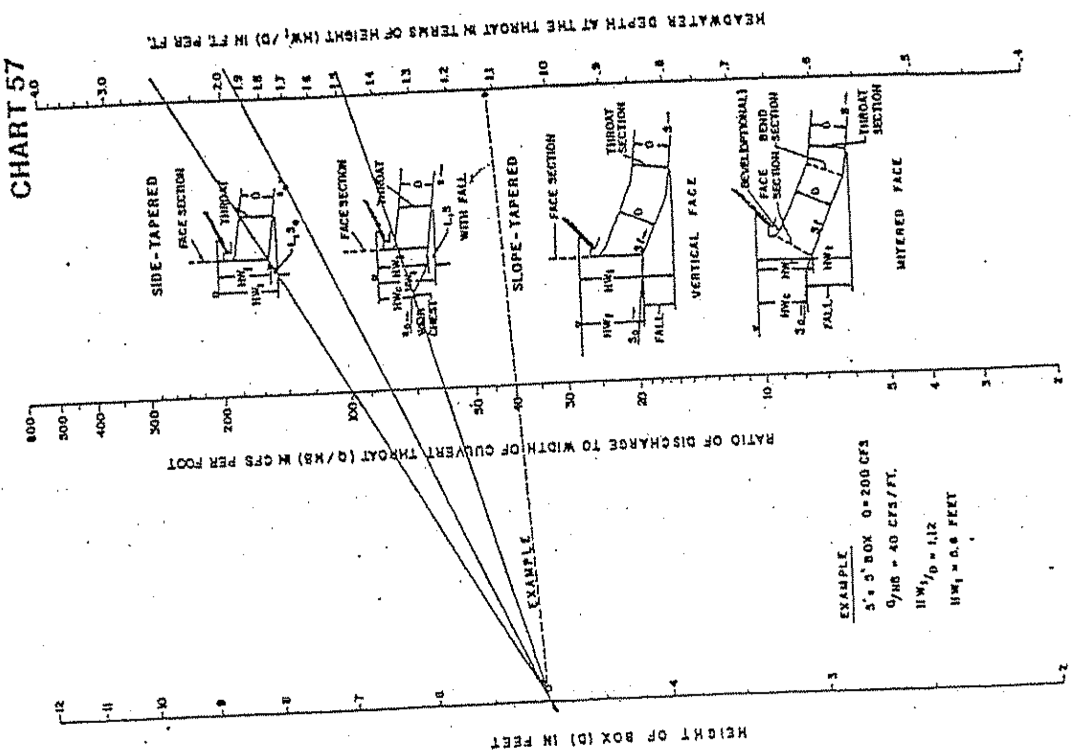
USE 26° TO 90° WINGWALLS FLARES WITH NO BEVELS ON A SLOPE-TAPERED INLET.

Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f/E (3)	Q/B_f (4)	MIN. B_f (5)	SELECTED B_f	SLOPE-TAPERED ONLY: MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	SIDE-TAPERED W/ FALL: EL. CREST INV.	HW_c (12)	MIN. W (13)
400.	195.0	185.5	187.5	7.5	1.5	50	8.0	8.0	2.5	4.0	3.5	—	4.33	6.5	/	/	/
300	193.2	↓	↓	5.7	1.14	37.5	—	8.0	(FACE	CONTROL	PERFORMANCE			DATA			
500	197.5	↓	↓	10.0	2.0	62.5	—	8.0	)								

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE
(2) $HW_f = EL_{hi} - $ EL. FACE INVERT
(3) $1.1 D \geq E \geq D$
(4) FROM DESIGN CHARTS
(5) MIN. $B_f = Q/(Q/B_f)$
(6) MIN. $L_3 = 0.5 NB$
(7) $L_2 = $ (EL. FACE INVERT − EL. THROAT INVERT) S_f
(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER $- L_3$
(9) IF (8)>(7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER $- L_2$
(10) IF (7)>(8), ADJ. TAPER $= (L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$
(11) SIDE-TAPERED: $L = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER
SLOPE-TAPERED: $L_1 = L_2 + L_3$
(12) $HW_c = EL_{hi} - $ EL. CREST INVERT
(13) MIN. $W = 0.35 Q / HW_c^{1.5}$

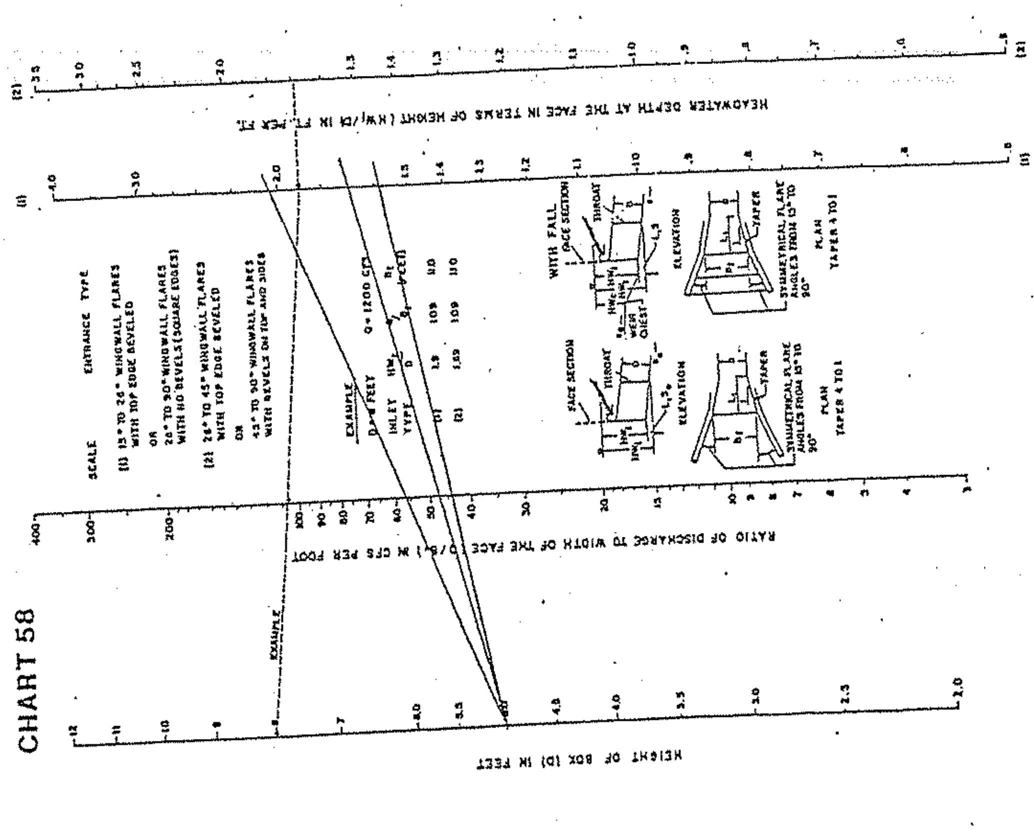
SELECTED DESIGN
B_f 8.0
L_1 6.5
L_2 4.0
L_3 2.5
BEVELS ANGLE 0°
b = 0 in; d = 2 in
TAPER 4.33 : 1
S_f = 2.0 : 1

CHART 57



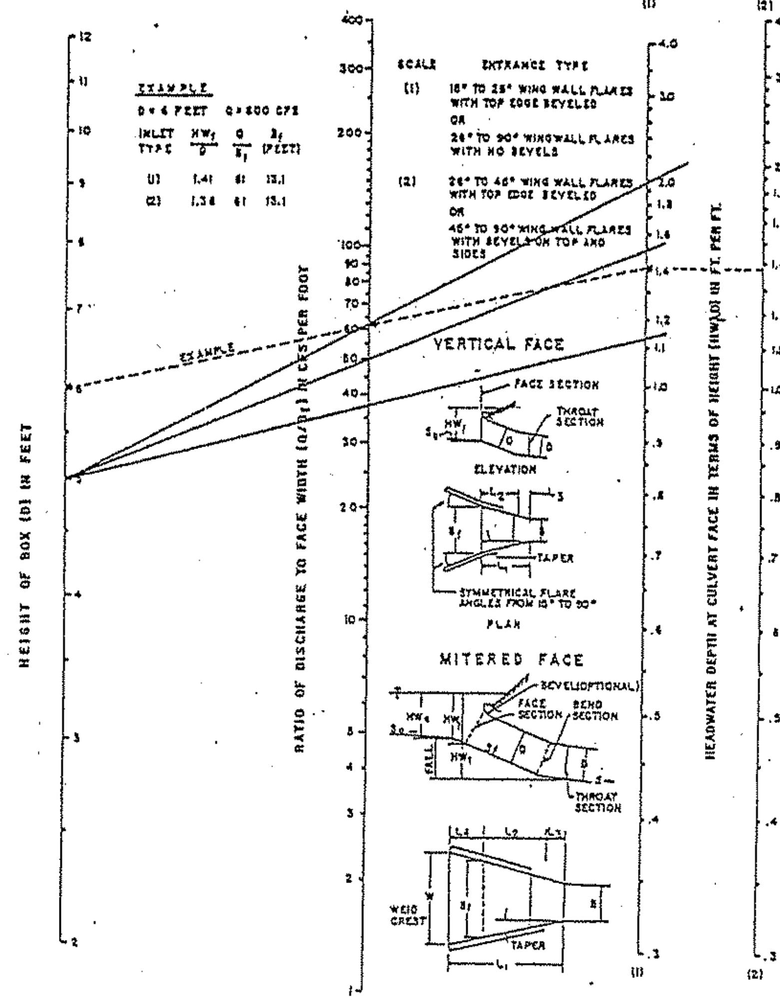
THROAT CONTROL FOR BOX CULVERTS WITH TAPERED INLETS

CHART 58



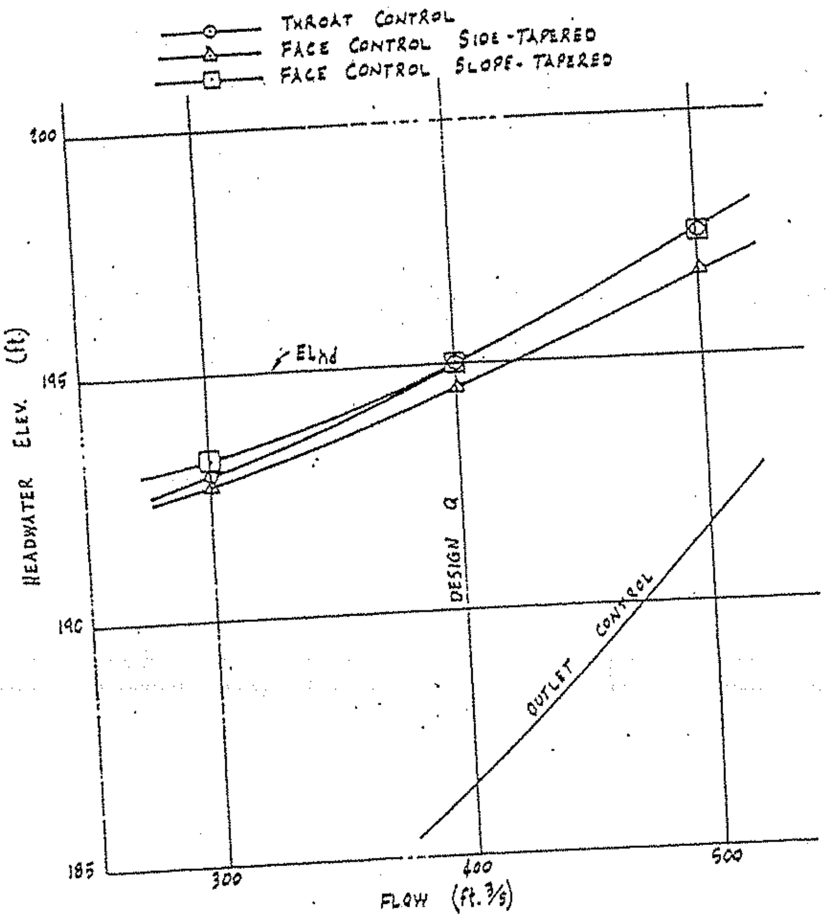
FACE CONTROL FOR BOX CULVERTS WITH SIDE TAPERED INLETS

CHART 59



FACE CONTROL FOR BOX CULVERTS WITH SLOPE TAPERED INLETS

PERFORMANCE CURVES FOR A 5 FT. x 5 FT. RECTANGULAR BOX CULVERT - TAPERED INLETS



Conclusions:

Use a slope-tapered inlet with a vertical face since it is the smallest inlet in this case. Note that since the FALL is less than D/2, a slope-tapered inlet with a mitered face cannot be used at this site.

Dimensions:

B = 5 ft D = 5 ft

B_f = 8 ft

TAPER = 4.33:1

S_f = 2:1

L_1 = 6.5 ft

L_2 = 4.0 ft

L_3 = 2.5 ft

Entrance: 26-degree to 90-degree wingwalls with no bevels

b. Problem No. 2. From example problem no. 4, chapter III, an existing 7 ft by 7 ft concrete box culvert was originally designed for a 50-year flood of 600 ft^3/s and an EL_{hd} of 114 ft. Upstream development has increased the 50-year runoff to 1,000 ft^3/s.

Given:

Inlet Invert Elevation: 100 ft

Existing Entrance Condition: Square Edge

Barrel Slope (S): 5 percent

Roadway Centerline Elevation: 115.5 ft

Culvert Length: 200 ft

Tailwater Information

Flow, ft^3/sec	T.W. (ft)
800	3.8
1,000	4.1
1,200	4.5

Requirements: In order to save the existing culvert barrel, design a new side-tapered inlet that will pass the new 50-year runoff of 1,000 ft^3/s at the original EL_{hd} of 114.0 ft. The side-tapered inlet will be constructed upstream of the existing barrel. Prepare outlet control, throat control, and face control performance curves for the new inlet.

NOTE: Charts 14, 15, 57, and 58 are used in this solution.

PROJECT: EXAMPLE PROBLEM No. 2 CHAPTER IV HDS No. 5

STATION: L-5C

SHEET 1 OF 3

CULVERT DESIGN FORM

DESIGNER/DATE: WJJ / 7/15

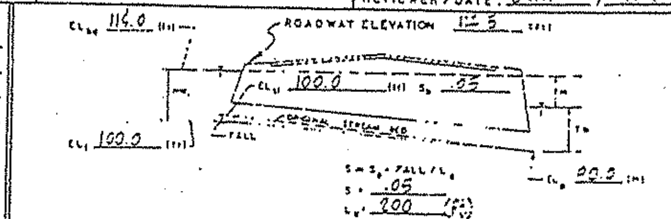
REVIEWER/DATE: JMN / 7/15

HYDROLOGICAL DATA

- METHOD: SCS
- DRAINAGE AREA: 400 Ac. STREAM SLOPE: 5.0 %
- CHANNEL SHAPE: TRAPEZOIDAL
- ROUTING: N/A OTHER: —

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
50	1000	4.1



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/B (1)	INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONC. - BOX - 7'x7' - TAPERED INLET	1000	142.9	2.0	14.0	—	114.0	4.1	≥7	7.0	7.0	0.02	10.0	107.0	114.0	10.5	MEETS EL_{hd}
↓	800	114.3	1.59	11.1	—	111.1	3.8	≥7	7.0	7.0	↓	6.75	103.6	111.1	35.3	PERFORMANCE
↓	1200	171.4	2.48	17.4	—	117.4	4.5	≥7	7.0	7.0	↓	15.0	112.0	117.4	41.0	DATA

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW/D$ OR HW_f/D FROM DESIGN CHARTS

(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) $h_o = TW$ or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L)/R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:

SIDE-TAPERED INLET WILL PASS NEW DESIGN FLOW (1000 ft^3/s) IF ATTACHED TO EXISTING BARREL.

CULVERT BARREL SELECTED:

SIZE: 7' x 7'

SHAPE: BOX

MATERIAL: CONC. n = .012

ENTRANCE: TAPERED INLET

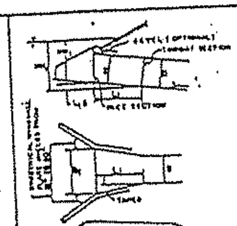
TAPERED INLET DESIGN FORM

PROJECT: EXAMPLE PROBLEM No. 2
CHAPTER IV HDS No. 5

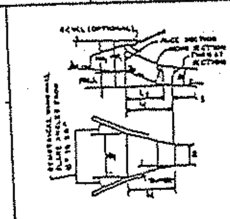
STATION: 6+50
SHEET 2 OF 3

DESIGNER/DATE: WJJ / 7/18
REVIEWER/DATE: JMN / 7/18

DESIGN DATA:
Q 50 , 1000 cfs ; EL_{hi} 116.0 ft
EL. THROAT INVERT 100.0 ft
EL. STREAM BED AT FACE 100.0 ft
FALL — ft TAPER 4 :1 (4:1 TO 6:1)
STREAM SLOPE, S_o = .05 ft/ft
SLOPE OF BARREL, S = .05 ft/ft
S_f — :1 (2:1 TO 3:1)
BARREL SHAPE AND MATERIAL: BOX - CONC.
N = 1 , B = 7 FT. , D = 7 FT.
INLET EDGE DESCRIPTION TAPERED INLET THROAT



SIDE-TAPERED



SLOPE-TAPERED

COMMENTS
FACE IS SIZED FOR 90° WING-WALLS WITH SQUARE EDGES

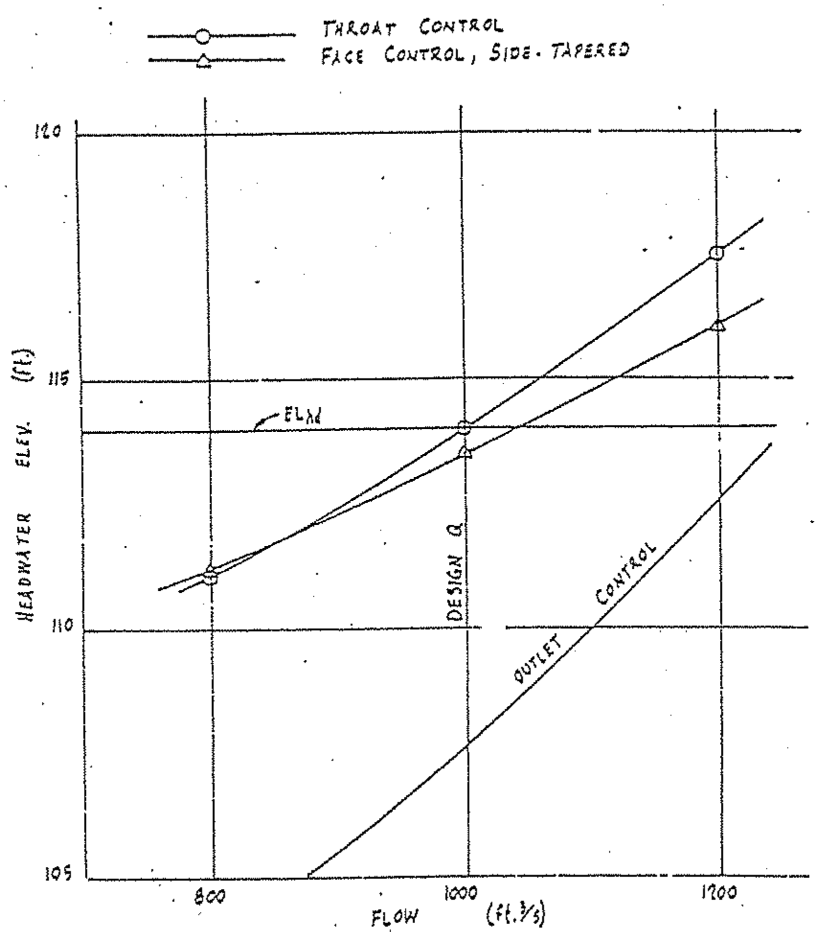
Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f/E (3)	Q/B_f (4)	MIN. B_f (5)	SELECTED B_f	MIN. L_2 (6) (SLOPE-TAPERED ONLY)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	EL. CREST INV. (SIDE-TAPERED W/ FALL)	HW_c (12)	MIN. W (13)
									/	/	/	/	/	10.0	/	/	/
1000	116.0	100.0	101.0	13.0	1.86	86	11.6	12									
1000	113.0	↓	*100.5	12.5	1.79	83	—	↓	}	FACE							
800	110.7	↓	↓	10.2	1.45	67	—	↓	} PER	FORMANCE							
1200	115.5	↓	↓	15.0	2.14	100	—	↓	}	DATA							

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE
(2) $HW_f = EL_{hi}$ - EL. FACE INVERT
(3) 1.1 D ≥ E ≥ D
(4) FROM DESIGN CHARTS
(5) MIN. $B_f = Q/(Q/B_f)$
(6) MIN. $L_2 = 0.5NB$
(7) L_2 = (EL. FACE INVERT - EL. THROAT INVERT) S_f
(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right]$ · TAPER - L_3
(9) IF (8) > (7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right]$ · TAPER - L_2
(10) IF (7) > (8), ADJ. TAPER = $(L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$
(11) SIDE-TAPERED: $L = \left[\frac{B_f - NB}{2}\right]$ · TAPER
SLOPE-TAPERED: $L_1 = L_2 + L_3$
(12) $HW_c = EL_{hi}$ - EL. CREST INVERT
(13) MIN. $W = 0.35Q / HW_c^{1.5}$

SELECTED DESIGN
B_f 12.0
L_1 10.0
L_2 —
L_3 —
BEVELS ANGLE 0°
b = 0 in; d = 0 in
TAPER 4 :1
S_f = — :1

*ACTUAL EL. FACE INVERT = EL$_t$ + $L_1 S$ = 100 + (10.0)(.05) = 100.5 ft.

PERFORMANCE CURVES FOR A 7 FT. x 7 FT. CONCRETE BOX CULVERT
WITH A SIDE-TAPERED INLET



Conclusions:

A side-tapered inlet added to the existing barrel will pass the increased 50-year runoff at the EL_{hd} of 114 ft.

Dimensions:

B = 7 ft D = 7 ft
B_f = 12 ft
TAPER = 4:1
L_1 = 10 ft
Face section has 90-degree wingwalls and square edges.

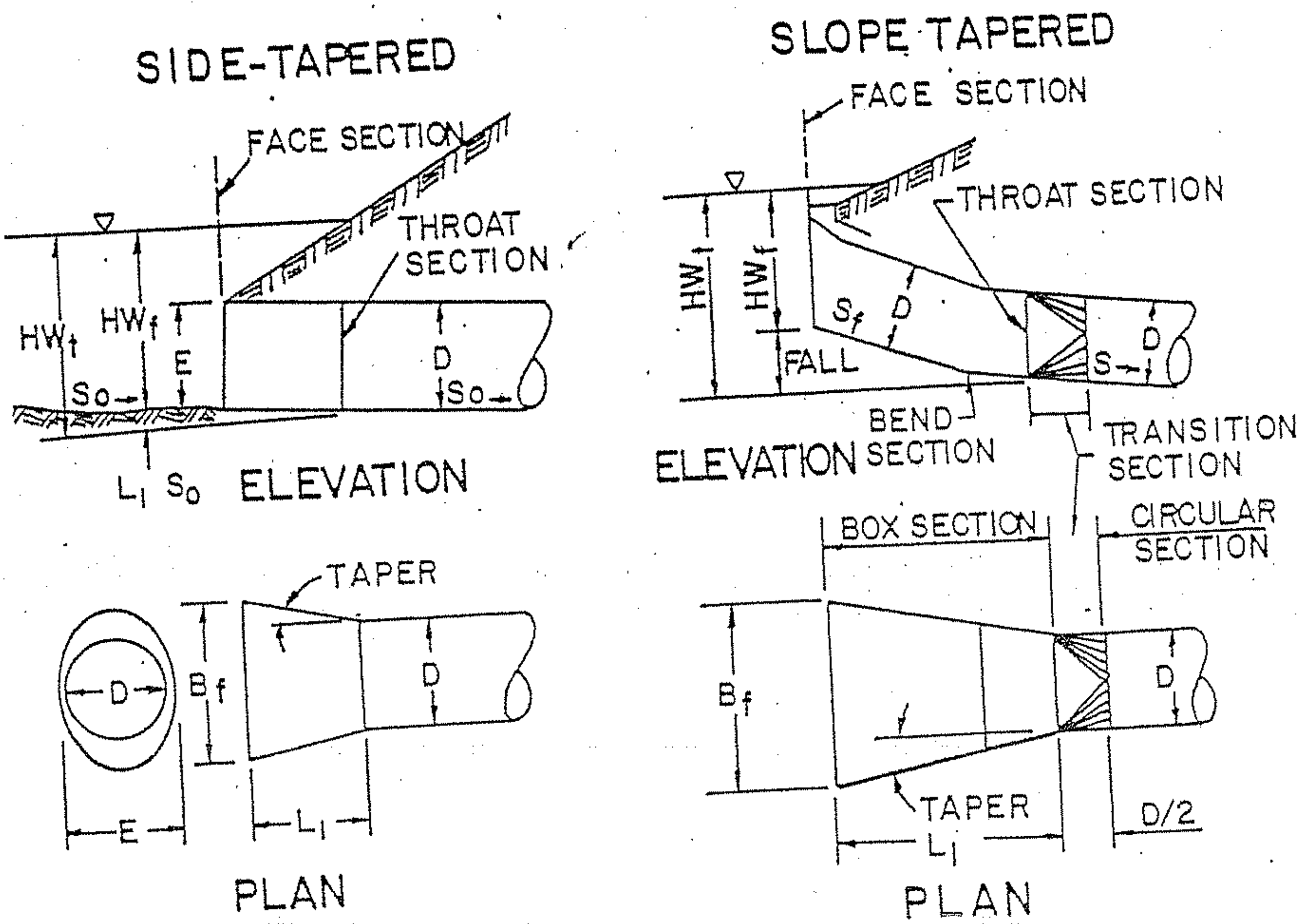


Figure IV-12--Tapered inlets for pipe culverts.

G. Circular Pipe Culverts.

1. Design Procedures. Design procedures and criteria are available for side- and slope-tapered inlets for circular pipe culverts. The inlet designs are shown in figure IV-12. For the side-tapered inlet, either prefabricated inlets with nonrectangular cross sections or cast-in-place rectangular inlets are used. The rectangular inlets are joined to the circular pipe using a square to circular throat transition section.

For slope-tapered inlets, the rectangular designs (vertical or mitered face) are the only option for which design charts are available. The square to circular transition section is used to join the slope-tapered inlet to the circular pipe.

a. Side-tapered Inlets. The throat and face control design nomographs for side-tapered inlets on circular pipe culverts are in appendix D. For throat control, there are two scales on the nomograph: one for smooth inlets and one for rough inlets. The difference in headwater requirement is due to the hydraulic resistance between the face and the throat of the inlet.

The design nomograph for sizing the face of a side-tapered inlet with a nonrectangular face includes three scales. Each scale is for a different edge condition, including thin-edge projecting, square edge, and bevel edged. The face area is larger than the barrel area and may be any nonrectangular shape, including an oval, a circle, a circular segment, or a pipe-arch. To design a rectangular side-tapered inlet for a circular pipe culvert, use the design nomographs in appendix D for rectangular side-tapered inlets. Additional head can be provided on the throat control section of a side-tapered inlet by constructing a depression upstream of the face section. The depression designs are the same as for box culverts.

b. Slope-tapered Inlets. Rectangular inlets are adapted to pipe culverts as shown in figure IV-13. The slope-tapered inlet is connected to the pipe culvert by use of a square to circular transition. The design of the slope-tapered inlet is the same as for box culverts. There are two throat sections, one square and one circular, but the circular throat section will control the flow because its area is much smaller than the square throat section.

2. Multiple Barrel Designs. Each barrel of the culvert must have an individual side-tapered inlet with a non-rectangular face design. For rectangular side-tapered inlets with a square to round transition, double barrel designs are the same as for box culverts. However, the center wall at the transition must be flared to provide adequate space between the pipes for proper backfill and compac-

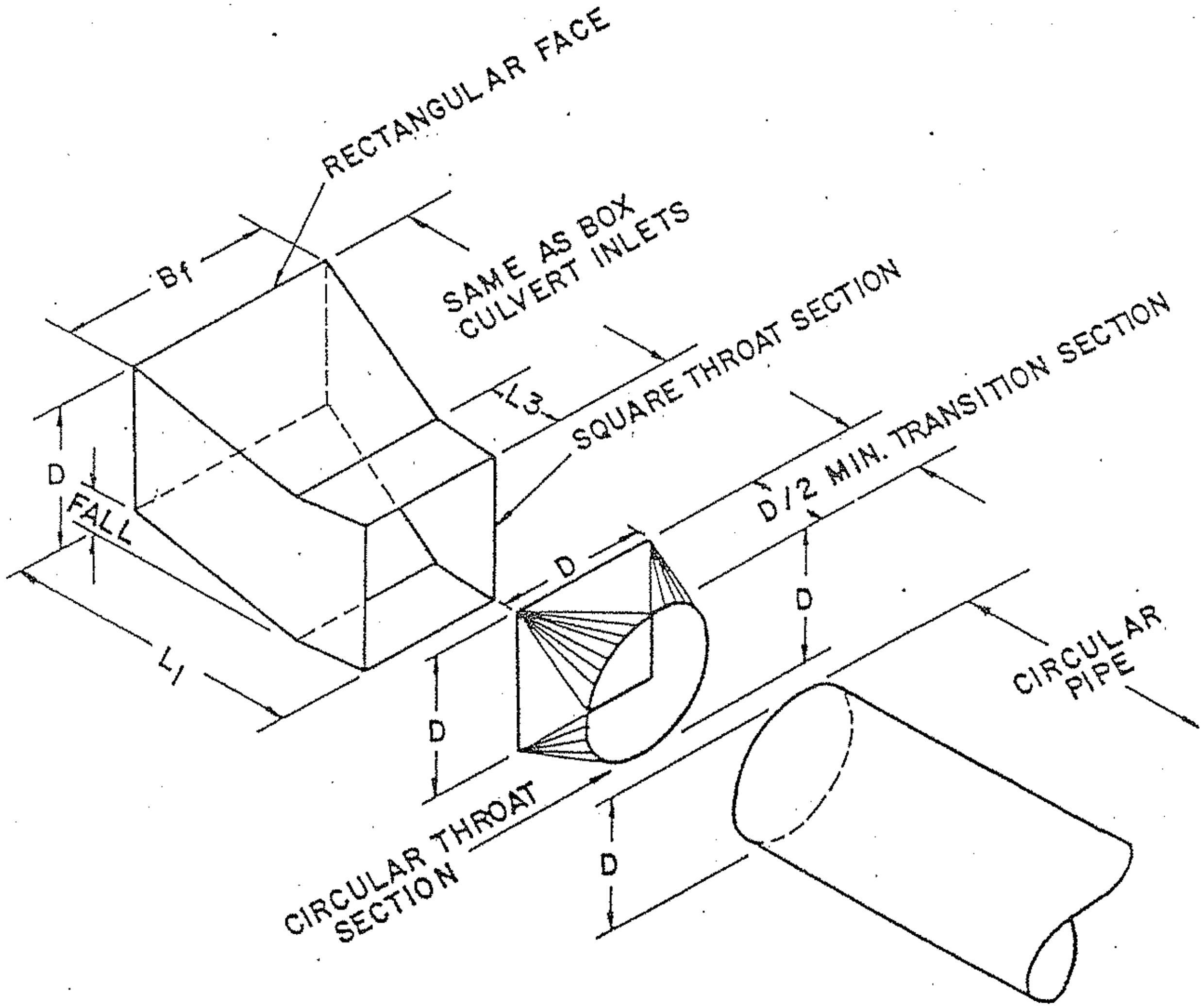


Figure IV-13--Slope-tapered inlet, circular pipe culvert.

tion. The amount of flare required will depend on the size of the pipes and the construction technique used. No more than two circular barrels may feed from the throat section of a rectangular side-tapered inlet.

Double barrel slope-tapered inlets may be designed in the same manner as for rectangular side-tapered designs. Again, no more than two barrels may feed from a single inlet structure.

3. **Dimensional Limitations.** In addition to the dimensional limitations given previously for all tapered inlets, the following criteria apply to the application of rectangular side- and slope-tapered inlets to circular pipe culverts.

a. The transition from the square throat section to the circular throat section must be $\geq D/2$. If excessive lengths are used, the frictional loss within the transition section of the culvert must be considered in the design using equation (12).

b. The square throat dimension must equal the diameter of the circular pipe culvert.

4. **Example Problem.**

a. Problem No. 3

Given:

Q_{50} = 150 ft^3/s

EL_{hd} = 96 ft

Outlet Invert Elevation = 75 ft

Approximate Culvert Length= 350 ft

S_o = 0.05 ft/ft

Shoulder Elevation = 102 ft

The downstream channel approximates a 5-ft bottom width trapezoid with 2:1 side slopes. The Manning n = 0.03

Requirements:

Design a culvert for the above conditions. Use corrugated metal pipe with standard (2-2/3 by 1/2 in) corrugations. Investigate both a corrugated side-tapered inlet and a concrete slope-tapered inlet. Use normal depth in the natural channel as the tailwater depth.

NOTE: Charts 4, 6, 55, and 56 are used in this solution.

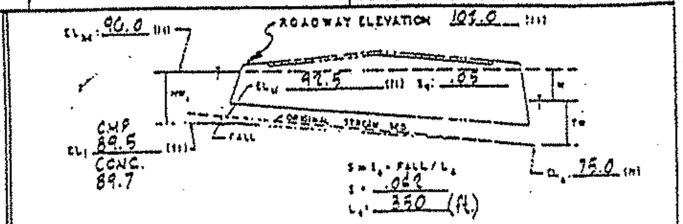
PROJECT: EXAMPLE PROBLEM NO. 3, CHAPTER IV, H.D.S. No. 5	STATION: 6+00 SHEET 1 OF 4	CULVERT DESIGN FORM DESIGNER/DATE: WJJ / 7/18 REVIEWER/DATE: JMN / 7/19

HYDROLOGICAL DATA

- ☐ METHOD: S.C.S.
- ☐ DRAINAGE AREA: 100 Ac. ☐ STREAM SLOPE: 5.0 %
- ☐ CHANNEL SHAPE: TRAPEZOIDAL
- ☐ ROUTING: N/A ☐ OTHER: —

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
50	150	1.6



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
C.M.P. - CIRC. - 48" - ROUGH INLET THROAT	150	—	1.62	6.5	3.0	96.0	1.6	3.6	3.8	3.8	0.25	16.0	94.8	96.0	29.0	O.K.
↓	100	—	1.22	4.9	3.0	94.4	1.4	3.1	3.5	3.5	↓	6.9	85.4	94.4	—	PERFORMANCE DATA
↓	200	—	2.22	8.9	3.0	98.4	1.9	3.4	4.0	4.0	↓	25.0	104.0	104.0	—	PERFORMANCE DATA
C.M.P. - CIRC. - 48" - SMOOTH INLET THROAT	150	—	1.57	6.3	2.8	96.0	1.6	3.0	3.8	3.8	↓	16.0	94.8	96.0	—	O.K.

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW_i/D$ OR HW_i/D FROM DESIGN CHARTS

(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) h_o = TW or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L) / R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:

DESIGN SIDE- & SLOPE- TAPERED INLETS FOR 48" STD. CMP PIPE

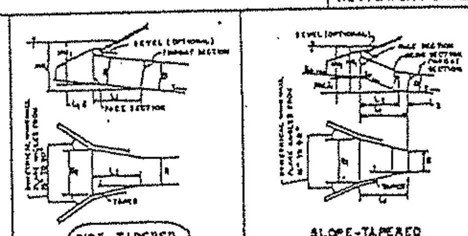
CULVERT BARREL SELECTED:

- SIZE: 48 IN.
- SHAPE: CIRCULAR
- MATERIAL: CMP n .024
- ENTRANCE: TAPERED INLET

PROJECT: EXAMPLE PROBLEM NO. 3, CHAPTER IV, H.D.S. No. 5	STATION: 6+00 SHEET 2 OF 4	TAPERED INLET DESIGN FORM DESIGNER/DATE: WJJ / 7/18 REVIEWER/DATE: JMN / 7/19

DESIGN DATA:

- Q50 = 150 cfs; EL_{hd}: 96.0 ft
- EL. THROAT INVERT: 89.5 ft
- EL. STREAM BED AT FACE: 92.5 ft
- FALL: 3.0 ft; TAPER: 4 :1 (4:1 TO 6:1)
- STREAM SLOPE, S_o = .05 ft/ft
- SLOPE OF BARREL, S = .042 ft/ft
- S_f = — :1 (2:1 TO 3:1)
- BARREL SHAPE AND MATERIAL: CIRC. - STD. C.M.P.
- N = 1, B = —, D = 48"
- INLET EDGE DESCRIPTION: ROUGH TAPERED INLET



COMMENTS

USE BEVELED EDGE ENTRANCE ON FACE OF TAPERED INLET

Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	$\frac{HW_f}{E}$ (3)	$\frac{Q}{B_f}$ (4)	MIN. B_f (5)	SELECTED B_f	SLOPE-TAPERED ONLY: MIN. L_2 (6)	L_3 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	SIDE-TAPERED W/ FALL: EL. CREST INV.	HW_c (12)	MIN. W (13)
150	190.0	189.5	190.5	5.5	1.38	25	6.0	6.0	/	/	/	/	/	4.0	93.0	3.0	10.1
100	194.1	↓	*189.7	4.2	1.06	17	←	PERFORMANCE DATA	FACE PERFORMANCE DATA								
200	196.9	↓	↓	7.2	1.81	33	←										
150	195.2	↓	↓	5.5	1.38	25	←										

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE

(2) $HW_f = EL_{hi}$ - EL. FACE INVERT

(3) $1.1 D^* \geq E \geq D$

(4) FROM DESIGN CHARTS

(5) MIN. $B_f = Q/(Q/B_f)$

(6) MIN. $L_2 = 0.5 NB$

(7) L_3 = (EL. FACE INVERT - EL. THROAT INVERT) S_f

(8) CHECK $L_2 \left[\frac{B_f - NB}{2}\right]$ · TAPER - L_3

(9) IF (8) > (7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right]$ · TAPER - L_2

(10) IF (7) > (8), ADJ. TAPER = $(L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$

(11) SIDE-TAPERED: $L = \left[\frac{B_f - NB}{2}\right]$ · TAPER
SLOPE-TAPERED: $L = L_2 + L_3$

(12) $HW_c = EL_{hi}$ - EL. CREST INVERT

(13) MIN. $W = 0.35 Q / HW_c^{1.5}$

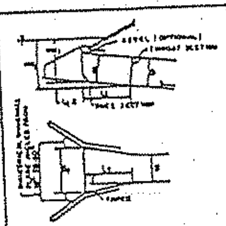
SELECTED DESIGN

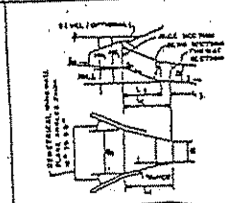
- B_f: 6.0
- L_1: 4.0
- L_2: —
- L_3: —
- BEVELS ANGLE 45°, b = —, d = 3.0 in
- TAPER: 4.0 :1
- S_f = — :1

*ACTUAL EL. FACE INVERT = $EL_t + L_1 S$ = 189.5 + (4)(.042) = 189.7 ft.

PROJECT: EXAMPLE PROBLEM No. 3 CHAPTER IV, H.D.S. No. 5	STATION: 0+00 SHEET 3 OF 4	TAPERED INLET DESIGN FORM DESIGNER / DATE: WJJ / 7/13 REVIEWER / DATE: JHY / 7/19

DESIGN DATA:
Q50 = 150 cfs ; EL hd = 96.0 ft
EL. THROAT INVERT 89.7 ft
EL. STREAM BED AT FACE 92.5 ft
FALL 2.8 ft TAPER 4 :1 (4:1 TO 6:1)
STREAM SLOPE, So = .05 ft/ft
SLOPE OF BARREL, S = .062 ft/ft
S_f 2 :1 (2:1 TO 3:1)
BARREL SHAPE AND MATERIAL: CIRC. - ST'D. C.M.P.
N = 1, B = —, D = 48"
INLET EDGE DESCRIPTION SMOOTH TAPERED INLET THROAT


SIDE - TAPERED


SLOPE - TAPERED

COMMENTS
USE 45° TO 90° WINGWALLS WITH BEVELS ON TOP AND SIDES.

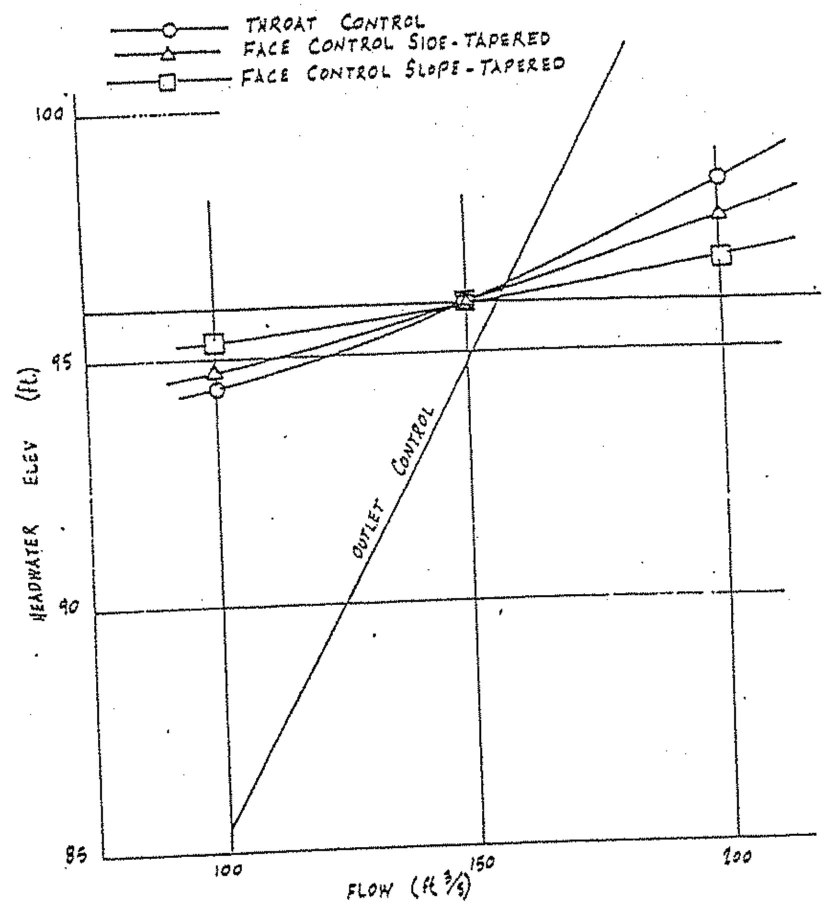
Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f/D (3)	Q/B_f (4)	MIN. B_f (5)	SELECTED B_f	SLOPE-TAPERED ONLY: MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	SIDE-TAPERED W/ FALL: EL. CREST INV.	HW_c (12)	MIN. W (13)
150	96.0	89.7	92.5	3.5	0.88	19	7.9	8.0	2.0	5.0	6.0	2.4	—	8.0	/	/	/
150	96.0	↓	↓	3.5	0.88	19	—	8.0	FACE								
100	95.3	↓	↓	2.8	0.69	13	—	↓	PERFORMANCE								
200	96.8	↓	↓	4.3	1.07	25	—	↓	DATA								

(1) SIDE - TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE - TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE
(2) $HW_f = EL_{hi}$ - EL. FACE INVERT
(3) $1.1 D \geq E \geq D$
(4) FROM DESIGN CHARTS
(5) MIN. $B_f = Q/(Q/B_f)$
(6) MIN. $L_3 = 0.5 NB$
(7) L_2 = (EL. FACE INVERT - EL. THROAT INVERT) S_f
(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right]$ · TAPER - L_3
(9) IF (8) > (7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right]$ · TAPER - L_2
(10) IF (7) > (8), ADJ. TAPER = $(L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$
(11) SIDE - TAPERED: $L = \left[\frac{B_f - NB}{2}\right]$ · TAPER
SLOPE - TAPERED: $L_1 = L_2 + L_3$
(12) $HW_c = EL_{hi}$ - EL. CREST INVERT
(13) MIN. $W = 0.35 Q / HW_c^{1.5}$

SELECTED DESIGN
B_f 8.0
L_1 8.0
L_2 5.0
L_3 2.4
BEVELS ANGLE 45°
b = 2 in, d = 2 in
TAPER 4 :1
S_f = 2 :1

PERFORMANCE CURVES FOR A 18" C.M.P. PIPE

CULVERT WITH SIDE AND SLOPE TAPERED INLETS



Conclusions: The selection of a side-tapered or a slope-tapered inlet would be based on economics since either design will pass the required Q at the EL_{hd} of 96 ft.

Dimensions:

Corrugated metal side-tapered inlet :
$D = 48$ in
$B_f = 6$ ft
TAPER = 4:1
$L_1 = 4$ ft
Face Edge Configuration: Beveled edges.
Min W= 10 ft

Smooth slope-tapered inlet, vertical face:

$D = 48$ in
$B_f = 8$ ft
$S_f = 2:1$
$L_1 = 8$ ft
$L_2 = 5.6$ ft
$L_3 = 2.4$ ft

Face Edge Configuration: 45-degree to 90-degree wingwalls with bevels on the top and sides.

H. Standard Designs

Standard structural designs for tapered inlets are found in the FHWA publication Structural Design Manual for Improved Inlets and Culverts. (26) The following standard designs are included.

1. Side-tapered Single Cell Box Inlets.
2. Side-tapered Two Cell Box Inlets.
3. Slope-tapered Single Cell Box Inlets.
4. Slope-tapered Two Cell Box Inlets
5. Side-tapered Pipe Inlet (Concrete).
6. Side-tapered Corrugated Metal Inlet.
7. Headwall Details For Box Inlets.
8. Headwall Details For Pipe Inlets.
9. Cantilever Wingwall Designs.
10. Miscellaneous Improved Inlet Details.
    a. Apron with Wingwalls < 60-degrees
    b. Apron with Wingwalls at 60-degrees to 90-degrees
    c. Circular to Square Transition Detail
    d. Skewed Headwall Details

The reference also contains structural design methods for culverts and inlets, including information on related structural design computer programs.

A. Introduction.

This appendix contains explanations of the equations and methods used to develop the design charts of this publication, where those equations and methods are not fully described in the main text. The following topics are discussed: the design equations for the unsubmerged and submerged inlet control nomographs, the dimensionless design curves for culvert shapes and sizes without nomographs, and the dimensionless critical depth charts for long span culverts and corrugated metal box culverts.

B. Inlet Control Nomograph Equations.

The design equations used to develop the inlet control nomographs are based on the research conducted by the National Bureau of Standards (NBS) under the sponsorship of the Bureau of Public Roads (now the Federal Highway Administration). Seven progress reports were produced as a result of this research. Of these, the first and fourth through seventh reports dealt with the hydraulics of pipe and box culvert entrances, with and without tapered inlets. (4,7 to 10) These reports were one source of the equation coefficients and exponents, along with other references and unpublished FHWA notes on the development of the nomographs. (56,57)

The two basic conditions of inlet control depend upon whether the inlet end of the culvert is or is not submerged by the upstream headwater. If the inlet is not submerged, the inlet performs as a weir. If the inlet is submerged, the inlet performs as an orifice. Equations are available for each of the above conditions.

Between the unsubmerged and the submerged conditions, there is a transition zone for which the NBS research provided only limited information. The transition zone is defined empirically by drawing a curve between and tangent to the curves defined by the unsubmerged and submerged equations. In most cases, the transition zone is short and the curve is easily constructed.

Table 8 contains the unsubmerged and submerged inlet control design equations. Note that there are two forms of the unsubmerged equation. Form (1) is based on the specific head at critical depth, adjusted with two correction factors. Form (2) is an exponential equation similar to a weir equation. Form (1) is preferable from a theoretical standpoint, but form (2) is easier to apply and is the only documented form of equation for some of the inlet control nomographs. Either form of unsubmerged inlet control equation will produce adequate results.

The constants for the equations in table 8 are given in table 9. Table 9 is arranged in the same order as the design nomographs in appendix D, and provides the unsubmerged and submerged equation coefficients for each shape, material, and edge configuration. For the unsubmerged equations, the form of the equation is also noted.

Table 8
Inlet control design equations.

UNSUBMERGED [1]

Form (1) $$\frac{HW_i}{D} = \frac{H_c}{D} + K\left[\frac{Q}{AD^{0.5}}\right]^M - 0.5S\ ^{2} \qquad (26)$$

Form (2) $$\frac{HW_i}{D} = K\left[\frac{Q}{AD^{0.5}}\right]^M \qquad (27)$$

SUBMERGED [3]

$$\frac{HW_i}{D} = c\left[\frac{Q}{AD^{0.5}}\right]^2 + Y - 0.5S\ ^{2} \qquad (28)$$

Definitions

HW_i	Headwater depth above inlet control section invert, ft
D	Interior height of culvert barrel, ft
H_c	Specific head at critical depth ($d_c + V_c^2/2g$), ft
Q	Discharge, ft^3/s
A	Full cross sectional area of culvert barrel, ft^2
S	Culvert barrel slope, ft/ft
K,M,c,Y	Constants from table 9

NOTES:
1. Equations (26) and (27) (unsubmerged) apply up to about $Q/AD^{0.5} = 3.5$.
2. For mitered inlets use +0.7S instead of -0.5S as the slope correction factor.
3. Equation (28) (submerged) applies above about $Q/AD^{0.5} = 4.0$.

A. Introduction.

This appendix contains explanations of the equations and methods used to develop the design charts of this publication, where those equations and methods are not fully described in the main text. The following topics are discussed: the design equations for the unsubmerged and submerged inlet control nomographs, the dimensionless design curves for culvert shapes and sizes without nomographs, and the dimensionless critical depth charts for long span culverts and corrugated metal box culverts.

B. Inlet Control Nomograph Equations.

The design equations used to develop the inlet control nomographs are based on the research conducted by the National Bureau of Standards (NBS) under the sponsorship of the Bureau of Public Roads (now the Federal Highway Administration). Seven progress reports were produced as a result of this research. Of these, the first and fourth through seventh reports dealt with the hydraulics of pipe and box culvert entrances, with and without tapered inlets. (4,7 to 10) These reports were one source of the equation coefficients and exponents, along with other references and unpublished FHWA notes on the development of the nomographs. (56,57)

The two basic conditions of inlet control depend upon whether the inlet end of the culvert is or is not submerged by the upstream headwater. If the inlet is not submerged, the inlet performs as a weir. If the inlet is submerged, the inlet performs as an orifice. Equations are available for each of the above conditions.

Between the unsubmerged and the submerged conditions, there is a transition zone for which the NBS research provided only limited information. The transition zone is defined empirically by drawing a curve between and tangent to the curves defined by the unsubmerged and submerged equations. In most cases, the transition zone is short and the curve is easily constructed.

Table 8 contains the unsubmerged and submerged inlet control design equations. Note that there are two forms of the unsubmerged equation. Form (1) is based on the specific head at critical depth, adjusted with two correction factors. Form (2) is an exponential equation similar to a weir equation. Form (1) is preferable from a theoretical standpoint, but form (2) is easier to apply and is the only documented form of equation for some of the inlet control nomographs. Either form of unsubmerged inlet control equation will produce adequate results.

The constants for the equations in table 8 are given in table 9. Table 9 is arranged in the same order as the design nomographs in appendix D, and provides the unsubmerged and submerged equation coefficients for each shape, material, and edge configuration. For the unsubmerged equations, the form of the equation is also noted.

Table 9

Constants for inlet control design equations.

CHART NO.	SHAPE AND MATERIAL	NOMOGRAPH SCALE	INLET EDGE DESCRIPTION	UNSUBMERGED EQUATION FORM	UNSUBMERGED K	UNSUBMERGED M	SUBMERGED c	SUBMERGED Y	References
1	Circular Concrete	1	Square edge w/headwall	1	0.0098	2.0	0.0398	0.67	(56) (57)
		2	Groove end w/headwall		.0078	2.0	.0292	.74	(56) (57)
		3	Groove end projecting		.0045	2.0	.0317	.69	(56) (57)
2	Circular CMP	1	Headwall	1	.0078	2.0	.0379	.69	(56) (57)
		2	Mitered to slope		.0210	1.33	.0463	.75	(57)
		3	Projecting		.0340	1.50	.0553	.54	(57)
3	Circular	A	Beveled ring, 45° bevels	1	.0018	2.50	.0300	.74	(57)
		B	Beveled ring, 33.7° bevels*		.0018	2.50	.0243	.83	(57)
8	Rectangular Box	1	30° to 75° wingwall flares		.026	1.0	.0385	.81	(56)
		2	90° and 15° wingwall flares	1	.061	0.75	.0400	.80	(56)
		3	0° wingwall flares		.061	0.75	.0423	.82	(8)
9	Rectangular Box	1	45° wingwall flare d=.0430	2	.510	.667	.0309	.80	(8)
		2	18° to 33.7° wingwall flare d=.0830		.486	.667	.0249	.83	(8)
10	Rectangular Box	1	90° headwall w/3/4" chamfers	2	.515	.667	.0375	.79	(8)
		2	90° headwall w/45° bevels		.495	.667	.0314	.82	(8)
		3	90° headwall w/33.7° bevels		.486	.667	.0252	.865	(8)
11	Rectangular Box	1	3/4" chamfers; 45° skewed headwall	2	.522	.667	.0402	.73	(8)
		2	3/4" chamfers; 30° skewed headwall		.533	.667	.0425	.705	(8)
		3	3/4" chamfers; 15° skewed headwall		.545	.667	.04505	.68	(8)
		4	45° bevels; 10°-45° skewed headwall		.498	.667	.0327	.75	(8)
12	Rectangular Box 3/4" chamfers	1	45° non-offset wingwall flares	2	.497	.667	.0339	.803	(8)
		2	18.4° non-offset wingwall flares		.493	.667	.0361	.806	(8)
		3	18.4° non-offset wingwall flares 30° skewed barrel		.495	.667	.0386	.71	(8)
13	Rectangular Box Top Bevels	1	45° wingwall flares - offset	2	.497	.667	.0302	.835	(8)
		2	33.7° wingwall flares - offset		.495	.667	.0252	.881	(8)
		3	18.4° wingwall flares - offset		.493	.667	.0227	.887	(8)
16-19	C M Boxes	1	90° headwall	1	.0083	2.0	.0379	.69	(57)
		2	Thick wall projecting		.0145	1.75	.0419	.64	(57)
		3	Thin wall projecting		.0340	1.5	.0496	.57	(57)

Table 9 (continued)

Constants for inlet control design equations.

CHART NO.	SHAPE AND MATERIAL	NOMOGRAPH SCALE	INLET EDGE DESCRIPTION	UNSUBMERGED EQUATION FORM	UNSUBMERGED K	UNSUBMERGED M	SUBMERGED c	SUBMERGED Y	Reference
29	Horizontal	1	Square edge with headwall	1	0.0100	2.0	.0398	.67	(57)
	Ellipse	2	Groove end with headwall		.0018	2.5	.0292	.74	(57)
	Concrete	3	Groove end projecting		.0045	2.0	.0317	.69	(57)
30	Vertical	1	Square edge with headwall	1	.0100	2.0	.0398	.67	(57)
	Ellipse	2	Groove end with headwall		.0018	2.5	.0292	.74	(57)
	Concrete	3	Groove end projecting		.0095	2.0	.0317	.69	(57)
34	Pipe Arch	1	90° headwall	1	.0083	2.0	.0496	.57	(57)
	18" Corner	2	Mitered to slope		.0300	1.0	.0463	.75	(57)
	Radius CM	3	Projecting		.0340	1.5	.0496	.53	(57)
35	Pipe Arch	1	Projecting	1	.0296	1.5	.0487	.55	(56)
	18" Corner	2	No Bevels		.0087	2.0	.0361	.66	(56)
	Radius CM	3	33.7° Bevels		.0030	2.0	.0264	.75	(56)
36	Pipe Arch	1	Projecting	1	.0296	1.5	.0487	.55	(56)
	31" Corner		No Bevels		.0087	2.0	.0361	.66	(56)
	Radius CM		33.7° Bevels		.0030	2.0	.0264	.75	(56)
40-42	Arch CM	1	90° headwall	1	.0083	2.0	.0379	.69	(57)
		2	Mitered to slope		.0300	2.0	.0463	.75	(57)
		3	Thin wall projecting		.0340	1.5	.0496	.57	(57)
54	Circular	1	Smooth tapered inlet throat	2	.534	.555	.0196	.89	(3)
		2	Rough tapered inlet throat		.519	.64	.0289	.90	(3)
55	Elliptical	1	Tapered inlet-beveled edges	2	.536	.622	.0368	.83	(3)
	Inlet Face	2	Tapered inlet-square edges		.5035	.719	.0478	.80	(3)
		3	Tapered inlet-thin edge projecting		.547	.80	.0598	.75	(3)
56	Rectangular	1	Tapered inlet throat	2	.475	.667	.0179	.97	(3)
57	Rectangular	1	Side tapered-less favorable edges	2	.56	.667	.0466	.85	(3)
	Concrete	2	Side tapered-more favorable edges		.56	.667	.0378	.87	(3)
58	Rectangular	1	Slope tapered-less favorable edges	2	.50	.667	.0466	.65	(3)
	Concrete		Slope tapered-more favorable edges		.50	.667	.0378	.71	(3)

The equations may be used to develop design curves for any conduit shape or size. Careful examination of the equation constants for a given form of equation reveals that there is very little difference between the constants for a given inlet configuration. Therefore, given the necessary conduit geometry for a new shape from the manufacturer, a similar shape is chosen from table 9, and the constants are used to develop new design curves. The curves may be quasi-dimensionless, in terms of $Q/AD^{0.5}$ and HW_i/D, or dimensional, in terms of Q and HW_i for a particular conduit size. To make the curves truly dimensionless, $Q/AD^{0.5}$ must be divided by $g^{0.5}$, but this results in small decimal numbers. Note that coefficients for rectangular (box) shapes should not be used for nonrectangular (circular, arch, pipe-arch, etc.) shapes and vice-versa. A constant slope value of 2 percent (0.02) is usually selected for the development of design curves. This is because the slope effect is small and the resultant headwater is conservatively high for sites with slopes exceeding 2 percent (except for mitered inlets).

Example: Develop a dimensionless design curve for elliptical structural plate corrugated metal culverts, with the long axis horizontal. Assume a thin wall projecting inlet. Use the coefficients and exponents for a corrugated metal pipe-arch, a shape similar to an ellipse.

From table 9, chart 34, scale 3:

Unsubmerged: equation form (1)
K = .0340
M = 1.5

Submerged: c = .0496
Y = 0.53

From table 8:

Unsubmerged, equation form 1 (equation 26):

$$\frac{HW_i}{D} = \frac{H_c}{D} + .0340\left(\frac{Q}{AD^{0.5}}\right)^{1.5} - (0.5)(0.02)$$

Submerged (equation 28):

$$\frac{HW_i}{D} = 0.0496\left(\frac{Q}{AD^{0.5}}\right)^{2} + 0.53 - (.5)(0.02)$$

A direct relationship between HW_i/D and $Q/AD^{0.5}$ may be obtained for the submerged condition. For the unsubmerged condition, it is necessary to obtain the flow rate and equivalent specific head at critical depth. At critical depth, the critical velocity head is equal to one-half the hydraulic depth.

$$\frac{V_c^2}{2g} = \frac{y_h}{2} = \frac{A_p}{2T_p}$$

Therefore:

$$\frac{H_c}{D} = \frac{d_c}{D} + \frac{y_h}{2D} \qquad (29)$$

Also, at critical depth, the Froude number equals 1.0.

$$F_r = \frac{V_c}{(gy_h)^{0.5}} = 1$$

Setting $V_c = Q_c/A_p$

$Q_c = A_p\,(gy_h)^{0.5}$, or

$$\frac{Q_c}{AD^{0.5}} = \frac{A_p}{A}\left(g \cdot \frac{y_h}{D}\right)^{0.5} \qquad (30)$$

From geometric data supplied by the manufacturer for a horizontal ellipse (58), the necessary geometry is obtained to calculate H_c/D and $Q_c/AD^{0.5}$.

d_c/D	y_h/D	(From equation 29) H_c/D	A_p/A	(From (equation 30) $Q_c/AD^{0.5}$
0.1	0.04	0.12	0.04	0.05
0.2	.14	0.27	.14	0.30
0.4	.30	.55	.38	1.18
0.6	.49	.84	.64	2.54
0.8	.85	1.22	.88	4.60
0.9	1.27	1.53	.97	6.20
1.0	---	---	1.00	---

From unsubmerged equation (26) with the appropriate constants for unsubmerged flow:

$Q_c/AD^{0.5}$	$.0340 \times (Q_c/AD^{0.5})^{1.5}$	$+ H_c/D$	$- 0.5S =$	HW_i/D
0.05	0.0004	0.12	0.01	0.11
0.30	.0054	0.27	.01	.27
1.18	.044	.55	.01	.58
2.54	.138	.84	.01	.55
4.60	.336	1.22	.01	1.54
6.20	.525	1.53	.01	2.05
---	---			

For the submerged equation, any value of $Q/AD^{0.5}$ may be selected, since critical depth is not involved. From equation (28), with the appropriate constants:

$Q/AD^{0.5}$	$.0496 \times (Q/AD^{0.5})^2$	+ Y	- 0.5S =	HW_i/D
1.0	0.05	0.53	0.01	*0.57
2.0	.20	0.53	.01	*.72
4.0	.79	0.53	.01	1.31
6.0	1.79	0.53	.01	2.31
8.0	3.17	0.53	.01	3.69

*Obviously unsubmerged

Note that overlapping values of HW_i/D were calculated in order to define the transition zone between the unsubmerged and the submerged states of flow.

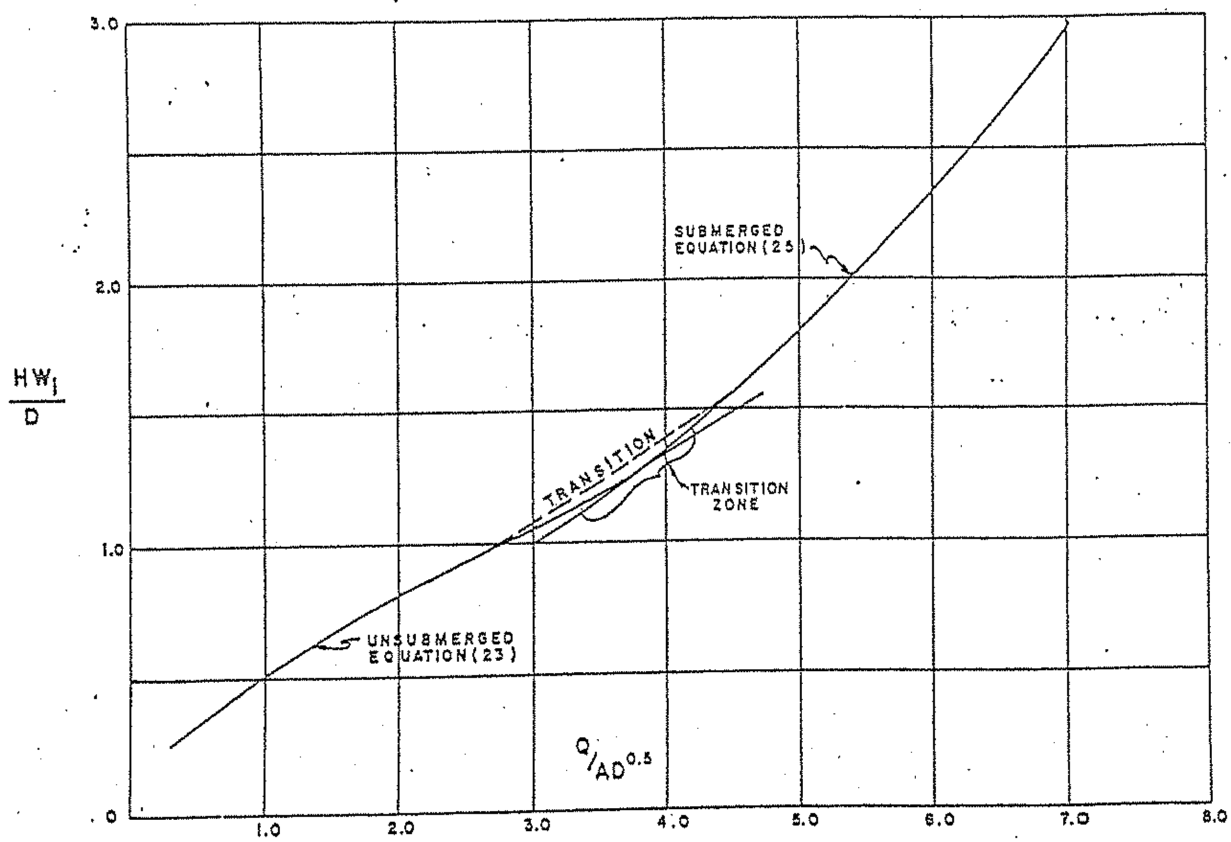


Figure A-1--Dimensionless performance curve for structural plate elliptical conduit, long axis horizontal, thin wall projecting entrance.

The results of the above calculations are plotted in figure A-1. A transition line is drawn between the unsubmerged and the submerged curves. The scales are dimensionless in figure A-1, but the figures could be used to develop dimensional curves for any selected size of elliptical conduit by multiplying $Q/AD^{0.5}$ by $AD^{0.5}$ and HW_i/D by D.

Similar calculations were used to develop the dimensionless inlet control design curves for the long span arches and elliptical pipe in chapter III.

To derive overall inlet control equations for use on a computer, it is necessary to plot the unsubmerged and submerged curves from these equations and draw the connecting transition line. Then, the coordinates of selected points can be read from the curve and a best fit statistical analysis performed. A polynomical curve of the following form has been found to provide an adequate fit.

$$\frac{HW_i}{D} = A' + B'\left[\frac{Q}{BD^{1.5}}\right] + C'\left[\frac{Q}{BD^{1.5}}\right]^2 + \ldots + X'\left[\frac{Q}{BD^{1.5}}\right]^n$$

The flow factor could be based on $AD^{0.5}$ rather than $BD^{1.5}$. The constants for the best fit equations are found in the user's manuals for various computer programs (20,53,54,55,59).

C. Development of Dimensionless Inlet Control Design Charts.

The dimensionless inlet control design charts provided for long span arches, circular and elliptical pipes were derived using the equations presented in table 13, selected constants from table 9, conduit geometry obtained from various tables, and manufacturer's information. (58,60,61) There are several inlet edge configurations for which no hydraulic tests have been performed. In lieu of such tests, the selected edge conditions should approximate the untested configurations and lead to a good estimate of culvert performance. In some cases, it will be necessary to evaluate the inlet edge configuration at a specific flow depth. For example, some inlets may behave as mitered inlets at low headwaters and as thin wall projecting inlets at high headwaters. The designer must apply engineering judgment in selection of the proper relationships for these major structures.

1. Unsubmerged Conditions. Equation (26) was used to calculate HW_i/D for selected inlet edge configurations. The following constants were taken from table 9, chart 34 for pipe-arches, except for the 45 degree beveled edge inlet. These constants were taken from chart 3, scale A, for circular pipe. No constants were available from tests on pipe-arch models with beveled edges.

Inlet Edge	K	M	Slope Correction
Thin wall projecting	0.0340	1.5	-0.01
Mitered to Embankment	.0300	1.0	+0.01
Square edge in headwall	.0083	2.0	-0.01
Beveled edge (45° bevels)	.0018	2.5	-0.01

Geometric relationships for the circular and elliptical (long axis horizontal) conduits were obtained from reference (60), tables 4 and 7 respectively. Geometric relationships for the high and low profile long span arches were obtained from reference (58) and the results were checked against tables in reference (61).

2. Submerged Conditions. Equation (28) was used to calculate HW_i/D for the same inlet configurations using the following constants:

Inlet Edge	c	Y	Slope Correction
Thin wall projecting	0.0496	0.53	-0.01
Mitered to Embankment	.0463	.75	+ .01
Square edge in headwall	.0496	.57	- .01
Beveled edge (45° bevels)	.0300	.74	- .01

In terms of $Q/AD^{0.5}$, all non-rectangular shapes have practically the same dimensionless curves for submerged, inlet control flow. This is not true if $Q/BD^{1.5}$ is used as the dimensionless flow parameter. To convert $Q/BD^{1.5}$ to $Q/AD^{0.5}$, divide by A/BD for the particular shape of interest as shown in equation (31). This assumes that the shape is geometrically similar, so that A/BD is nearly constant for a range of sizes.

$$\frac{Q/BD^{1.5}}{(A/BD)} = \left(\frac{Q}{BD^{1.5}}\right)\left(\frac{BD}{A}\right) = \frac{Q}{AD^{0.5}} \qquad (31)$$

3. Dimensionless Curves. By plotting the results of the unsubmerged and submerged calculations and connecting the resultant curves with transition lines, the dimensionless design curves shown in charts 51 and 52 were developed. All high and low profile arches can be represented by a single curve for each inlet edge configuration. A similar set of curves was developed for circular and elliptical shapes. It is recommended that the high and low profile arch curves in chart 52 be used for all true arch shapes (those with a flat bottom) and that the curves in chart 51 be used for curved shapes including circles, ellipses, pipe-arches, and pear shapes.

D. Dimensionless Critical Depth Charts.

Some of the long span culverts and special culvert shapes had no critical depth charts. These special shapes are available in numerous sizes, making it impractical to produce individual critical depth curves for each culvert size and shape. Therefore, dimensionless critical depth curves were developed for the shapes which have adequate geometric relationships in the manufacturer's literature. (58) It should be noted that these special shapes are not truly geometrically similar, and any generalized set of geometric relationships will involve some degree of error. The amount of error is unknown since the geometric relationships were developed by the manufacturers.

The manufacturers' literature contains geometric relationships which include the hydraulic depth divided by the rise (inside height) of the conduit (y_h/D) and area of the flow prism divided by the barrel area (A_p/A) for various partial depth ratios, y/D. From equation (30):

$$\frac{Q}{AD^{0.5}} = \frac{A_p}{A}\left(g \cdot \frac{y_h}{D}\right)^{0.5} \quad (32)$$

Setting y/D equal to d_c/D, it is possible to determine A_p/A and y_h/D at a given relative depth and then to calculate $Q/AD^{0.5}$.

Dimensionless plots of d_c/D versus $Q_c/AD^{0.5}$ have been developed for the following culvert materials and shapes:

1. Structural plate corrugated metal box culverts with the following span to rise (B/D) ratios:

$B/D < 0.3$

$0.3 \leq B/D < 0.4$

$0.4 \leq B/D < 0.5$

$B/D \geq 0.5$

2. Structural plate corrugated metal arches with the following B/D ratios:

$0.3 \leq B/D < 0.4$

$0.5 \leq B/D \leq 0.5$

3. Structural plate corrugated metal ellipses, long axis horizontal.

4. Low profile, long span, structural plate corrugated metal arches.

5. High profile, long span, structural plate corrugated metal arches with the following B/D ratios:

$B/D \leq 0.56$

$B/D > 0.56$

E. Precision of Nomographs.

In formulating inlet and outlet control design nomographs, a certain degree of error is introduced into the design process. This error is due to the fact that the nomograph construction involves graphical fitting techniques resulting in scales which do not exactly match the equations. Checks by the authors and others indicate that all of the nomographs from HEC No. 5 have precisions of ± 10 percent of the equation values in terms of headwater (inlet control) or head loss (outlet control).

Extensive checking of the corrugated aluminum structural plate conduit nomographs provided by Kaiser aluminum indicates that most are within ± 5 percent, except for the outlet control nomograph for structural plate corrugated metal box culverts. This nomograph is within the ± 10 percent range of precision.

The new nomographs constructed for tapered inlets have errors of less than 5%, again in terms of headwater or head loss.

HYDRAULIC RESISTANCE OF CULVERT BARRELS

A. General.

In outlet control, the hydraulic resistance of the culvert barrel must be calculated using a friction loss equation. Numerous equations, both theoretical and empirical, are available, including the Darcy equation and the Manning equation. The Darcy equation, shown in equation (33), is theoretically correct, and is described in most hydraulic texts.

$$h_f = f \left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right) \qquad (33)$$

h_f is the friction head loss, ft

f is the Darcy resistance factor

L is the conduit length, ft

D is the conduit diameter, ft

V is the mean velocity, ft/s

g is the acceleration due to gravity, 32.2 ft/s/s

The Darcy friction factor, f, is selected from a chart commonly referred to as the Moody diagram, which relates f to Reynolds number (flow velocity, conduit size, and fluid viscosity) and relative roughness (ratio of roughness element size to conduit size). To develop resistance coefficients for new and untested wall roughness configurations, the Darcy f value can be derived theoretically and then converted to a Manning n value through use of the relationship shown in equation (34).

$$n = 0.0926\, R^{1/6} f^{1/2} \qquad (34)$$

R is the hydraulic radius, ft

A comprehensive discussion of the Darcy f, its derivation, and its relationship to other resistance coefficients is given in reference (62).

The Manning equation, an empirical relationship, is commonly used to calculate the barrel friction losses in culvert design. The usual form of the Manning equation is as follows:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} \qquad (35)$$

V is the mean velocity of flow, ft/s
R is the hydraulic radius, ft
S is the slope of the conduit, ft/ft, equal to the slope of the water surface in uniform flow.

Substituting H_f/L for S and rearranging equation (35) results in equation (4b).

The Manning n value in equation (35) is based on either hydraulic test results or resistance values calculated using a theoretical equation such as the Darcy equation and then converting to the Manning n. As is seen from equation (34), the Manning n varies with the conduit size (hydraulic radius) to the 1/6 power and has dimensions of $ft^{1/6}$. Therefore, for very large or very small conduits, the Manning n should be adjusted for conduit size. Most hydraulic tests for Manning n values have been conducted on moderate size conduits, with pipes in the range of 2 to 5 ft in diameter or on open channels with hydraulic radii in the range of 1 to 4 ft. For large natural channels, backwater calculations are used to match observed water surface profiles by varying the Manning n. The resultant Manning n accounts for channel size and roughness.

Using a constant value of Manning n regardless of conduit size or flow rate assumes that the Manning n is a function of only the absolute size of the wall roughness elements and is independent of conduit size and Reynolds number. This assumption is best for rough conduits where Reynolds number has little influence and the inherent variation with conduit size to the 1/6 power holds true. Thus, the Manning equation has found wide acceptance for use in natural channels and conduits with rough surfaces. For smooth pipes, other empirical resistance equations, such as the Hazen-Williams equation, are more often used.

Extensive tables of Manning n values are provided in references (23) and (31). For natural channels, the designer is referred to Table 11 in Appendix D as well as to references (16 through 18). Manning n values for commonly used culvert materials are discussed in the following sections.

B. Concrete Pipe Culverts.

Concrete pipes are manufactured (pre-cast) using various methods, including centrifugally spun, dry cast, packerhead, tamp, and wet cast. (63) The interior finish (wall roughness) varies with the method of manufacture. For instance, the tamped process generally results in a rougher interior finish than the wet cast process. The quality of the joints and aging (abrasion and corrosion) also affect the hydraulic resistance of concrete pipe. Laboratory tests on tamped pipe (24 to 36 in., average to good joints) resulted in Manning n values of about 0.009. (64) These values are increased to 0.011 to 0.013 based on field installation and aging. Suggested values of Manning n for concrete pipes are shown in Table 10.

C. Concrete Box Culverts.

The hydraulic resistance of concrete box culverts is based on the method of manufacture, installation practices, and aging. Concrete box culverts are either pre-cast or cast-in-place. For pre-cast boxes, the smoothness of the walls, the quality of the joints, and aging affect the Manning n values. For cast-in-place boxes, the quality of the formwork, construction practices, and aging are factors. Suggested Manning n values range from 0.012 to 0.018 for concrete box culverts. (23)

D. Corrugated Metal Culverts.

The hydraulic resistance coefficients for corrugated metal conduits are based on the size and shape of the corrugations, spacing of the corrugations, type of joints,

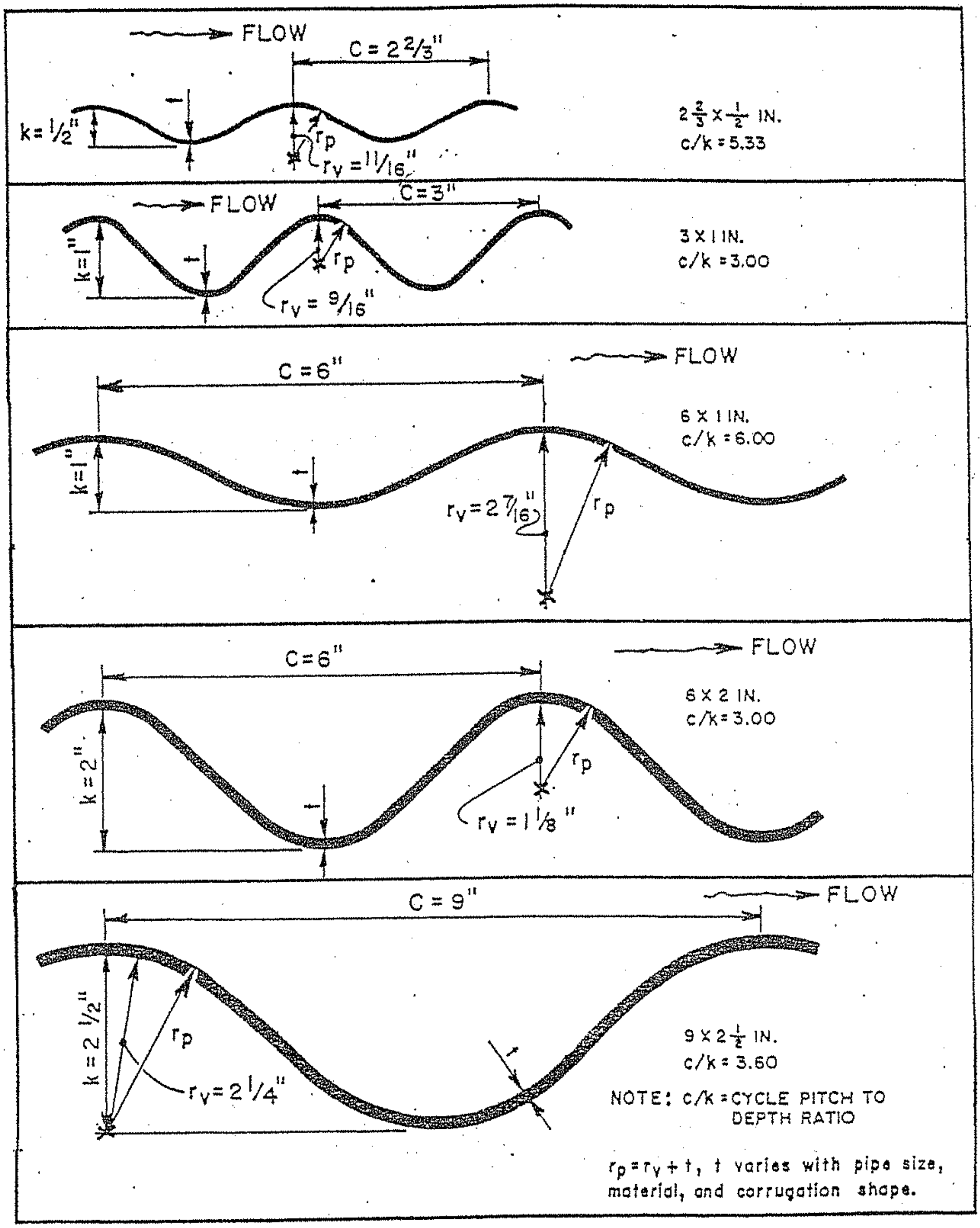


Figure B-1--Shapes of Annular Corrugations bolt or rivet roughness, method of manufacture, size of conduit, flow velocity, and aging. A complete description of the hydraulic resistance of corrugated metal conduits is presented in the publication, "Hydraulic Flow Resistance Factors for Corrugated Metal Conduits." (25). Information from that report has been condensed and included herein. The resistance values provided in this appendix are based on specific criteria, including the use of a typical culvert flow rate ($Q/D^{2.5} = 4.0$). Bolt and joint effects, where appropriate, are included.

1. Annular Corrugations. In reference (25), resistance factors are developed for the annular corrugation shapes shown in figure B-1. Methods are also presented for estimating the hydraulic resistance of new or untested corrugation types. Those methods have been used to estimate the resistance of 5- by 1-inch corrugations, shown in figure B-2, for which no test results are yet available. (61)

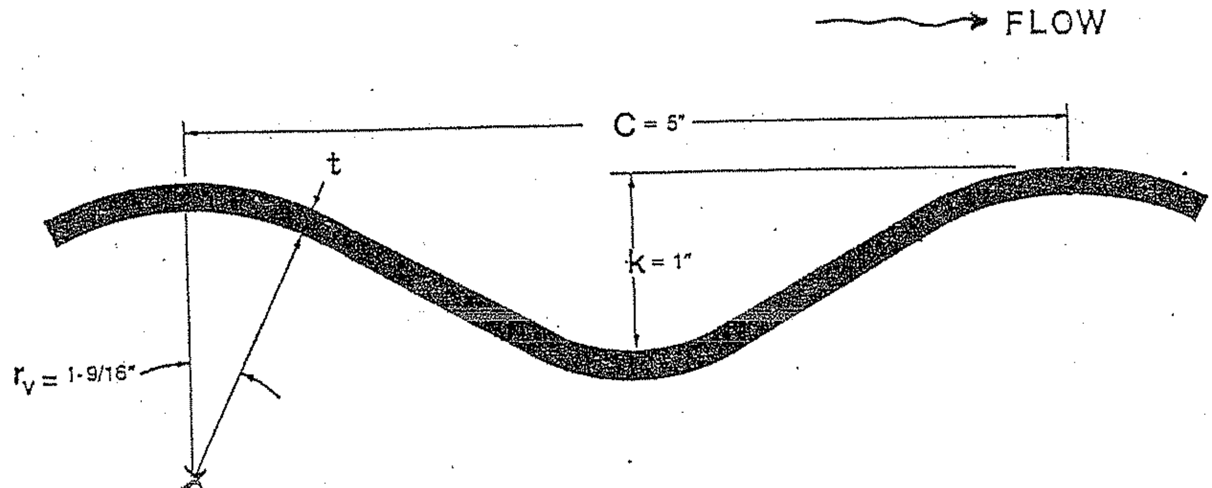


Figure B-2--Shape of 5- by 1-inch corrugation.

A series of charts were developed in reference (25) depicting the Manning n resistance value for various corrugation shapes over a range of conduit sizes. The charts show the variation of Manning n value with diameter, flow rate, and depth. The curves for structural plate conduits have discontinuities due to changes in the number of plates used to fabricate the conduits. Curves are presented for two flow rates, $Q/D^{2.5} = 2.0$ and $Q/D^{2.5} = 4.0$. Under design conditions, culvert flow rates approximate the $Q/D^{2.5} = 4.0$ curves.

2. Helical Corrugations. In pipes less than about 6 feet in diameter, helical corrugations may provide lower resistance values. This is due to the spiral flow which develops when such conduits flow full. As the pipe size increases, the helix angle approaches 90 degrees, and the Manning n value is the same as for pipes with annular corrugations. In reference (25) it is demonstrated that the lower resistance of small diameter helically corrugated metal conduits may provide a safety factor in culvert design. If the culvert initially flows partly full over its length, spiral flow will not develop. However, as the headwater rises, the pipe will eventually flow full, spiral flow will develop, and lower hydraulic resistance will result.

In general, it is recommended that the annular resistance factors be used for corrugated metal pipes with helical corrugations unless certain specific design criteria are met. These criteria include:

a. The conduit flows full.

b. The conduit is circular in shape.

c. There is no erosion resistant sediment build-up in the conduit.

d. The conduit is greater than 20 diameters long.

e. The conduit is unlined.

In most cases, culverts will not meet all of the above criteria. However, charts are provided in reference (25) for those instances where a reduced Manning n value is appropriate.

3. Design Relationships. Based on the charts of reference (25) for annular and helical corrugations, figure B-3 has been developed to assist the designer in the selection of a Manning n value for corrugated metal conduits. The figure is based on certain assumptions which reduce the complexity of the relationships.

a. The curves are based on $Q/D^{2.5} = 4.0$, which is typical of culvert design flow rates.

b. The discontinuities inherent in the structural plate curves have been ignored in favor of a smooth curve.

c. The only helically corrugated metal conduit curve shown is for 2-2/3 by 1/2 inch corrugations, with a 24 inch plate width.

Curves are shown for 2-2/3 by 1/2 inch, 3 by 1 inch, 6 by 1 inch, 6 by 2 inch, and 9 by 2-1/2 inch corrugations. A curve has also been developed for annular 5 by 1 inch corrugated metal conduits.

To use figure B-3, enter the horizontal scale with the circular conduit diameter and read the Manning n from the curve for the appropriate corrugation. For non-circular or partly full conduits, calculate an equivalent diameter equal to four times the hydraulic radius of the flow prism ($D_e = 4R$) and enter the figure using the equivalent diameter. Figure B-3 should not be used for very shallow flow depths, below about 0.4D.

D. <u>Composite Roughness</u>

Corrugated metal culverts are often fabricated using different materials for portions of the perimeter. Examples are corrugated metal arches with unlined bottoms and corrugated metal box culverts with concrete bottoms. In order to derive a composite Manning n value for the above situations, a common practice is to derive a weighted n value based on the estimated Manning n value for each material and the perimeter of the pipe composed of each material. The method assumes a constant Manning n value for each material (no variation with size or flow velocity). In addition, the perimeters should be adjusted for partly full flow. The method ignores the dynamic interaction between the flow prisms affected by each roughness.

A better method is based on the assumption that the conveyance section can be broken into G parts with associated wetted perimeters (p) and Manning n values.

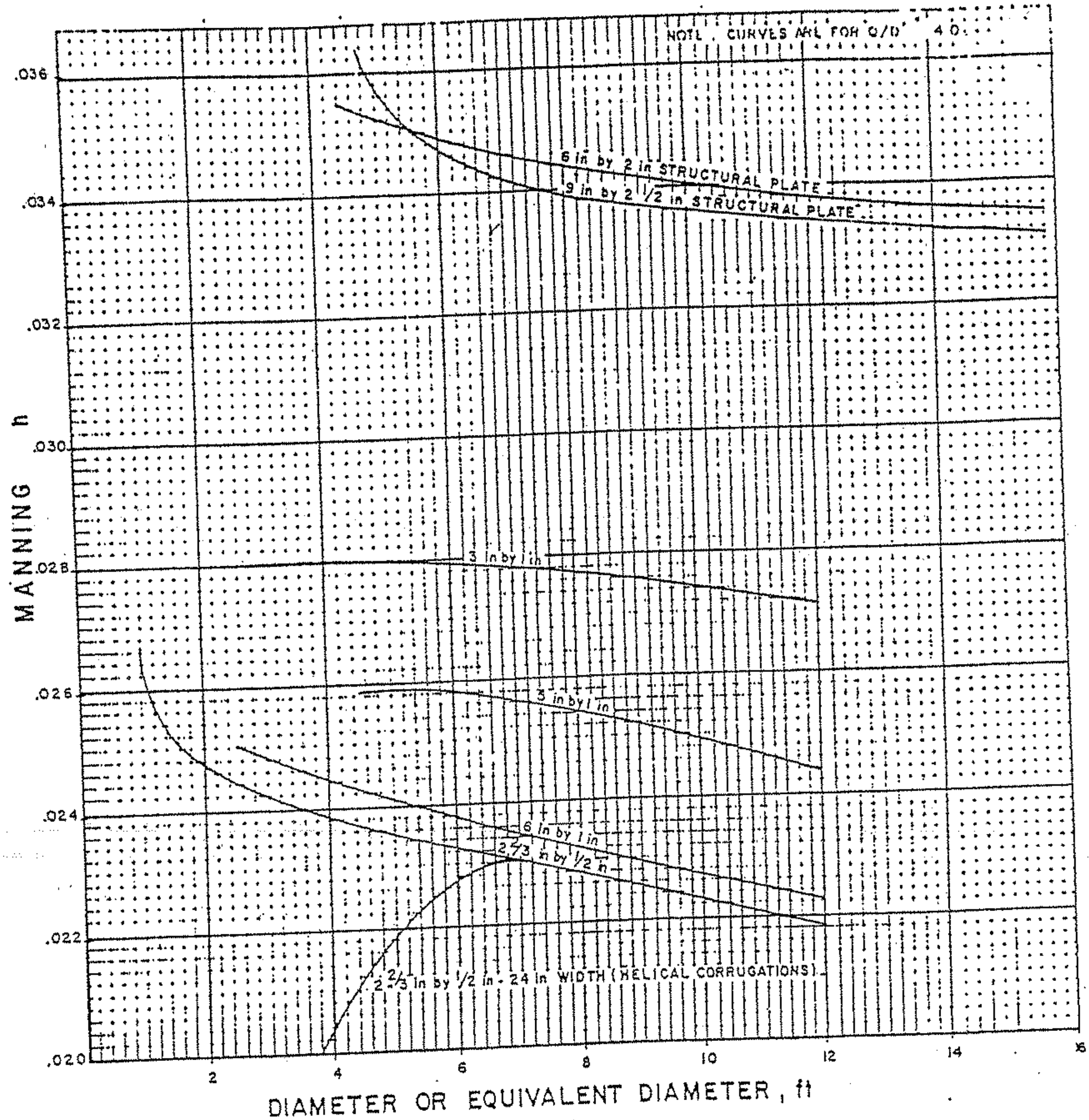


Figure B-3--Manning n versus diameter for corrugated metal conduits.

Each part of the conveyance section is then assumed to have a mean velocity equal to the mean velocity of the entire flow section. These assumptions lead to equation (36).

$$n = \left[\frac{\sum_{i=1}^{G} (p_i n_i^{1.5})}{p} \right]^{0.67} \qquad (36)$$

APPENDIX I-

$\bar{n}$ is the weighted manning n value.

G is the number of different roughnesses in the perimeter,

p_1 is the wetted perimeter in ft. influenced by the material 1, p_2 is the perimeter influenced by material 2, etc.

n_1 is the Manning n value for material 1, n_2 is for material 2, etc.

p is the total wetted perimeter, ft

Example: Compute the Manning n value for a 6 ft. diameter corrugated metal pipe with 5 by 1 in annular corrugations, and a smooth lining over 40 percent of the perimeter.

1. Determine the Manning n for the 6 ft corrugated metal pipe with 5 by 1 in corrugations.

   n = 0.026 (figure B-3)

2. Determine the Manning n for smooth lining.

   n = 0.013 (assume concrete lining)

3. Determine the relative perimeters composed of each material.

   p = D = (3.14)(6) = 18.84 ft (total wetted perimeter)

   p_1 (corrugated) = (0.60)(18.84) = 11.30 ft

   p_2 (smooth) = (0.40)(18.84) = 7.54 ft

4. Use equation (36) to calculate the Manning n value

$$\bar{n} = \left[\frac{(11.30)(0.026)^{1.5} + (7.54)(0.013)^{1.5}}{18.84}\right]^{0.67}$$

$$= 0.021$$

E. Spiral Rib Pipe.

Spiral rib pipe is smooth walled metal pipe fabricated using helical seams. Roughness elements include the joints and a helical, recessed rib running spirally around the pipe. Based on tests of 2 and 3 feet diameter spiral rib pipe (65), the pipe has essentially the same hydraulic resistance as smooth steel pipe, plus joint and aging effects. The laboratory test results indicate Manning n values of from 0.010 to 0.011. Allowing for aging and higher joint resistance, Manning n values in the range of 0.012 to 0.013 are recommended for design use. In using these low resistance values, the designer should ascertain that no large roughness elements such as projecting interior ribs or poor joints are present.

F. <u>Summary</u>.

Table 10 summarizes the Manning n values for materials commonly used in culvert construction. For the corrugated metal conduits, the specified range of n values is related to the size of the conduit. For other conduits, the range shown relates to the quality of the conduit construction. In all cases, judgment is necessary in selecting the proper Manning n value, and the designer is directed to other references for additional guidance in special situations.

Table 10. Recommended Manning n Values for Selected Conduits.

Type of Conduit	Wall & Joint Description	Manning n	Reference
Concrete Pipe	Good joints, smooth walls	0.011-0.013	(62)
	Good joints, rough walls	0.014-0.016	(62)
	Poor joints, rough walls	0.016-0.017	(62)
Concrete Box	Good joints, smooth finished walls	0.012-0.015	(23)
	Poor joints, rough, unfinished walls	0.014-0.018	(23)
Corrugated Metal Pipes and Boxes, Annular Corrugations (Manning n varies with size. Refer to fig. B-3)	2-2/3 by 1/2 in corrugations	0.027-0.022	Fig. B-3
	6 by 1 inch corrugations	0.025-0.022	Fig. B-3
	5 by 1 inch corrugations	0.026-0.025	Fig. B-3
	3 by 1 inch corrugations	0.028-0.027	Fig. B-3
	6 by 2 inch structural plate	0.035-0.033	Fig. B-3
	9 by 2-1/2 structural plate	0.037-0.033	Fig. B-3
Corrugated Metal Pipes, Helical Corrugations, Full Circular Flow	2-2/3 by 1/2 inch corrugations, 24 inch plate width	0.012-0.024	(25)
Spiral Rib Metal Pipe	3/4 x 3/4 in recesses at 12 inch spacing, good joints	0.012-0.013	(65)

This Page Left Intentionally Blank

CULVERT DESIGN OPTIMIZATION USING PERFORMANCE CURVES

A. Introduction.

Performance curves are an integral part of the culvert design process and can be used to optimize the selected culvert design, particularly when using tapered inlets and/or upstream depressions. This optimization may involve further reduction in the barrel size required to pass the design flow at the design headwater, provision of a factor of safety against damages, or a more balanced design. The visualization of culvert performance provided by performance curves may lead to a further reduction in the size of the culvert barrel. At many culvert sites, designers provide a safety factor in the design. The safety factor may compensate for: (1) uncertainty in the design discharge estimate, (2) potentially disastrous results in property damage or damage to the highway from headwater elevations which exceed the design headwater, (3) the potential for development upstream or downstream of the culvert, or (4) the chance that the design frequency flood will be exceeded during the life of the installation. The procedures described here enable the designer to maximize the performance of the selected culvert or to optimize the design in accordance with his evaluation of site constraints, design parameters, and costs for construction and maintenance.

B. Outlet Control Performance Curves.

The outlet control performance curves for various barrel sizes and inlet configurations are used first to evaluate the operation of the selected barrel. The full flow outlet control performance curve for a given culvert (size, inlet edge configuration, barrel shape, material) defines its maximum performance. Inlet improvements beyond the beveled edge or changes in inlet invert elevations will not reduce the required outlet control headwater elevation. Therefore, the outlet control performance curve is an ideal minimum limit for culvert design.

When the barrel size is increased, the outlet control curve is shifted to the right, indicating a higher capacity for a given head. Also, it is generally true that increasing the barrel size will flatten the slope of the outlet control curve. (figure C-1)

The outlet control curve passing closest to and below the design point (design Q and design headwater elevation) on the performance curve graph defines the smallest possible barrel which meets the hydraulic design criteria. The curve for the smallest possible barrel may be very steep (rapidly increasing headwater requirements for discharges higher than the design discharge) and use of such a small barrel may not be practical due to high outlet velocities or flooding from flows exceeding the design flow.

To define the outlet control performance curves, perform the following steps:

1. Calculate the headwater elevations at the design discharge for a selected series of culvert sizes, inlet configurations, shapes, and materials.

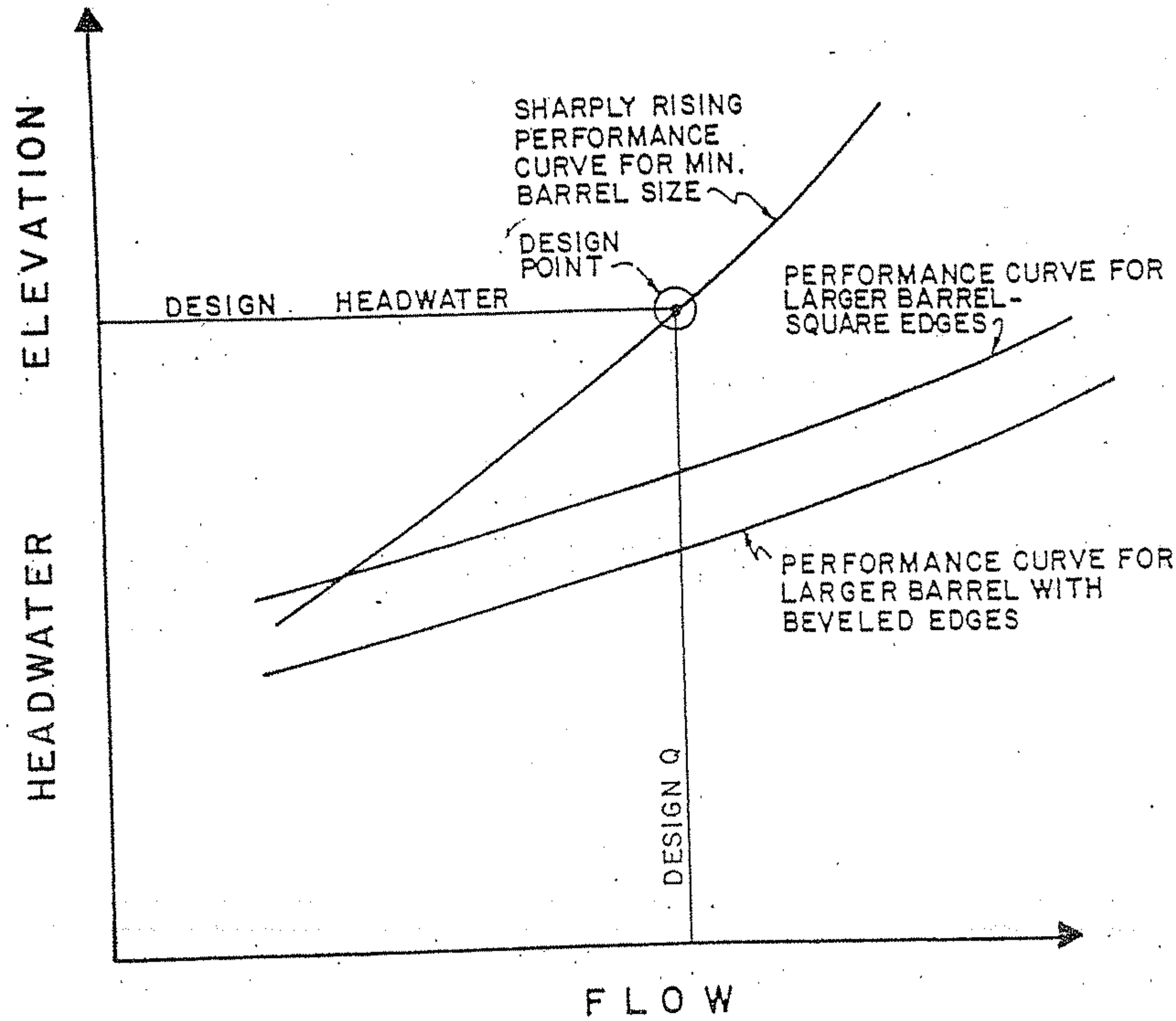


Figure C-1--Outlet control performance curves.

2. Calculate the required headwater elevations at discharges above and below the design discharge, to obtain at least three points on each performance curve.

3. Plot the outlet control performance curves.

4. Select a culvert barrel size, shape and material based on the series of performance curves. This selection is based on the design headwater and flow rate (the design point), the slope of the performance curve and the site considerations discussed previously.

A typical series of outlet control performance curves is shown in figure C-2.

C. Inlet Control Performance Curves.

Next, inlet control performance curves should be drawn for the inlet edge configurations selected. These edges may include square edges, beveled edges, or the throat

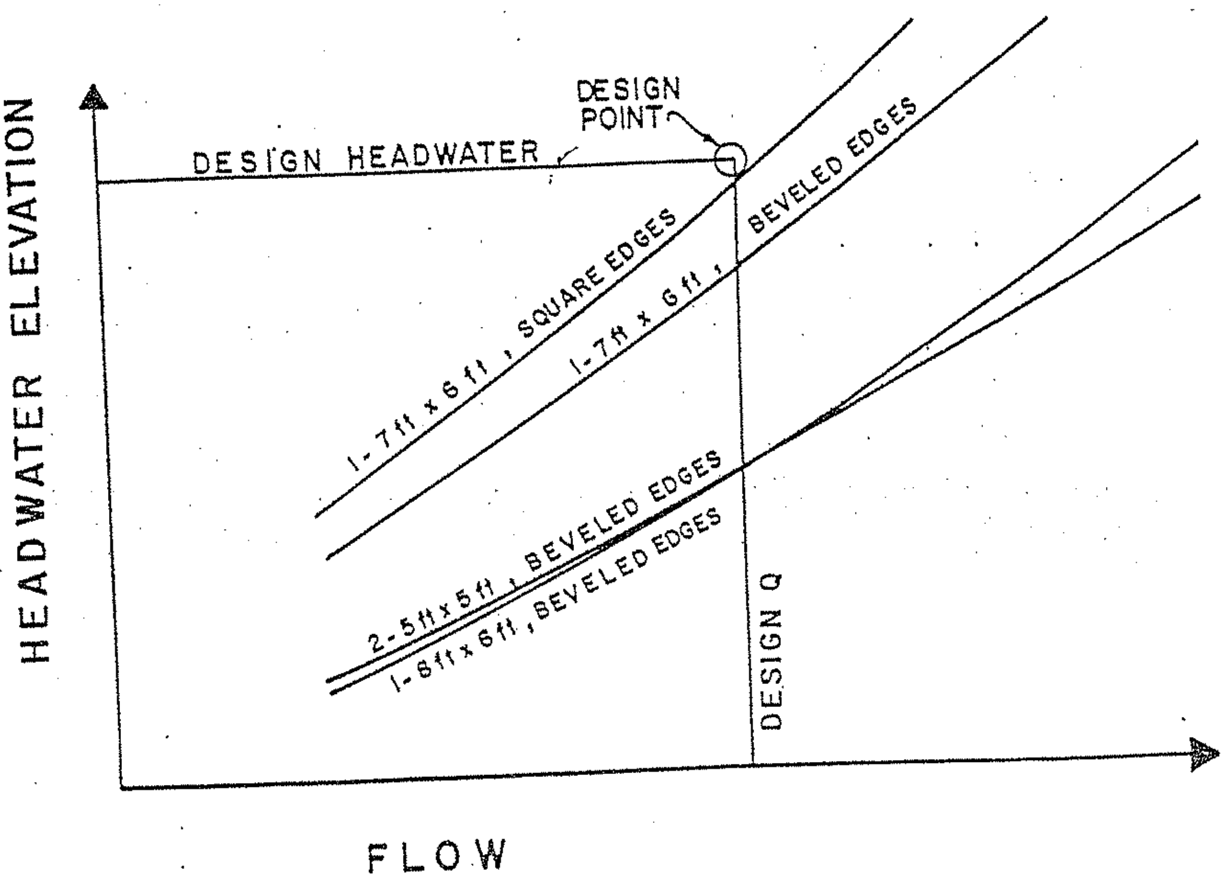


Figure C-2--Box culvert outlet control performance curves.

section of a tapered inlet. A depression may also be incorporated upstream of the inlet control section to lower the inlet control headwater elevation. To construct the inlet control performance curves, perform the following steps:

1. Calculate the inlet control headwater for the culvert barrel selected based on outlet control.

2. Determine the required face invert elevation to pass the design discharge by subtracting the headwater depth from the design headwater elevation.

a. If the inlet invert elevation is above the stream bed elevation at the control section, the invert should be lowered to the stream bed. The culvert will then have a capacity exceeding the design flow with the headwater at the design headwater elevation.

b. If the required invert elevation is below the stream bed elevation at the face, the invert must be depressed using a FALL.

c. If, in the designer's judgment, the required FALL is excessive, the inlet geometry must be improved or a larger barrel must be used.

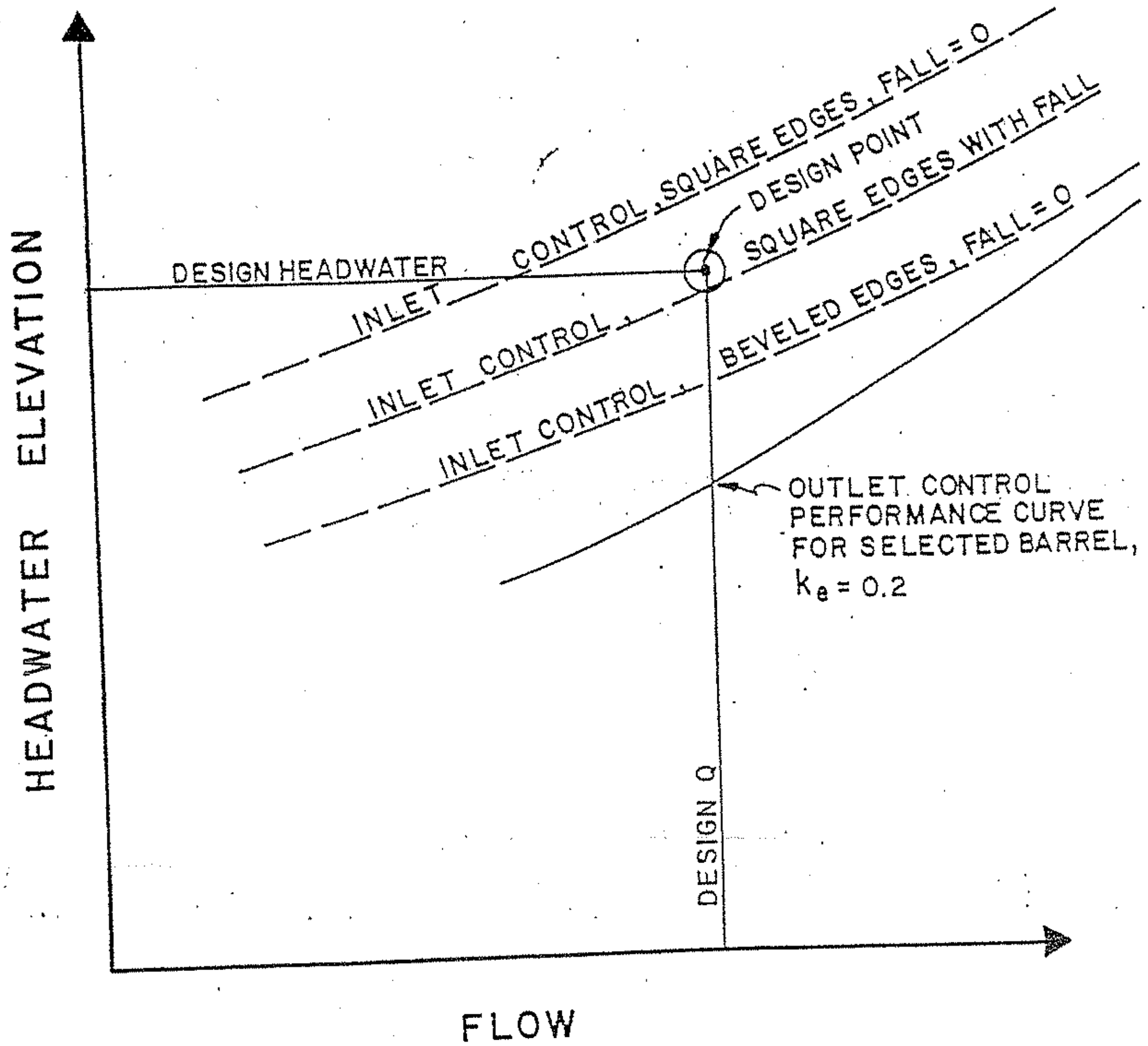


Figure C-3--Inlet control performance curves various inlet configurations.

d. If the FALL is acceptable, plot the inlet control performance curve. Again, at least three points are necessary; one at the design flow rate and one on either side of the design flow rate.

Figure C-3 depicts a series of inlet edge configurations, along with the outlet control performance curve for the selected barrel. Note that an inlet with square edges and no FALL will not meet the design conditions. Either square edges with a FALL or beveled edges with no FALL satisfy the design criteria.

D. Analyze the Effects of Additional FALL.

From figure C-3, one can see that additional FALL or inlet improvements such as a

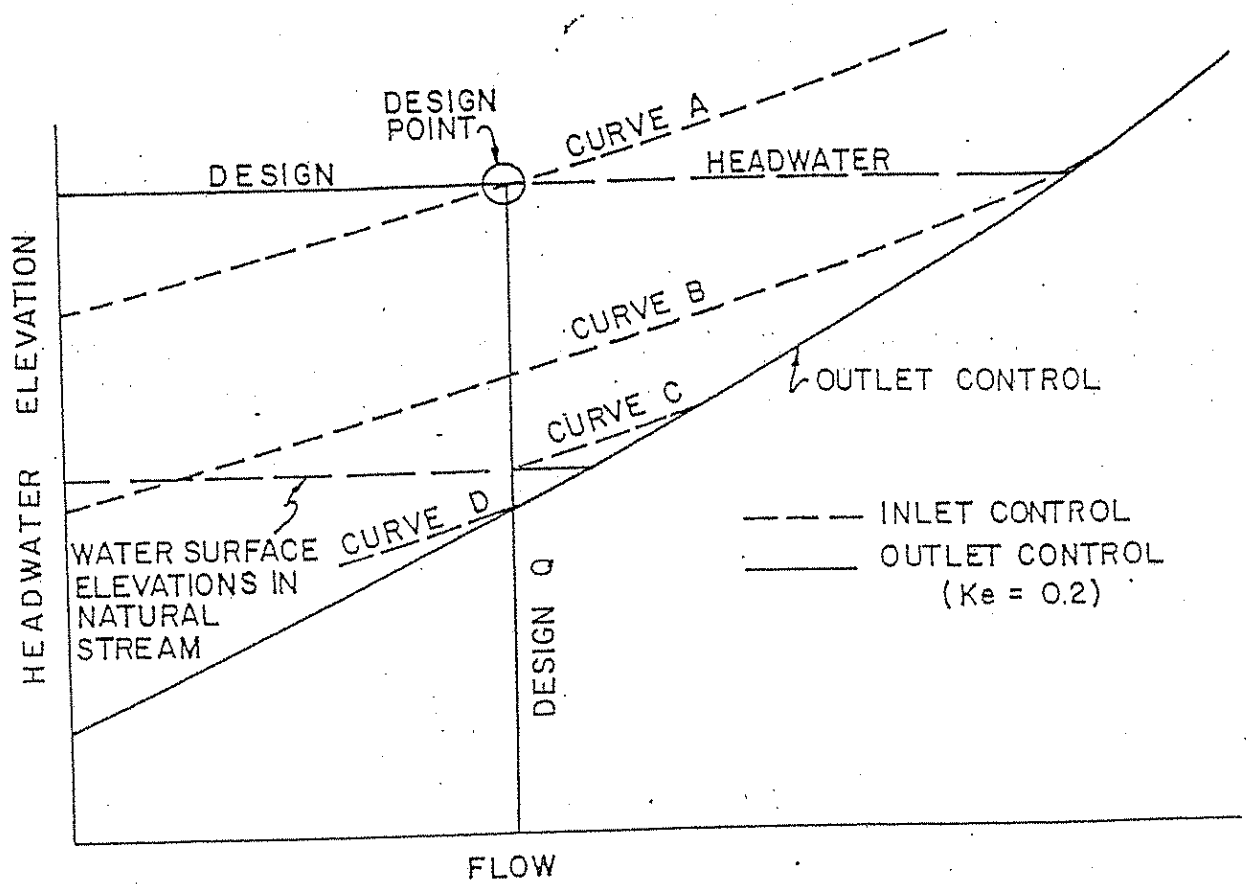


Figure C-4--Optimization of performance in inlet control.

tapered-inlet would increase the culvert capacity in inlet control. The inlet control performance curve would be closer to the outlet control curve for the selected culvert barrel, which passes below the design point. Of course, all such considerations are limited by the designer's appraisal of the acceptable FALL.

Some possibilities are illustrated in figure C-4. The minimum inlet control performance which will meet the design point is illustrated by curve A. In this design, the cost for inlet improvements and/or FALL is at a minimum and the inlet will pass a flood exceeding the design flow before performance is governed by outlet control. This performance is adequate in many locations, including those where headwaters in excess of the allowable would be tolerable.

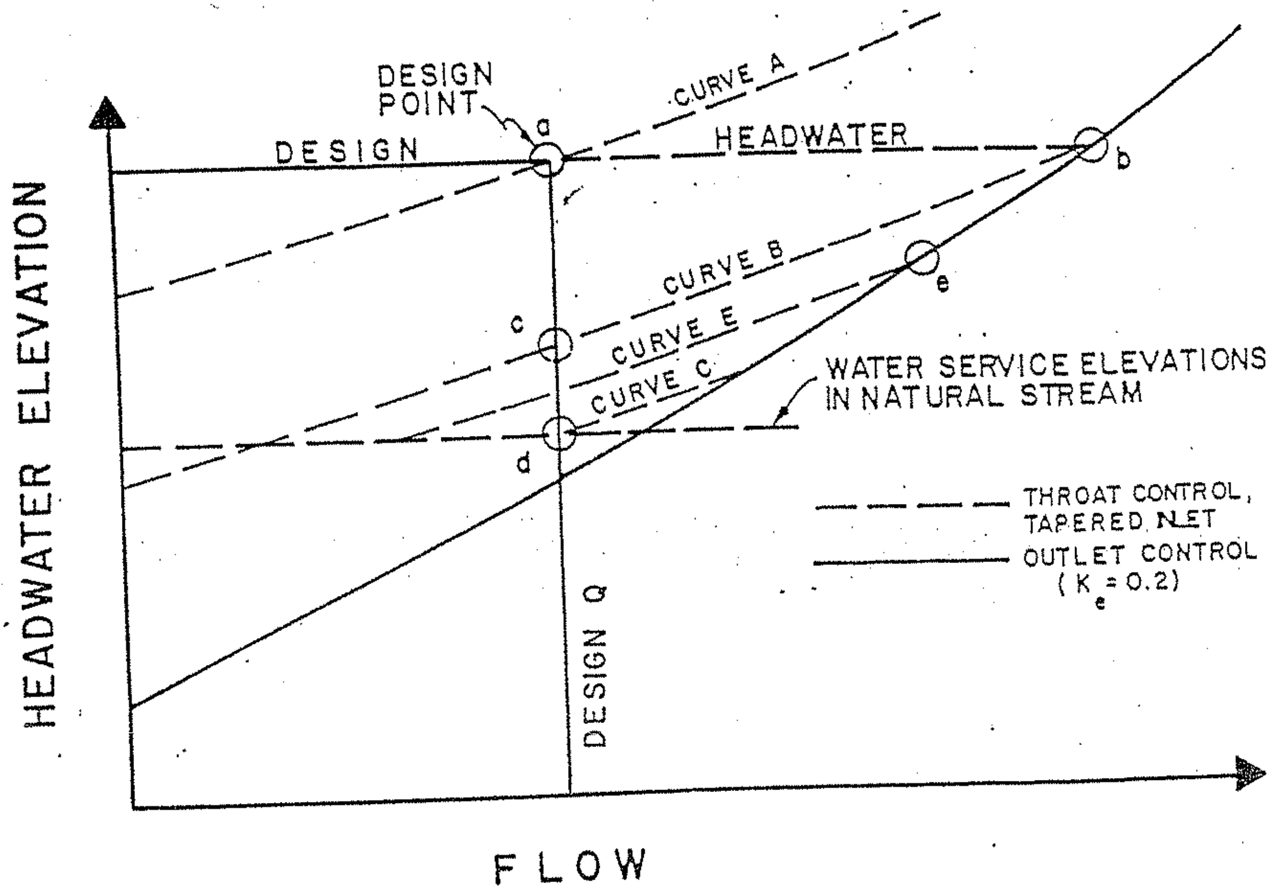


Figure C-5--Possible face design selections tapered inlet.

Curve B illustrates the performance of a design which takes full advantage of the potential capacity of the selected culvert and the site to pass the maximum possible flow at the design headwater elevation. A safety factor in capacity is thereby incorporated by geometric improvements at the inlet, by a FALL, or by a combination of the two. Additional inlet improvements and/or FALL will not increase the capacity at or above the design headwater elevation.

Curve C illustrates the performance of a design which passes the design flow at the lowest possible headwater. Additional inlet improvements and/or FALL will not reduce the required headwater elevation at the design flow rate.

The water surface elevation in the natural stream may be a limiting factor in design. The reduction in headwater elevation illustrated by curve C is limited by the natural water surface elevation in the stream The reduction is also limited by the outlet control performance curve. If the water surface elevations in the natural stream had fallen below curve D, curve D gives the maximum reduction in headwater elevation at the design flow. Flow depths calculated by assuming normal depth in the stream channel may be used to estimate natural water surface elevations in the stream at the culvert inlet.

Curve A has been previously established for the inlet control section. To define control section:

1. Select the point of interest on the outlet control performance curve.

2. Measure the vertical distance from that point to curve A. This is the difference in FALL between curve A and the curve to be established. For example, the FALL on the control section for curve A plus the distance between curves A and B is the FALL on the control section for curve B.

E. Tapered Inlet Face Control Performance Curves.

Either a side-tapered inlet with an upstream sump or slope-tapered inlet design may be used if a FALL is required at the throat control section of a tapered inlet. The minimum face design for the tapered inlet is one with a performance curve which does not exceed the design point. However, a "balanced" design requires that full advantage be taken of the increased capacity and/or lower headwater gained through use of various FALLs. This suggests a face performance curve which intersects the throat control curve either: (1) at the design headwater elevation, (2) at the design flow rate, (3) at its intersection with the outlet control curve, or (4) at other points selected by the designer. These options are illustrated in figure C-5 by points a through e representing various points on the throat control performance curves. The options are:

1. Intersection of face and throat control performance curves at the design headwater elevation (points a or b).

2. Intersection of face and throat control performance curves at the design flow rate (points a, c or d). This option makes full use of the FALL to increase capacity and reduce headwater requirements at flows equal to or greater than the design flow rate.

3. Intersection of the face control performance curve with throat control performance curve at its intersection with the outlet control performance curve (points b or e). This option results in the minimum face size which can be used to make full use of the increased capacity available from the FALL at the throat.

4. Variations in the above options are available to the designer. For example, the culvert face can be designed so that culvert performance will change from face control to throat control at any discharge at which inlet control governs. Options 1 through 3, however, appear to fulfill most design objectives. Generally, the design objective will be to design either the minimum face size to achieve the maximum increase in capacity possible for a given FALL, or the maximum possible decrease in the required headwater for a given depression for any discharge equal to or greater than the design discharge.

Figure C-6 illustrates some of the possible tapered inlet designs for a specific design situation. The dimensions of the side-tapered inlet are the same for all options. This is because performance of the side-tapered inlet face nearly parallels the performance of the throat and an increase in headwater on the throat by virtue of an increased FALL results in an almost equal increase in headwater on the face. Depressing the throat of a culvert with a side-tapered inlet requires additional barrel length.

Face dimensions and inlet length increase for the slope-tapered inlet as the capacity of the culvert is increased by additional FALL on the throat. No additional headwater depth is created at the face by placing additional depression on the throat. However, use of a greater depression at the throat of a culvert with a slope-tapered inlet does not increase the barrel length.

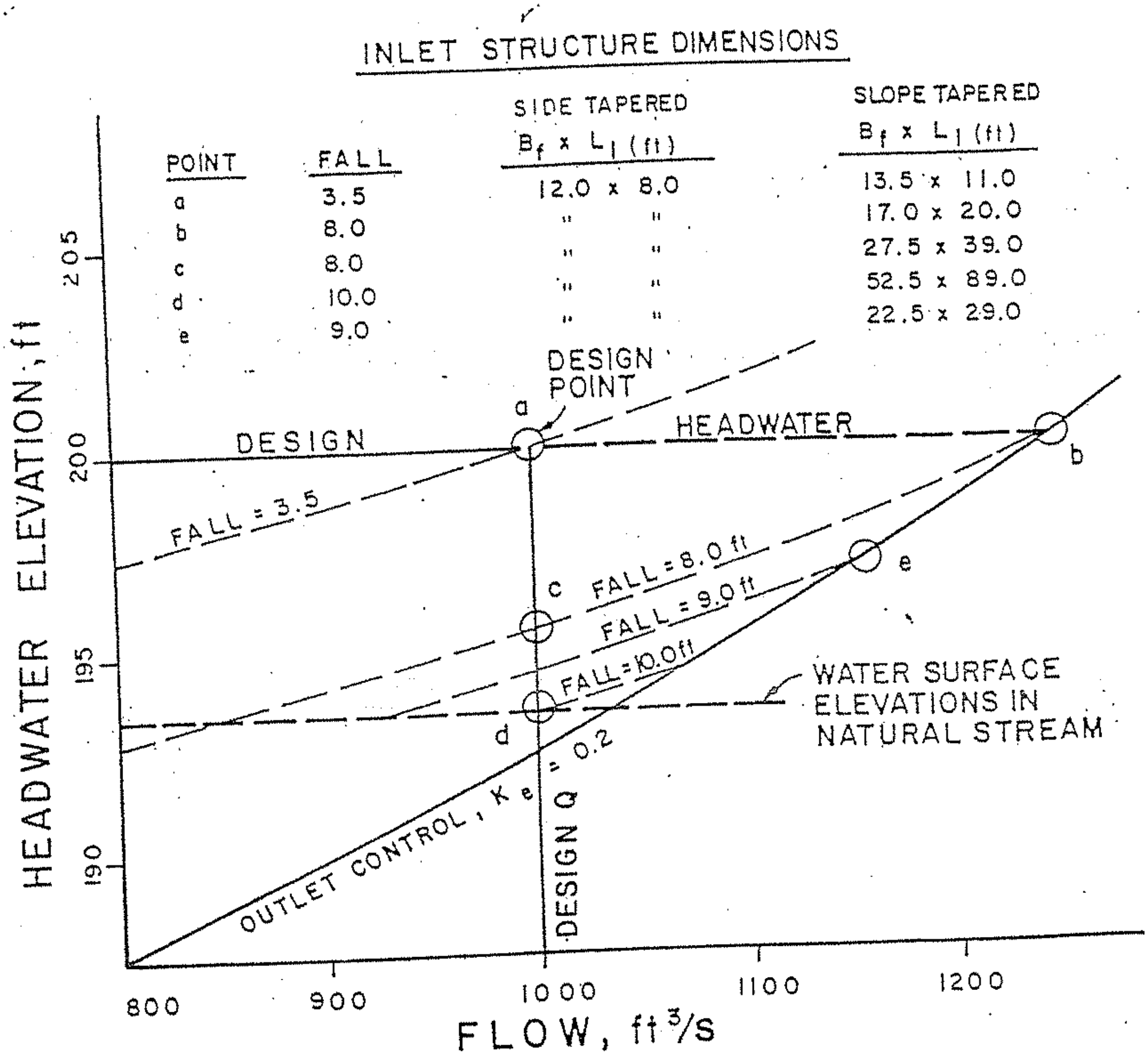


Figure C-6--Tapered inlet design options for 8 ft by 6 ft reinforced concrete box culvert.

DESIGN CHARTS, TABLES, AND FORMS

Note: Each design chart has a small symbol in the upper outside corner representing the shape involved.

Elliptical Culverts

Pipe/Arch Culverts

Rectangular Tapered Inlets

Design Forms

Table 11 - MANNING n FOR SMALL NATURAL STREAM CHANNELS

(Surface width at flood stage less than 100 ft.)

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

TABLE 12 - ENTRANCE LOSS COEFFICIENTS

Outlet Control, Full or Partly Full Entrance head loss

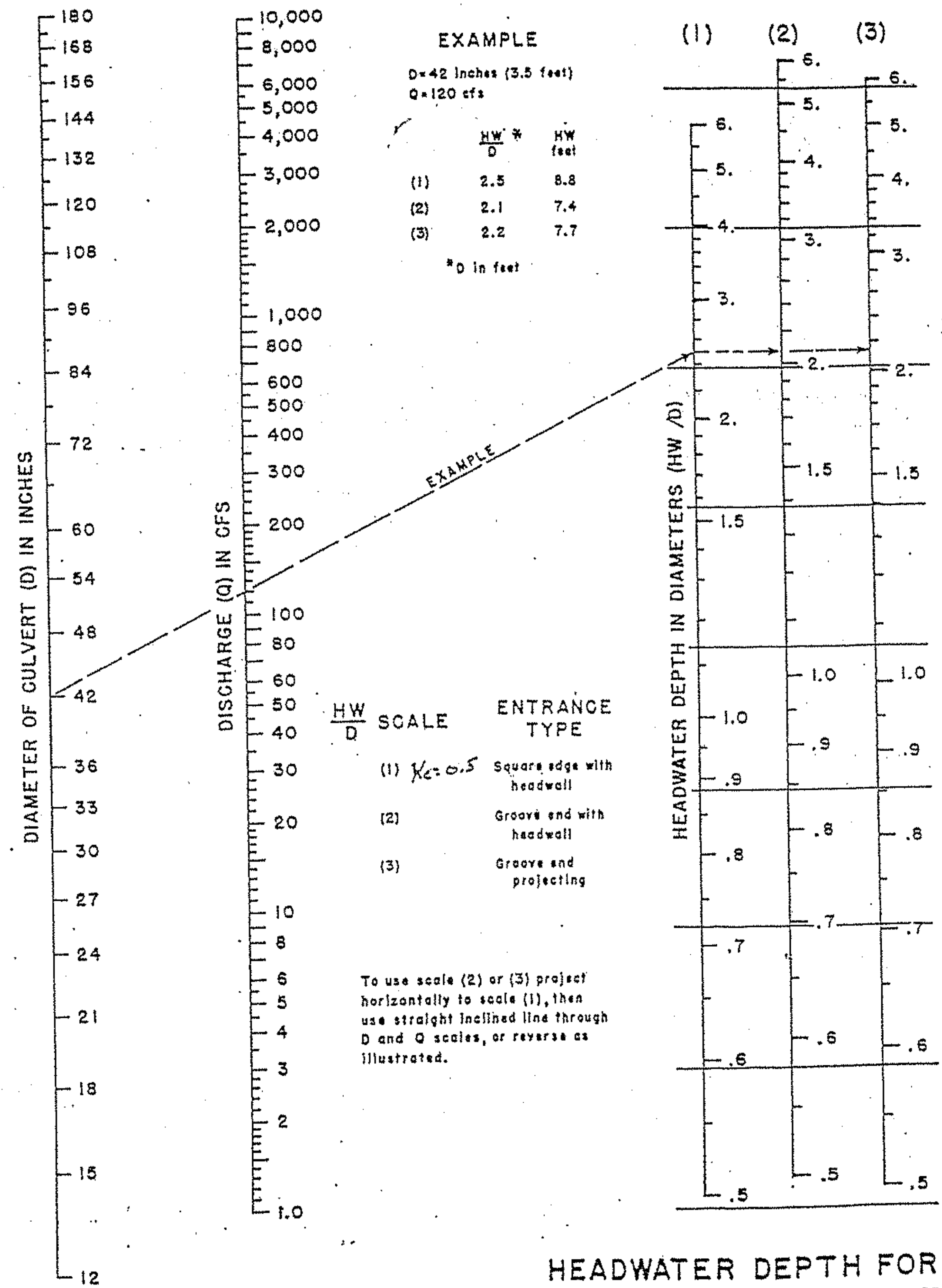
$$H_e = k_e \left(\frac{V^2}{2g} \right)$$

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

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

APPENDIX I-

CHART 1

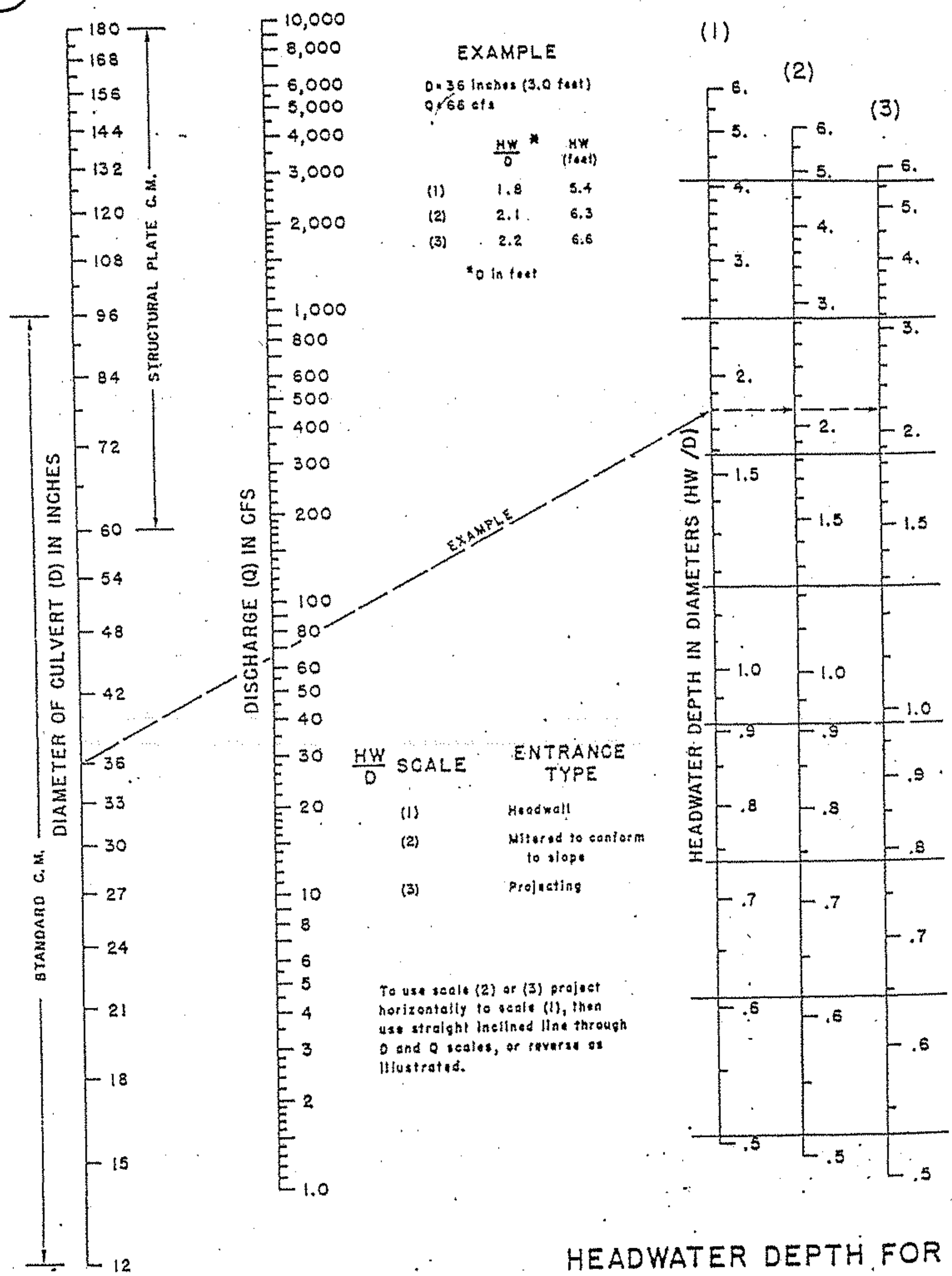


HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

HEADWATER SCALES 2&3
REVISED MAY 1964

BUREAU OF PUBLIC ROADS JAN. 1963

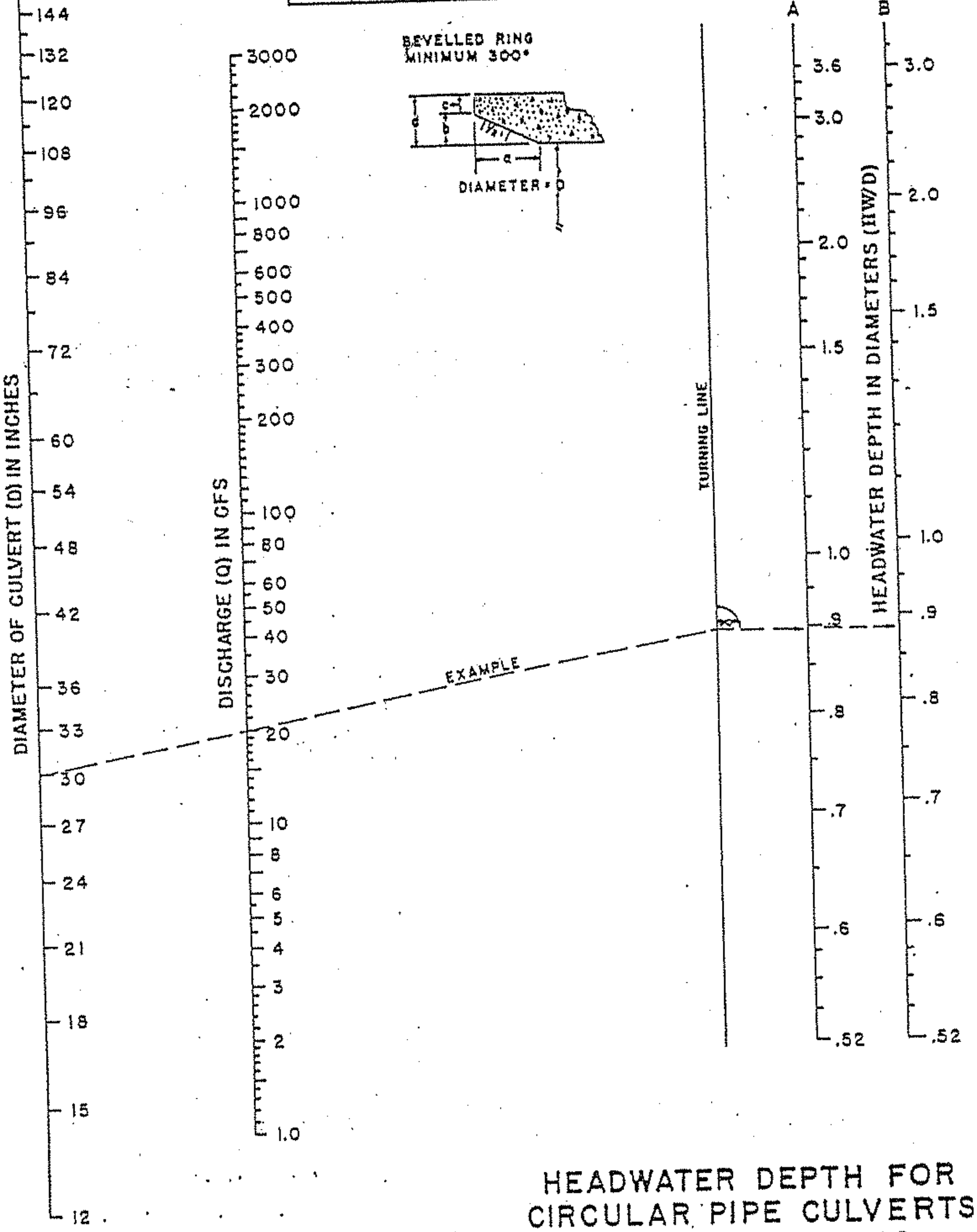
CHART 2



HEADWATER DEPTH FOR C. M. PIPE CULVERTS WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

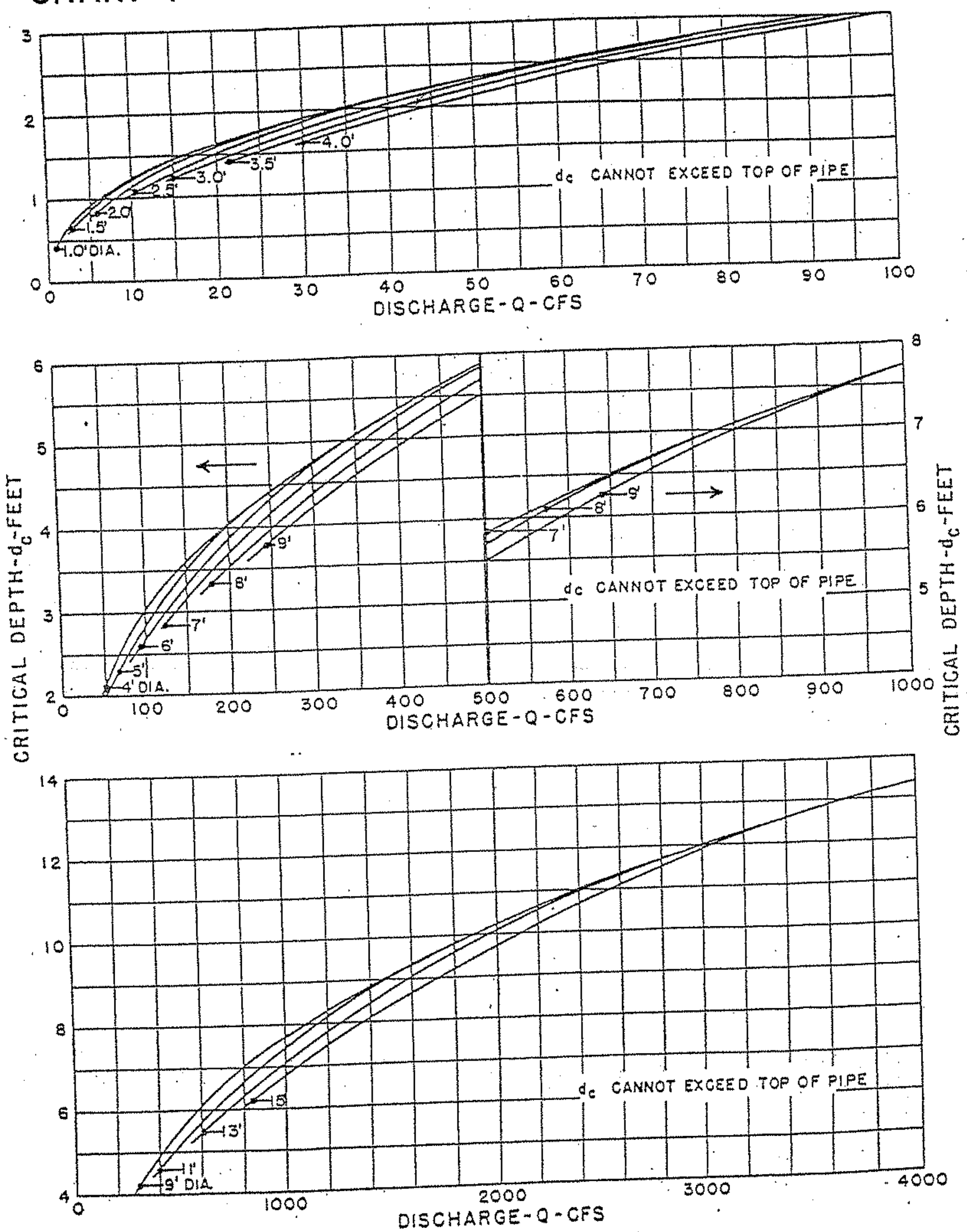
$\frac{b}{D}$	$\frac{a}{D}$	$\frac{c}{D}$	$\frac{d}{D}$	ENTRANCE TYPE
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B



HEADWATER DEPTH FOR CIRCULAR PIPE CULVERTS WITH BEVELED RING INLET CONTROL

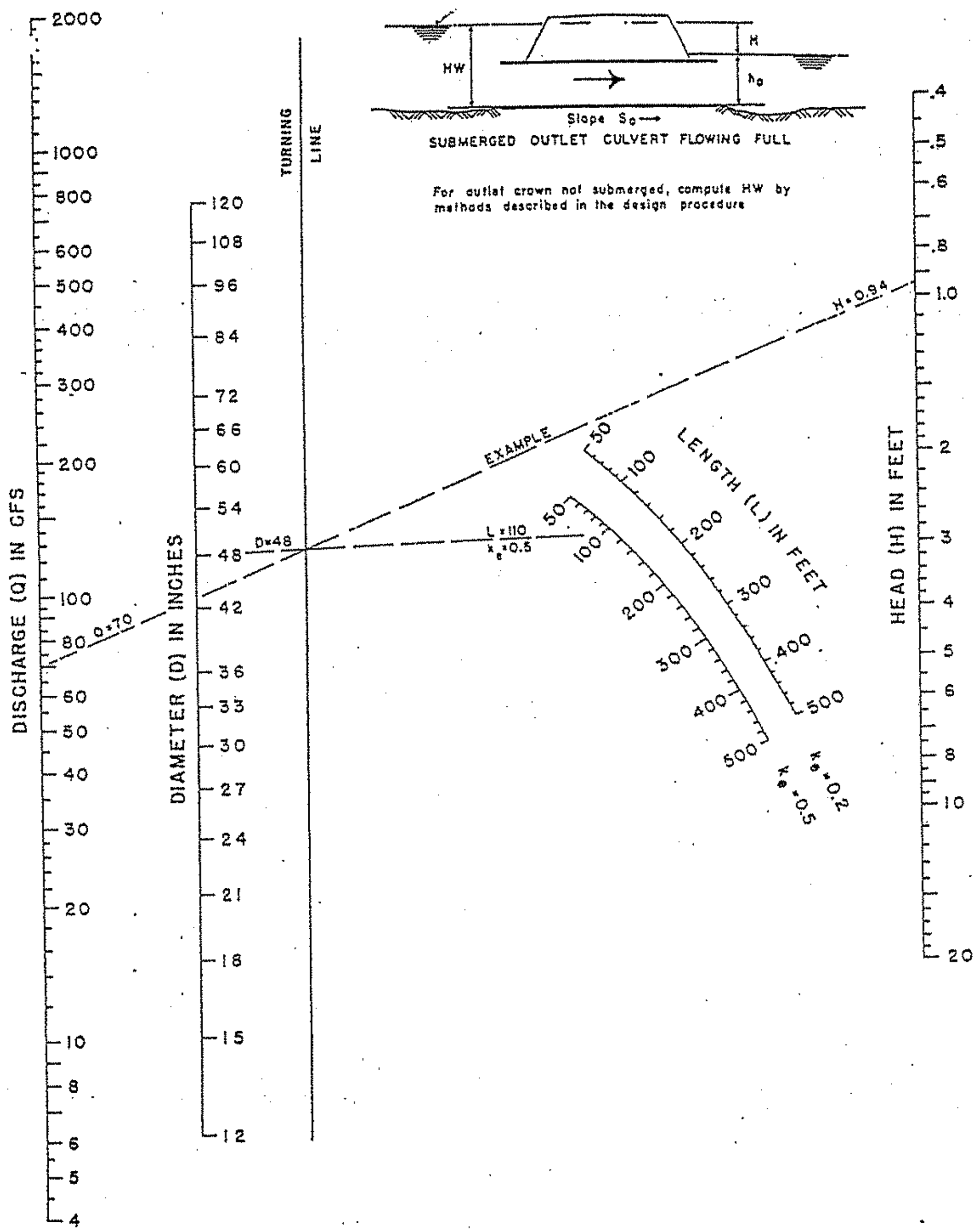
)ERAL HIGHWAY ADMINISTRATION
MAY 1973

CHART 4



BUREAU OF PUBLIC ROADS
JAN. 1964

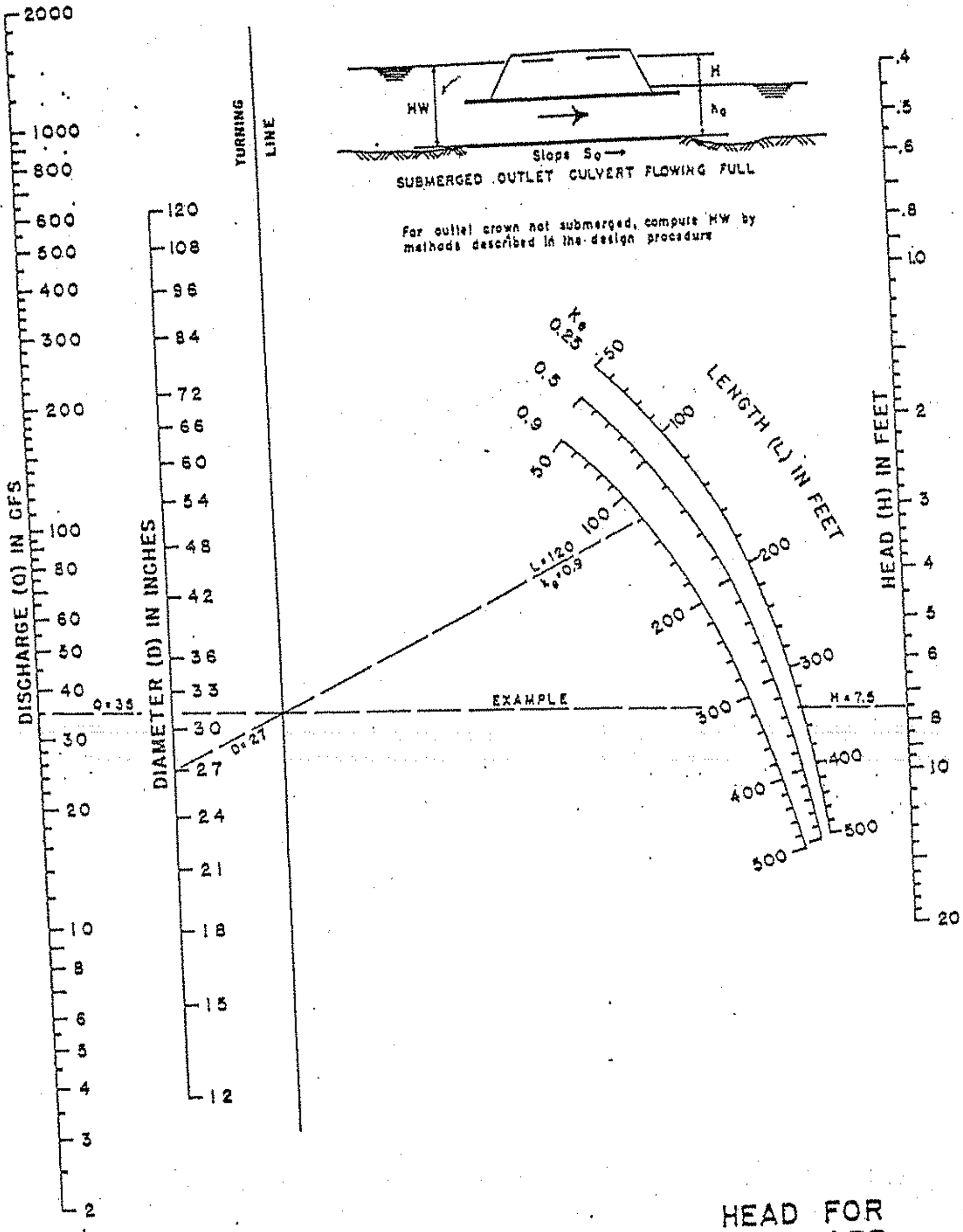
CRITICAL DEPTH
CIRCULAR PIPE



# HEAD FOR CONCRETE PIPE CULVERTS FLOWING FULL
n = 0.012

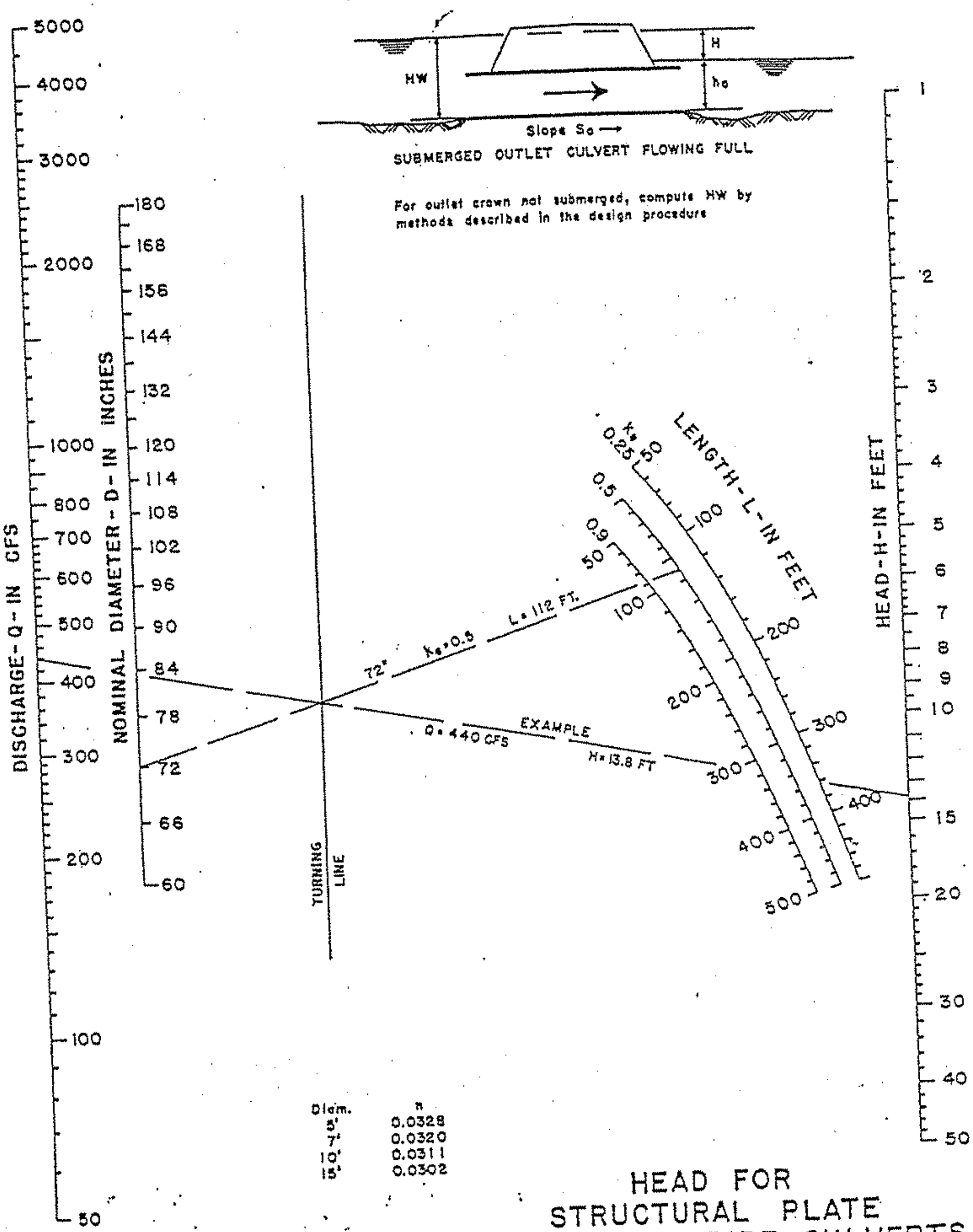
BUREAU OF PUBLIC ROADS JAN. 1963

CHART 6



HEAD FOR STANDARD C. M. PIPE CULVERTS FLOWING FULL
n = 0.024

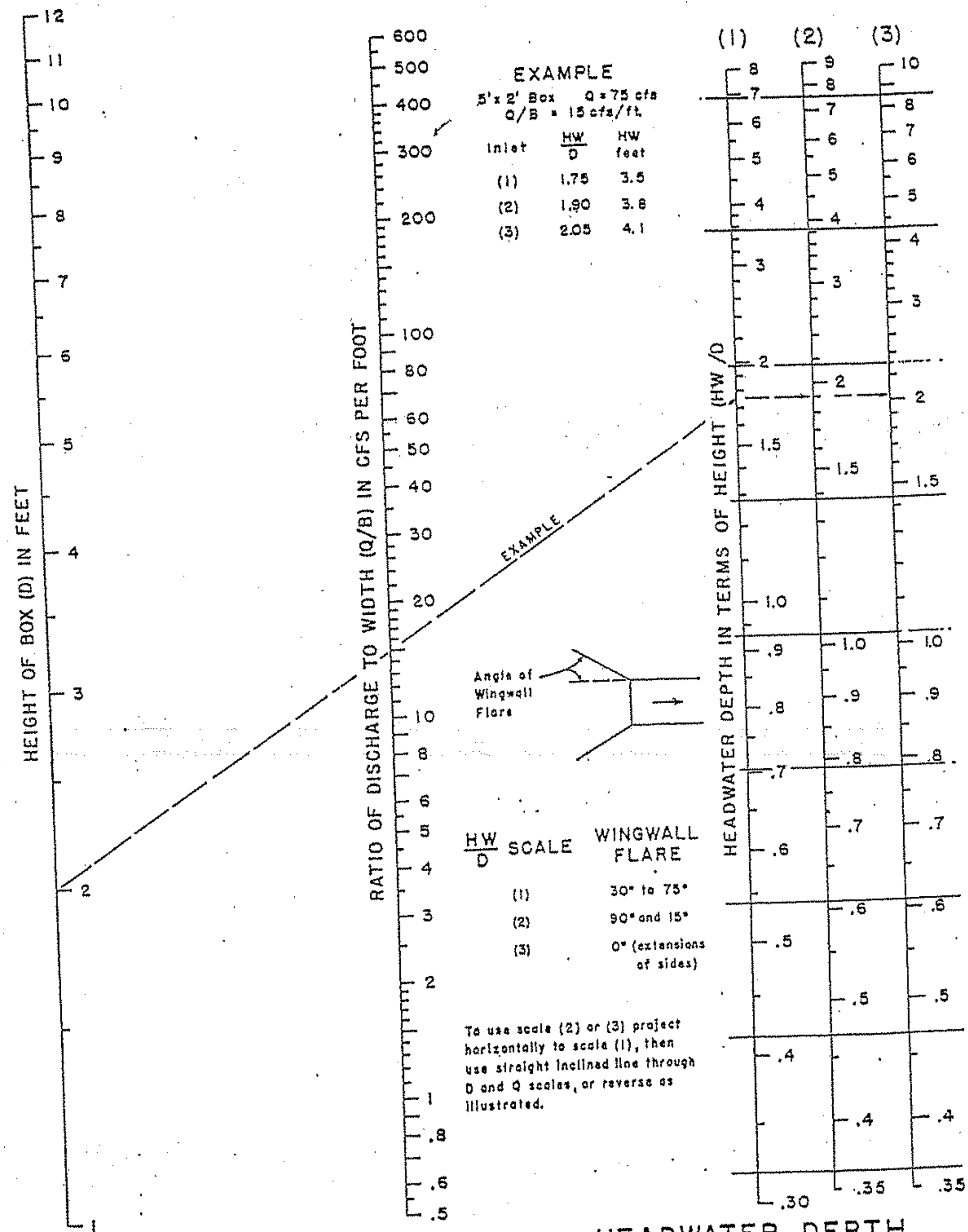
BUREAU OF PUBLIC ROADS JAN. 1963



HEAD FOR STRUCTURAL PLATE CORR. METAL PIPE CULVERTS FLOWING FULL
n = 0.0328 TO 0.0302

BUREAU OF PUBLIC ROADS JAN. 1963

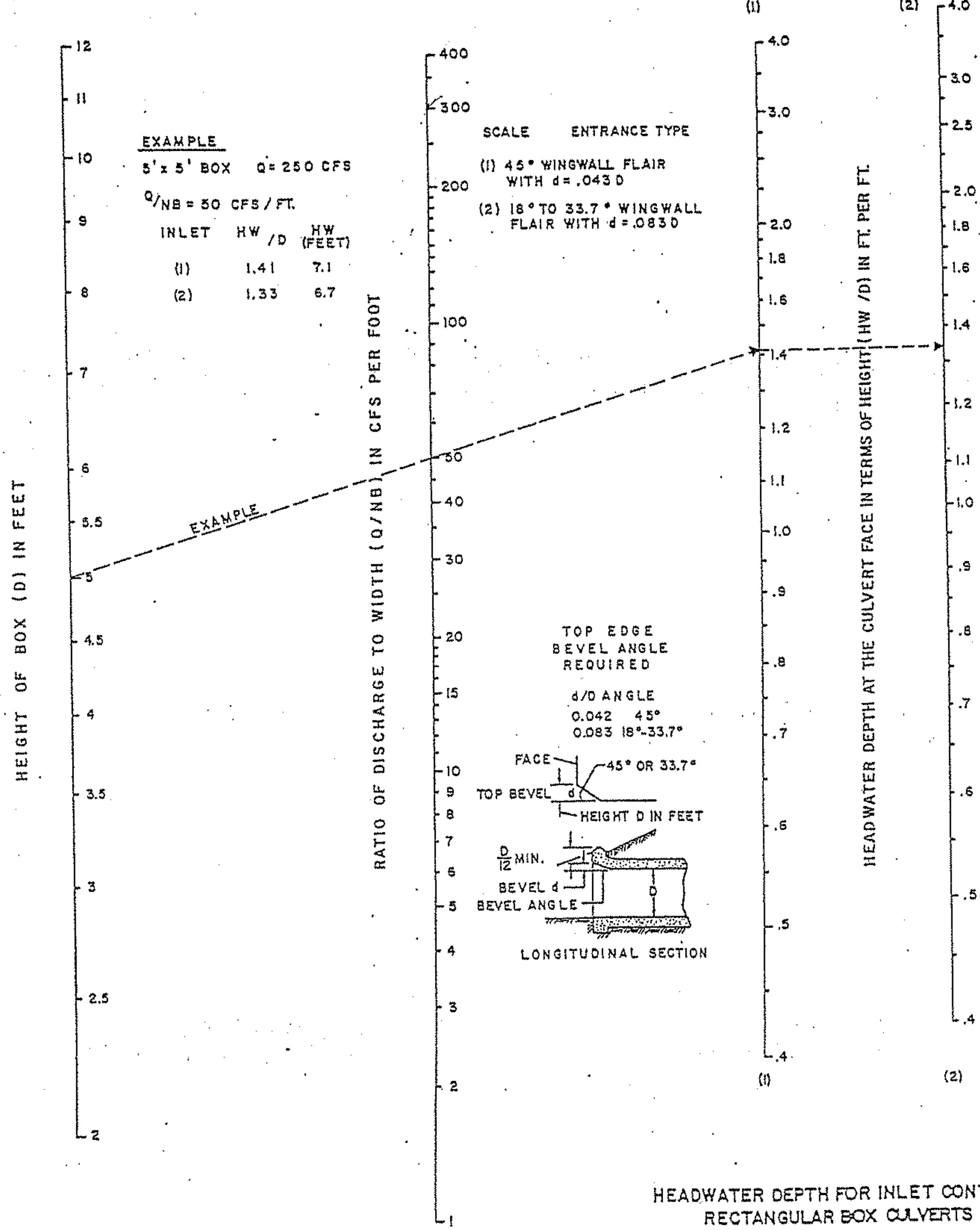
CHART 8



HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL

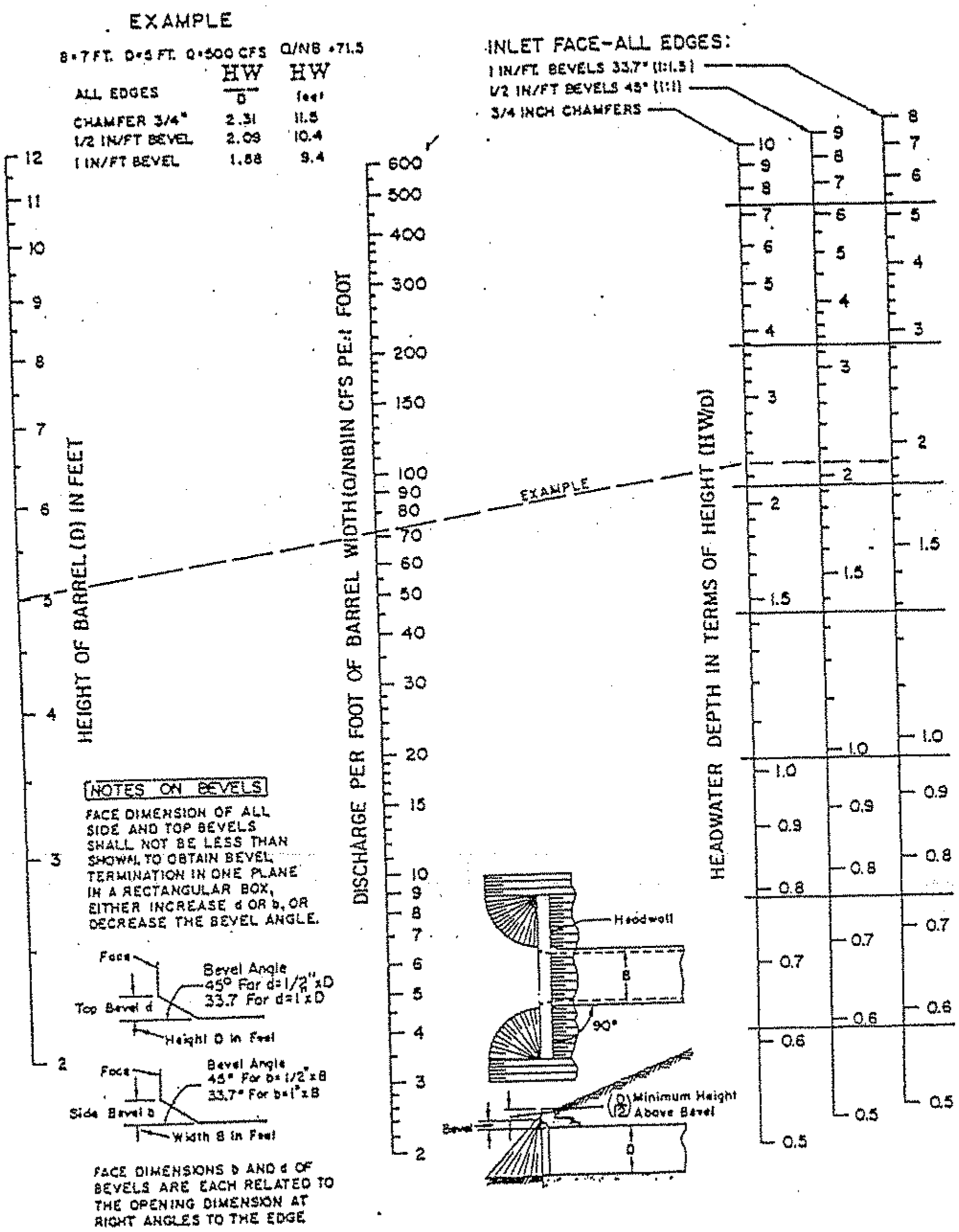
BUREAU OF PUBLIC ROADS JAN. 1963

CHART 9



HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
FLARED WINGWALLS 18° TO 33.7° & 45°
WITH BEVELED EDGE AT TOP OF INLET

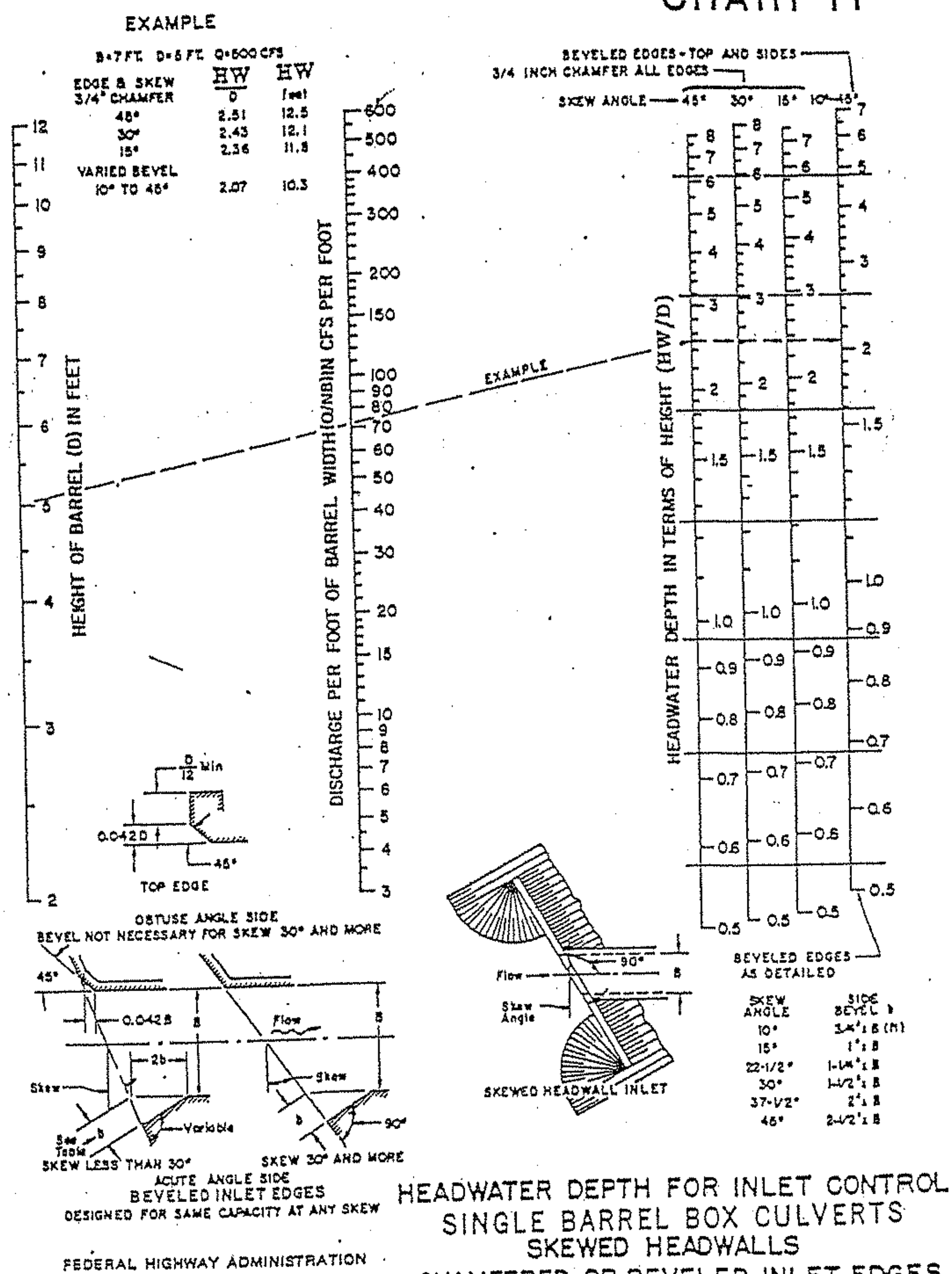
CHART 10



HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
90° HEADWALL
CHAMFERED OR BEVELED INLET EDGES

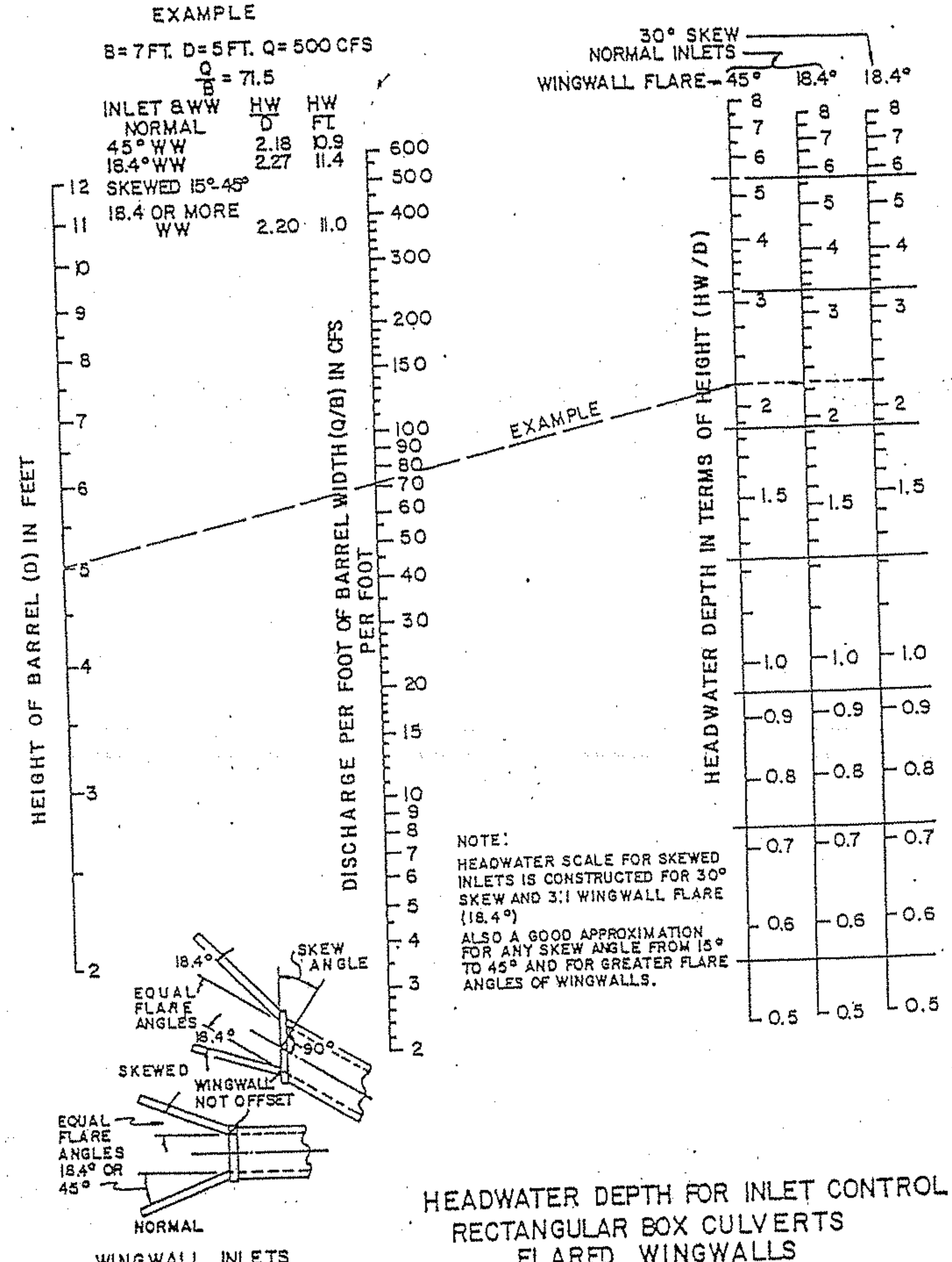
FEDERAL HIGHWAY ADMINISTRATION
MAY 1973

CHART 11



HEADWATER DEPTH FOR INLET CONTROL
SINGLE BARREL BOX CULVERTS
SKEWED HEADWALLS
CHAMFERED OR BEVELED INLET EDGES

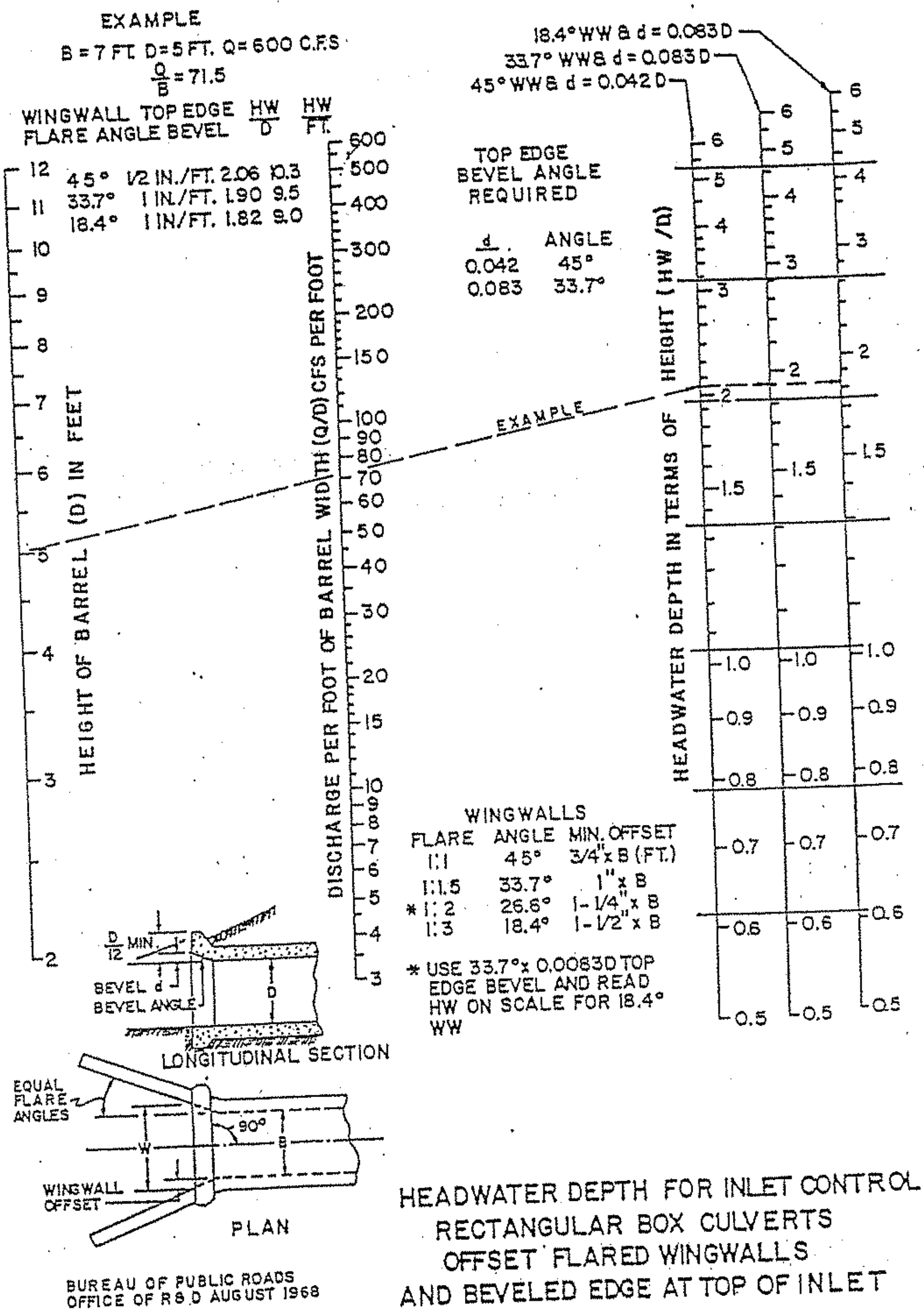
CHART 12



BUREAU OF PUBLIC ROADS
OFFICE OF R & D AUGUST 1968

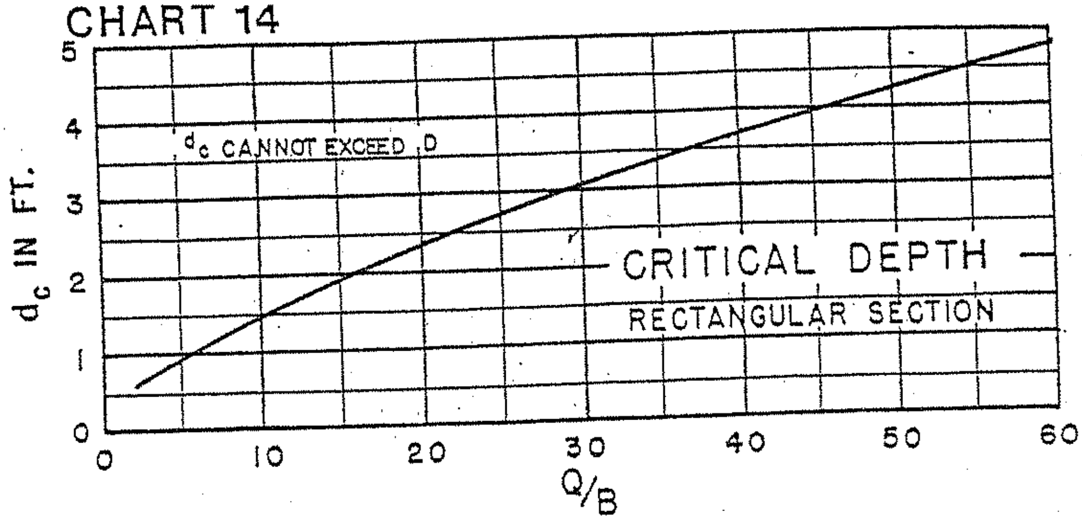
HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
FLARED WINGWALLS
NORMAL AND SKEWED INLETS
3/4" CHAMFER AT TOP OF OPENING

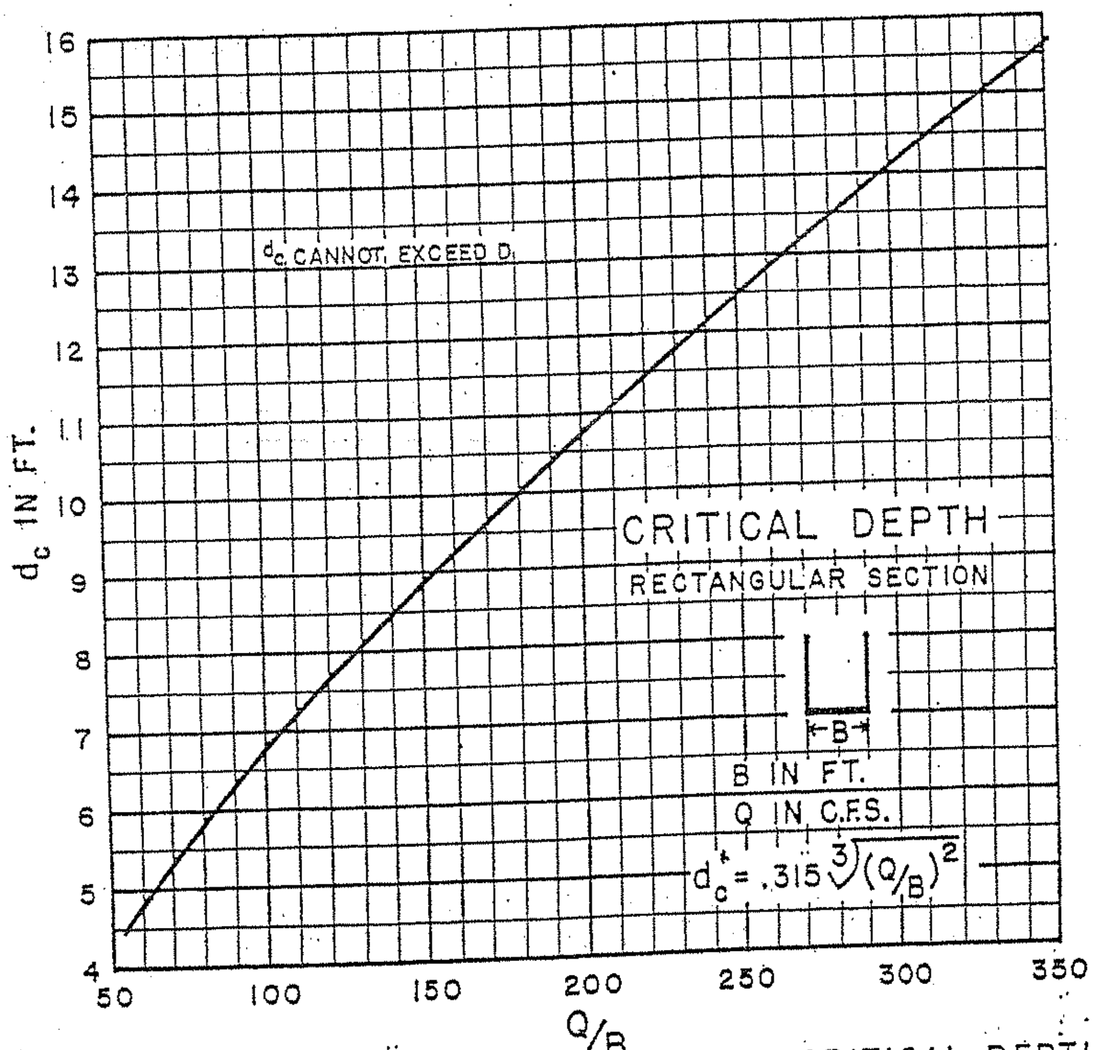
CHART 13



HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
OFFSET FLARED WINGWALLS
AND BEVELED EDGE AT TOP OF INLET

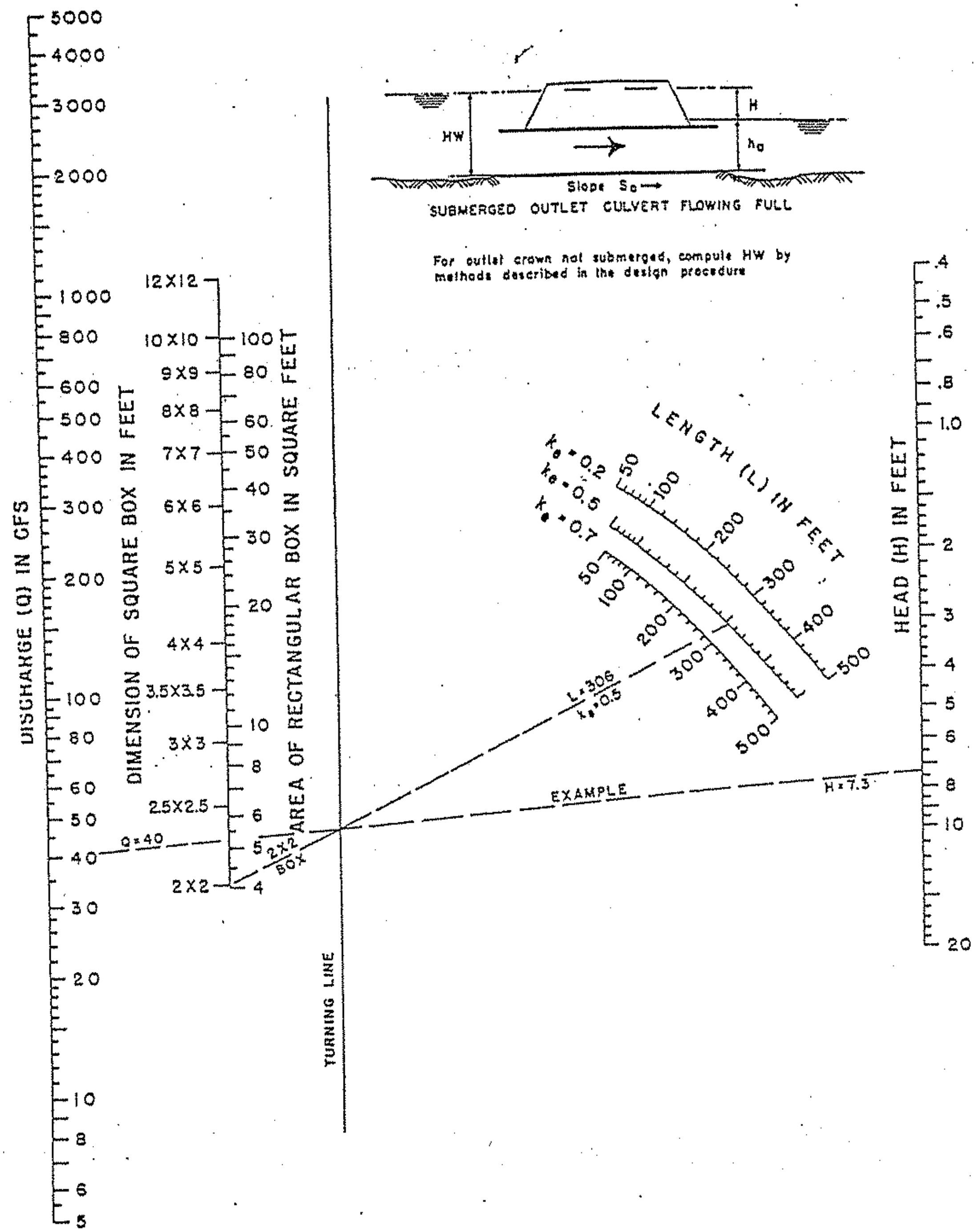
CHART 14





CRITICAL DEPTH
RECTANGULAR SECTION

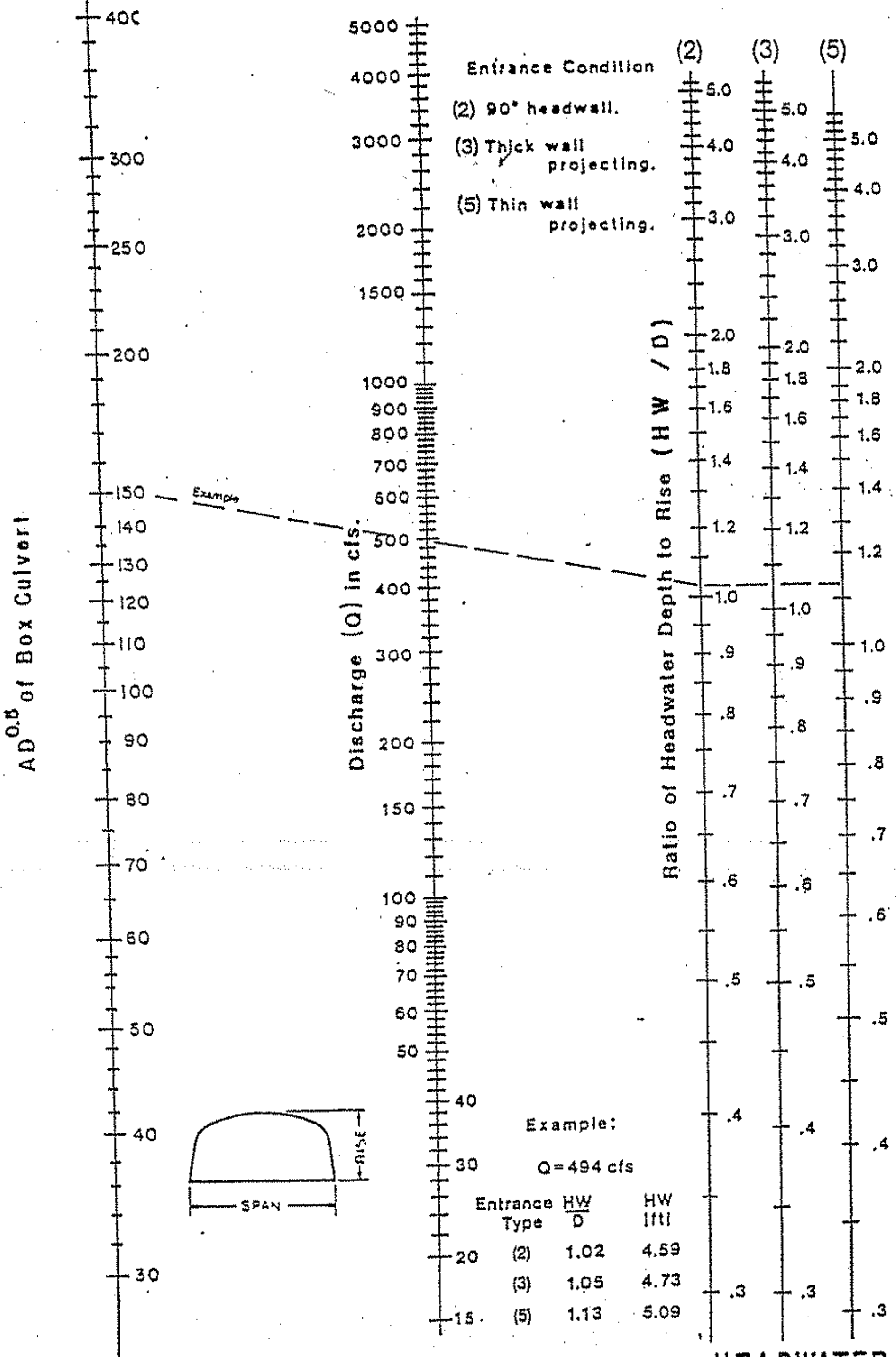
BUREAU OF PUBLIC ROADS JAN. 1963



# HEAD FOR CONCRETE BOX CULVERTS FLOWING FULL
n = 0.012

AU OF PUBLIC ROADS JAN. 1963

CHART 16

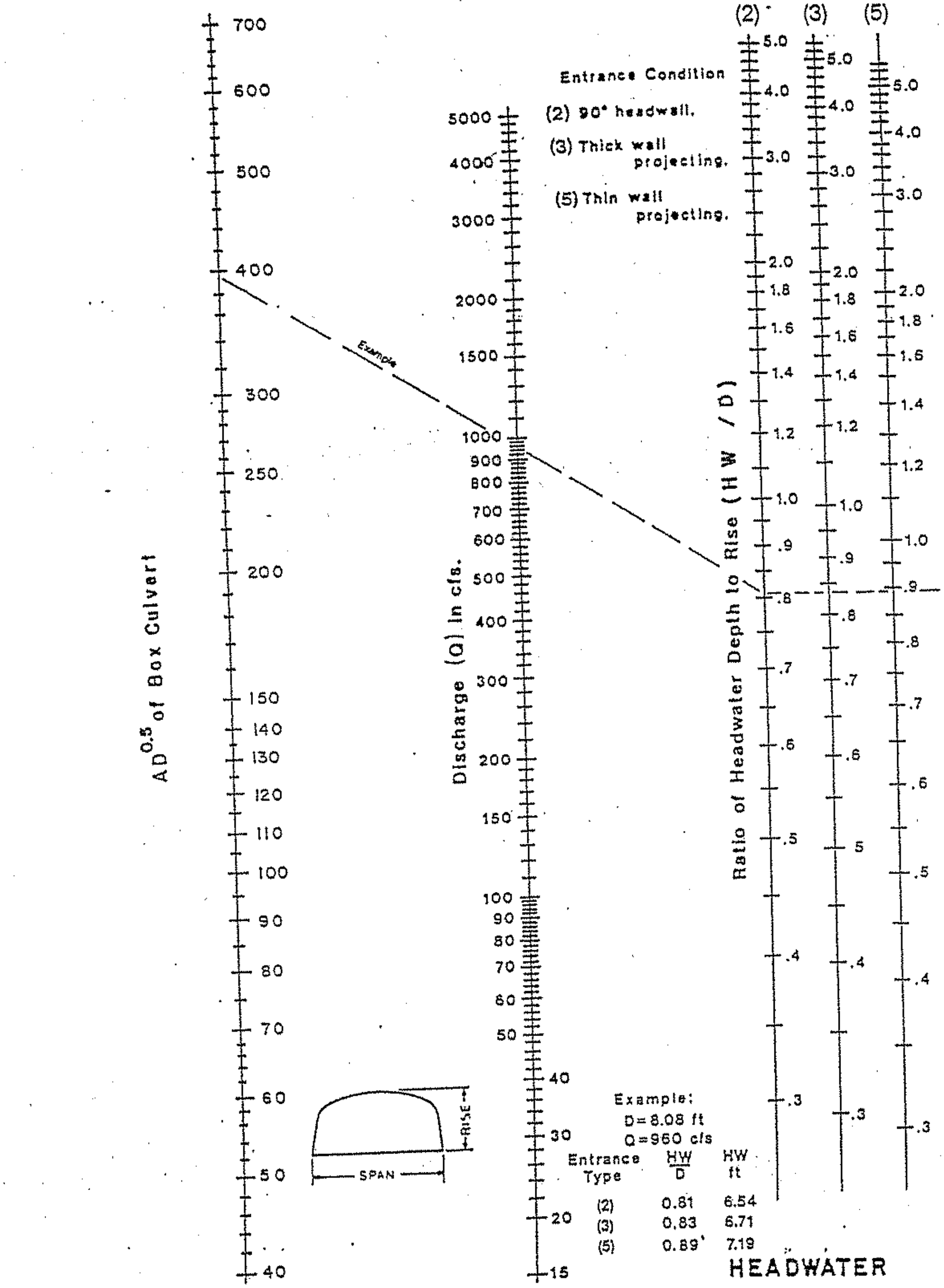


Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

HEADWATER DEPTH FOR C.M. BOX CULVERTS RISE / SPAN < 0.3 WITH INLET CONTROL

APPENDIX I-

CHART 17

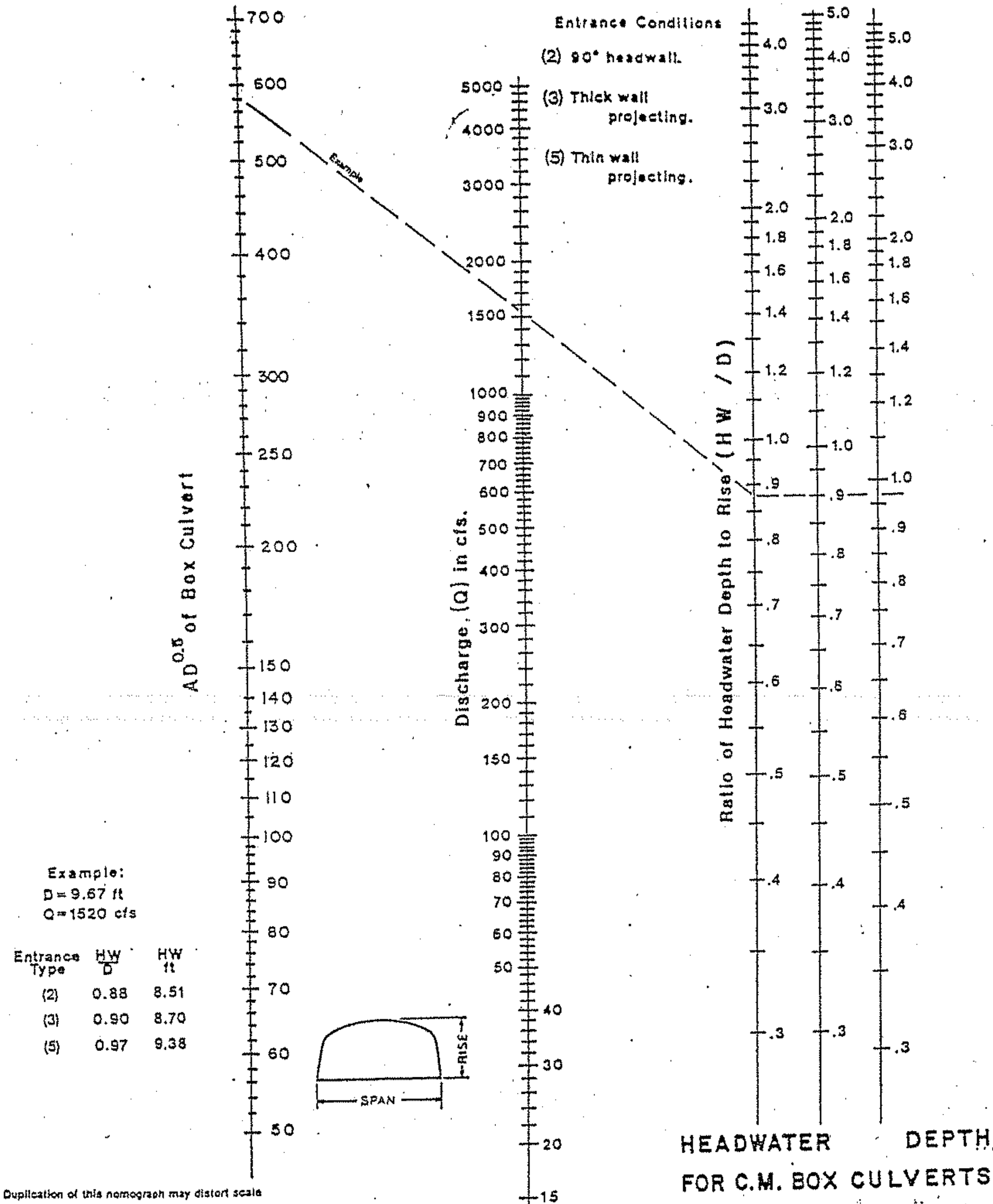


Duplication of this nomograph may distort scale

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

HEADWATER DEPTH FOR C.M. BOX CULVERTS $0.3 \leq$ RISE / SPAN < 0.4 WITH INLET CONTROL

CHART 18

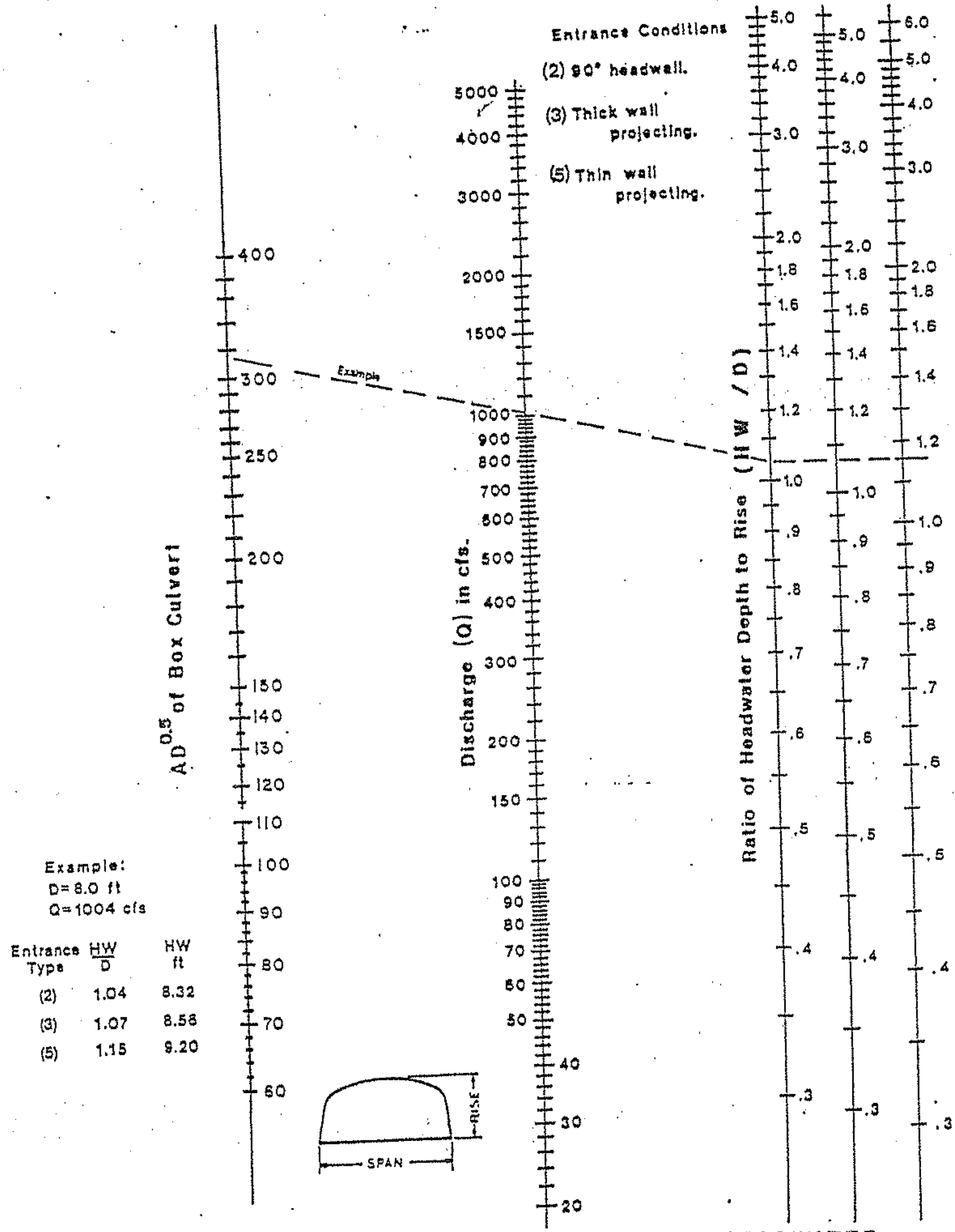


HEADWATER DEPTH
FOR C.M. BOX CULVERTS
$0.4 \leq$ RISE / SPAN < 0.5
WITH INLET CONTROL

Nomographs adapted from material furnished by
Kaiser Aluminum and Chemical Corporation

APPENDIX I-

CHART 19



Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

HEADWATER DEPTH FOR C.M. BOX CULVERTS $0.5 \leq$ RISE / SPAN WITH INLET CONTROL

CHART 20

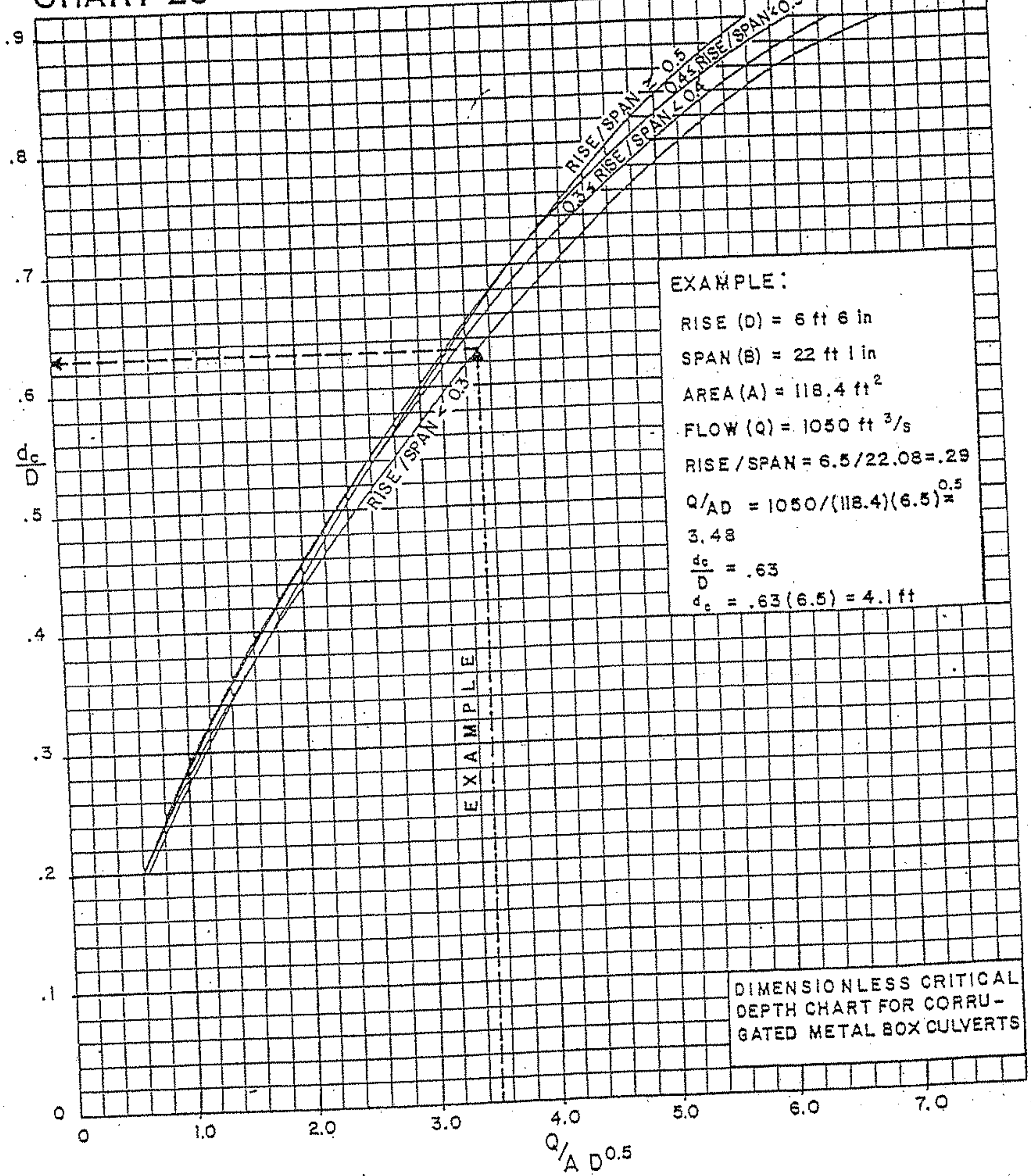
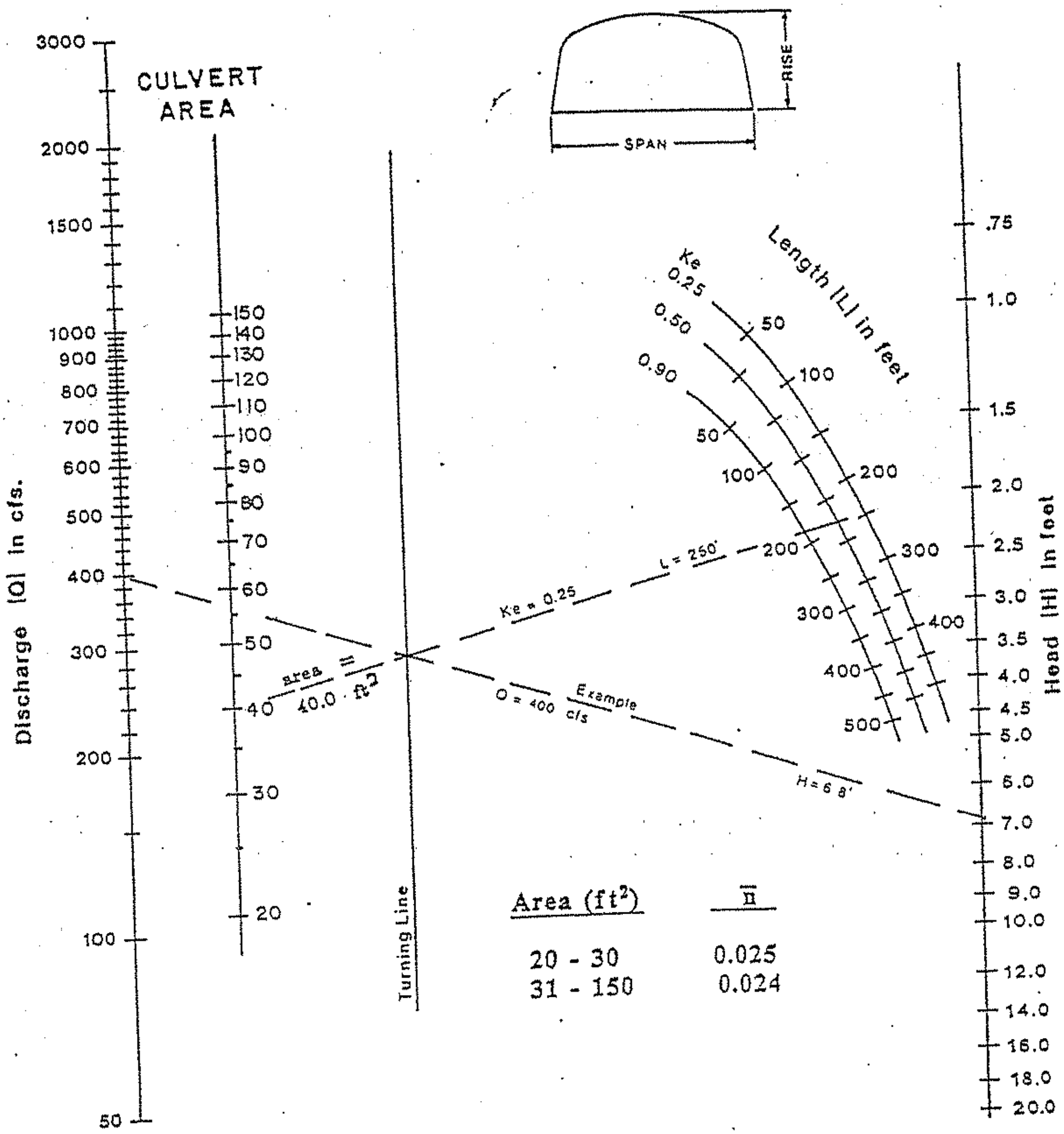
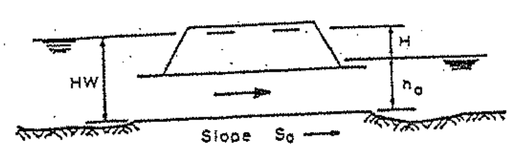

RISE/SPAN ≥ 0.5
0.4 ≤ RISE/SPAN < 0.5
0.3 ≤ RISE/SPAN < 0.4
RISE/SPAN < 0.3
EXAMPLE
EXAMPLE:
RISE (D) = 6 ft 6 in
SPAN (B) = 22 ft 1 in
AREA (A) = 118.4 ft²
FLOW (Q) = 1050 ft ³/s
RISE / SPAN = 6.5/22.08 = .29
Q/AD = 1050/(118.4)(6.5)^0.5 = 3.48
dc/D = .63
dc = .63 (6.5) = 4.1 ft
dc/D
Q/A D^0.5
DIMENSIONLESS CRITICAL DEPTH CHART FOR CORRUGATED METAL BOX CULVERTS

CHART 21



Area (ft²)	n
20 - 30	0.025
31 - 150	0.024



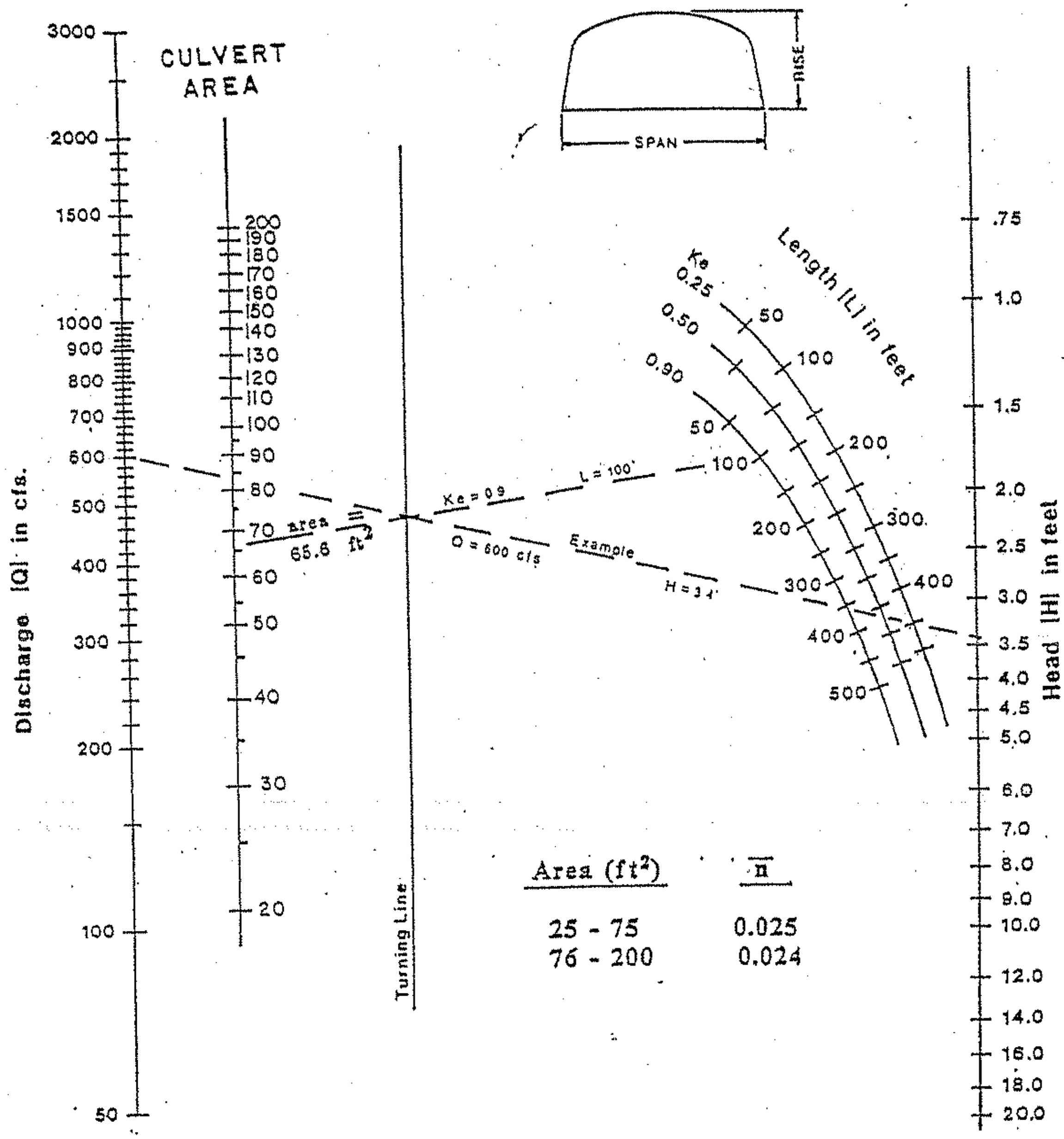
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR
C.M. BOX CULVERTS
FLOWING FULL
CONCRETE BOTTOM
RISE/SPAN < 0.3

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 22

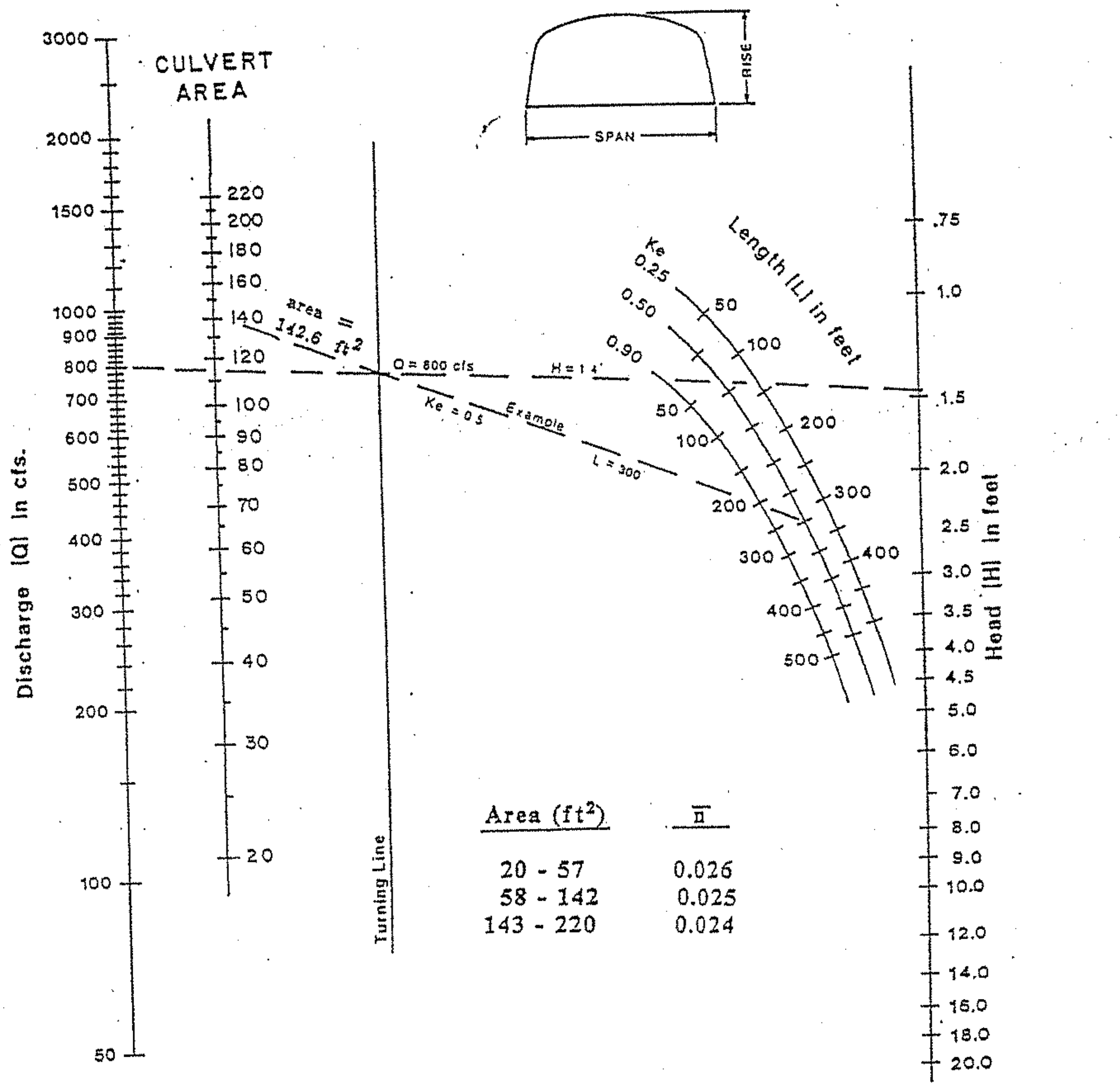


SUBMERGED OUTLET CULVERT FLOWING FULL

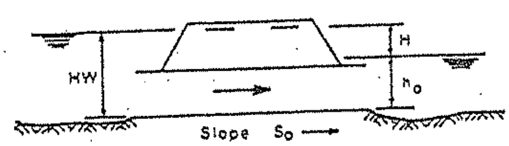
HEAD FOR C. M. BOX CULVERTS FLOWING FULL CONCRETE BOTTOM $0.3 \leq$ RISE/SPAN < 0.4

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale



Area (ft²)	n
20 - 57	0.026
58 - 142	0.025
143 - 220	0.024



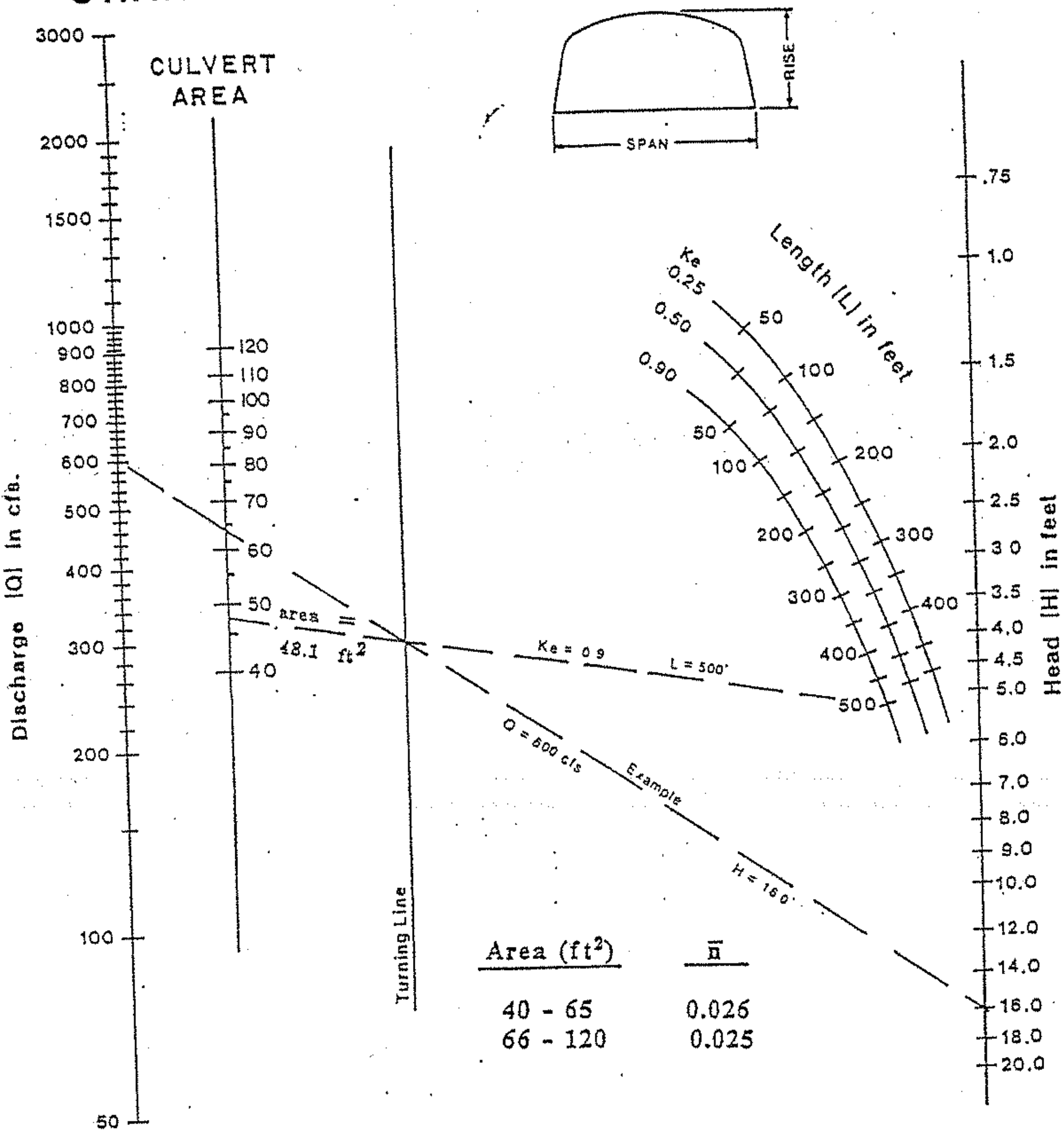
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR
C. M. BOX CULVERTS
FLOWING FULL
CONCRETE BOTTOM
$0.4 \leq$ RISE/SPAN < 0.5

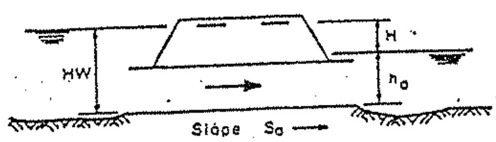
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 24



Area (ft²)	n
40 - 65	0.026
66 - 120	0.025



SUBMERGED OUTLET CULVERT FLOWING FULL

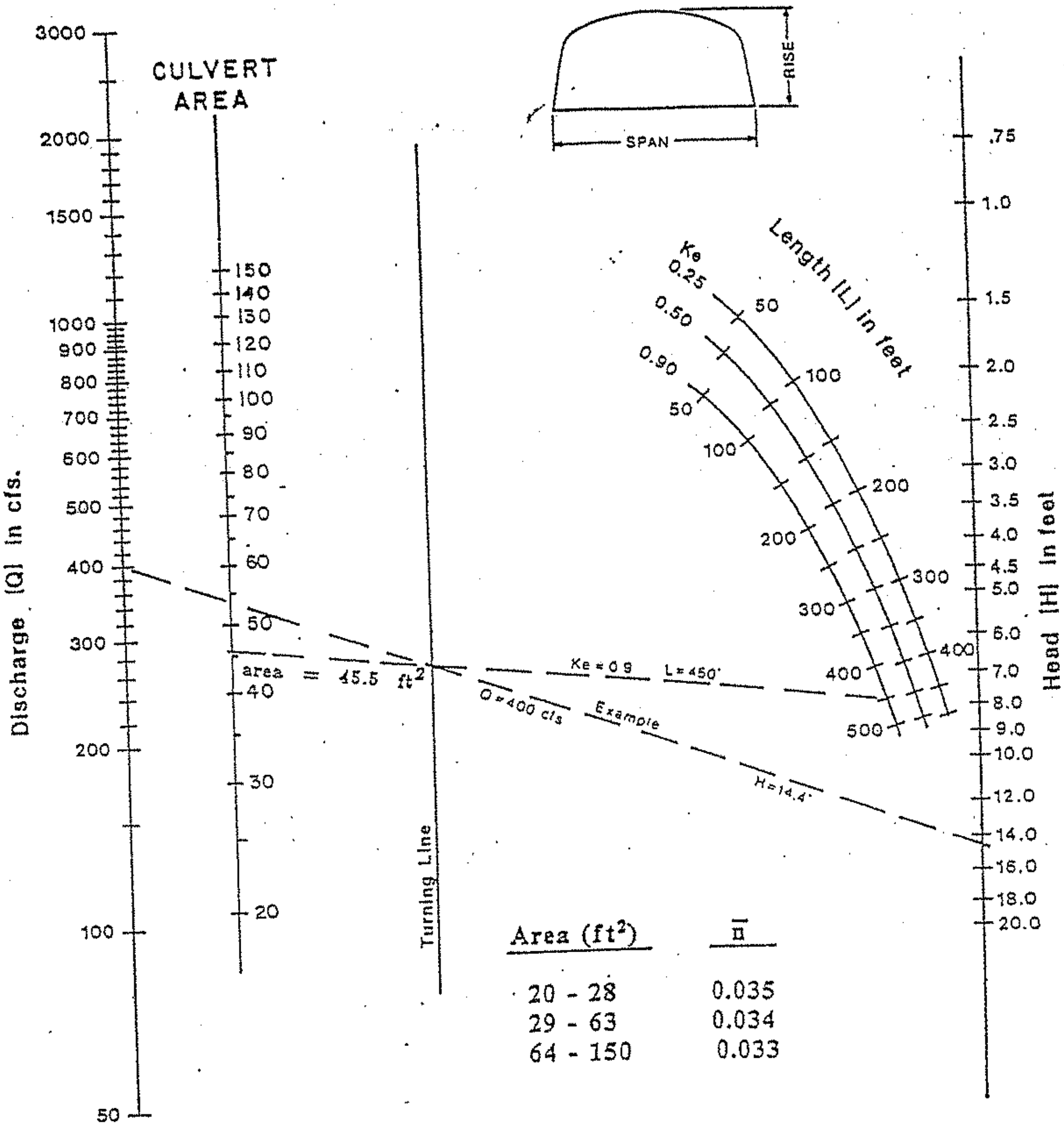
HEAD FOR C. M. BOX CULVERTS FLOWING FULL CONCRETE BOTTOM

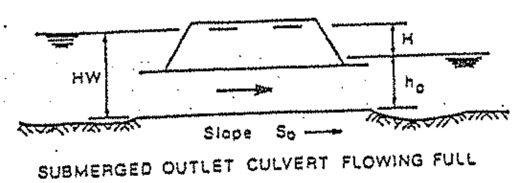
$0.5 \leq$ RISE / SPAN

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 25



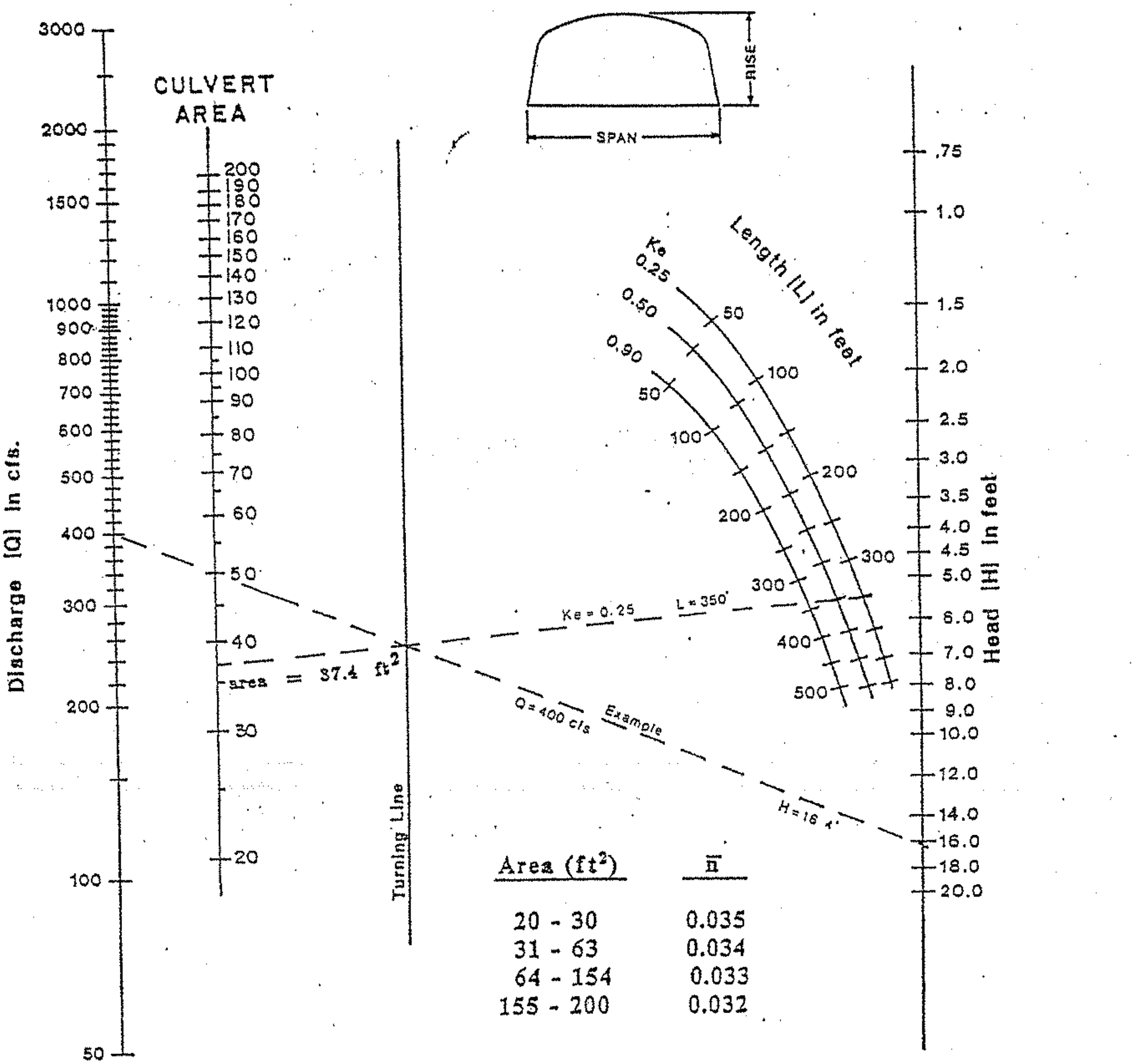


HEAD FOR
C. M. BOX CULVERTS
FLOWING FULL
CORRUGATED METAL BOTTOM
RISE / SPAN < 0.3

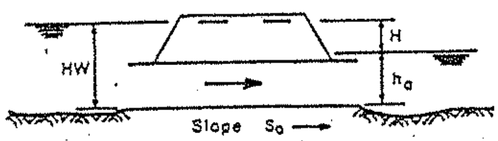
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 26



Area (ft²)	n
20 - 30	0.035
31 - 63	0.034
64 - 154	0.033
155 - 200	0.032



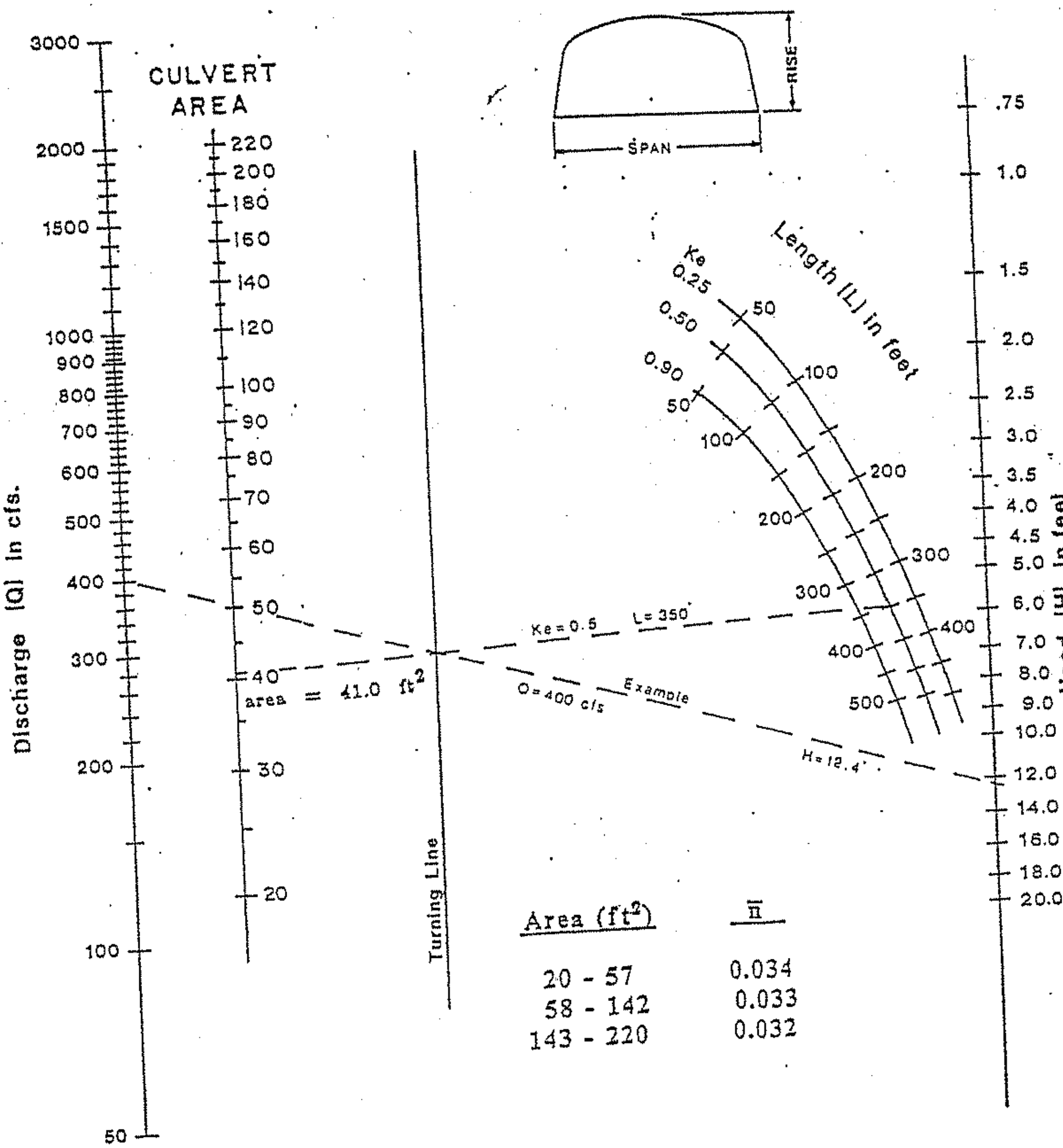
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR
C. M. BOX CULVERTS
FLOWING FULL
CORRUGATED METAL BOTTOM
0.3 ≤ RISE / SPAN < 0.4

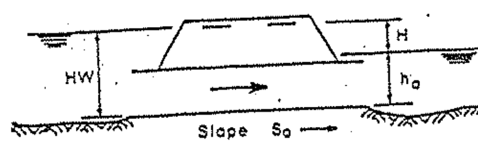
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 27



Area (ft²)	n
20 - 57	0.034
58 - 142	0.033
143 - 220	0.032



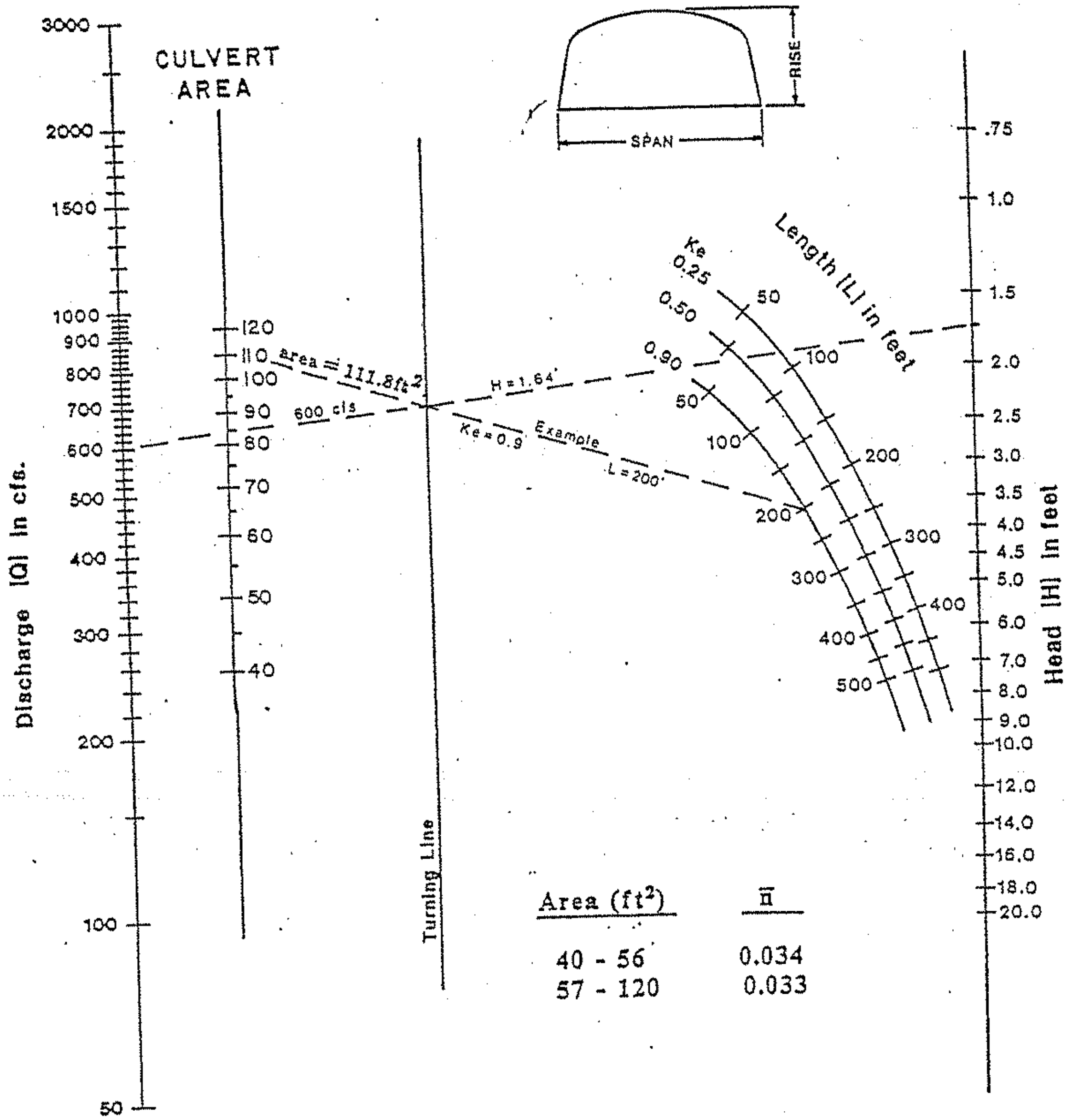
SUBMERGED OUTLET CULVERT FLOWING FULL

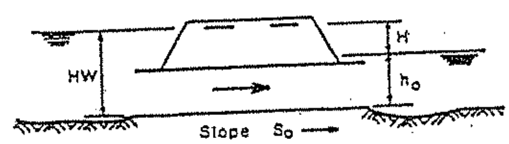
HEAD FOR C. M. BOX CULVERTS FLOWING FULL CORRUGATED METAL BOTTOM 0.4 ≤ RISE/SPAN < 0.5

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 28



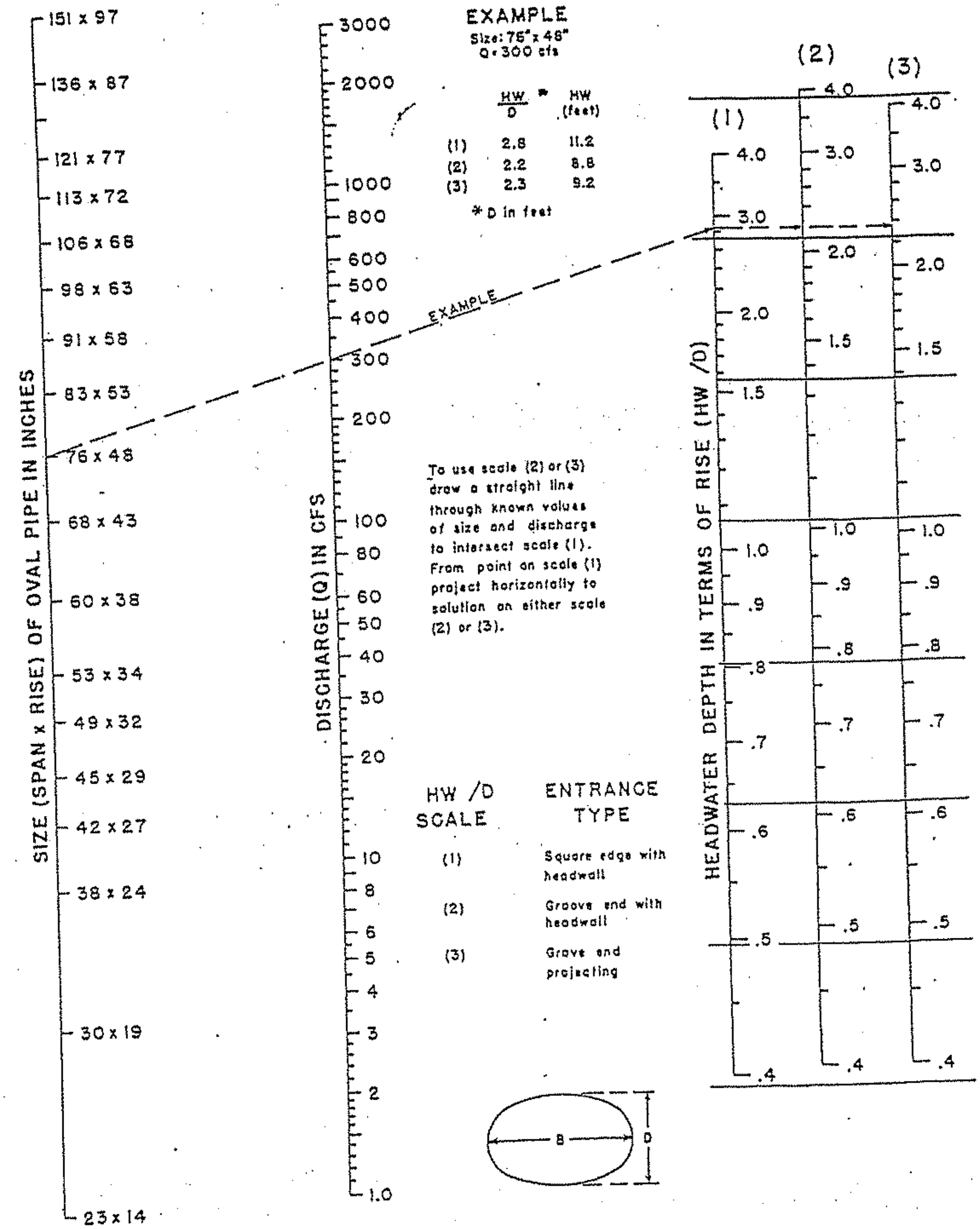


SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C. M. BOX CULVERTS FLOWING FULL CORRUGATED METAL BOTTOM 0.5 ≤ RISE / SPAN

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

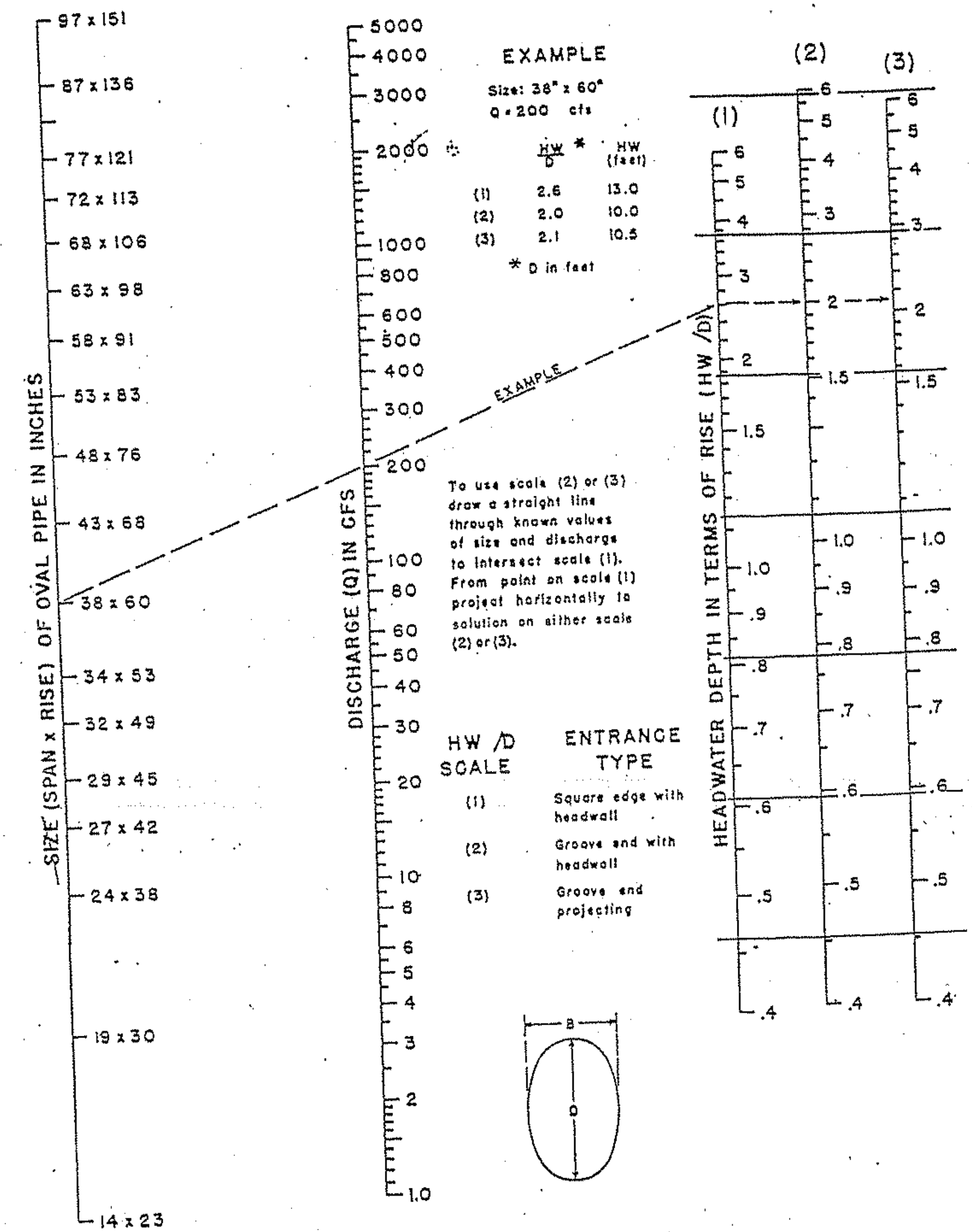
Duplication of this nomograph may distort scale



HEADWATER DEPTH FOR
OVAL CONCRETE PIPE CULVERTS
LONG AXIS HORIZONTAL
WITH INLET CONTROL

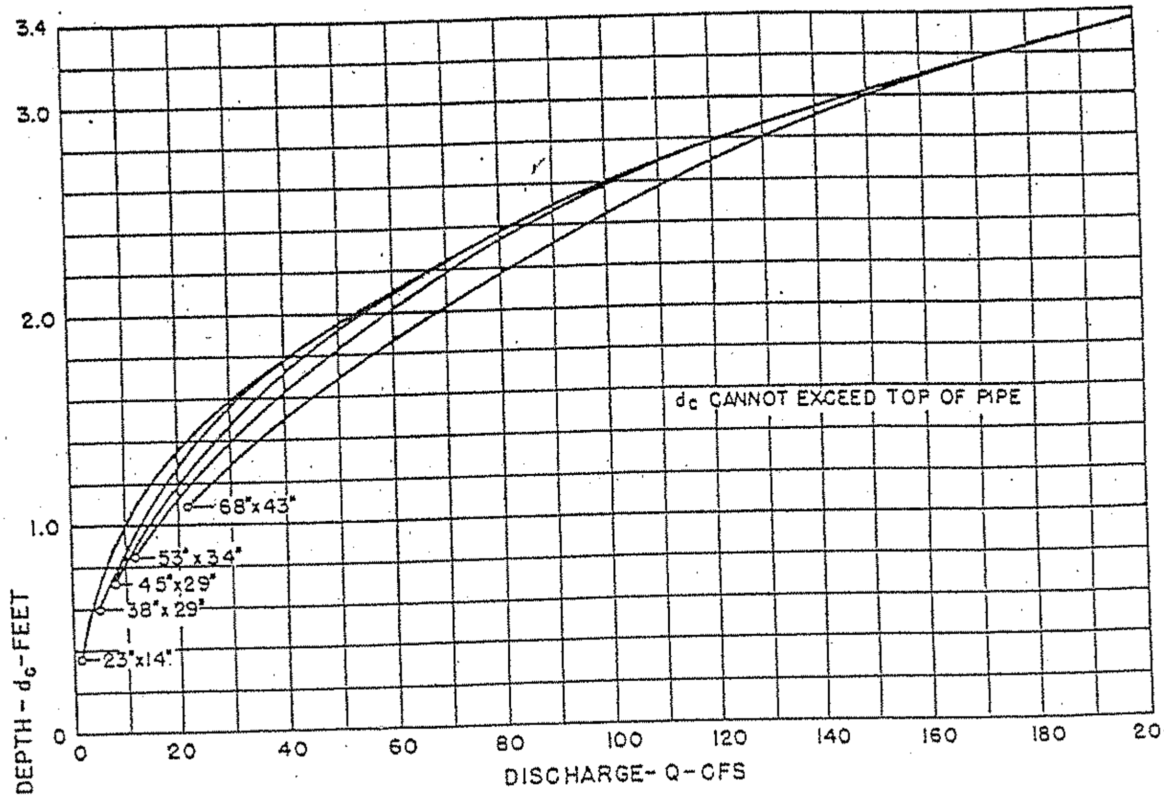
BUREAU OF PUBLIC ROADS JAN. 1963

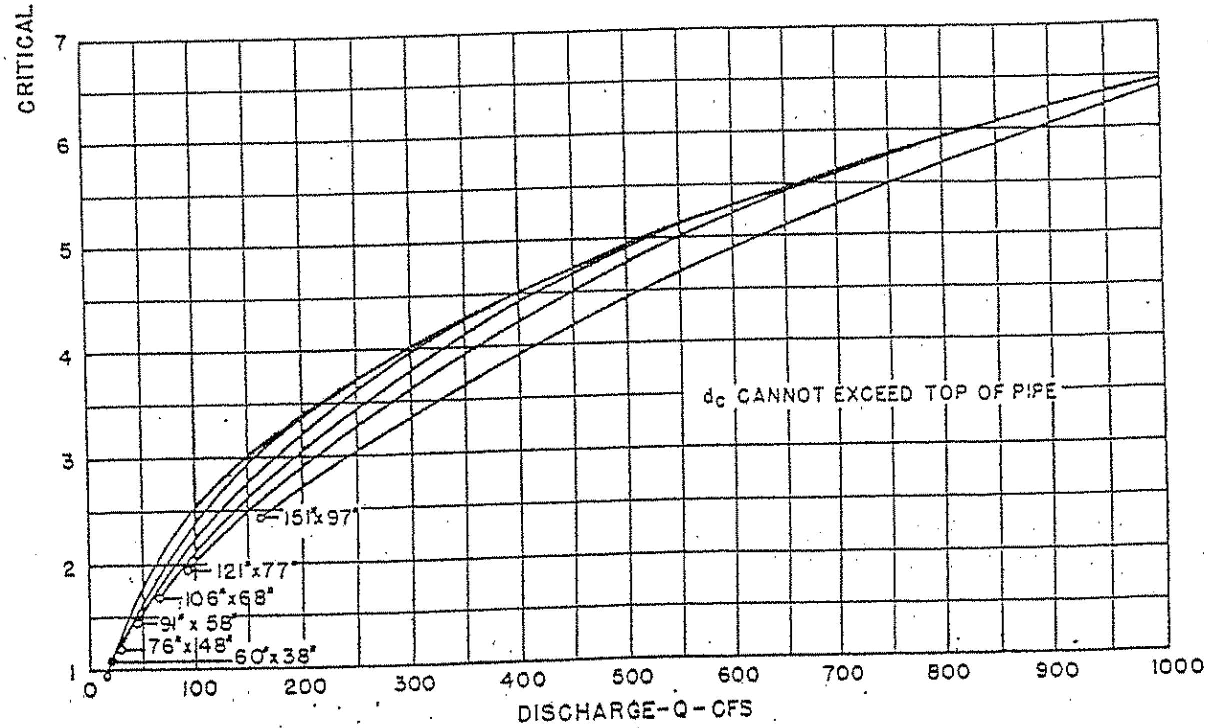
CHART 30



HEADWATER DEPTH FOR
OVAL CONCRETE PIPE CULVERTS
LONG AXIS VERTICAL
WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963



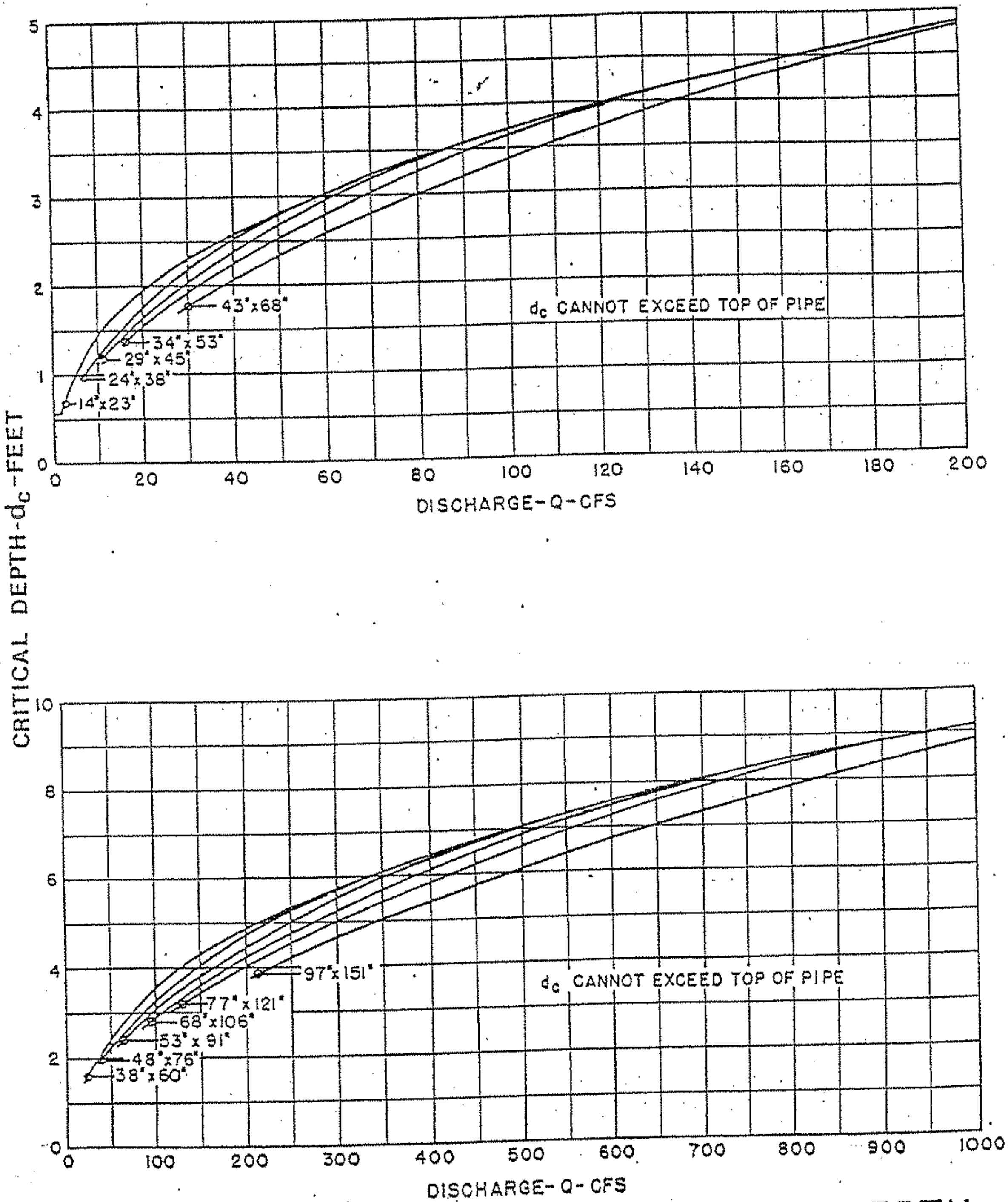


BUREAU OF PUBLIC ROADS

JAN. 1964

CRITICAL DEPTH
OVAL CONCRETE PIPE
LONG AXIS HORIZONTAL

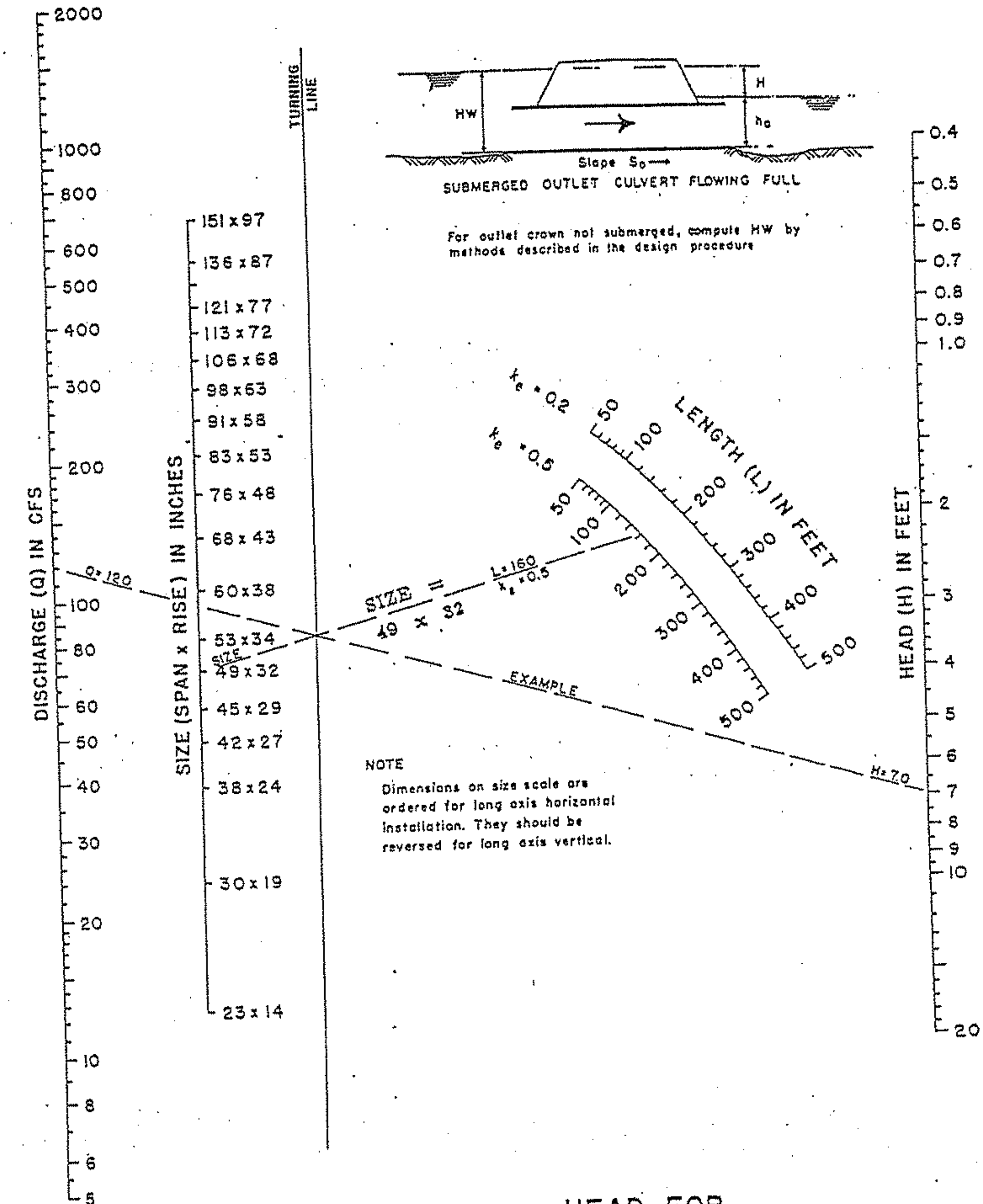
CHART 32



BUREAU OF PUBLIC ROADS
JAN. 1964

CRITICAL DEPTH
OVAL CONCRETE PIPE
LONG AXIS VERTICAL

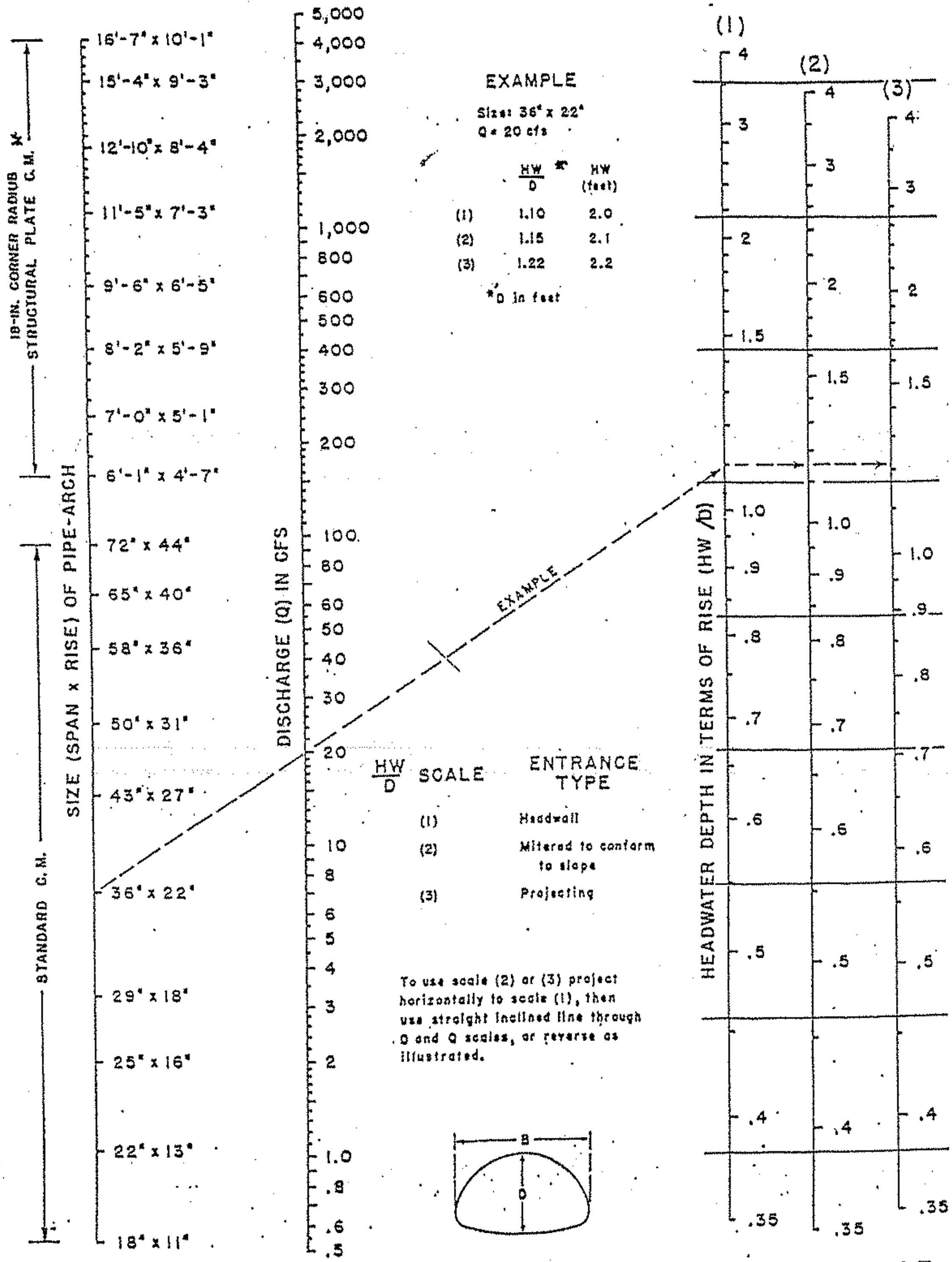
CHART 33



HEAD FOR
OVAL CONCRETE PIPE CULVERTS
LONG AXIS HORIZONTAL OR VERTICAL
FLOWING FULL
n = 0.012

BUREAU OF PUBLIC ROADS JAN. 1963

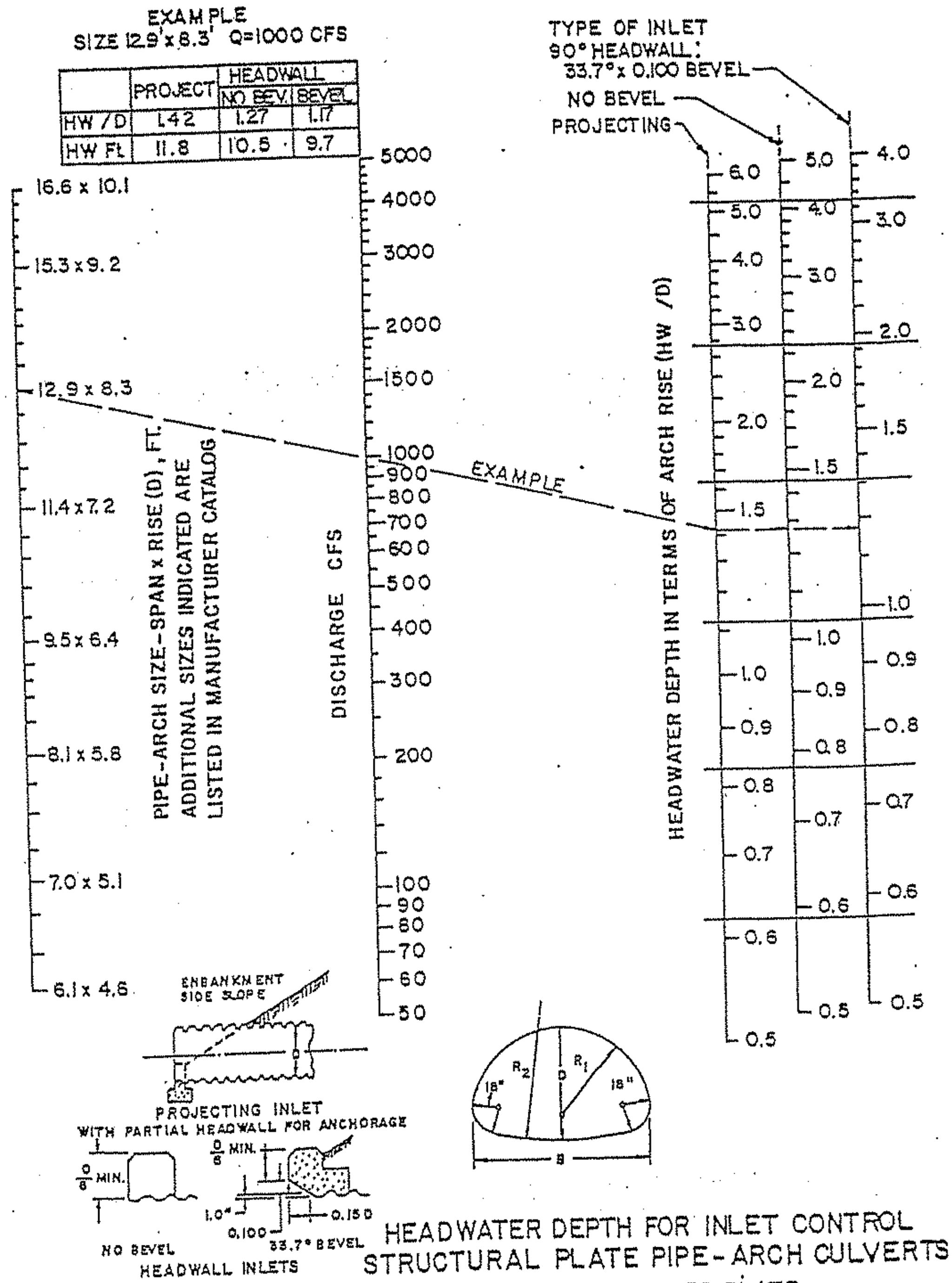
CHART 34



*ADDITIONAL SIZES NOT DIMENSIONED ARE LISTED IN FABRICATOR'S CATALOG

BUREAU OF PUBLIC ROADS JAN. 1963

HEADWATER DEPTH FOR C. M. PIPE-ARCH CULVERTS WITH INLET CONTROL



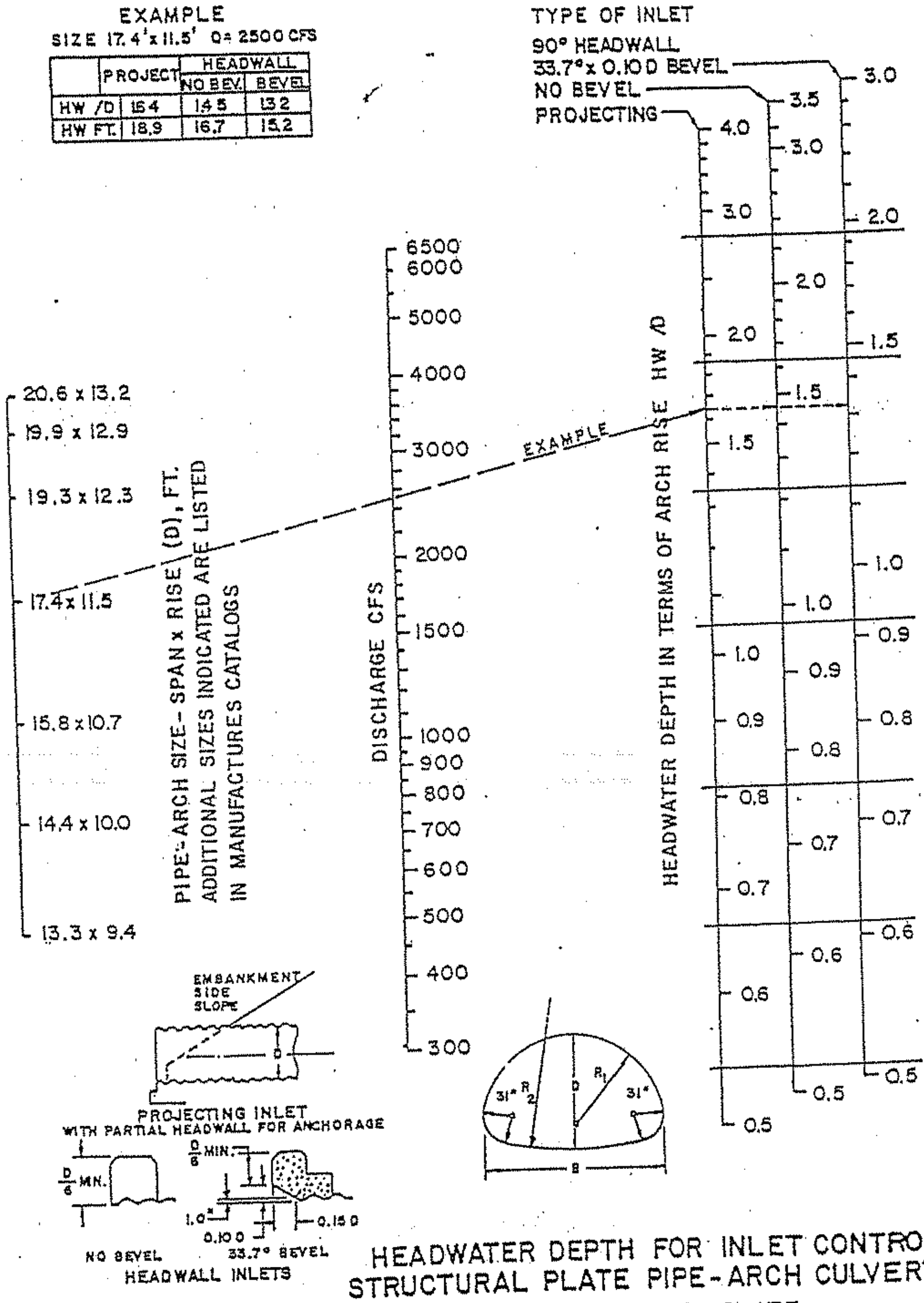
HEADWATER DEPTH FOR INLET CONTROL
STRUCTURAL PLATE PIPE-ARCH CULVERTS
18-IN. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

BUREAU OF PUBLIC ROADS
OFFICE OF R&D JULY 1968

CHART 36

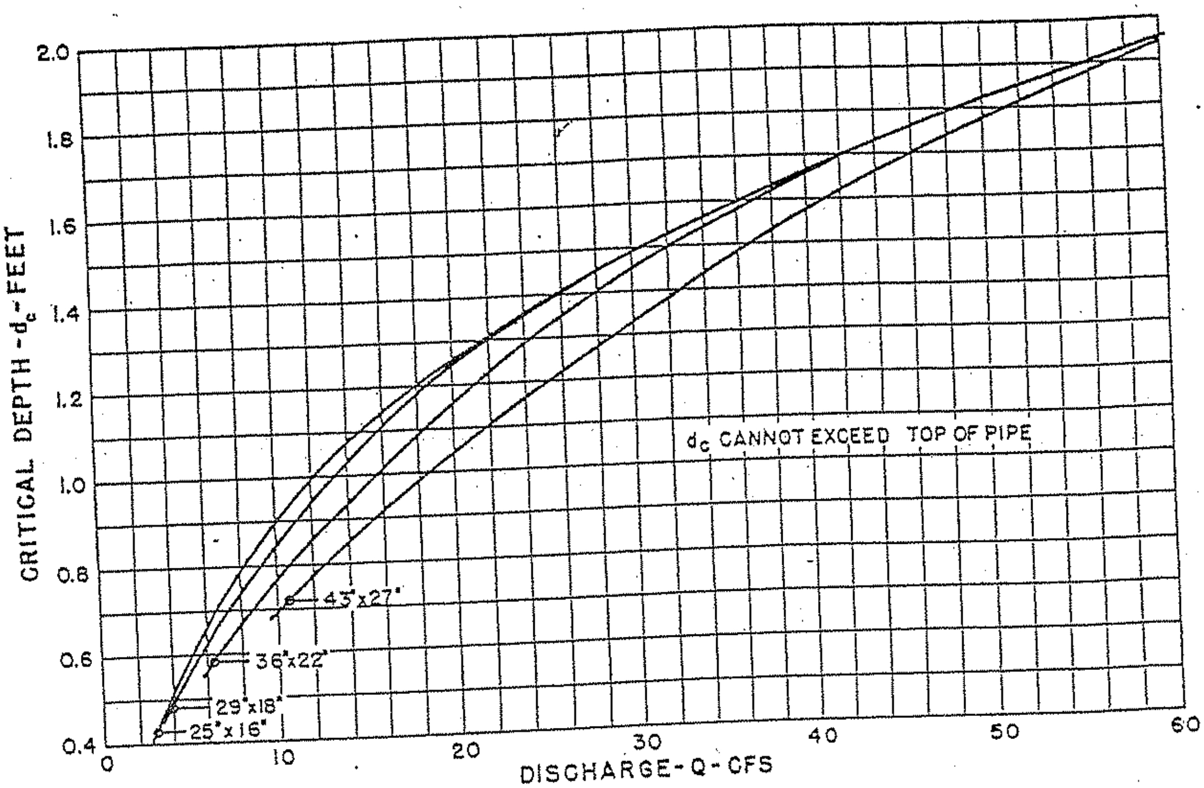
EXAMPLE
SIZE 17.4'x 11.5' Q= 2500 CFS

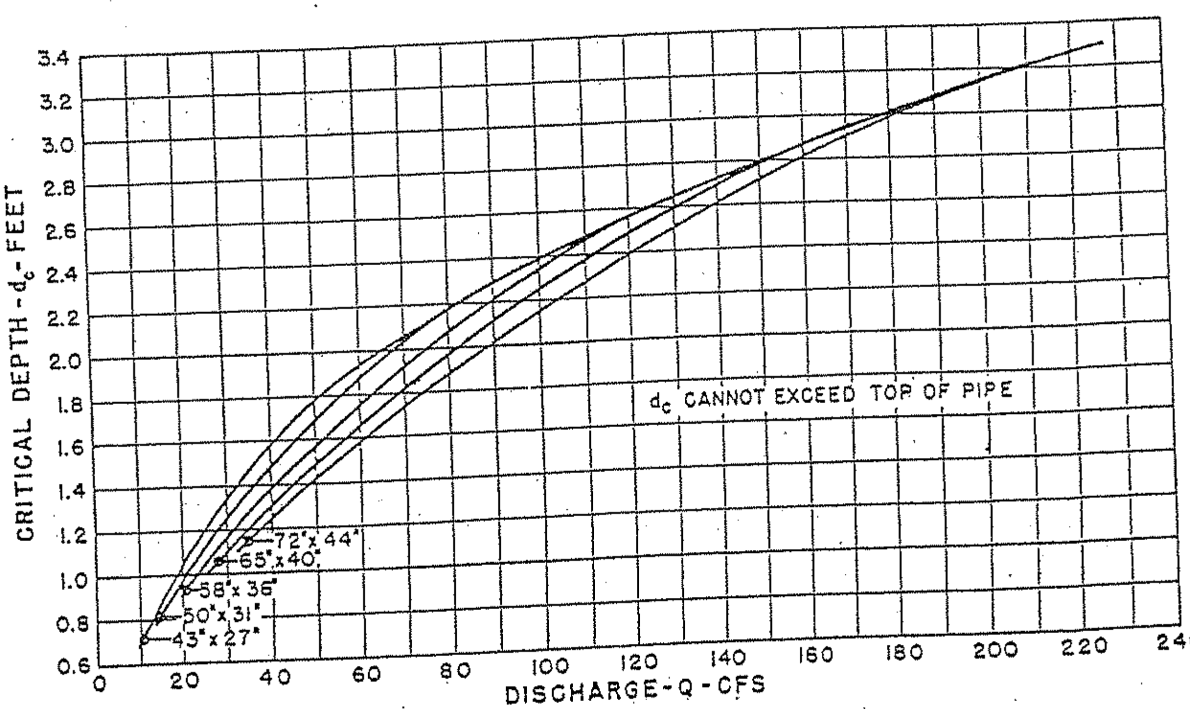
	PROJECT	HEADWALL NO BEV.	HEADWALL BEVEL
HW /D	16.4	14.5	13.2
HW FT.	18.9	16.7	15.2



HEADWATER DEPTH FOR INLET CONTROL
STRUCTURAL PLATE PIPE-ARCH CULVERTS
31-IN. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

BUREAU OF PUBLIC ROADS
OFFICE OF R&D JULY 1965

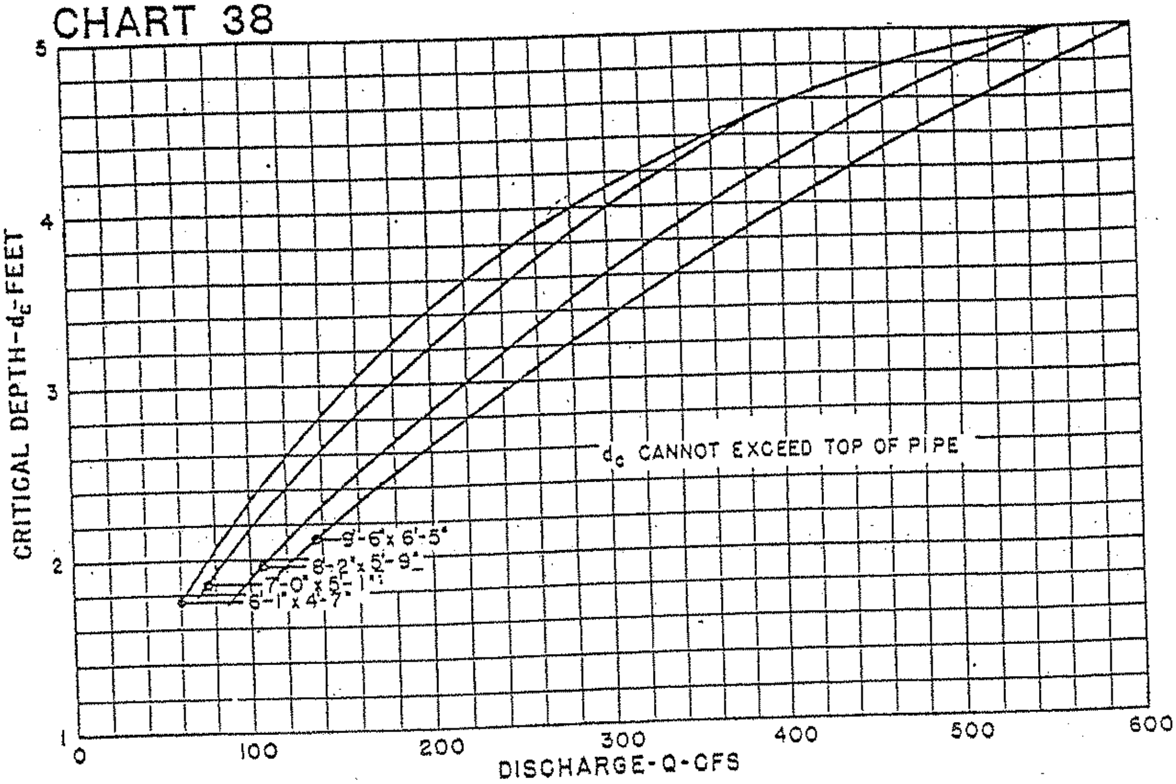


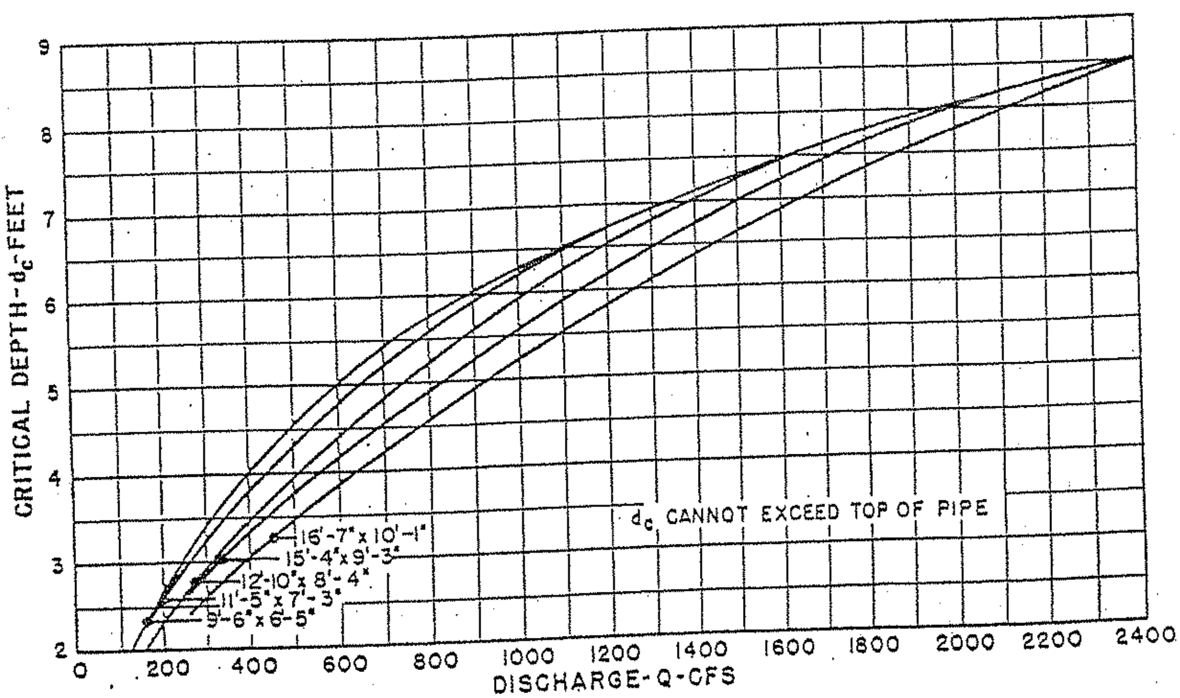


BUREAU OF PUBLIC ROADS
JAN. 1964

CRITICAL DEPTH
STANDARD C.M. PIPE-ARCH

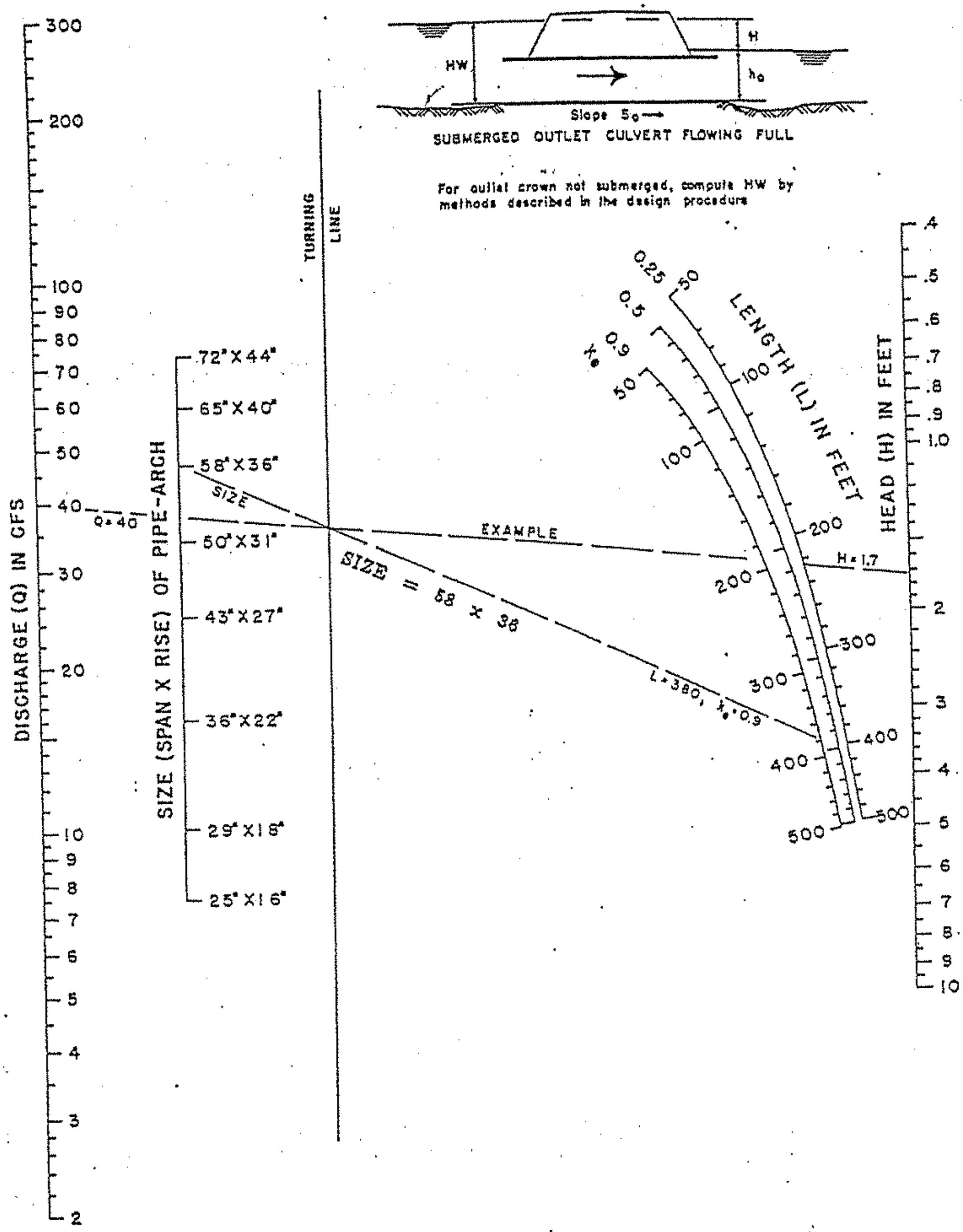
CHART 38





BUREAU OF PUBLIC ROADS
JAN. 1964

CRITICAL DEPTH
STRUCTURAL PLATE
C.M. PIPE-ARCH
18 INCH CORNER RADIUS

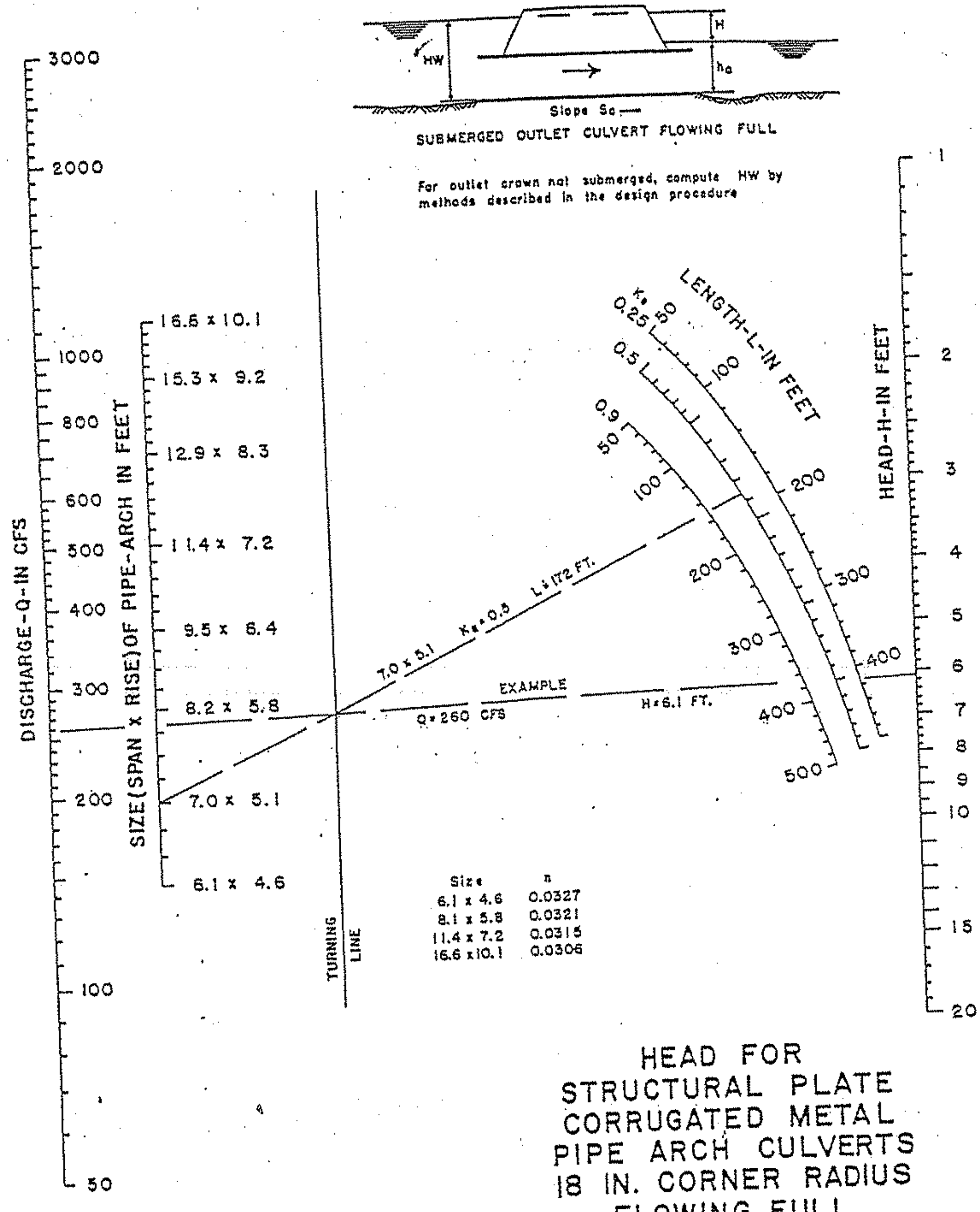


HEAD FOR STANDARD C. M. PIPE-ARCH CULVERTS FLOWING FULL

n=0.024

BUREAU OF PUBLIC ROADS JAN. 1963

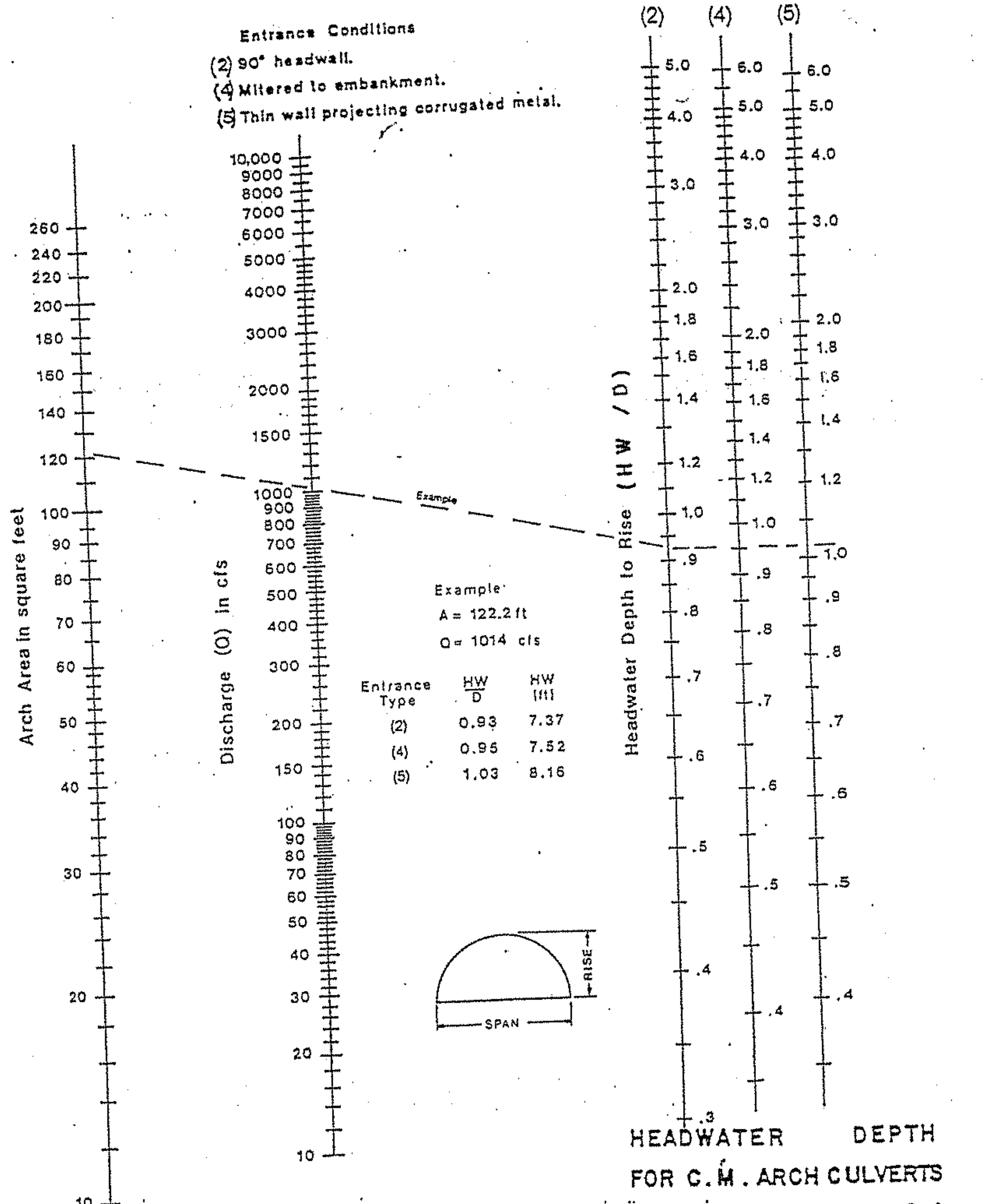
CHART 40



HEAD FOR
STRUCTURAL PLATE
CORRUGATED METAL
PIPE ARCH CULVERTS
18 IN. CORNER RADIUS
FLOWING FULL
n=0.0327 TO 0.0306

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 41



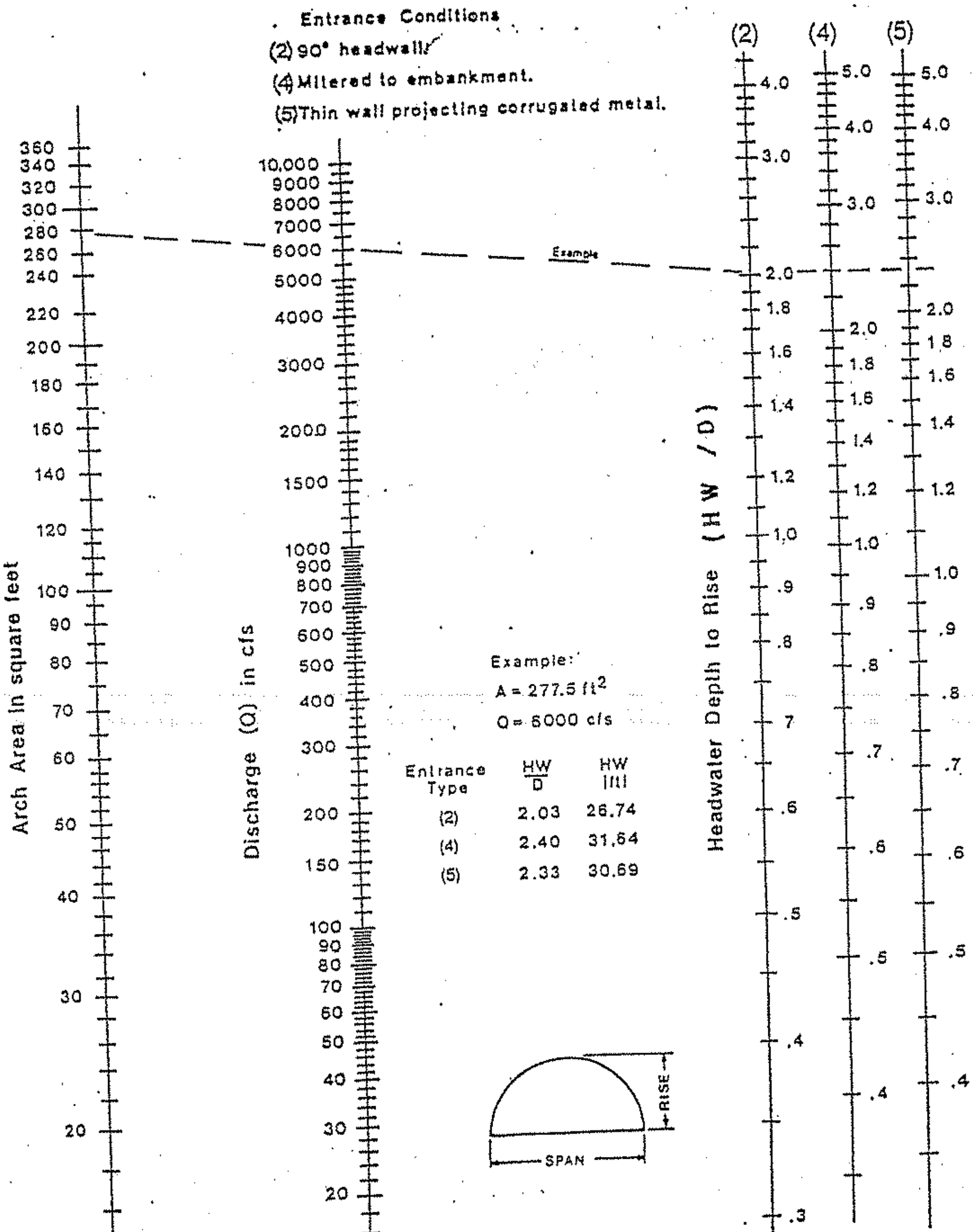
Entrance Type	HW/D	HW (ft)
(2)	0.93	7.37
(4)	0.95	7.52
(5)	1.03	8.16

HEADWATER DEPTH FOR C.M. ARCH CULVERTS 0.3 ≤ RISE / SPAN < 0.4 WITH INLET CONTROL

Duplication of this nomograph may distort scale

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

CHART 42

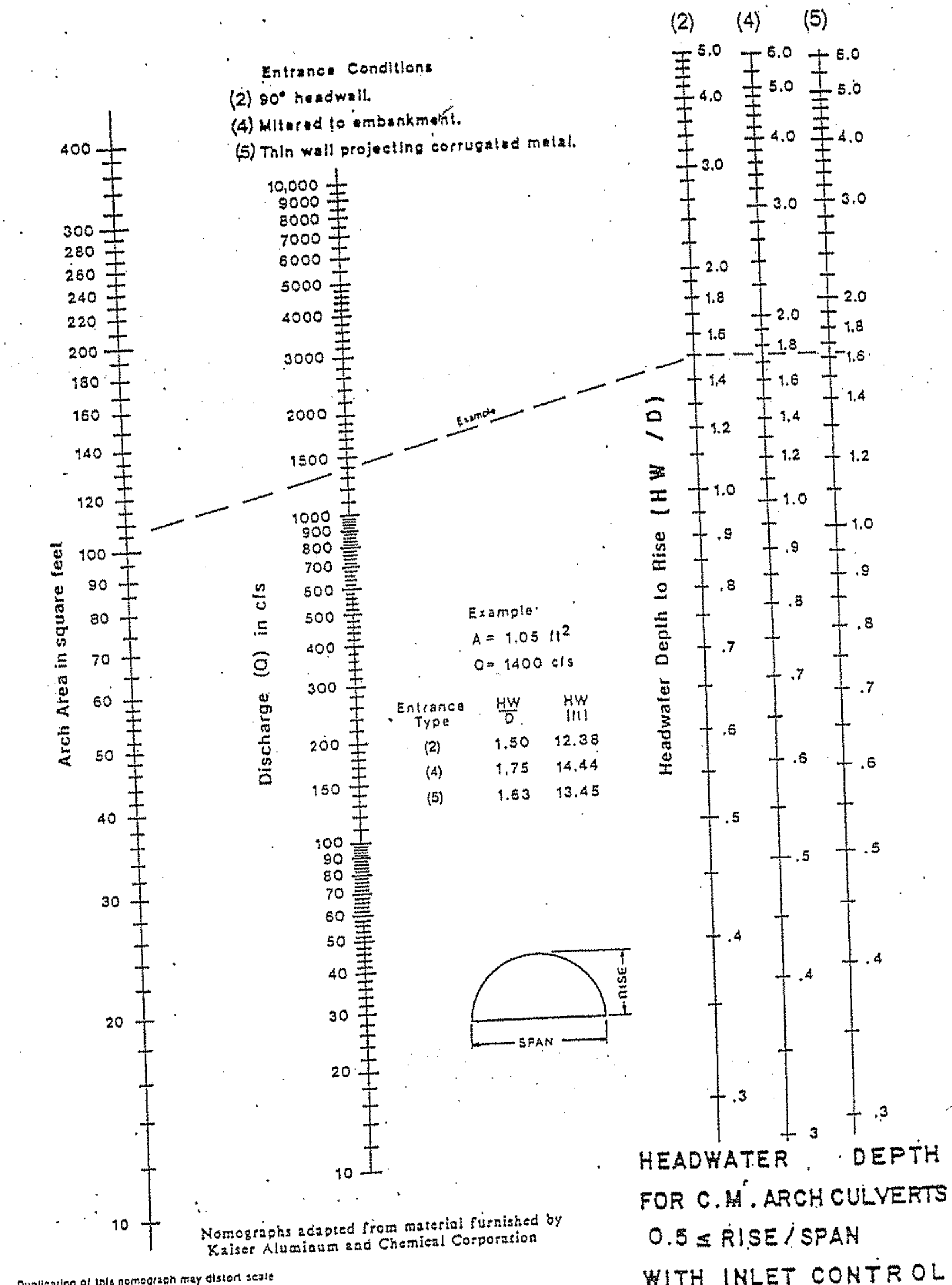


Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

HEADWATER DEPTH FOR C.M. ARCH CULVERTS $0.4 \leq$ RISE / SPAN < 0.5 WITH INLET CONTROL

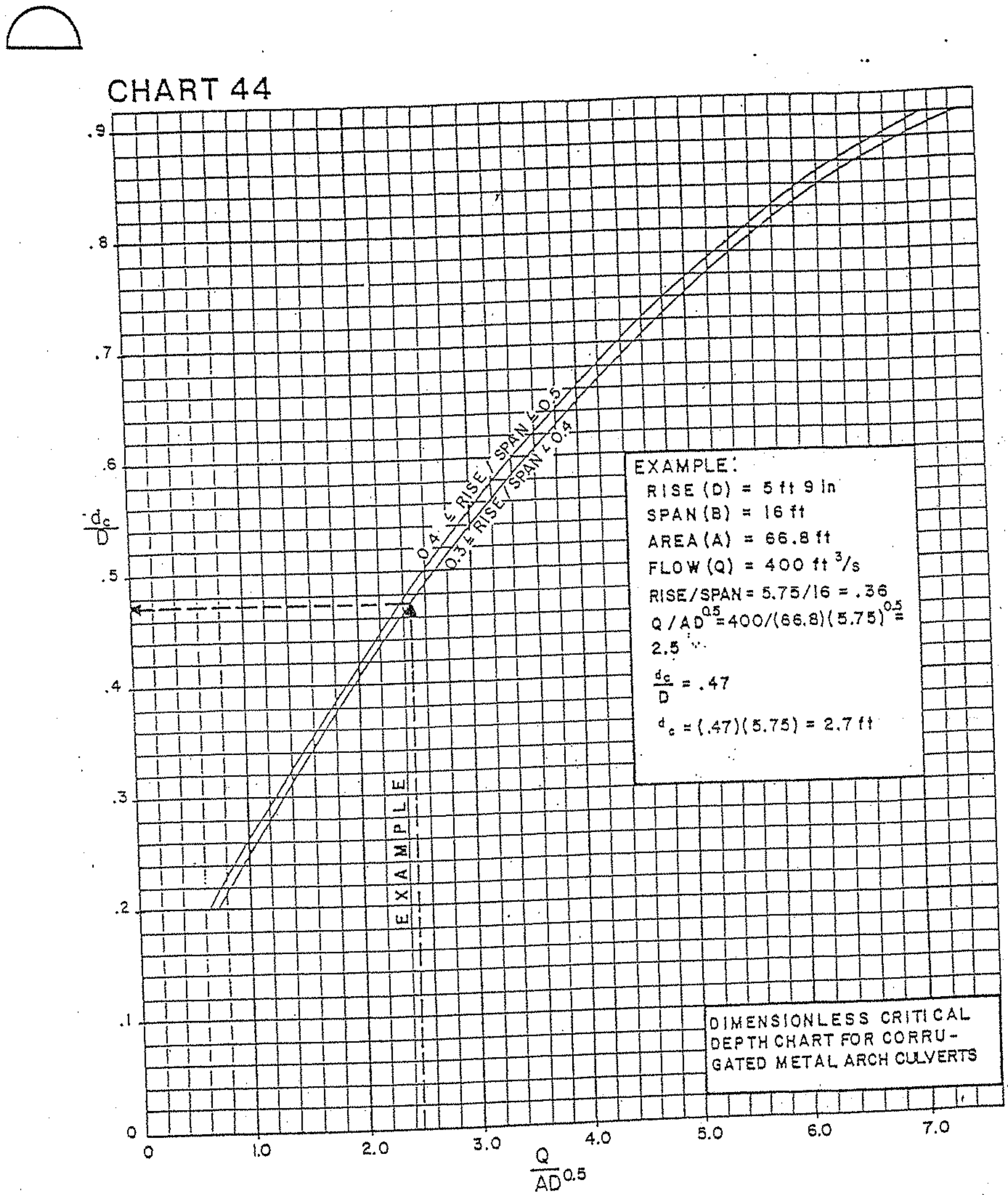
Duplication of this nomograph may distort scale

CHART 43



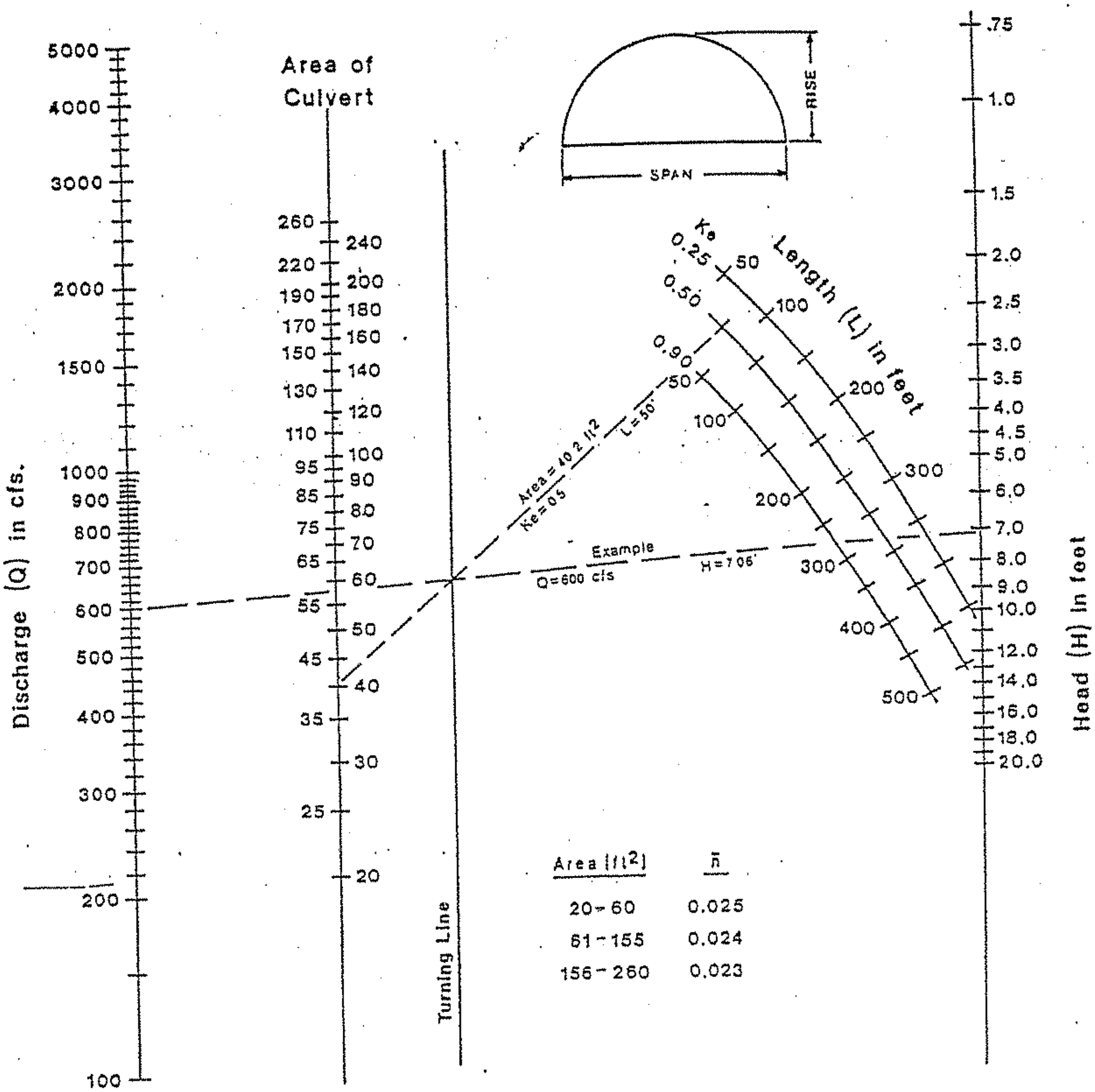
HEADWATER DEPTH
FOR C.M. ARCH CULVERTS
0.5 ≤ RISE / SPAN
WITH INLET CONTROL

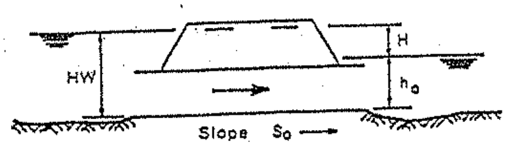
CHART 44



$\frac{d_c}{D}$
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
$\frac{Q}{AD^{0.5}}$
0.4 ≤ RISE / SPAN ≤ 0.5
0.3 ≤ RISE / SPAN ≤ 0.4
EXAMPLE
EXAMPLE:
RISE (D) = 5 ft 9 in
SPAN (B) = 16 ft
AREA (A) = 66.8 ft
FLOW (Q) = 400 ft ³/s
RISE/SPAN = 5.75/16 = .36
Q / AD^0.5 = 400/(66.8)(5.75)^0.5 = 2.5
dc/D = .47
dc = (.47)(5.75) = 2.7 ft
DIMENSIONLESS CRITICAL DEPTH CHART FOR CORRUGATED METAL ARCH CULVERTS

CHART 45





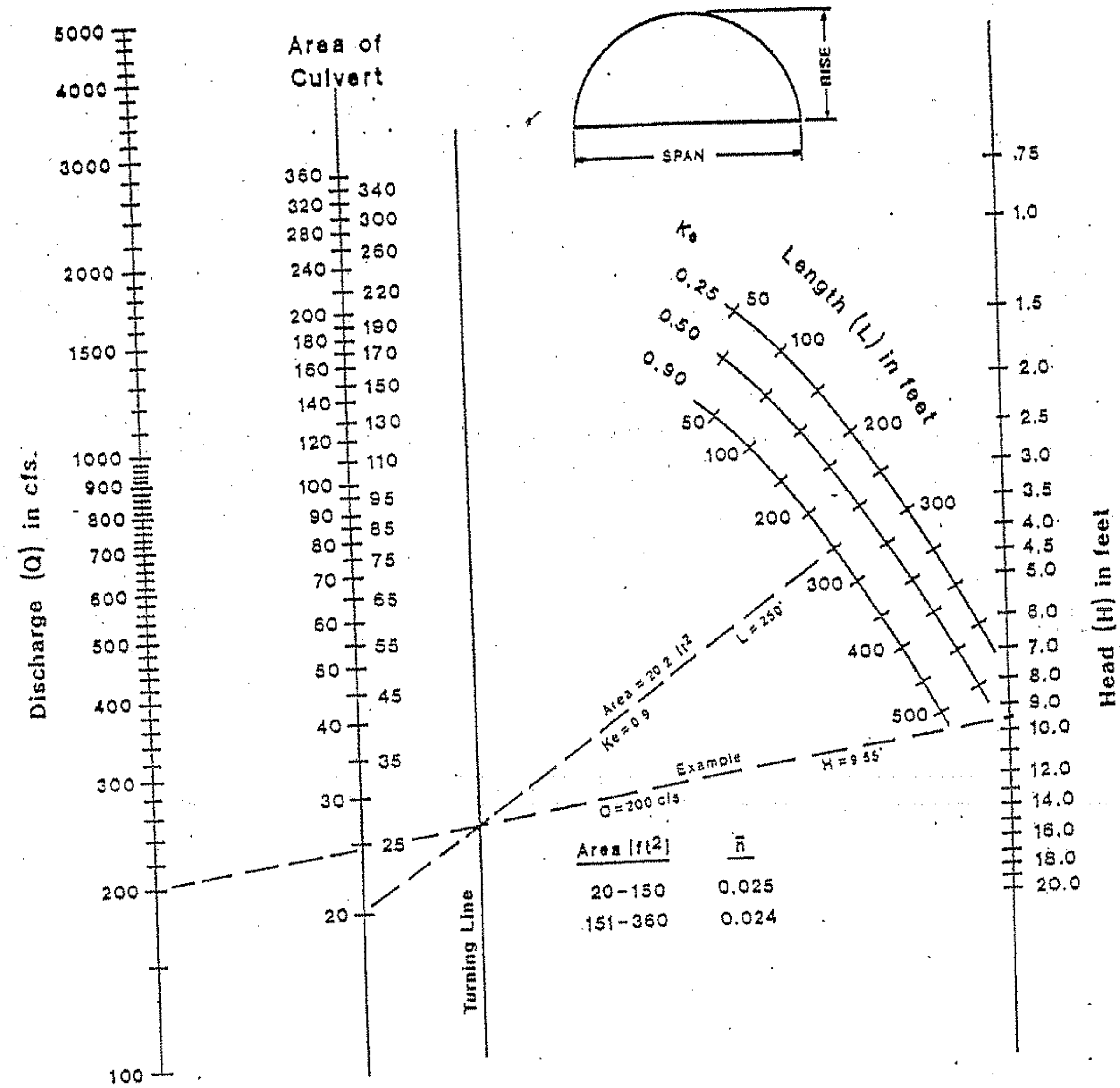
SUBMERGED OUTLET CULVERT FLOWING FULL

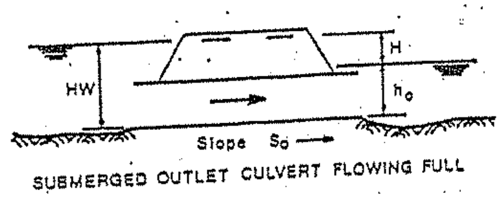
HEAD FOR C.M. ARCH CULVERTS FLOWING FULL CONCRETE BOTTOM $0.3 \leq$ RISE / SPAN < 0.4

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 46

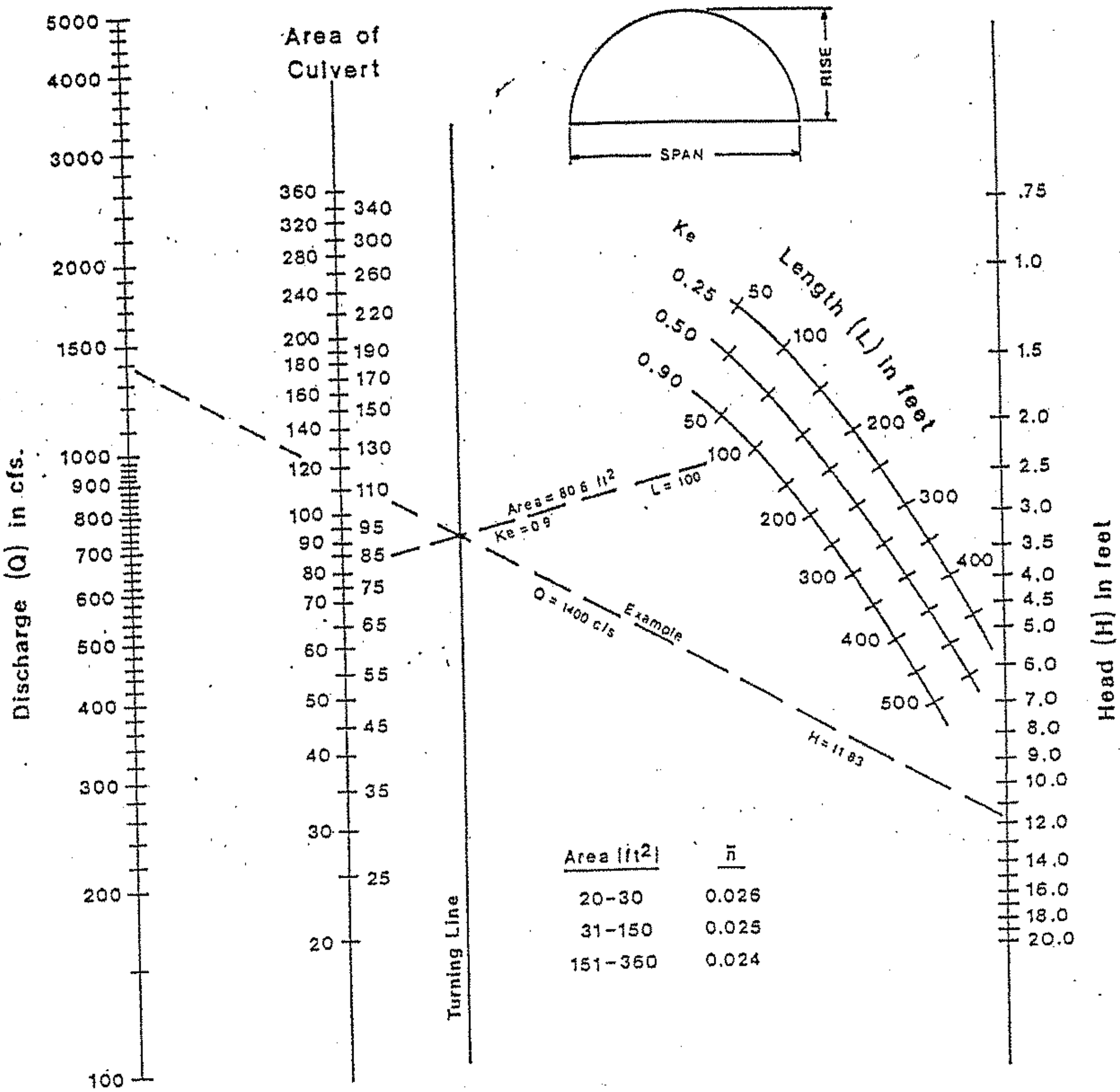




HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
CONCRETE BOTTOM
0.4 ≤ RISE / SPAN < 0.5

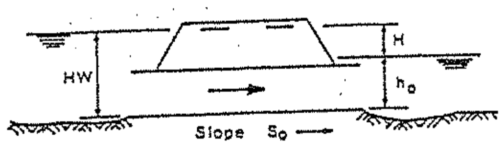
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale



Area (ft²)	n
20-30	0.026
31-150	0.025
151-360	0.024

HEAD FOR C.M. ARCH CULVERTS FLOWING FULL CONCRETE BOTTOM 0.5 ≤ RISE / SPAN

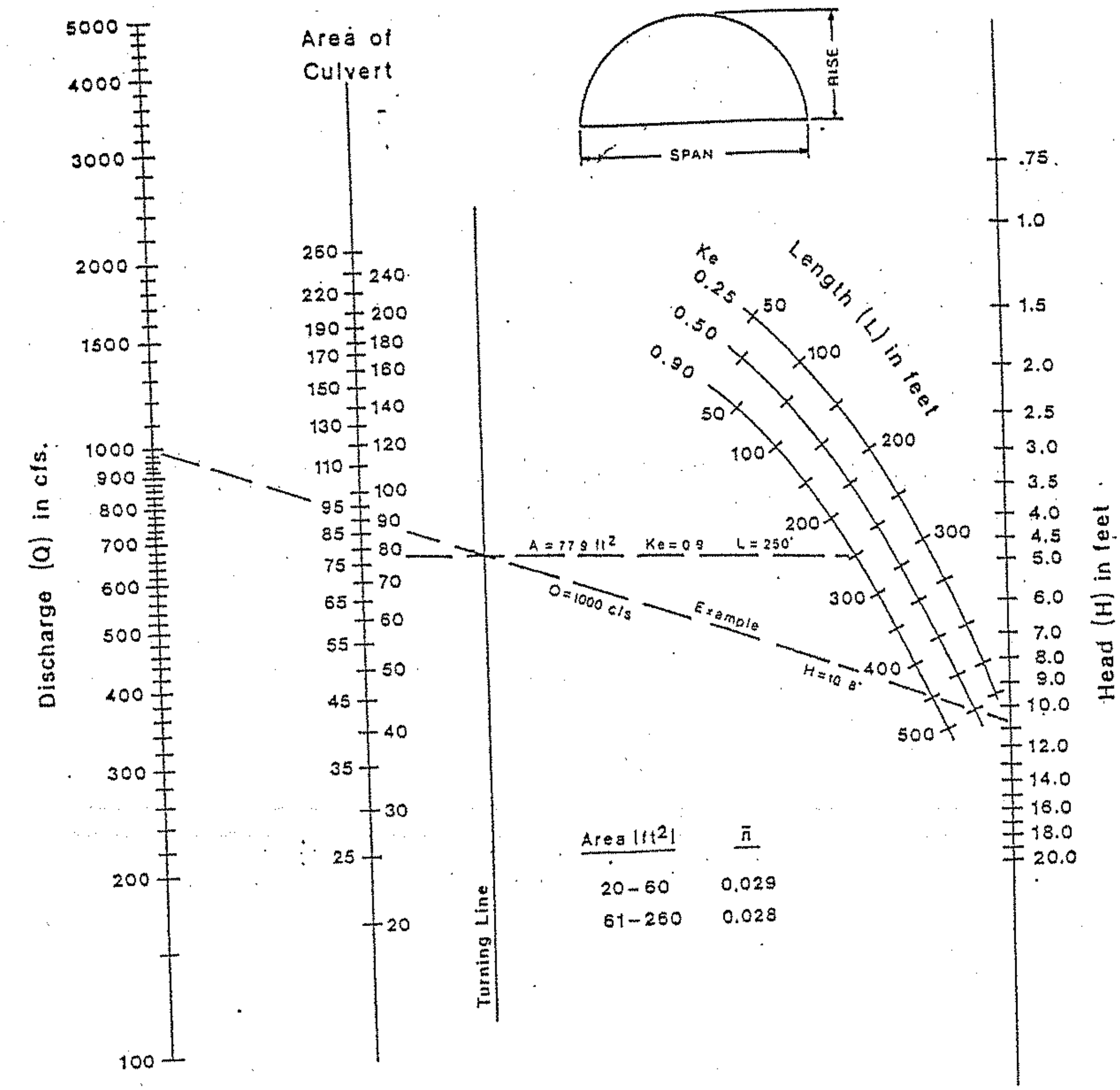


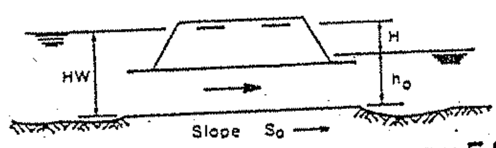
SUBMERGED OUTLET CULVERT FLOWING FULL

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 48





SUBMERGED OUTLET CULVERT FLOWING FULL

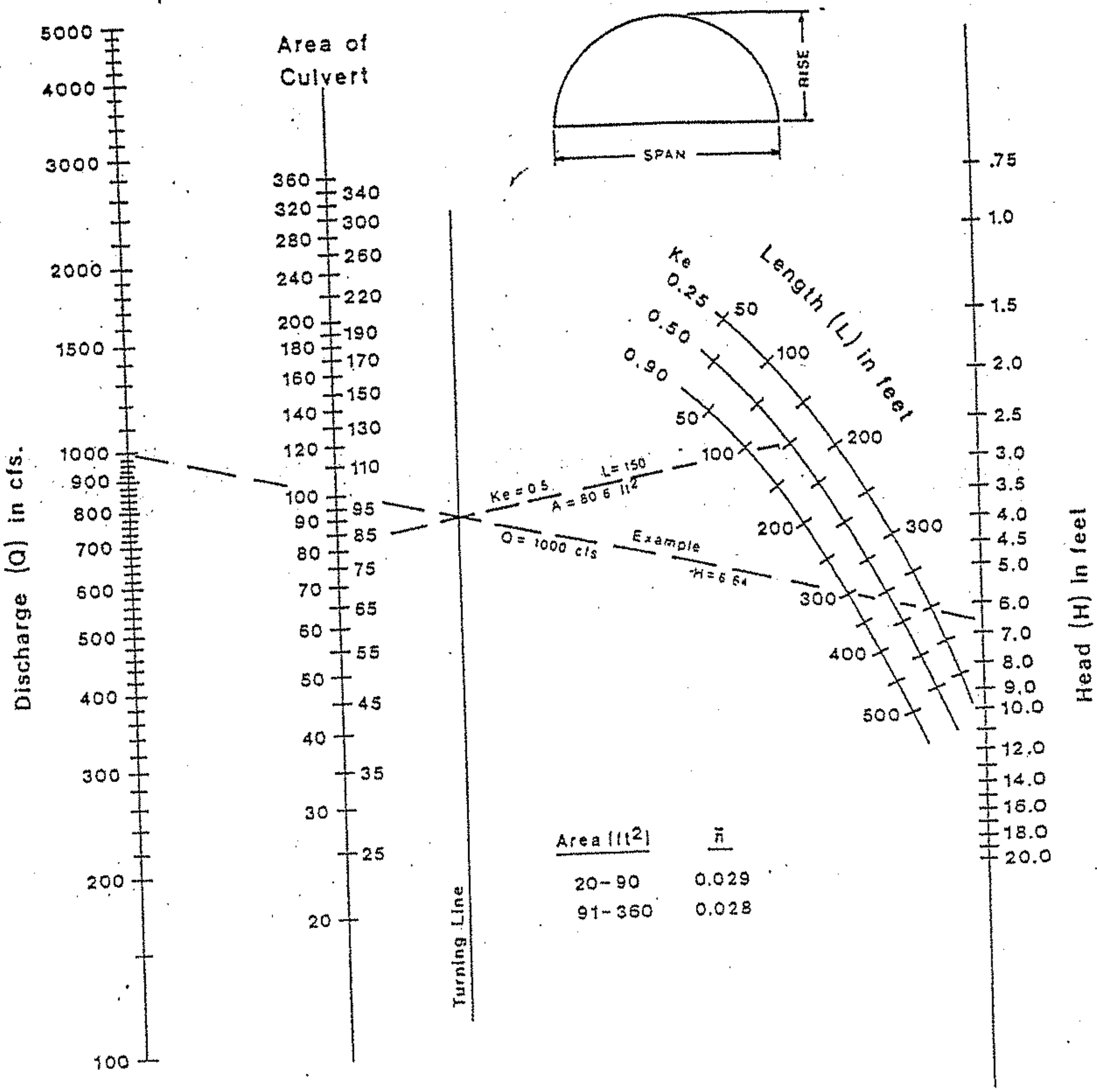
HEAD FOR C.M. ARCH CULVERTS FLOWING FULL EARTH BOTTOM (n_b = 0.022)

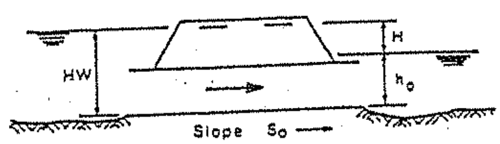
0.3 ≤ RISE / SPAN < 0.4

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 49





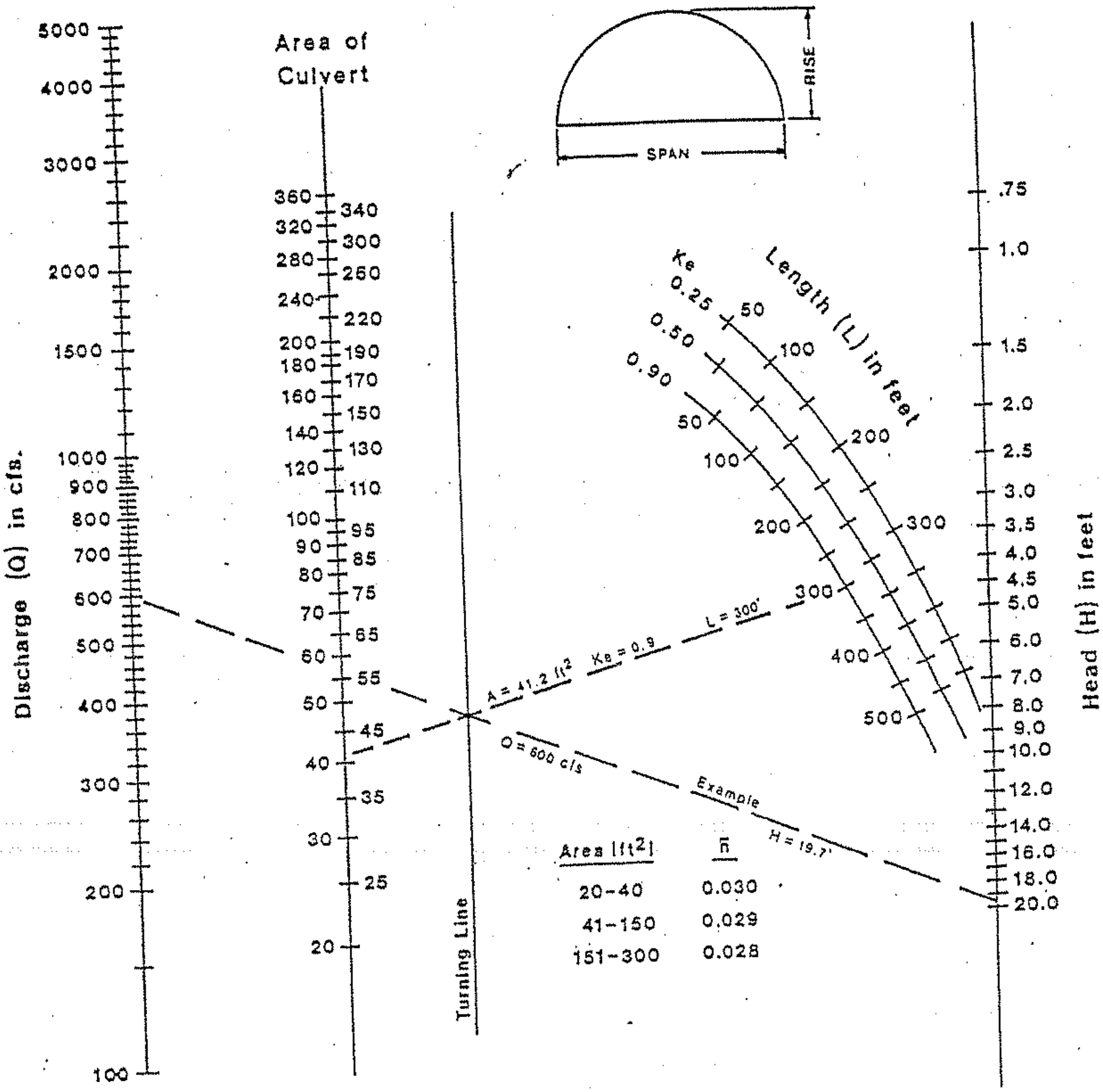
SUBMERGED OUTLET CULVERT FLOWING FULL

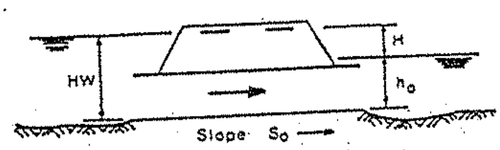
HEAD FOR C.M. ARCH CULVERTS FLOWING FULL
EARTH BOTTOM (n_b = 0.022)
0.4 ≤ RISE / SPAN < 0.5

" Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 50





SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C.M. ARCH CULVERTS FLOWING FULL EARTH BOTTOM (n_b = 0.022) 0.5 ≤ RISE / SPAN

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 51

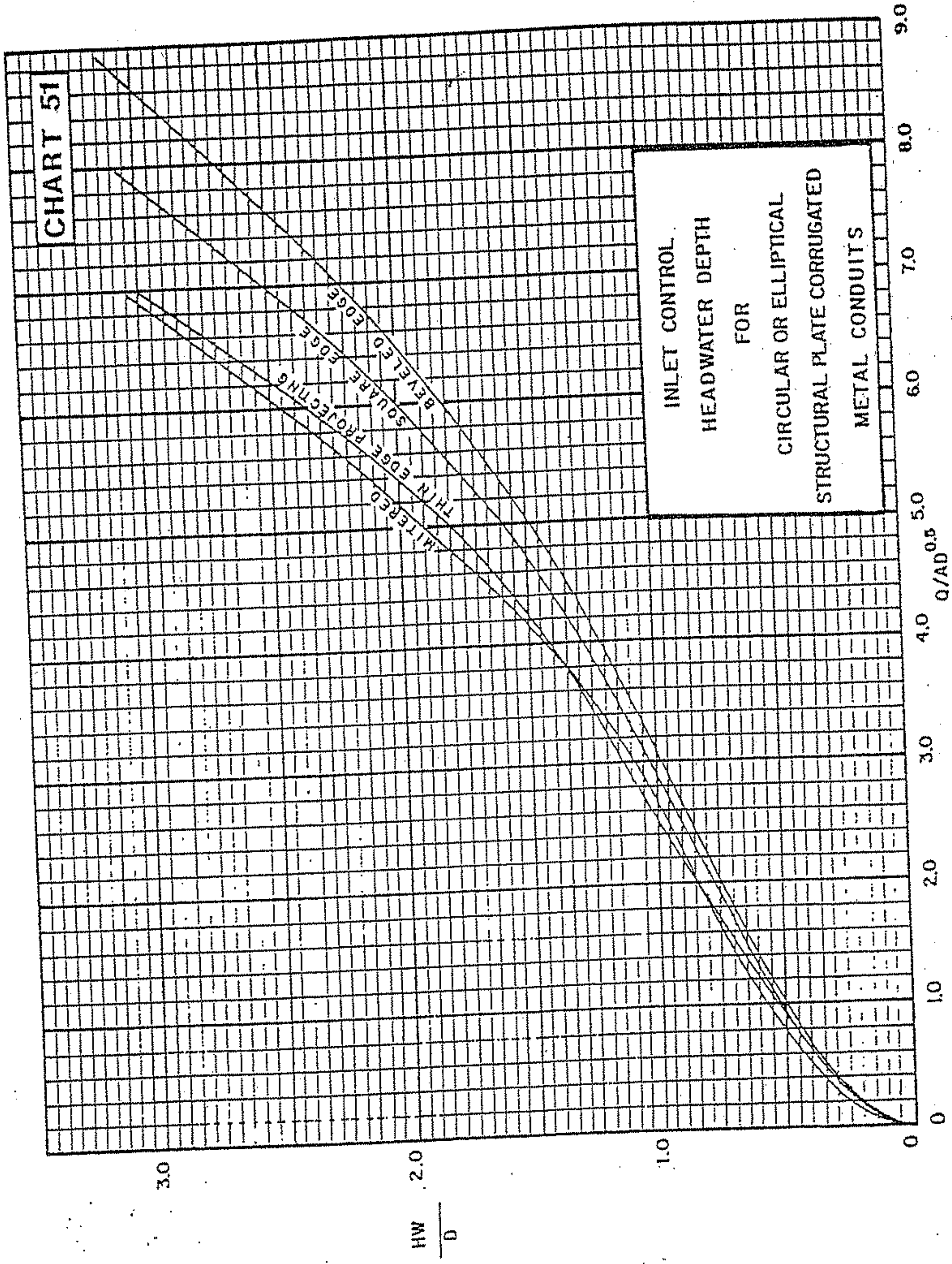


CHART 51
INLET CONTROL
HEADWATER DEPTH
FOR
CIRCULAR OR ELLIPTICAL
STRUCTURAL PLATE CORRUGATED
METAL CONDUITS
BEVELED EDGE
SQUARE EDGE
THIN EDGE PROJECTING
MITERED
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
Q/AD^0.5
HW/D

CHART 52

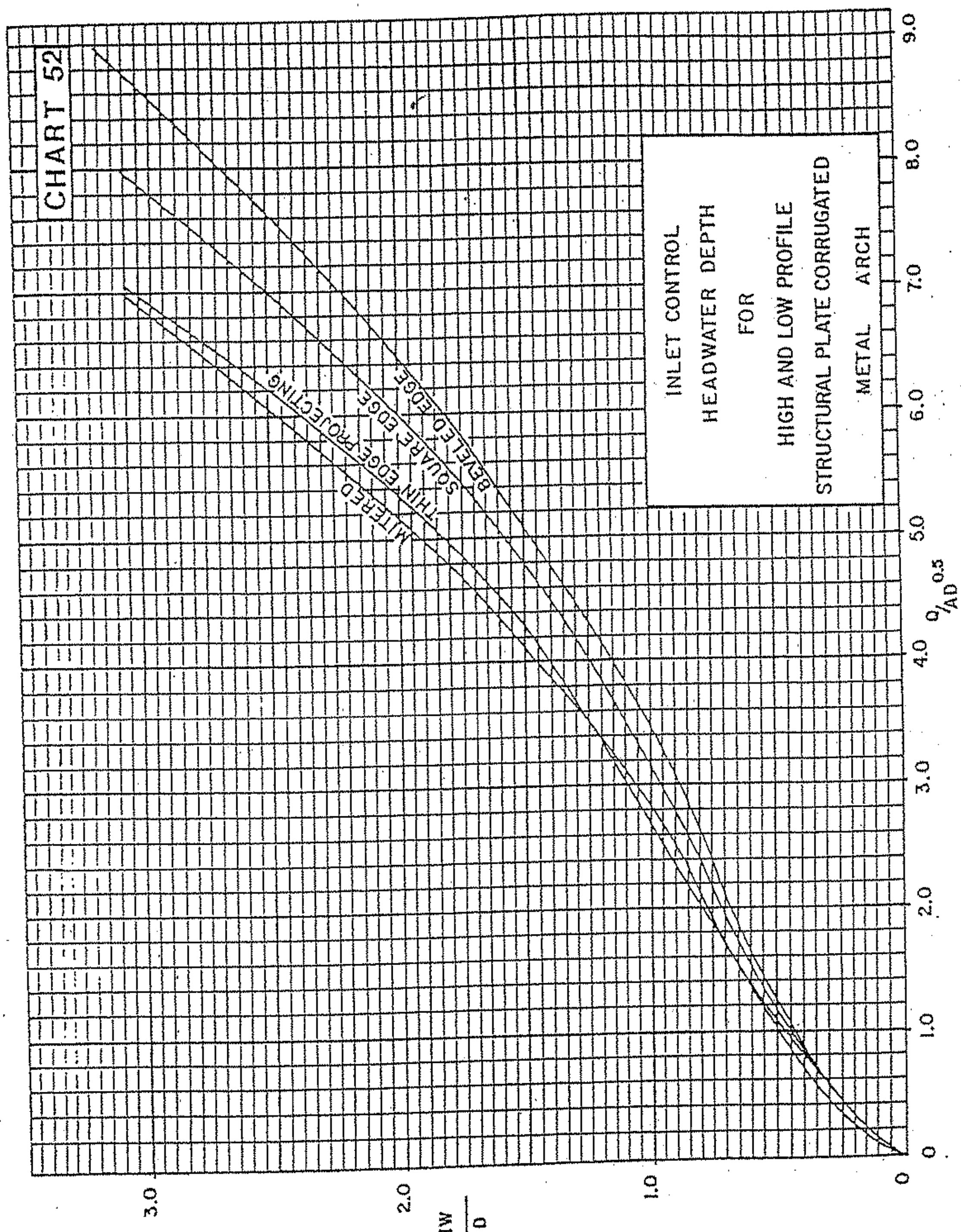
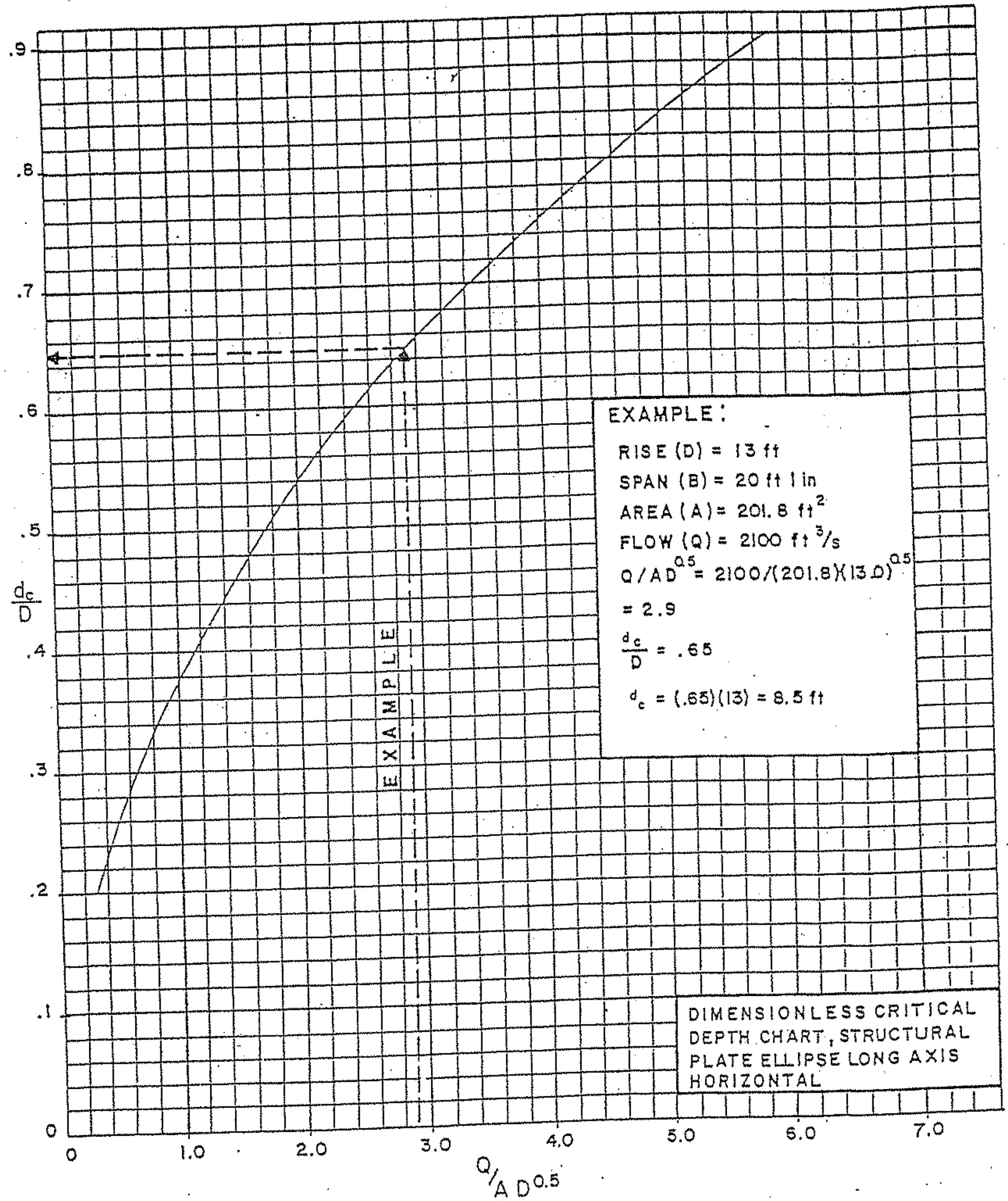


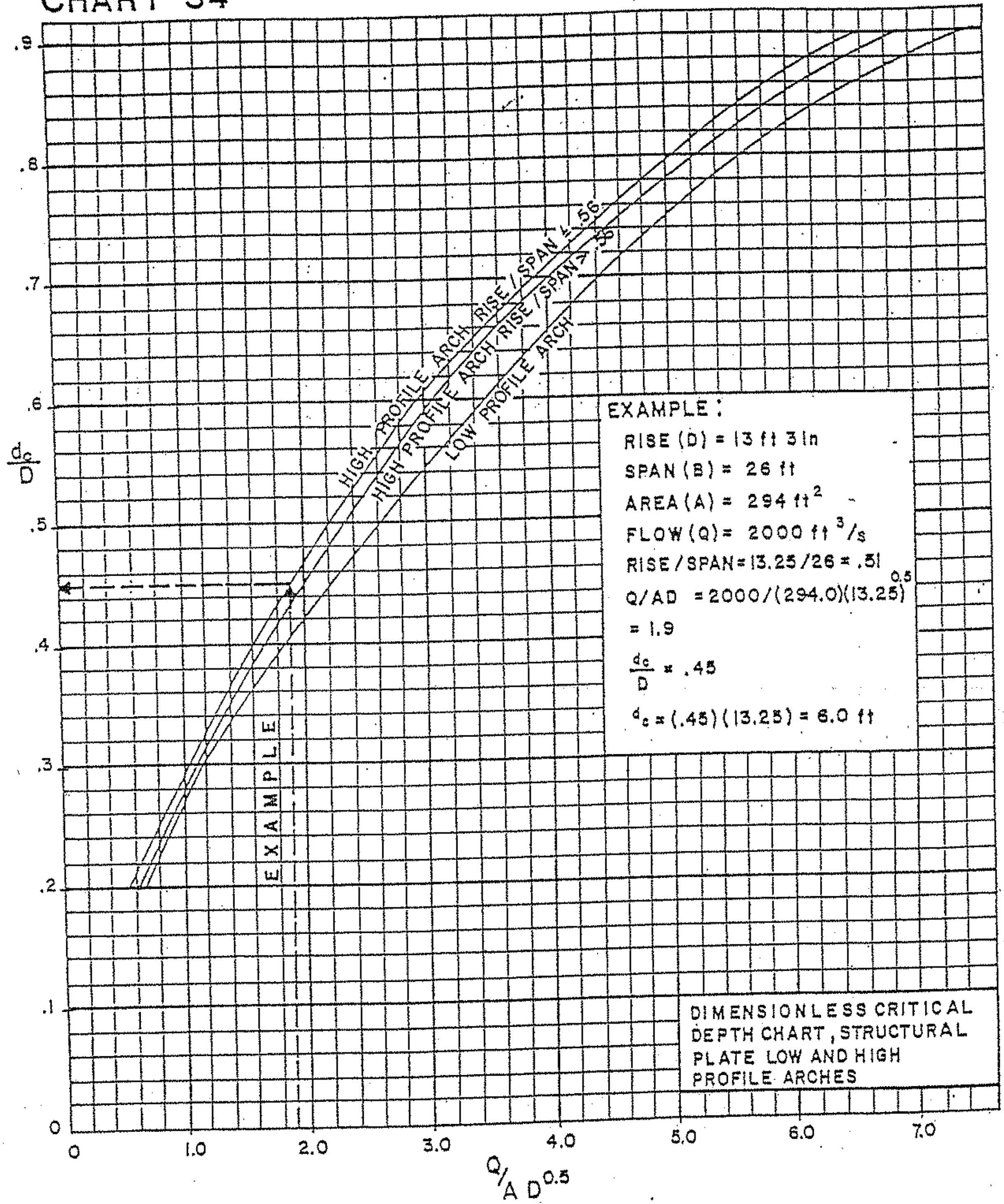
CHART 52
INLET CONTROL
HEADWATER DEPTH
FOR
HIGH AND LOW PROFILE
STRUCTURAL PLATE CORRUGATED
METAL ARCH
BEVELED EDGE
SQUARE EDGE
THIN EDGE PROJECTING
MITERED
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
$Q/AD^{0.5}$
HW/D

CHART 53



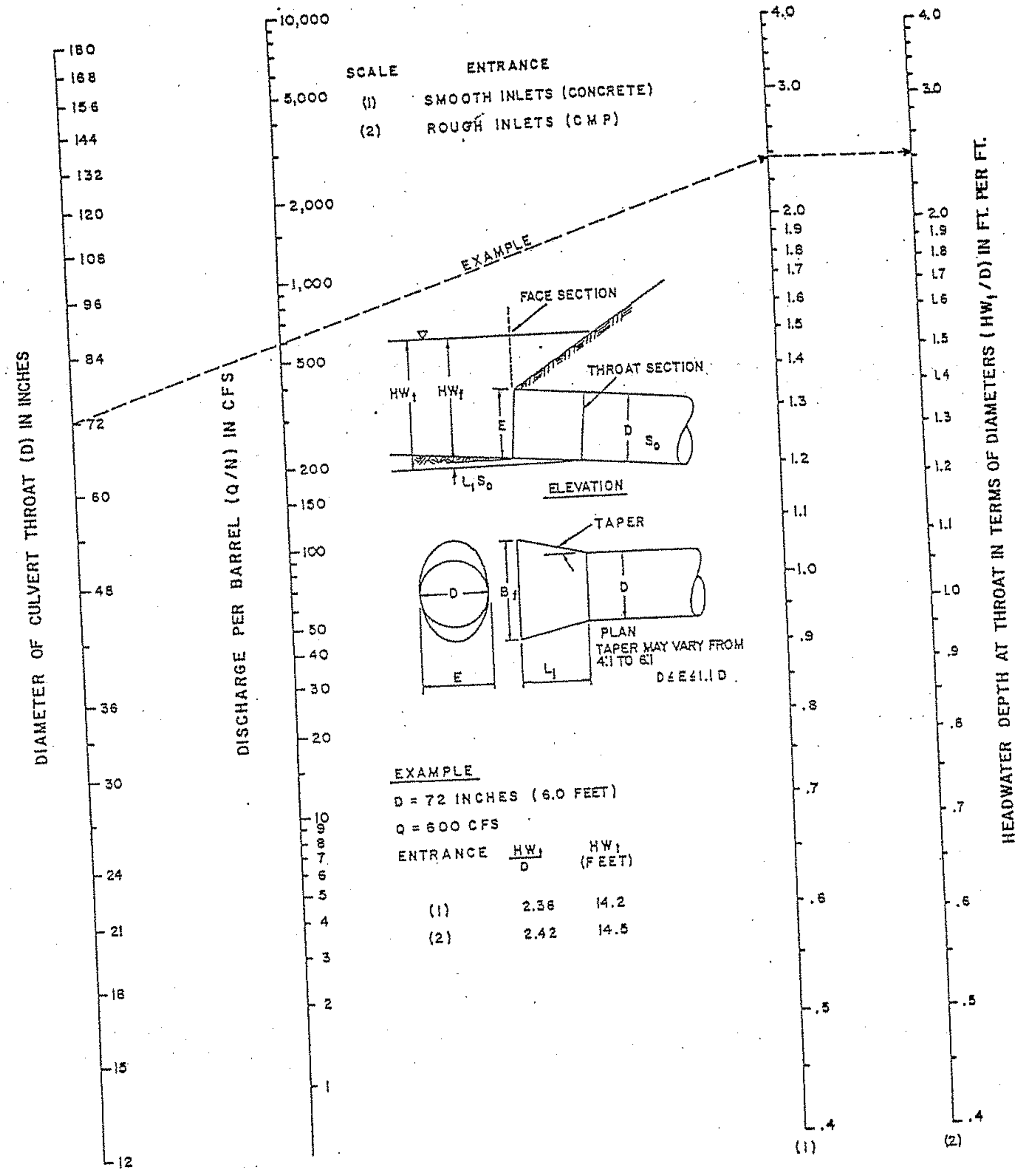
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
$\frac{d_c}{D}$
EXAMPLE
EXAMPLE:
RISE (D) = 13 ft
SPAN (B) = 20 ft 1 in
AREA (A) = 201.8 ft²
FLOW (Q) = 2100 ft³/s
Q/AD^0.5 = 2100/(201.8)(13.0)^0.5
= 2.9
dc/D = .65
dc = (.65)(13) = 8.5 ft
DIMENSIONLESS CRITICAL DEPTH CHART, STRUCTURAL PLATE ELLIPSE LONG AXIS HORIZONTAL
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Q/A D^0.5

CHART 54



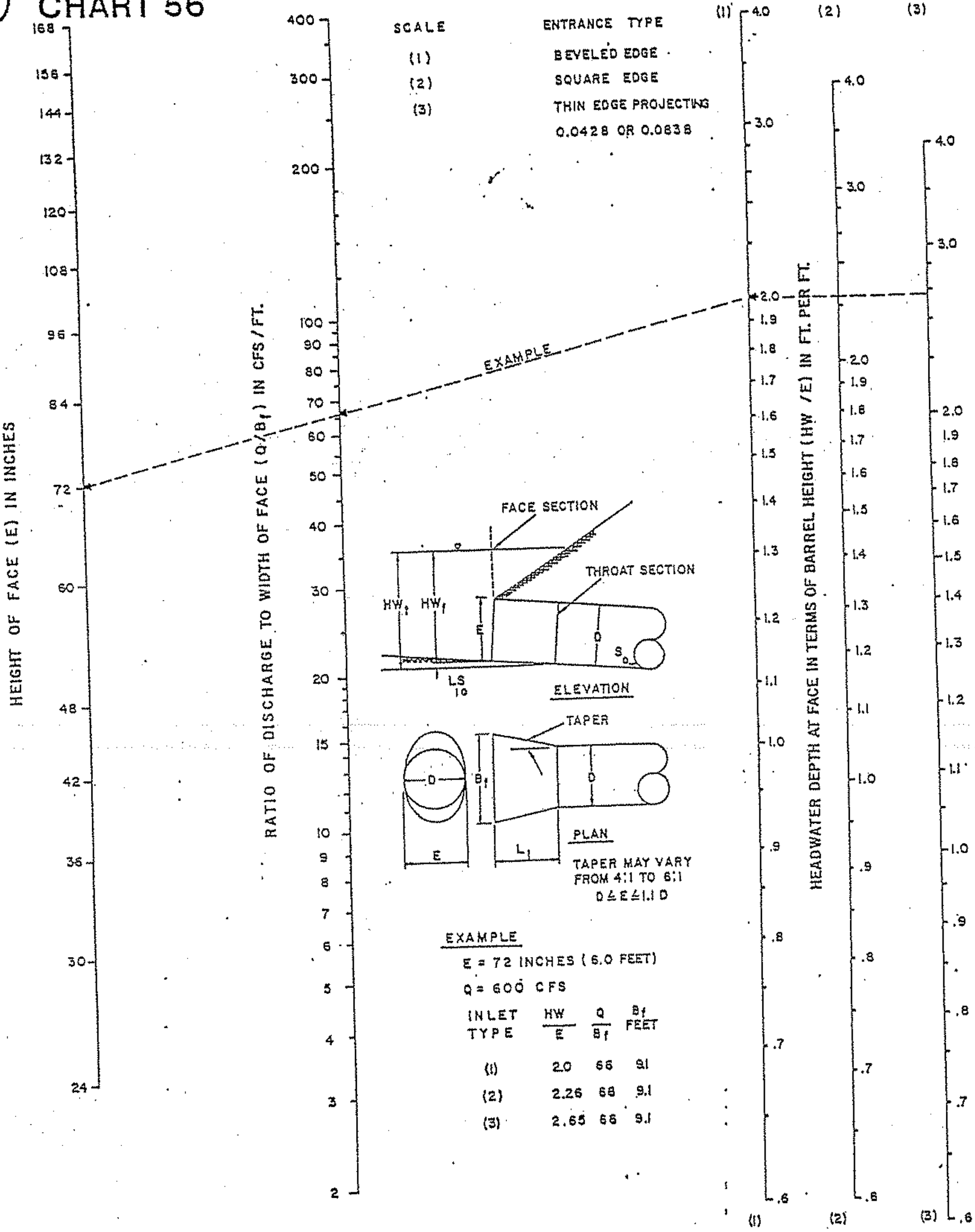
HIGH PROFILE ARCH, RISE / SPAN ≤ .56
HIGH PROFILE ARCH RISE / SPAN > .56
LOW PROFILE ARCH
EXAMPLE:
RISE (D) = 13 ft 3 in
SPAN (B) = 26 ft
AREA (A) = 294 ft²
FLOW (Q) = 2000 ft³/s
RISE / SPAN = 13.25 / 26 = .51
Q/AD = 2000/(294.0)(13.25)^0.5
= 1.9
dc/D = .45
dc = (.45)(13.25) = 6.0 ft
EXAMPLE
DIMENSIONLESS CRITICAL DEPTH CHART, STRUCTURAL PLATE LOW AND HIGH PROFILE ARCHES
dc/D
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Q/A D^0.5

CHART 55

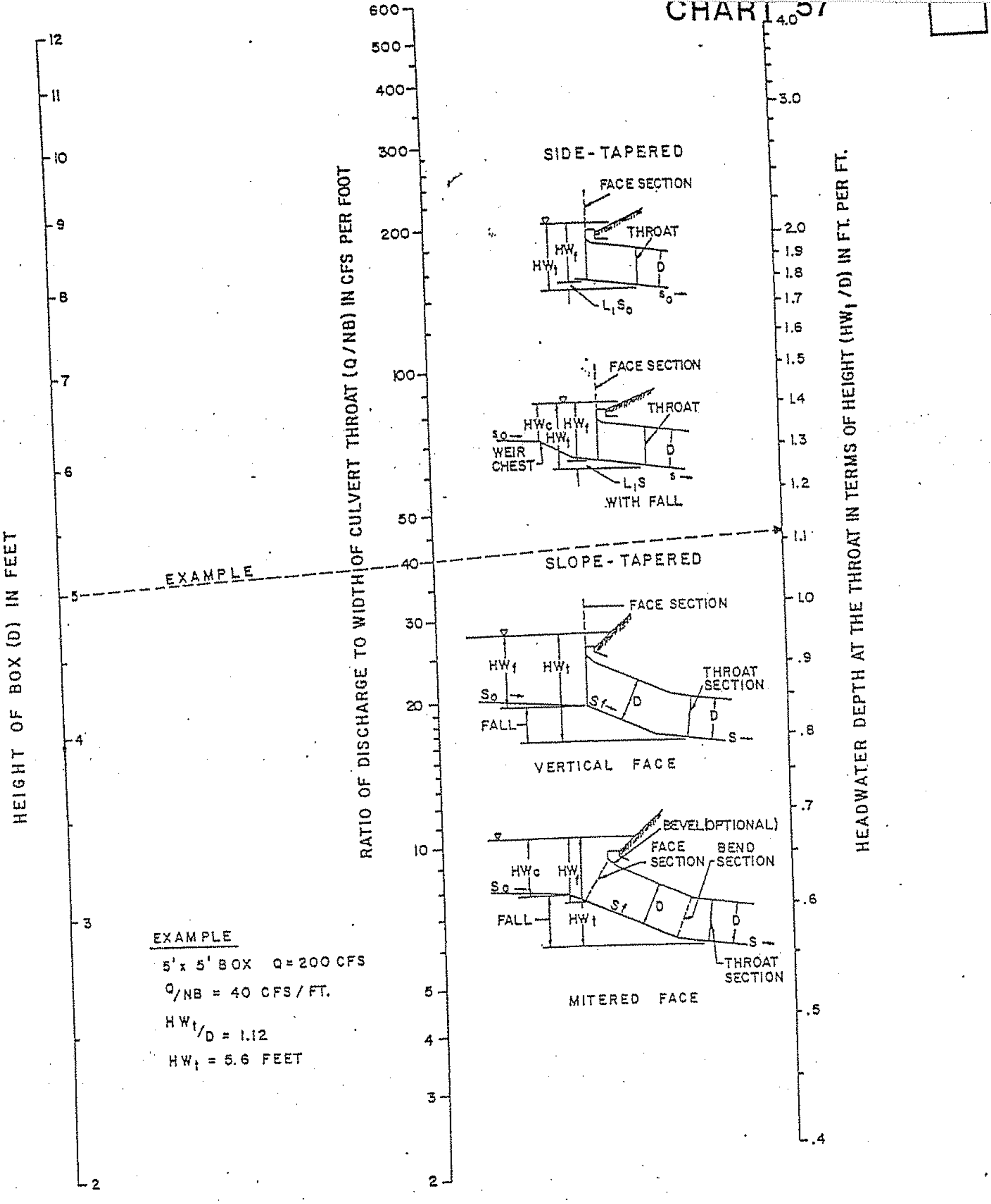


THROAT CONTROL
FOR SIDE-TAPERED INLETS TO PIPE CULVERT
(CIRCULAR SECTION ONLY)

CHART 56

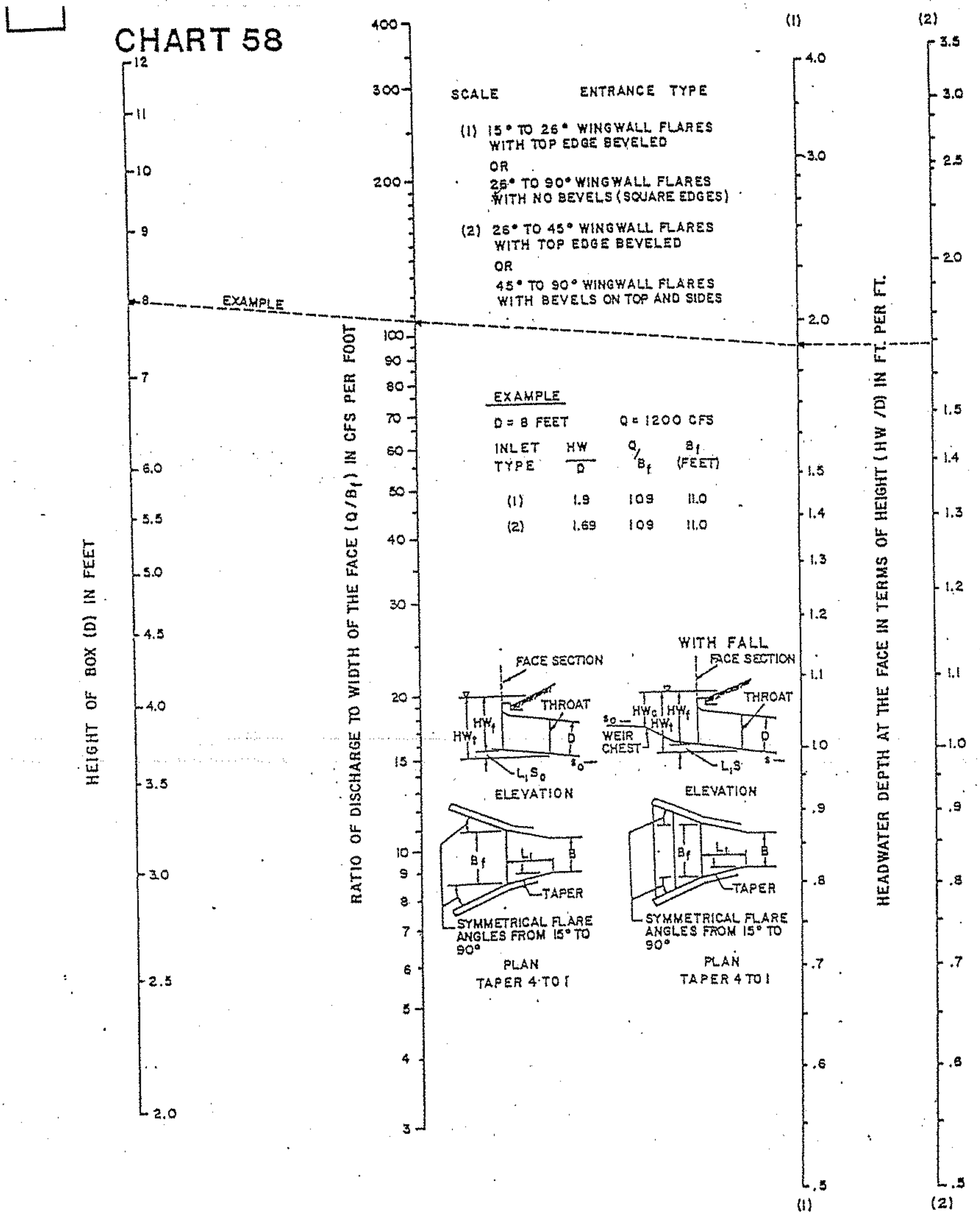


FACE CONTROL FOR SIDE-TAPERED INLETS TO PIPE CULVERTS (NON-RECTANGULAR SECTIONS ONLY)

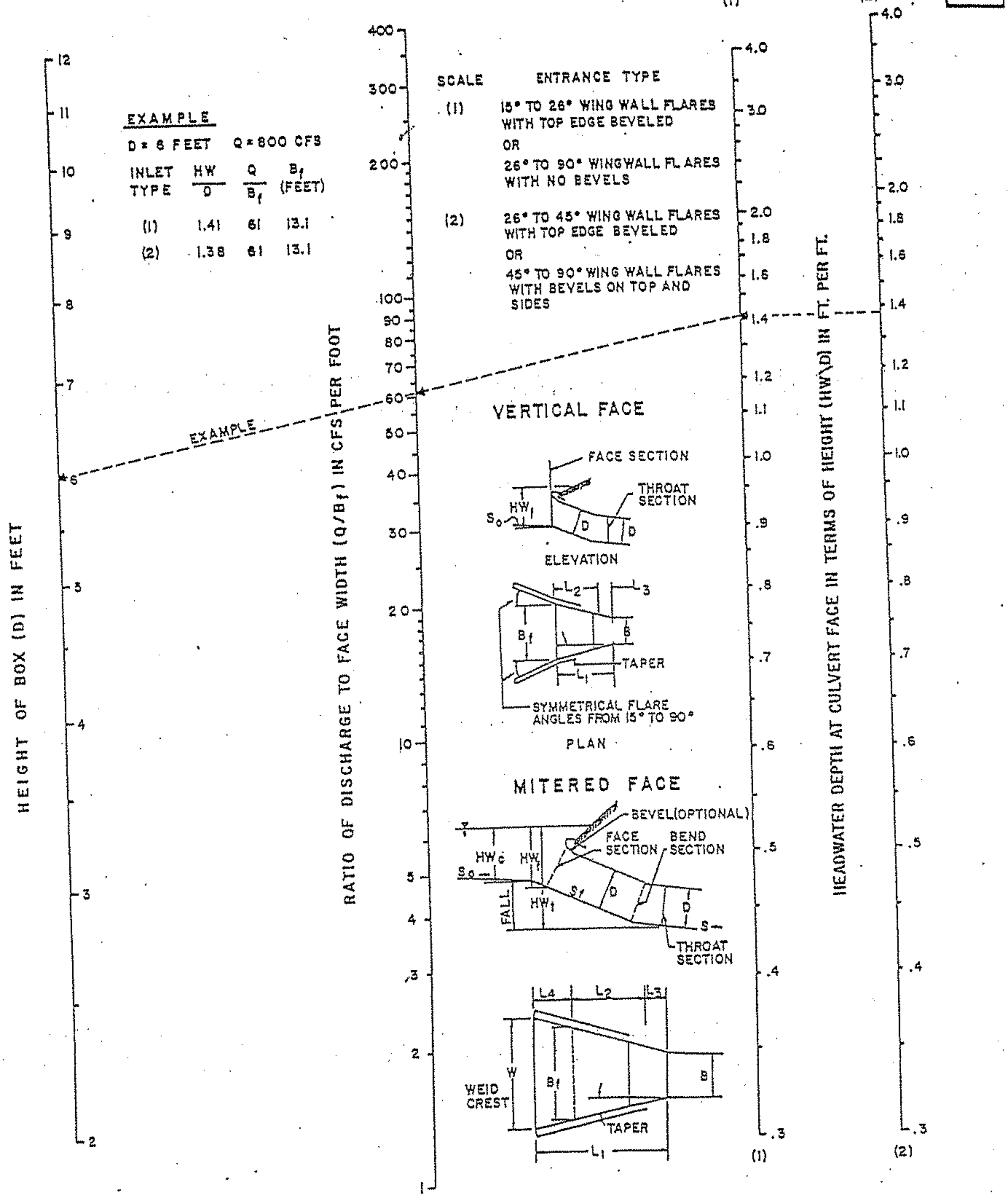


THROAT CONTROL FOR BOX CULVERTS WITH TAPERED INLETS

CHART 58



FACE CONTROL FOR BOX CULVERTS WITH SIDE TAPERED INLETS



FACE CONTROL FOR BOX CULVERTS WITH SLOPE TAPERED INLETS

CULVERT DESIGN FORM

PROJECT: ______________________

STATION: ____________

SHEET ______ OF ______

DESIGNER / DATE: ________ / ________

REVIEWER / DATE: ________ / ________

HYDROLOGICAL DATA

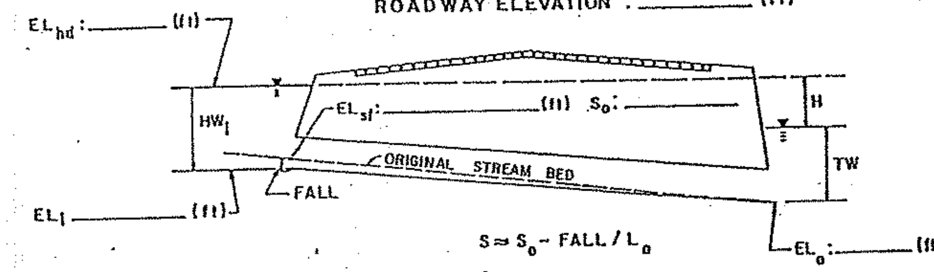
SEE ADD'L SHTS.

- ☐ METHOD: ____________
- ☐ DRAINAGE AREA: ________ ☐ STREAM SLOPE: ________
- ☐ CHANNEL SHAPE: ____________
- ☐ ROUTING: ________ ☐ OTHER: ________

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)

ROADWAY ELEVATION: ________ (ft)



$S \approx S_o - FALL / L_o$

S = ______

L_o = ______

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW_I/D (2)	HW_I	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_I/D = HW/D$ OR HW_I/D FROM DESIGN CHARTS

(3) $FALL = HW_I - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_I + EL_I$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) $h_o = TW$ or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29n^2 L)/R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

- a. APPROXIMATE
- f. CULVERT FACE
- hd. DESIGN HEADWATER
- hi. HEADWATER IN INLET CONTROL
- ho. HEADWATER IN OUTLET CONTROL
- i. INLET CONTROL SECTION
- o. OUTLET
- sf. STREAMBED AT CULVERT FACE
- tw. TAILWATER

COMMENTS / DISCUSSION:

CULVERT BARREL SELECTED:

SIZE: ____________

SHAPE: ____________

MATERIAL: ________ n ____

ENTRANCE: ____________

TAPERED INLET DESIGN FORM

PROJECT: ______________________

____

STATION: ______________

SHEET ______ OF ______

DESIGNER / DATE: __________ / ______

REVIEWER / DATE: __________ / ______

COMMENTS

DESIGN DATA:

Q ____ = ______ cfs ; EL_{hI} ________ ft

EL. THROAT INVERT ________ ft

EL. STREAM BED AT FACE ________ ft

FALL ______ ft TAPER ______ : 1 (4:1 TO 6:1)

STREAM SLOPE, So = ________ ft/ft

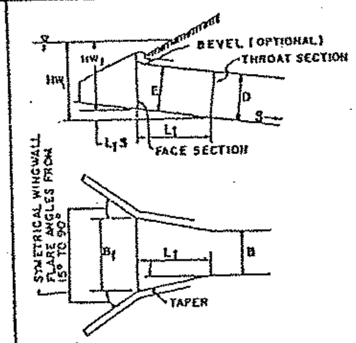
SLOPE OF BARREL, S = ________ ft/ft

S_f ______ : 1 (2:1 TO 3:1)

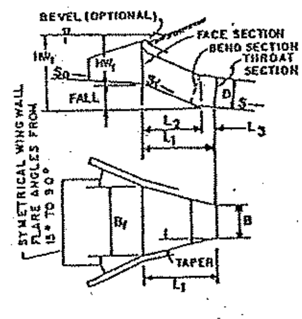
BARREL SHAPE AND MATERIAL: ________

N = ________, B = ________, D = ________

INLET EDGE DESCRIPTION ________



SIDE-TAPERED



SLOPE-TAPERED

									SLOPE-TAPERED ONLY						SIDE-TAPERED W/ FALL		
Q (cfs)	EL_{hI}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f / E (3)	Q / B_f (4)	MIN. B_f (5)	SELECTED B_f	MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	EL. CREST INV.	HW_c (12)	MIN. W (13)

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE

(2) $HW_f = EL_{hI} -$ EL. FACE INVERT

(3) $1.1 D \geq E \geq D$

(4) FROM DESIGN CHARTS

(5) MIN. $B_f = Q/(Q/B_f)$

(6) MIN. $L_3 = 0.5 NB$

(7) $L_2 =$ (EL. FACE INVERT - EL. THROAT INVERT) S_f

(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right] \cdot \text{TAPER} - L_3$

(9) IF (8)>(7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right] \cdot \text{TAPER} - L_2$

(10) IF (7)>(8), ADJ. TAPER $= (L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$

(11) SIDE-TAPERED: $L = \left[\frac{B_f - NB}{2}\right] \cdot \text{TAPER}$
SLOPE-TAPERED: $L_1 = L_2 + L_3$

(12) $HW_c = EL_{hI} -$ EL. CREST INVERT

(13) MIN. $W = 0.35 Q / HW_c^{1.5}$

SELECTED DESIGN

B_f ________

L_1 ________

L_2 ________

L_3 ________

BEVELS ANGLE ______ °

b = ______ in; d = ______ in

TAPER ________ : 1

S_f = ________ : 1

MITERED INLET DESIGN FORM

PROJECT: ____________________
____

STATION: ____________________
SHEET ______ OF ______

DESIGNER / DATE: __________ / ______
REVIEWER / DATE: __________ / ______

DESIGN DATA: N ______ ; B ______ ; D ______

Q ______ = ______ cfs ; EL_{hi} ______ ft

EL. THROAT INVERT ______ ft EL. STREAM BED AT CREST ______ ft

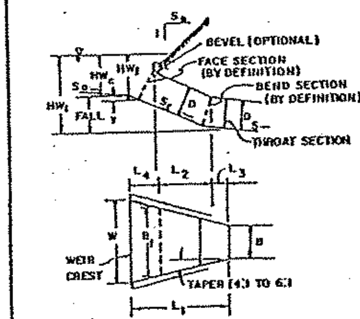
FALL ______ ft ; TAPER ______ : (4:1 TO 6:1)

STREAM SLOPE, S_0 ______ ft/ft ; BARREL SLOPE, S = ______ ft/ft

SLOPE OF THE EMBANKMENT S_e = ______ :1 ; S_f ______ :1 (2:1 TO 3:1)

BARREL SHAPE AND MATERIAL: ____________________

INLET EDGE DESCRIPTION: ____________________



SLOPE-TAPERED INLET/MITERED FACE

COMMENTS

Q (cfs)	EL_{hi}	EL. THROAT INVERT	y (1)	EL. FACE INVERT (2)	HW_f (3)	$\frac{HW_f}{E}$ (4)	$\frac{Q}{B_f}$ (5)	MIN. B_f (6)	SELECTED B_f	MIN. L_3 (7)	L_4 (8)	L_2 (9)	CHECK L_2 (10)	ADJ. L_3 (11)	ADJ. TAPER (12)	L_1 (13)	EL. CREST INV.	HW_c (14)	MIN. W (15)	W (16)

(1) $y = \left[\frac{(S_e \cdot S_f) - 1}{(S_e + S_f)(S_f^2 + 1)^{0.5}}\right] \cdot D$

(2) EL. FACE INVERT = EL. STREAM BED AT CREST − y

(3) $HW_f = EL_{hi}$ − EL. FACE INVERT

(4) $1.1 D \geq E \geq D$

(5) FROM DESIGN CHARTS

(6) MIN. $B_f = Q/(Q/B_f)$

(7) MIN. $L_3 = 0.5 NB$

(8) $L_4 = S_f y + D/S_f$

(9) L_2 = (EL. CREST INVERT − EL. THROAT INVERT) $S_f - L_4$

*** IF L_2 IS NEGATIVE DO NOT USE THIS INLET

(10) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right]$ TAPER − L_3

(11) IF (10)>(9), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right]$ TAPER − L_2

(12) IF (9)>(10), ADJ. TAPER $= (L_2 + L_3) / \left[\frac{B - NB}{2}\right]$

(13) $L_1 = L_2 + L_3 + L_4$

(14) $HW_c = EL_{hi}$ − EL. CREST INVERT

(15) MIN. $W = 0.35 Q / (HW_c)^{1.5}$

(16) $W = NB + 2\left[\frac{L_1}{TAPER}\right]$

IF W<MIN. W, ADJUST TAPER

SELECTED DESIGN

B_f ______

L_1 ______

L_2 ______

L_3 ______

L_4 ______

BEVELS ANGLE ______ °

b = ______ in; d = ______ in

TAPER ______ :1

S_f ______ :1

STORAGE ROUTING FORM

1. INFLOW HYDROGRAPH GENERATION
   a. Hydrograph method used:
   b. Time interval selected for routing:
   (inflow hydrograph attached)

2. APPROXIMATE FLOW REDUCTION DUE TO ROUTING
   a. Peak inflow: Q_p=_________ ft^3/s
   b. Upstream storage: S=_________ ft^3
   c. Time to peak: t_p=_______ min

$$Q_r = Q_p - \frac{S}{80\, t_p} =$$

3. ELEVATION - DISCHARGE RELATIONSHIP FOR TRIAL CULVERT

ELEVATION ft								
DISCHARGE ft^3/s								

4. ELEVATION - STORAGE RELATIONSHIP FOR UPSTREAM PONDING

ELEVATION ft	AREA ft^2	INCREMENTAL VOLUME ft^3	ACCUMULATED VOLUME ft^3

5. STORAGE - OUTFLOW RELATIONSHIP

Elevation ft	Discharge (O) ft^3/s	Storage (S) ft^3	$2s/\Delta t$ ft^3/s	$2s/\Delta t + O$ ft^3/s

6. STORAGE - INDICATION ROUTING TABLE

(1) TIME min	(2) INFLOW (I) ft^3/s	(3) $2s/\Delta t - O$ ft^3/s	(4) $2s/\Delta t + O$ ft^3/s	(5) OUTFLOW (O) ft^3/s

APPENDIX I-

REFERENCES

1. "Hydraulic Charts for the Selection of Highway Culverts," L.A. Herr and H.G. Bossy, HEC No. 5, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, 1965.

2. "Capacity Charts for the Hydraulic Design of Highway Culverts," Lester A. Herr and Herbert G. Bossy, Hydraulic Engineering Circular (HEC) No. 10, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, November 1972.

3. "Hydraulic Design of Improved Inlets for Culverts," L.J. Harrison, J.L. Morris, J.M. Normann and F.L. Johnson, HEC No. 13, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, August 1972.

4. "Hydraulics of Short Pipes, Hydraulic Characteristics of Commonly Used Pipe Entrances, First Progress Report," John L. French, NBS Report No. 4444, National Bureau of Standards, Washington D.C., December 1955.

5. "Hydraulics of Culverts, Second Progress Report, Pressure and Resistance Characteristics of a Model Pipe Culvert," John L. French, NBS Report No. 4911, National Bureau of Standards, Washington, D.C., October 1956.

6. "Hydraulics of Culverts, Third Progress Report, Effects of Approach Channel Characteristics on Model Pipe Culvert Operation," John L. French, NBS Report 5306, National Bureau of Standards, Washington, D.C., June 1957.

7. "Hydraulics of Improved Inlet Structures for Pipe Culverts, Fourth Progress Report," John L. French, NBS Report 7178, Nationl Bureau of Standards, Washington, D.C., August 1961.

8. "Hydraulics of Culverts, Fifth Progress Report, Nonenlarged Box Culvert Inlets," John L. French, NBS Report 9327, National Bureau of Standards, Washington, D.C., June 1966.

9. "Hydraulics of Culverts, Sixth Progress Report, Tapered Box Culvert Inlets," John L. French, NBS Report 9355, National Bureau of Standards, Washington, D.C., June 1966.

10. "Hydraulics of Culverts, Seventh Progress Report, Tapered Box Inlets with Fall Concentration in the Inlet Structure," John L. French and Herbert G. Bossy, NBS Report No. 9528, National Bureau of Standards, Washington, D.C., July 1967.

11. "Hydrology," Frank D. Masch, HEC No. 19, IP-84-15, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590

12. "Hydrology," Victor Mockus, National Engineering Handbook - Section 4, Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C., 1964.

13. "Local Design Storm," Ben Chie Yen and Ven Te Chow, Report No. FHWA/RD-82/063, Office of Research, FHWA, Washington, D.C., May 1983.

14. "Flood Routing - Culvert Design," B.P. Durow, The South African Institution of Engineers, March 1982.

15. "Stability of Relocated Stream Channels," J. C. Brice, Report No. FHWA/RD-80/158, U. S. Geological Survey, March 1981. Available from the National Technical Information Service, Springfield, Virginia 22161.

16. "Roughness Characteristics of Natural Channels," Harry H. Barnes, Jr., Water Supply Paper 1849, U.S. Geological Survey, Reston, Virginia, 1967.

17. "Estimating Hydraulic Roughness Coefficients," Woody L. Cowan, Agricultural Engineering, Vol. 37, No. 7, pp. 473-475, July 1956.

18. "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains," G.J. Arcement, Jr. and V.R. Schneider, U. S. Geological Survey, Baton Rouge Louisiana, 70896, Available from the National Technical Information Service, Springfield, Virginia 22161., April 1984.

19. "Assessment of the Impacts of the National Flood Insurance Program on Highways," George Davis, Report No. FHWA/RD-80/015, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, April 1980.

20. "Culvert Design System," FHWA-TS-80-245, Hydraulics Section, Wyoming Highway Department, Cheyenne, Wyoming 82001, December 1980.

21. "Hydraulics of Bridge Waterways," J. N. Bradley, HDS No. 1, Second Edition, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, September 1973.

22. "Bridge Waterways Analysis Model," J. O. Shearman, W. H. Kirby, V. R. Schneider, and H. N. Flippo, Contract No. 9-3-0189, Office of Research, Washington, D. C. 20590, unpublished research report.

23. "Design Charts For Open Channel Flow," HDS No. 3, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, 1973.

24. "Handbook of Hydraulics," Horace Williams King and Ernest F. Brater, Sixth Edition, McGraw-Hill Book Co., 1976.

25. "Hydraulic Flow Resistance Factors for Corrugated Metal Conduits," J.M. Normann, FHWA-TS-80-216, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, January 1980. Available from the National Technical Information Service, Springfield, Virginia 22161.

26. "Structural Design Manual for Improved Inlets and Culverts," Timothy J. McGrath and Frank J. Heger, FHWA-IP-83-6, Bridge Division, Office of Engineering, FHWA, Washington, D.C., 20590, June 1983.

27. "Basic Stormwater Management in Virginia - Course C Training Notebook," Jerome M. Normann and Robert J. Houghtalen, Virginia Soil and Water Conservation Commission, Richmond, Virginia, January 1985.

28. "Design Approaches for Stormwater Management in Urban Areas," H. R. Malcom, Jr., North Carolina State University, Raleigh, N.C., 1975.

29. "Peak Runoffs From Small Basins Using Culvert Flood Measurements," J. D. Harris, Ontario MTC Drainage and Hydrology Section, Downsville, Ontario, 1975.

30. "Guidelines for the Hydraulic Design of Culverts," Task Force on Hydrology and Hydraulics AASHTO Operating Subcommittee on Design, American Association of State Highway and Transportation Officials, 341 National Press Bldg., Washington, D.C. 20045, 1975.

31. "Open Channel Hydraulics," V.T. Chow, McGraw-Hill-Civil Engineering Series, New York, 1959.

32. "Water Resources Engineering," Ray F. Linsley and Joseph B. Franzini, McGraw-Hill Book Company, 1972.

33. "Design of Urban Highway Drainage - The State of the Art," Stifel W. Jens, FHWA-TS-79-225, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, August 1979.

34. "The Design of Supercritical Flow Channel Junctions," C. E. Behike and H. D. Pritchett, Research Record Number 123, Highway Research Board, Washington, D.C., 1966.

35. "California Culvert Practice," 2nd Edition, California Department of Public Works, Division of Highways, Sacramento, Calif., 1956.

36. "Experiences in the Use of Minimum and Constant Energy Bridges and Culverts," N.H. Cottman, Institution of Engineers, Australia, 11 National Circuit Barton A.C.T. 26000 Australia 0 85825 157 4, October 1981.

37. "Hydraulics of Minimum Energy Culverts and Bridge Waterways," C.J. Apelt, Institute of Engineers, Australia, 11 National Circuit, Barton A.C.T. 2600 Australia 0 85825 157 4, October 1981.

38. "Hydraulic Design of Culverts - Ontario Ministry of Transportation and Communication Drainage Manual, Chapter D," J.D. Harris, Ontario Ministry of Transportation and Communications, Dawnsview, Ontario, August 1982.

39. "Design Considerations and Calculations for Fishways Through Box Culverts," Fred F.M. Chang and J. M. Normann, Unpublished Text, Hydraulics Branch, Bridge Division, FHWA, Office of Engineering, Washington, D.C. 20590, September 1976.

40. "Hydraulic Design of Energy Dissipators for Culverts and Channels," M. L. Corry, P.L. Thompson, F.J. Watts, J.S. Jones and D.L. Richards, HEC No. 14, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, September 1983.

41. "Evaluating Scour at Culvert Outlets," J.F. Ruff and S.R. Abt, Transportation Research Board Record N785, Transportation Research Board, Publications Office, 2101 Constitution Avenue, NW Washington, D.C. 20418, 1980.

42. "Field and Laboratory Evaluation of Energy Dissipators for Culverts and Storm Drain Outlets. Volume I - Modular Energy Dissipators, Internal Energy Dissipators and Rock Channel Protection," S. Sarikelle and A.L. Simon, FHWA-OH-79-03, Akron University Department of Civil Engineering, Akron, Ohio 44325, December 1980. Available from the National Technical Information Service, Springfield, Virginia 22161.

43. "Field and Laboratory Evaluation of Energy Dissipators for Culvert and Storm Outlets. Volume II--Field Performance of Corrugated Metal Culverts," S. Sarikelle and A.L. Simon, FHWA-OH-79-04, Akron University, 302 East Buchtel Avenue, Akron, Ohio 44325, December 1980. Available from the National Technical Information Service, Springfield, Virginia 22161.

44. "Highways in the River Environment - Hydraulic and Environmental Design Considerations," Civil Engineering Department, Colorado State University, Fort Collins, Colorado, May 1975.

45. "Debris Control Structures," G. Reihsen and L. J. Harrison, HEC No. 9, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, 1971.

46. "The Design of Encroachments on Flood Plains Using Risk Analysis," M.L. Corry, J.S. Jones and P.L. Thompson, HEC No. 17, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, October 1980.

47. "Handbook of Applied Hydraulics," Calvin V. Davis, McGraw-Hill Book Co., Inc., New York, N.Y., 1952.

48. "Wastewater Engineering," Metcalf & Eddy, Inc., McGraw-Hill Book Co., New York, N.Y., 1972

49. "Hydraulic Performance of Culverts with Safety Grates," L.W. Mays, M.E. Walker, M.S. Bennet, and R.P. Arbuckle, FHWA/TX-82/55T301-1F; PB83-219626, Texas University, Austin Center for Transportation Research, Austin, Texas 78712, March 1983. Available from the National Technical Information Service, Springfield, Virginia 22161.

50. "Standard Specifications for Highway Bridges," 13th Edition, American Association of State Highway and Transportation Officials, 1983.

51. "Corrosion Performance of Aluminum Culvert," T.A. Lowe and A.H. Koepf, Highway Research Record No. 56, Highway Research Board, National Research Council, Washington, D.C., 1964, pp 98-115.

52. "Evaluation of the Durability of Metal Drainage Pipe," R.W. Kinchen, Transportation Research Record N762, pp. 25-32, Transportation Research Board Publications Office, 2101 Constitution Avenue, NW Washington, D.C. 20418, 1980.

53. "Hydraulic Design of Improved Inlets for Culverts Using Programmable Calculations," P.D. Wlaschin, M.M. Chatfield, A.H. Lowe, R.G. Magalong, Calculator Design Series 1, 2, & 3 for the Compucorp-325 Scientist, the HP-65, and the TI-59 programmable calculators, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, October 1980.

54. "Hydraulic Analysis of Pipe-Arch and Elliptical Shape Culverts Using Programmable-Calculators," Caluclator Design Series 4, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, March 1982.

55. "Electronic Computer Program for Hydraulic Analysis of Pipe - Arch Culverts," HY-2, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, May 1969.

56. "Hydraulic Design of Highway Culverts," Herbert G. Bossy, Draft HDS, Unpublished notes furnished by Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, April 1963.

57. "Hydraulic Design of Large Structural Plate Corrugated Metal Culverts," Jerome M. Normann, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, January 1974.

58. "Hydraulic Design Detail," DP-131, Edition 1, Kaiser Aluminum and Chemical Corporation, Oakland, California, 1984.

59. "Electronic Computer Program for Hydraulic Analysis of Culverts," Mario Marques, HY-6, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, 1979.

60. "Computation of Uniform and Nonuniform Flow in Prismatic Channels," Paul N. Zelensky, Office of Research, FHWA, Washington, D.C. 20590, November 1972.

61. "Handbook of Steel Drainage and Highway Construction Products," American Iron and Steel Institute, 1000 - 16th, N.W., Washington, D.C. 20036, 1983.

62. "Applied Hydraulics in Engineering," Henry M. Morris and James M. Wiggert, John Wiley & Sons, 1972.

63. "Concrete Pipe Handbook," American Concrete Pipe Association (ACPA), 8320 Old Courthouse Road, Vienna, Virginia 22180, June 1980.

64. "Resistance to Flow in Two Types of Concrete Pipe," Technical Paper No. 22, Series B, Lorenz G. Straub, Charles E. Bowers, and Meir Pilch, University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, December 1960.

65. "Friction Factor Tests on Spiral Rib Pipes," Hydraulic Program Report No. 83, U. Paul Tullis, Utah Water Research Laboratory, Utah State University, Logan, Utah, April 1983.

SELECTED ADDITIONAL REFERENCES

In Alphabetic Order

"A Commentary and Bibliography on The Hydraulics of Culvert Design, Chapter 4," N. H. Cottman, Australian Road Research Board, 500 Burwood Hwy, Vermont South, Victoria, May 1980.

"A Study of Detention in Urban Stormwater Management," H. R. Malcom, PB80-220577; UNC-WRRI-80-156; OWRT-B-093-NC(2), North Carolina Water Resources Research Institute, 124 Riddick Bldg., N.C. State University, Raleigh, North Carolina 27650, July 1980. Available from the National Technical Information Service, Springfield, Virginia 22161.

"Approximate Method for Computing Backwater Profiles in Corrugated Metal Pipes," P. N. Zelensky, FHWA-RD-76-42, Office of Research, FHWA, Washington, D.C. 20590, April 1976.

"Comparative Study of Coatings on Corrugated Metal Culvert Pipe," David K. Curtice and John E. Funnell, Southwest Research Institute Project No. 07-2733, Southwest Research Institute, P.O. Drawer 28510, 8500 Culebra Road, San Antonio Texas 78228, March 15, 1971.

"Concrete Pipe Design Manual," American Concrete Pipe Association (ACPA), 8320 Old Courthouse Road, Vienna, VA 22180, February, 1985.

"Concrete Pipe Handbook," American Concrete Pipe Association (ACPA), 8320 Old Courthouse Road, Vienna, VA 22180, April 1981.

"Culvert Design Aids: An Application of US - BPR Culvert Capacity Charts," Portland Cement Association, Chicago, Illinois, 1962.

"Culvert Design and Analysis Using a Micro-Computer," A. C. Miller, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, 1985.

"Culverts - Hydrology and Hydraulics," Gerard P. Lennon, Jerome M. Normann, and Richard N. Weisman, Lehigh University, Bethlehem, Pennsylvania, June 1982.

"Culvert Outlet Protection Design: Computer Program Documentation," M. G. Schilling, FHWA-RD-74-501, Wyoming State Highway Department, P.O. Box 1708, Cheyenne, Wyoming 82001. Available from the National Technical Information Service, Springfield, Virginia 22161.

"Determining Design Flows for Culverts and Bridges on Ungauged Streams," John F. Orsborn, TRB/TRR-685; PB-298102/5ST, Transportation Research Board, Washington, D.C., 1978, p. 32.

"Drainage Structures for Low-Cost Roads in Desert Areas," T.D. Raikes, Vol. P-208, Planning and Transport Research and Computation (PTRC) Education and Research Services Limited, 110 Strand, London WC2 England, 0143-4446 08650-090-X, July 1981.

"Effective Minor Drainage Design Overseas," R. J. Freer-Hewish, P-208, Planning and Transport Research and Computation (PTRC) Education Research Services Limited, 110 Strand London WC2 England, 0143-4446 086050-090-X, July 1981.

"Evaluation of the Flood Risk Factor in the Design of Box Culverts," RD75-54, G.K. Young; R.S. Taylor, and L.S. Costello, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, September 1970.

"Fish Passage Through Highway Culverts," T.J. McClellan, PB 204 983, Federal Highway Administration, Region 8, Portland, Oregon, October 1971 (Reprinted July 1980). Available from the National Technical Information Service, Springfield, Virginia 22161.

"Hydraulic Aspects of Fish-Ladder Baffles in Box Culverts," Jerome M. Normann, Hydraulics Branch, Bridge Division, Office of Engineering, FHWA, Washington, D.C. 20590, Draft Report, January 1974.

"The Hydraulics of Culverts," F. T. Mavis, Bulletin No. 56, The Pennsylvania State College Bulletin, State College, Pennsylvania, February 1943.

"Hydraulics of Box Culverts with Fish Ladders," R.H. Shoemaker, Proceedings of the 35th Annual Meeting, Highway Research Board, National Academy of Sciences, Highway Research Board, Washington, D.C., January 1956.

"Hydraulic Tests on Pipe Culverts," C.R. Neill, Report 62-1, Alberta Co-operative Highway Research Program, Research Council of Alberta, 87th Street Edmonton, Alberta, Canada, 1962.

"The Impact of Stream Relocation on Fish Populations and Bottom Fauna with Emphasis on Movement of Fishes Through Long Culverts," E.L. Cooper, FHWA/PA 81-019; PB82-202524, Pennsylvania State University, University Park Institute for Research on Land and Water, University Park, PA 16802, May 1981.

"Improved Inlets for Concrete Pipe Culverts," Hydraulic Research Group - Office of Research and Development - Bureau of Public Roads (now the FHWA), Washington, D.C., unpublished paper, November, 1964

"Improved Inlets for Highway Culverts," Jerome M. Normann, Civil Engineering, Vol 45, Number 3, American Society of Civil Engineers, New York, New York, March 1975.

"Optimal Design of Culverts Under Uncertainties," Larry W. Mays, Journal of the Hydraulics Division, Vol. 105, American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017, May 1979.

"Optimal Design for Highway Drainage Culverts," G. Young, M. Childrey; R. Trent, Journal of the Hydraulics Division, Vol. 100 No. HY-7 (Proc Paper 10676), American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017, 1974.

"Optimal Risk-Based Design of Water Resource Engineering Projects," Y.K. Tung, L.W. Mays, CRWR-171 (420 pages), University of Texas, Center for Research in Water Resource, Austin, Texas 87812, August 1980.

Division Journal, Vol. 106, American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017, May 1980, pp. 893-913.

"Some Sample Calculations For Oversize Culverts," G. Fiala, Portland Regional Office, FHWA, Portland, Oregon, Unpublished paper, April 1976.

"Theory, Development and Application of a Perfect Curvilinear Flow Net for Transitioning Open Channels," N.H. Cottman and D.J. Treloar, Institution of Engineers, Australia, 11 National Circuit Barton A.C.T. 2600 Australia 0 85825 157 4, 1980.

"Translation of Japanese Highway Design Manual: Part 3, Drainage," O.G. Ingles, ARR No. 55, Australian Road Research Board, 506 Burwood Road, Vermont South Victoria 3133 Australia 0313-3842, May 1979.

"Usefulness of the Storage Parameter," Alfred R. Pagan, Civil Engineering, American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017, October 1975.

FEDERAL HIGHWAY ADMINISTRATION

Publications listed below with an (*) are available from the Government Printing Office, Washington, D.C. 20402. The other publications are available in limited numbers to State highway agencies and other public agencies from the Federal Highway Administration. Requests for these documents and suggestions on the contents of any publications should be addressed to the Bridge Division, HNG-31, Federal Highway Administration, 400 Seventh St. SW., Washington, D.C. 20590.

HYDRAULIC DESIGN SERIES

HDS No. 1 HYDRAULICS OF BRIDGE WATERWAYS - Second Edition - Revised 1978

HDS No. 3 DESIGN CHARTS FOR OPEN-CHANNEL FLOW - 1961, Reprinted 1973

HDS No. 4 DESIGN OF ROADSIDE DRAINAGE CHANNELS - 1965

* HDS No. 5 HYDRAULIC DESIGN OF HIGHWAY CULVERTS - 1985

HYDRAULIC ENGINEERING CIRCULARS

HEC No. 1 SELECTED BIBLIOGRAPHY OF HYDRAULIC AND HYDROLOGIC SUBJECTS - 1985

HEC No. 9 DEBRIS-CONTROL STRUCTURES - 1971

HEC No. 11 USE OF RIPRAP FOR BANK PROTECTION - 1967

* HEC No. 12 DRAINAGE OF HIGHWAYS PAVEMENTS - 1984 (GPO 050-001-00280-9, $5.50)

HEC No. 14 HYDRAULIC DESIGN OF ENERGY DISSIPATORS FOR CULVERTS AND CHANNELS - 1975, revised 1983

HEC No. 15 DESIGN OF STABLE CHANNELS WITH FLEXIBLE LININGS - 1975

HEC No. 16 ADDENDUM TO HIGHWAYS IN THE RIVER ENVIRONMENT - 1980

HEC No. 17 THE DESIGN OF ENCROACHMENTS ON FLOOD PLAINS USING RISK ANALYSIS - 1980

* HEC No. 19 HYDROLOGY - 1984 (GPO 050-001-00287-6, $9.50)

APPENDIX J

Torrington Area Health District Applicatioon

SUBDIVISION REQUIREMENTS FOR ENGINEERS

T.A.H.D. must be notified at least ten (10) working days prior to any subdivision testing. Applications for subdivision review (attached) must be completed and returned to this office with the appropriate fee prior to site testing.

IN FIELD

1. In ledge areas or where ledge is encountered at less than 7 ft.. enough observation pits, dug to show suitable area for system and 100% reserve.
2. All observation pits, regardless of results, identified in field by numbers corresponding to report submitted. Standpipes must be located in all deep test pits to a depth of 7 feet and be labeled with test hole number.
3. All wetlands must be field identified by a soil scientist. Identification flags must be numbered.

ON PLANS

1. Provide site location map at 1-800 scale.
2. Show boundaries and S.C.S. soil types.
3. Show completely any water courses, seasonal tributaries, proposed or existing storm water and road drainage systems, retention ponds, and/or easements.
4. Inland wetland boundaries must be established by a soil scientist and located on subdivision map by a surveying method. Field identification numbers must be shown on map. In cases where wetlands soils have not been found, a letter from the soil scientist to that effect should be submitted with the subdivision report.
5. Show original and finished contours and elevations including road and driveway cuts. Contours must be a 2 ft. intervals unless otherwise approved by T.A.H.D.
6. Locate all observation pits and percolation tests on map with corresponding numbers. Test hole locations must be accurately established by a licensed surveyor or engineer.
7. Indicate tentative house site (in compliance with zoning or land use requirements), driveway, well and proposed primary and reserve septic sites.
8. Where ledge rock, hardpan and/or ground water conditions are such that fill will be required as part of the final subsurface disposal design, the subdivision plan should include finish contours in the primary and reserve septic areas.