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16. Abstract

This manual provides programmable design procedures for both box and pipe culverts with either conventional or improved inlets, for the Hewlett Packard, HP-65 calculator.

The same terminology and algorithms used in "The Design of Improved Inlets for Culverts" (HEC No. 13) are used in these programs.

Each program listed in the manual is accompanied by an explanation and an illustration of its use.

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INTRODUCTION

The programable calculator as a culvert designing tool offers many desirable features. Compared with the hand method, the calculator is more accurate, less time consuming, and eliminates all the searching through charts and nomographs. In one quarter of the time it takes to design one culvert by hand, the designer could use the calculator to design the culvert, checking four or five different sizes to find the best one, while also evaluating several inlet configurations including both side- and slope-tapered inlets.

In an office where it is not feasible to use a computer for culvert design, the programable calculator becomes a desireable alternative. The accuracy remains the same, and the calculator method offers a segment by segment design approach. This method allows the culvert design parameters to be changed as the design is proceeding along.

The procedure herein covers both box and circular pipe culverts and follows the culvert design methods presented in "Hydraulic Design of Improved Inlets for Culverts," Hydraulic Engineering Circular No. 13 (HEC 13), dated August 1972. The programs begin with the computation of tailwater, proceed through the design of the culvert barrel, and conclude with the design of the culvert inlet most applicable to the site. The programs produce detailed inlet dimensions, performance curve data, and the outlet velocity.

Since the procedure is subdivided into a series of programs, the designer may enter the sequence at any point, provided the necessary input data is available, and obtain the desired design results.

These box and pipe culvert programs have been written for use on the Hewlett Packard - 65 calculator. It is expected that with the equations, examples, and program listings, a designer will be able to write similar programs for any other calculator he may have available.

Terminology used in this publication assumes that the designer is familiar with HEC 13 and understands the principles and design philosophy expressed therein.

This document was written by Mr. Patrick Wlaschin and edited by Mr. Philip L. Thompson.

PROGRAM LIMITATIONS

When computing headwater depths, H_f and H_t, the upper and lower limits for these values are 4.5 D and 0.5 D. These limits indicate the range over which research was performed on these culverts. Because polynomial best-fit equations are used to produce the chart values from HEC #13, values outside these limits can be obtained. Since the programs do not check for these conditions, it is left to the designer.

When designing either a side-tapered of slope-tapered inlet, the number of barrels, N, is limited to two. For multiple barrels, each barrel should be designed individually.

In programs for circular pipes where d_n/D is greater than 0.89, the program assumes the pipe to be flowing full in calculating the outlet velocity.

In calculating the "H" value in the outlet control performance programs, it is assumed that the culvert is flowing full.

In the design of slope-tapered inlets, the FALL slope, S_f, must range between a 2:1 and a 3:1 ratio.

In any of the programs which use FALL, this value is limited to a range of ¼D to 1½D for slope-tapered inlets.

For side-tapered inlets the value of side taper, ST, must be between 4:1 and 6:1.

The value of L_3 must be greater than or equal to ½B. This value has been set so that control will occur at the throat section rather than at the bend section.

In addition to the design limitations given previously for box culverts with slope-tapered inlets, the following criteria apply to slope-tapered and rectangular side-tapered inlets for pipe culverts:

The rectangular throat of the inlet must be a square section with sides equal to the diameter of the pipe culvert.

The transition from the square throat section to the circular throat section must be no shorter than half the culvert diameter. If excessive lengths are used, the frictional losses within this section of the culvert should be considered in the design.

The design of multiple barrels for circular culverts using slope-tapered improved inlets can be performed the same as for box culverts except that the center wall must be flared in order to provide adequate space between the pipes for proper compaction of the backfill. The amount of flare required will depend on the size of the pipes and the construction techniques used. No more than two barrels may feed from the same inlet structure using the design methods of these programs.

An alternative would be to design a series of individual circular culverts with slope-tapered inlets. This permits the use of an unlimited number of barrels and the design programs are applicable.

The wingwall flare angles used in side-tapered inlets are limited from 15° to 26° with the top edge beveled, and from 26° to 90° with or without bevels.

The socket entrance used in these programs refers to the bell and spigot type of pipe.

All the dimensions used in these programs are in English units. The programs require all of their inputs to be in this type of format.

The use of slopes equal to a value of zero will produce incorrect results.

These programs do not check for errors in input values.

Several of the equations given in the equation section of a program may not be the exact formula used in the program. This is due to the size limitations of the HP-65 calculator. It was determined that these small differences did not significantly change the final results.

Generally the order of program execution is from Label A, through Labels B, C, and D. The user should refrain from performing calculations between using these labels.

For the most part, these limitations are repeated in the discussions with the programs.

LIST OF SYMBOLS

Symbol	Units	Description
A	sq.ft.	Area, generally the cross-sectional area of flow
a	ft.	Bevel dimension used for circular pipe culverts
ADJ.L	ft.	Adjusted length of a culvert, after its original length has been altered by the addition of an improved inlet.
ADJ.S		Adjusted slope of a culvert, after its original slope has been lowered by the use of FALL
Alpha		Velocity distribution factor used with pipe culverts, 1.04 for concrete, 1.12 for corrigated metal
AHW EL.	ft.	Allowable headwater elevation at the culvert entrance
B	ft.	Width of the box culvert barrel or the diameter of a pipe culvert
b	ft.	Bevel dimension used for circular pipe culverts
B_f	ft.	Width of the face section of an improved inlet
BW	ft.	Base width of a rectangular or trapezoidal channel section
c	ft.	Bevel dimension used for circular pipe culverts
CW	ft.	Width of the weir crest
D	ft.	Height of a box culvert or the diameter of a pipe culvert
d	ft.	Bevel dimension used for circular pipe culverts
d_c	ft.	Critical depth of flow
d_n	ft.	Normal depth of flow
d_2, d_3, d_4	ft.	Variable depths of flow

Symbol	Units	Description
E	ft.	Height of side-tapered pipe culvert face section, excluding bevel dimension
EL.FACE	ft.	Invert elevation of the face section of a culvert
EL.FD	ft.	Catch point elevation of the fill slope at the downstream end of the cross section
EL.FU	ft.	Catch point elevation of the fill slope at the upstream end of the cross section
EL.IN	ft.	Invert elevation of the culvert before any improved inlet adjustments
EL.OUT	ft.	Invert elevation of the culvert outlet
EL.THR	ft.	Invert elevation of the culvert throat section
FALL	ft.	Distance between the culvert inlet and the control section. Measured in a downward direction
g	ft./sec^2	Acceleration of gravity; 32.2
H	ft.	Head or energy required to pass a given quantity of water through a culvert flowing in outlet control
H_c	ft.	The depth of pool, or head, above the weir crest
H_e	ft.	Head loss at a culvert due to the entrance configuration
H_f	ft.	Depth of pool, or head, above the face section invert
H_t	ft.	Depth of pool, or head, above the throat section invert
H_v	ft.	Head due to velocity
HW EL.	ft.	Headwater elevation at the entrance to a culvert
k_e		Entrance energy loss coefficient
L	ft.	The length of the culvert, measured along the barrel

Symbol	Units	Description
L_1, L_2, L_3, L_4	ft.	Dimensions relating to the improved inlet as shown in sketches of the different inlet types
N		Number of culvert barrels
n		Manning roughness coefficient
Q	cfs.	The volume rate of flow
R	ft.	Hydraulic radius
r	ft.	Variable parameter equal to the absolute value of the difference between the flow depth in a pipe culvert and the radius
S	ft./ft.	Slope of the culvert barrel
S_{FD}	ft./ft.	Downstream fill slope
S_{FU}	ft./ft.	Upstream fill slope
S_f	ft./ft.	Slope of FALL for slope tapered inlets, (ratio of horizontal to vertical) See design sketches
S_o	ft./ft.	Slope of the natural channel
ST	ft./ft.	Sidewall taper
TW	ft.	Tailwater depth at the culvert outlet
V	fps.	Mean velocity of flow
WA	degree	Wingwall taper angle
WP	ft.	Wetted perimeter
WT	ft./ft.	Wingwall taper
X		Variable parameter used to simplify calculations
Y,y		Variable parameter used to simplify calculations
Y_a, Y_b	ft.	Parameters used to indicate the equations of various slope lines
Z		Variable parameter used to simplify calculations
Z_1, Z_2	ft./ft	Side slopes of a channel section

PROGRAM OUTLINE

PROGRAM OUTLINE

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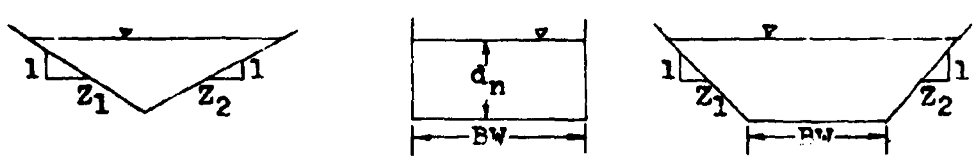
CULVERT PROGRAMS

PROGRAM #1 - NORMAL DEPTH

In calculating the performance of a culvert, the tailwater depth is required. This tailwater depth is used in determining the water surface elevation at the outlet of the culvert. One method of estimating this depth is to set it equal to the normal depth of the flow in the channel.

Program #1 calculates the normal depth of water flowing in a natural channel. For the program to operate, the channel cross-section is assumed to be prismatic in shape. Depending upon the inputs, a triangular, rectangular, or trapezoidal section may be evaluated. These various shapes are dimensioned as follows:



triangular　　rectangular　　trapezoidal

EQUATIONS

$$Q = 1.486(AR^{.67}S_o^{.5})/n$$

$$A = d_n(BW+d_n(Z_1+Z_2)/2)$$

$$WP = BW+d_n((Z_1^2+1)^{.5}+(Z_2^2+1)^{.5})$$

$$R = A/WP$$

$$V = Q/A$$

REMARKS

For the program to operate properly, the base width (BW) and the stream roughness value (n), must be stored together as a sum in register #2. To avoid the mixing of data, the base width (BW), must be an integer.

The channel depth (d_n) must be calculated using Label A before the channel velocity (V_o) can be determined.

STEP	INSTRUCTION	INPUTS	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		BW	ENTER	BW
		n	+ STO 2	BW+n
		S_o	STO 3	S_o
		Z_1	STO 4	Z_1
		Z_2	STO 5	Z_2
3	Calculate normal depth		A	d_n
4	Calculate channel velocity		B	V_o
5	For a change in any of the channel properties go to step #2 and change only the necessary data.			

EXAMPLE #1

Find the normal depth for a trapezoidal channel with a base width of 6 feet and side slopes of 2:1 and 3:1. The channel slope is 0.048 and the roughness value is 0.045. The estimated flowrate is 650 c.f.s.

KEYSTROKES	DISPLAY
650 STO 1	650.00
6 ENTER .045 + STO 2 . .	6.05
.048 STO 3	0.05
2 STO 4	2.00
3 STO 5	3.00
A	3.61 ft. normal depth
B	11.97 fps. channel velocity

EXAMPLE #2

Evaluate the previous example for a triangular cross-section. The base width (BW) is set to zero.

KEYSTROKES	DISPLAY
.045 STO 2	0.05
A	4.64 ft.
B	12.05 fps.

LISTING - PROGRAM #1

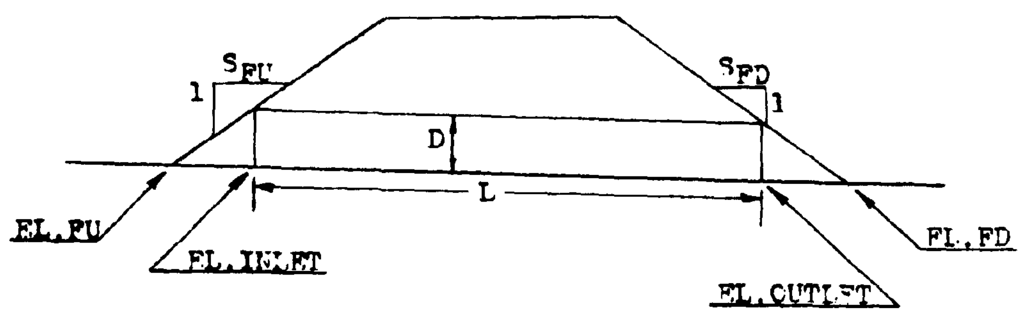
LBL A 1 STO 6 STO 8 LBL 1 RCL 4 RCL 5 + RCL 6 x 2
÷ RCL 2 f INT + RCL 6 x RCL 4 ENTER x 1 + f $\sqrt{x}$
RCL 5 ENTER x 1 + f $\sqrt{x}$ + RCL 6 x RCL 2 f INT + ÷
2 ENTER 3 ÷ g y^x x RCL 3 f $\sqrt{x}$ x 1 . 4 8 6 x
RCL 2 f^{-1} INT ÷ RCL 1 - 0 g x≷y g x=y RCL 6 RTN RCL 7
g x≷y STO 7 - g x=y RCL 6 RTN RCL 7 RCL 8 x g x≷y ÷
STO 8 STO - 6 GTO 1 LBL B g R↑ RCL 1 g x≷y ÷ RTN
(95 STEPS)

PROGRAM #2 - CULVERT LENGTH, INLET AND OUTLET ELEVATIONS

This program uses the site characteristics to determine the culvert length for a given barrel height. The inlet and outlet elevations for the culvert are also calculated by this program.

Both box and pipe culverts can be evaluated by this program.

The necessary input data are indicated in the diagram below:



Roadway Cross section

EQUATIONS

$$L = (EL.INLET - EL.OUTLET)(S_o^2+1)^{.5}/S_o$$

$$EL.INLET = EL.FU - (DS_oS_{FU}(S_o^2+1)^{.5}/(1+S_oS_{FU}))$$

$$EL.OUTLET = EL.FD + (DS_oS_{FD}(S_o^2+1)^{.5}/(1-S_oS_{FD}))$$

The derivations of these equations are found in the appendix.

REMARKS

The length of the culvert (L) is measured along the barrel and is not a horizontal dimension.

REMARKS (cont.)

The ends of the culvert are assumed to be vertical.

STEP	INSTRUCTIONS	INPUTS	KEYS	DISPLAY
1	Load program			
2	Input register values	D	STO 2	D
		S_o	STO 3	S_o
		S_{FD}	STO 5	S_{FD}
		S_{FU}	STO 6	S_{FU}
		EL.FU	STO 8	EL.FU
		EL.FD	STO 9	EL.FD
3	Calculate the culvert length		A	L
4	Calculate inlet elevation		B	EL.IN
5	Calculate outlet elevation		C	EL.OUT
6	For a change in any of the register values go to step #2 and change only the necessary data.			

EXAMPLE #1

Find the length of a 9x5 box culvert on a 4% slope. Both the upstream and the downstream fill slopes are on a 3:1 ratio. The elevation of the catch point on the upstream fill is 100 feet. The catch point elevation for the downstream slope is 90 feet.

KEYSTROKES	DISPLAY
5 STO 2	5.00

KEYSTROKES	DISPLAY
.04 STO 3	0.04
3 STO 5	3.00
STO 6	3.00
100 STO 8	100.00
90 STO 9	90.00
A	219.71 ft. LENGTH
B	99.46 ft. EL.INLET
C	90.68 ft. EL.OUTLET

EXAMPLE #2

It was later decided to use a 66 inch pipe culvert at this location instead of the 9x5 box culvert. Find the length and the inlet and outlet invert elevations for this situation.

KEYSTROKES	DISPLAY
66 ENTER 12 ÷ STO 2 . .	5.50
A	216.66 ft. LENGTH
B	99.41 ft. EL.INLET
C	90.75 ft. EL.OUTLET

LISTING - PROGRAM #2

LBL A E C - RCL 3 + RCL 3 ENTER x 1 + f √x x STO 7 RTN LBL B RCL 3 ENTER x 1 + f √x RCL 2 x RCL 3 x RCL 6 x RCL 3 RCL 6 x 1 + CHS + RCL 8 + RTN LBL C RCL 3 ENTER x 1 + f √x RCL 2 x RCL 3 x RCL 5 x RCL 3 RCL 5 CHS x 1 + ÷ RCL 9 + STO 4 RTN (68 STEPS)

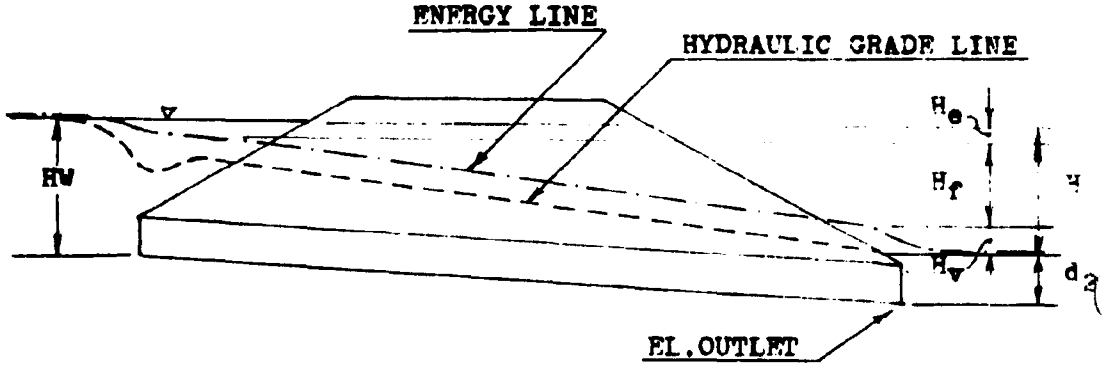
PROGRAM #3 - BOX CULVERT; SIZE AND OUTLET CONTROL PERFORMANCE

This program has two functions. First, it can be used to select the appropriate box culvert size. Second, once this box size has been selected, the program will evaluate its performance for various flowrates. The outlet control performance curve can be made by plotting these flowrates versus the generated headwater elevations (HW EL.).

In determining the best box culvert size, the designer must first select a trial height (D) and width (B). For these two values the program computes the water surface elevation of the headwater pool at the culvert inlet. A visual comparison of this value to the allowable headwater elevation (AHW EL.) is made and the designer adjusts the height (D) and width (B) accordingly.

Once the box size has been determined, various flowrate values can be placed into the program to obtain the performance curve.

The following diagram indicates the location of the energy losses associated with culvert flow.



EQUATIONS

$$H_e = k_e V^2/2g$$

$$H_f = 29n^2LV^2/2gR^{1.33}$$

$$H_v = V^2/2g$$

$$H = H_e+H_f+H_v$$
$$= (1+k_e+29n^2L/(BL/2(B+D))^{1.33})(Q/DBN)^2/2g$$

$d_2 = (d_c+D)/2$ or the Tailwater depth, whichever is largest

$$HW\ EL. = H+d_2+EL.OUTLET$$

$$d_c = 0.315(Q/BN)^{.67}$$

REMARKS

The critical depth (d_c) cannot be greater than the height of the box (D). The program includes a test for this situation.

Since the water at the inlet is considered to be a pool, the velocity at this point is assumed to be approximately zero. This allows the hydraulic grade line to be equated to the energy line.

For the program to operate properly, the number of barrels (N) and the barrel roughness value (n), must be stored together as a sum in register #8. The limitations of the assumptions made also require that the number of barrels (N) be limited to a value of 1 or 2.

Label A (HW EL.) must be executed before Label D (d_2).

STEP	INSTRUCTIONS	INPUTS	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		B	STO 3	B
		EL.OUT	STO 4	EL.OUT
		k_e	STO 5	k_e
		TW	STO 6	TW
		L	STO 7	L
		N	ENTER	N
		n	+ STO 8	N+n
3	Calculate headwater elevation		A	HW EL.
4	Calculate critical depth		B	d_c
5	Calculate total head loss		C	H
6	Calculate depth of water at outlet		D	d_2
7	To evaluate another box size, reenter another height and/or width and go to step #3. *			
8	To obtain outlet control performance curve coordinates, input various flowrates and calculate the corresponding headwater elevations. **			

* If the length and the elevation of the outlet of the culvert change with the depth, they must also be reentered.

** If the tailwater depth changes, it must be reentered.

EXAMPLE #1

For a flowrate of 400 cfs., and an entrance loss coefficient of 0.5, find an appropriate box culvert size. The tailwater depth for this flowrate is 2 feet. From the site conditions, it has been determined that for a 5 foot box height, a 255.00 foot barrel is required. The outlet elevation for this box would be 99.70 feet. If a 6 foot box height is selected the length would change to 250.00 feet with an outlet elevation of 100.00 feet. The culvert is to be constructed of concrete with a roughness factor of 0.012. The allowable headwater elevation is set at 130.00 feet.

KEYSTROKES	DISPLAY	
400 STO 1	400.00	
.5 STO 5	0.50	
2 STO 6	2.00	
1 ENTER .012 + STO 8 . .	1.01	

Try a 5x5 box.

KEYSTROKES	DISPLAY	
5 STO 2	5.00	
STO 3	5.00	
255 STO 7	255.00	
99.7 STO 4	99.70	
A	113.81 ft.	HW EL.

HW EL. is lower than AHW EL. Try 4x5 box.

KEYSTROKES	DISPLAY	
4 STO 3	3.00	
A	119.76 ft.	HW EL.

HW EL. is closer to the AHW EL. Try 3x5 box.

KEYSTROKES	DISPLAY
3 STO 3	3.00
A	134.08 ft. HW EL.

HW EL. exceeds the AHW EL. The 4x5 box will work.

Try a 4x6 box.

6 STO 2	6.00
4 STO 3	4.00
250 STO 7	250.00
100 STO 4	100.00
A	116.00 ft. HW EL.

HW EL. is less than the AHW EL. Try a 3x6 box.

3 STO 3	3.00
A	125.51 ft. HW EL.

HW EL. is close to the AHW EL. Try 2x6 box.

2 STO 3	2.00
A	158.31 ft. HW EL.

HW EL. exceeds the AHW EL.

Use either a 4x5 or a 3x6 box culvert.

EXAMPLE #2

Evaluate the performance curve in outlet control for the 3x6 box culvert designed above. Plot four points on the curve corresponding to the 0.6Q, 0.8Q, Q, and 1.2Q.

KEYSTROKES	DISPLAY
400 ENTER .6 x STO 1 . .	240.00
6 STO 2	6.00

KEYSTROKES	DISPLAY	
3 STO 3	3.00	
100 STO 4	100.00	
.5 STO 5	0.50	
2 STO 6	2.00	
250 STO 7	250.00	
1 ENTER .012 + STO 8 . .	1.01	
A	112.95 ft.	HW EL. @ .6Q
400 Enter .8 x STO 1 . .	320.00	
A	118.48 ft.	HW EL. @ .8Q
400 ENTER 1.2 x STO 1 .	480.00	
A	134.09 ft.	HW EL. @ 1.2Q
400 STO 1	400.00	
A	125.51 ft.	HW EL.
B	8.22 ft.	d_c
C	19.51 ft.	H
D	6.00 ft.	d_2

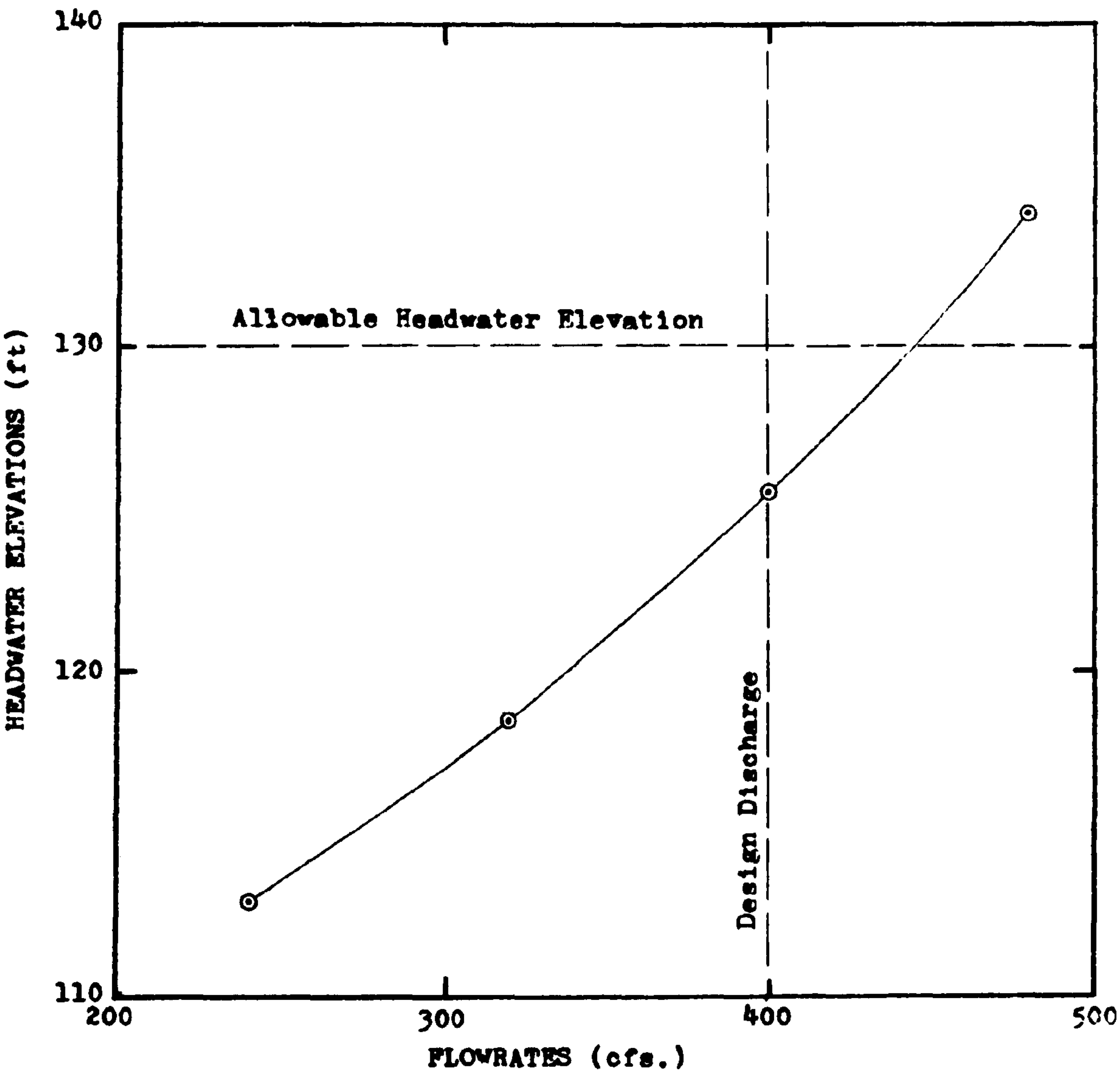
LISTING - PROGRAM #3

LBL A B RCL 2 g x≤y RCL 2 g NOP + 2 + RCL 6 g x≤y
g x≥y g NOP STO 9 C RCL 4 + RCL 9 + RTN LBL P RCL 1
RCL 3 + RCL 8 f INT + 2 ENTER 3 + g y^x . 3 1 5 x
RTN LBL C 2 9 RCL 8 f^{-1} INT ENTER x x RCL 7 x RCL 3
RCL 2 x RCL 3 RCL 2 + 2 x + 4 ENTER 3 + g y^x +
RCL 5 + 1 + RCL 1 RCL 3 + RCL 2 + RCL 8 f INT +
ENTER x 6 4 . 4 + x RTN LBL D RCL 9 RTN (99 STEPS)

Plot of the performance of a 3x6 box culvert operating in outlet control.

Plotting Coordinates

Q	240.00	320.00	400.00	480.00
HW EL.	112.95	118.48	125.51	134.09



PROGRAM #4 - BOX CULVERT; OUTLET CONTROL OUTLET VELOCITY

This program determines the outlet velocity of a box culvert operating in outlet control.

The formula incorporated in this program is simply V = Q/A. The depth of flow used in the computation of the cross-sectional area is equal to the critical depth or the tailwater depth, whichever is larger. However, if this depth is found to be greater than the height of the box culvert, then the box culvert height is used as the depth of flow.

EQUATIONS

$$V = Q/A = Q/(BNd_3)$$

$d_3 = d_c$ or TW, whichever is larger, not to exceed D

$$d_c = 0.315(Q/BN)^{.67}$$

REMARKS

The outlet velocity, Label A, must be calculated before the depth of flow value, Label C, can be displayed.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		B	STO 3	B
		TW	STO 6	TW
		N	STO 8	N

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
3	Calculate outlet velocity		A	V
4	Calculate critical depth		B	d_c
5	Calculate depth of flow		C	d_3
6	For a change in any of the culvert properties go to step #2 and change only the necessary data.			

EXAMPLE #1

What is the outlet velocity of a 9x5 box culvert at a flowrate of 600 cfs.? The tailwater depth is 4.5 feet.

KEYSTROKES	DISPLAY	
600 STO 1	600.00	
5 STO 2	5.00	
9 STO 3	9.00	
4.5 STO 6	4.50	
1 STO 8	1.00	
A	13.33 fps.	V
B	5.18 ft.	d_c
C	5.00 ft.	d_3

EXAMPLE #2

What velocity values could be expected for the box culvert in the above example at discharges of 400, 500, and 800 cfs.?

KEYSTROKES	DISPLAY

With the previous problem still stored in the calculator.

400 STO 1 . . . . 400.00

A . . . . 9.88 fps. V

500 STO 1 . . . . 500.00

A . . . . 12.11 fps. V

800 STO 1 . . . . 800.00

A . . . . 17.78 fps. V

LISTING - PROGRAM #4

```
LBL A P RCL 6 g x>y GTO 1 g x≷y RCL 2 g x>y g x≷y
g NOP GTO 2 LBL 1 RCL 2 g x>y g x≷y g NOP LBL 2
  STO 9 RCL 3 x RCL 8 f INT x RCL 1 g x≷y + RTN
LBL B RCL 1 RCL 3 + RCL 8 f INT + 2 ENTER 3 ÷
g y^x . 3 1 5 x RTN LBL C RCL 9 RTN (60 STEPS)
```

PROGRAMS #5-8 BOX CULVERT: INLET CONTROL PERFORMANCE

Program #5: Square Edged Inlet with Headwalls

Program #6: Square Edged Inlet with 30°-75° Wingwalls

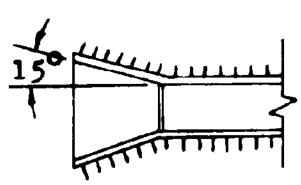
Program #7: 1:1 Bevel Edged Inlet with Headwalls

Program #8: 1:1 Bevel Edged Inlet with 45° Wingwalls or

1½:1 Bevel Edged Inlet with 18°-33.7° Wingwalls

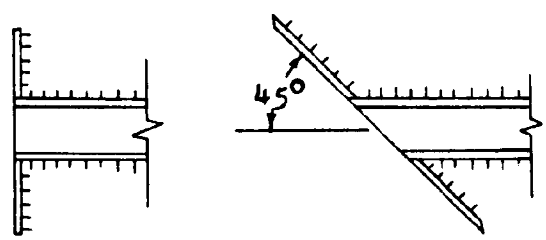
These programs evaluate the hydraulic performance for the above inlet configurations. Although the shape of the inlet faces differ dramatically, the analysis formulas are very similar. For this reason, these programs are grouped together. A further detailed explanation of the geometry of these inlets is depicted in the diagrams below:

Program #5



90° and 15° Wingwalls

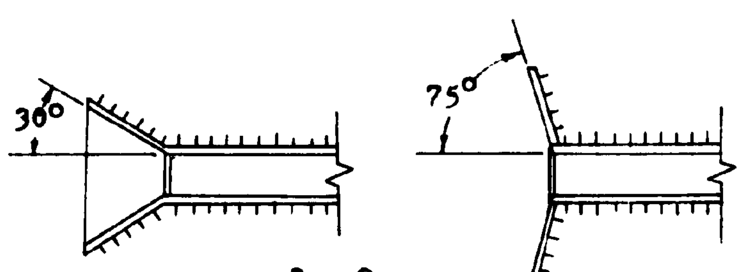
Square Edges



Headwalls - Normal or Skewed to

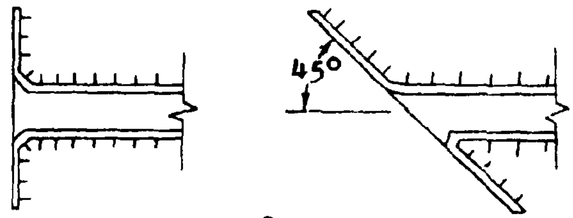
45° Square Edges

Program #6



Wingwalls 30°-75° Flare Square Edges

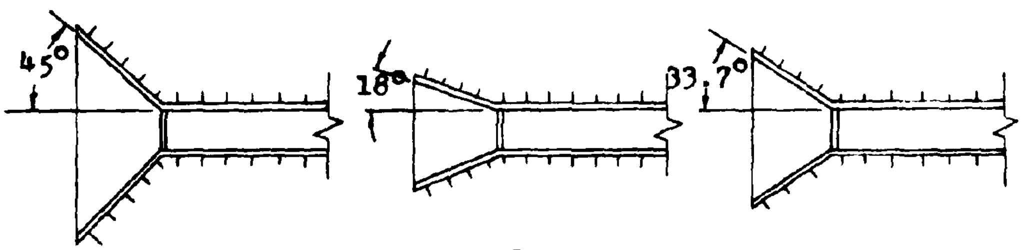
Program #7



Headwalls - Normal to 45° Skew, 1:1 Bevel Edged,

Variable Bevel on Acute Angle of Skewed Headwall

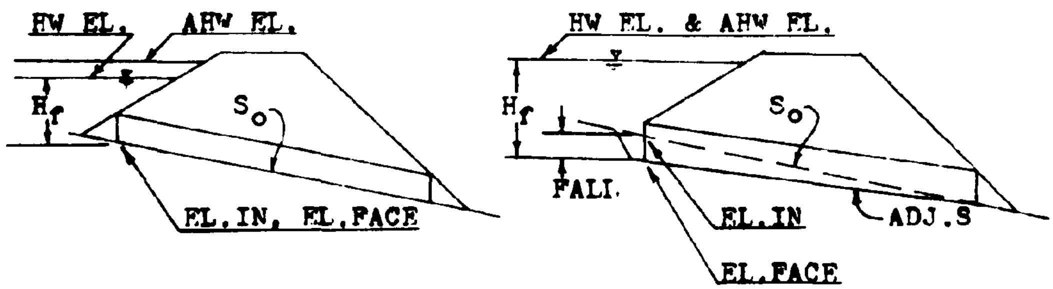
Program #8



45° Wingwall Flare
1:1 Beveled Top Edge

18° to 33.7° Wingwall Flare
1½:1 Beveled Top Edge

For each particular inlet, the program calculates the height of the water at the face of the culvert (H_f). This value is then added to the culvert inlet invert elevation (H_f + EL.IN). If this sum is less than the allowable headwater elevation (AHW EL.), then the inlet elevation becomes the elevation of the face (EL.FACE). However, if the sum of the height of the water at the face of the culvert and the elevation of the inlet exceeds the allowable headwater elevation, the difference between this sum and the allowable headwater elevation is subtracted from the inlet invert elevation. This new elevation is now called the elevation of the face (FL.FACE). For the culvert to operate properly, the inlet invert must be reset to this elevation. The drop in elevation of the inlet invert is called the FALL. The diagrams below graphically show this occurrence. It should be noted that as the inlet invert elevation drops, the culvert barrel rotates about the outlet invert.



No FALL Required

$FL.IN + H_f < AHW\ FL.$

FALL Required

$FL.IN + H_f \geq AHW\ FL.$

As indicated in the diagrams, when the calculated headwater elevation is above the allowable headwater elevation, the headwater elevation is set equal to the allowable and the difference is taken up by the FALL.

Generally speaking, the invert elevation of the culvert can always be thought of as the elevation of the face (FL.FACE). The original elevation of the culvert inlet invert before considering the affects of inlet control and FALL, can be taken as the elevation of the inlet (FL.INLET).

Once the culvert has been sized for the design flowrate conditions, the same program can be used to evaluate the performance of the culvert for other flowrate values. In this manner a performance curve for the culvert operating in inlet control can be drawn.

EQUATIONS

EL.FACE = AHW EL.-H_f (With FALL)

= EL.INLET (Without FALL)

HW EL. = EL.FACE+H_f

FALL = EL.FACE-EL.INLET

Note: The FALL is measured in a downward direction and therefore is always a positive value.

$$X = Q/(PND)^{1.5}$$

Program #5

$$H_f = D(0.122117+0.505435X-0.108560X^2+0.0207809X^3 -0.00136757X^4+0.00003456X^5)$$

Program #6

$$H_f = D(0.0724927+0.507087X-0.117474X^2+0.0221702X^3 -0.00148958X^4+0.0000380X^5)$$

Program #7

$$H_f = D(0.1566086+0.3989353X-0.0640392X^2+0.01120135X^3 -0.0006449X^4+0.000014566X^5)$$

Program #8

$$H_f = D(0.0895633+0.4412465X-0.0743498X^2+0.01273183X^3 -0.0007588X^4+0.00001774X^5)$$

REMARKS

In evaluating these inlets, the box size must be determined before the culvert performance values can be generated. Once the box culvert has been sized and the elevation of the face (EL.FACE) established using the design flowrate, the program can then be used for performance evaluations. In calculating the performance curve values, the elevation of the face (EL.FACE) must remain a constant. To insure that this value does remain a constant, Label A on the calculator should not be used during the performance curve evaluation.

These programs have been written with the input values stored in the same registers for each program. This allows the designer to store the input data once and evaluate all four inlet configurations by just loading the individual program cards.

Whenever applicable, a bevel edged inlet is recommended for use in lieu of a square edged inlet. The large increase in hydraulic performance gained by using the bevel edged inlet, greatly outweighs the small additional cost.

To insure the proper operation of these inlets, the FALL value is limited to a minimum value of ¼D and a maximum value of 1½D. If the minimum value is exceeded, ie., FALL = 0.2D, one of three alternatives may be considered. First, since the FALL is so small, the culvert will operate as though no FALL is present. Therefore, in this case, the culvert should be designed with no FALL present. Second, the box size could be reduced for the same inlet configuration. This would increase the amount of FALL produced. And third, the same box size can be used only with another inlet design. If the maximum value for FALL, 1½ D, is exceeded, either a larger box size or a more efficient inlet is required.

Polynomial best-fit equations are used to determine the headwater depths for these inlets. Since these equations are an approximation for the curves in HEC #13, they are subject to the same limitations. Therefore, the headwater depth (H_f) is limited to a maximum of 4½D and a minimum of ½D. To avoid the possibility of culvert failure due to buoyancy forces, it is recommended that H_f be limited to a value around 2D.

For the programs to operate properly, the width of the box culvert (B) and the number of barrels (N), must be stored together as a product in register #3.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		B	ENTER	B
		N	x STO 3	BxN

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
2	Input register values	EL.IN	STO 5	EL.IN
		AHW EL.	STO 6	AHW EL.
3	Calculate the EL.FACE		A	EL.FACE
4	Calculate the headwater elev.		B	HW EL.
5	Calculate the FALL		C	FALL
6	Calculate the headwater depth		D	H_f
7	To evaluate the same inlet with different design criteria, go to step #2.			
8	To evaluate another inlet, load the desired program card and go to step #3.			
9	To obtain the performance curve coordinates, input the selected flowrates in register #1 and press Label B to obtain the headwater elev.			

Note: Label A must not be used during the performance curve evaluation.

EXAMPLE #1

For a 10-year discharge of 600 cfs., an allowable headwater elevation of 113.00 feet, and an inlet elevation of 98.00 feet, determine an appropriate box culvert size. The site characteristics indicate a box height of 5 feet should be used. A headwall configuration with a 30° skew should be employed.

Load program #5

KEYSTROKES	DISPLAY
600 STO 1	600.00
5 STO 2	5.00
98 STO 5	98.00
113 STO 6	113.00

Try a 5 foot width. And a single barrel.

5 STO 3	5.00
A	85.45 ft. EL.FACE
C	12.55 ft. FALL

The allowable FALL is $1\frac{1}{2}$D or 7.5 ft. Try larger width.

6 STO 3	6.00
A	92.73 ft. EL.FACE
C	5.27 ft. FALL

The FALL value is between $\frac{1}{2}$D and $1\frac{1}{2}$D. Check the H_f.

D	20.27 ft. H_f

H_f is below the maximum value of $4\frac{1}{2}$D.

This 6x5 square edged box culvert may be used if anchored securely.

For the same site, design a beveled inlet.

Load program #7

KEYSTROKES	DISPLAY
5 STO 3	5.00
A	90.86 ft. EL.FACE

KEYSTROKES	DISPLAY
C	7.14 ft. FALL

The FALL is in the acceptable range.

D	22.14 ft. H_f

The headwater depth is in the acceptable range.

A 5x5 bevel edged box culvert may be used.

Other alternatives

6 STO 3	6.00
A	96.38 ft. FL.FACE
C	1.62 ft. FALL = .32D
D	16.62 ft. H_f = 3.32D
7 STO 3	7.00
A	98.00 ft. FL.FACE = FL.IN
C	0.00 ft. FALL
B	111.28 ft. HW EL.
D	13.28 ft. H_f = 2.7D

A 6x5 bevel edged inlet with 1.62 ft. of FALL, or a 7x5 bevel edged inlet box culvert with no FALL.

EXAMPLE #2

For the conditions in Example #1, using the 5x5 bevel edged box culvert, calculate the performance curve coordinates.

Load program #7

KEYSTROKES	DISPLAY	
600 STO 1	600.00	
5 STO 2	5.00	
5 STO 3	5.00	N = 1
98 STO 5	98.00	
113 STO 6	113.00	
A	90.86 ft.	EL.FACE
B	113.00 ft.	HW EL.
400 STO 1	400.00	
B	102.96 ft.	HW EL. @ Q = 400cfs.
500 STO 1	500.00	
B	107.48 ft.	HW EL.
700 STO 1	700.00	
B	119.53 ft.	HW EL.

Note: In the above calculations, Label A was only pressed while the design flowrate (600 cfs.) was in register #1. While other flowrates are being used for performance curve evaluations, Label A should not be pressed.

EXAMPLE #3

For a design flowrate of 1000 cfs., an inlet elevation of 437.50 feet and an allowable headwater elevation of 448.20 feet, design an appropriate box culvert. The stream requires 45° wingwalls. The bottom width of the stream measures 15 feet across and therefore a twin 7-foot wide box culvert is chosen. Site conditions require that the culvert be placed on the stream bed. No FALL can be employed.

Note: When no FALL is specified for a design, a short-cut method of analysis is possible. The inlet elevation is stored in register #8 instead of register #5. Also instead of the allowable headwater elevation, a very large number is stored in register #6. By visually comparing the calculated headwater elevations with the allowable value, a box culvert design can be quickly obtained.

Load program #6

KEYSTROKES	DISPLAY	
1000 STO 1	1000.00	
5 STO 2	5.00	Trial height
7 ENTER 2 x STO 3 . .	14.00	
437.5 STO 8	437.50	
10000 STO 6	10000.00	Any number>>ALW EL.
B	448.61	ft. HW EL.

This HW EL. exceeds the AHW EL. Try a 6 foot height.

6 STO 2	6.00	
B	446.98	ft. HW EL.

This HW EL. is within the allowable. A twin 7x6 square top edged box culvert would work.

Try a bevel edged inlet.

Load program #8.

KEYSTROKES	DISPLAY

Note: The width still equals 6 feet from the previous problem.

B . . . . 446.89 ft. HW EL.

This HW EL. is satisfactory. Try a smaller height.

5 STO 2 . . . . 5.00

B . . . . 448.09 ft. HW EL.

This HW EL. is within the allowable. Therefore, a twin 7x5 box culvert with a beveled top edge could be used.

LISTING - PROGRAM #5

LBL A D RCL 6 RCL 5 - g x≤y g x≥y g NOP RCL 6 g x≥y - STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8 - RTN LBL D RCL 1 RCL 3 + RCL 2 ENTER f √x x ÷ ENTER ENTER ENTER 3 4 . 5 6 x 1 3 6 7 . 5 7 - x 2 0 7 8 0 . 9 + x 1 0 8 5 6 0 - x 5 0 5 4 3 5 + x 1 2 2 1 1 7 + 6 f⁻¹ LOG ÷ RCL 2 x RTN (94 STEPS)

LISTING - PROGRAM #6

LBL A D RCL 6 RCL 5 - g x≤y g x≥y g NOP RCL 6 g x≥y - STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8 - RTN LBL D RCL 1 RCL 3 + RCL 2 ENTER f √x x + ENTER ENTER ENTER 3 8 0 x 1 4 8 9 5 . 8 - x 2 2 1 7 0 2 + x 1 1 7 4 7 4 0 - x 5 0 7 0 8 7 0 + x 7 2 4 9 2 7 + 7 f⁻¹ LOG + RCL 2 x RTN (93 STEPS)

LISTING - PROGRAM #7

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y
- STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8
- RTN LBL D RCL 1 RCL 3 + RCL 2 ENTER f √x x +
ENTER ENTER ENTER 1 4 5 . 6 6 x 6 4 4 9 - x 1
1 2 0 1 3 . 5 + x 6 4 0 3 9 2 - x 3 9 8 9
3 5 3 + x 1 5 6 6 0 8 6 + 7 f⁻¹ LOG + RCL 2
x RTN (95 STEPS)

LISTING - PROGRAM #8

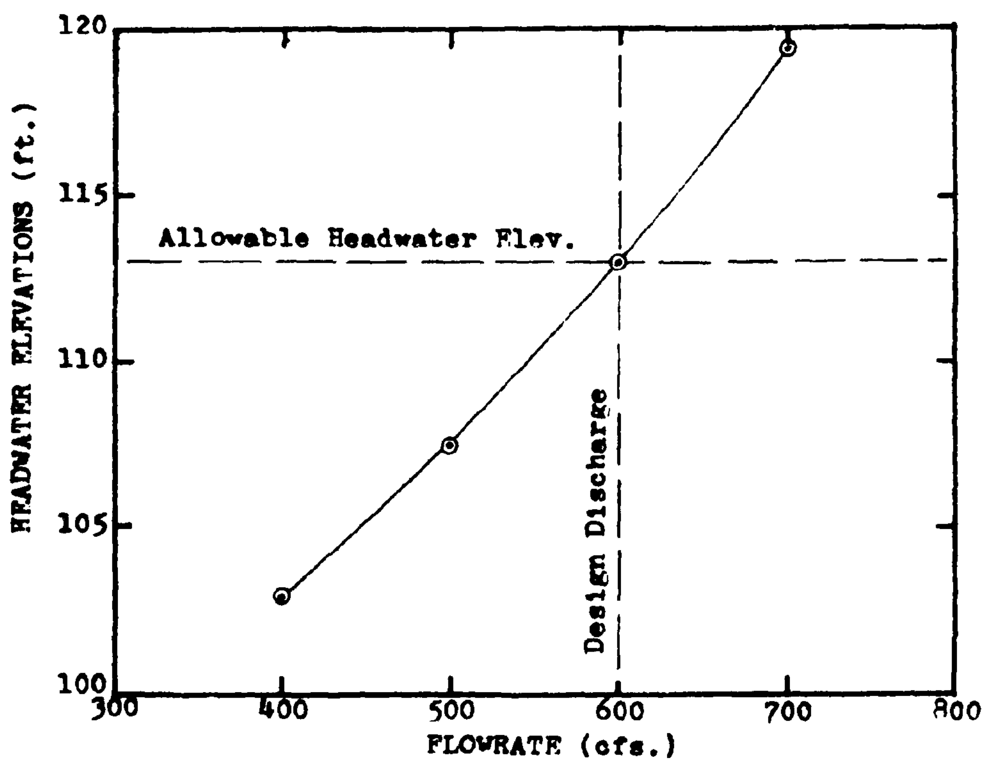
LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y
- STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8
- RTN LBL D RCL 1 RCL 3 + RCL 2 ENTER f √x x ÷
ENTER ENTER ENTER 1 7 7 . 4 x 7 5 8 8 - x 1
2 7 3 1 8 . 3 + x 7 4 3 4 9 8 - x 4 4 1
2 4 6 5 + x 8 9 5 6 3 3 + 7 f⁻¹ LOG + RCL 2
x RTN (93 STEPS)

Plot of the performance of a 5x5 bevel edged box culvert operating in inlet control.

Data taken from Example #2.

Plotting Coordinates

Q	400.00	500.00	600.00	700.00
HW EL.	102.96	107.48	113.00	119.53

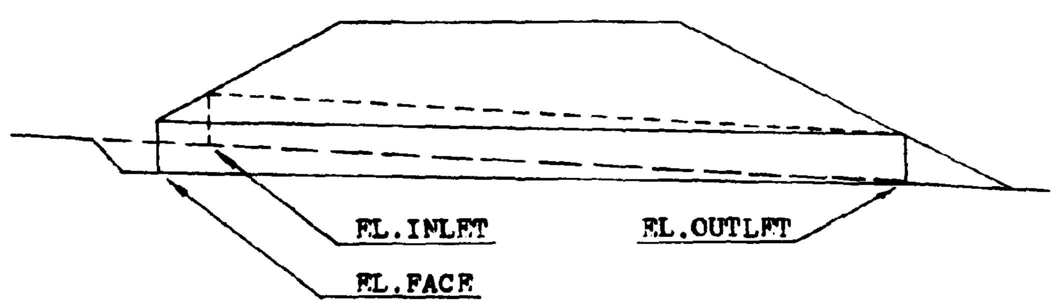


PROGRAM #9 - INLET CONTROL; SLOPE AND LENGTH ADJUSTMENTS

Once a culvert has been designed for inlet control with FALL, an adjustment must be made to the slope and the length of the culvert. The need for an adjustment in the slope of the culvert results from the lowering of the elevation of the culvert inlet while keeping the elevation of the outlet a constant. Since the culvert pivots about the outlet invert, the culvert slope decreases. Since the height of the culvert (D) remains constant, the lowering of the inlet forces the culvert to be lengthened to again intersect the fill slope.

Both box and pipe culverts can be evaluated by this program.

The existing streambed and original culvert are altered to allow for inlet control with FALL. The diagram below depicts the changes.



EQUATIONS

$$ADJ.S = (LS_o - FALL(S_o^2+1)^{.5})/(L+yS_{FU}(S_o^2+1)^{.5})$$

EQUATIONS

$$y = FALL+D((S_o^2+1)^{.5}-(ADJ.S^2+1)^{.5})$$

The equations for ADJ.S and y are solved by trial and error.

$$ADJ.L = ((LS_o/(S_o^2+1)^{.5})-FALL)/(((ADJ.S)^2+1)^{.5}/ADJ.S)$$

The derivations of these equations are found in the appendix.

REMARKS

Since this program does not use the width of the culvert in any of its equations, the program can be applied to multiple barrel applications.

Both the original culvert length (L) and the adjusted culvert length (ADJ.L) are measured along the barrel. They are not horizontal measurements.

In the design of the streambed in front of the entrance to the culvert, the adjusted slope (ADJ.S) should be extended a minimum distance of ½D. The transition slope which connects the stream slope (S_o) to the adjusted culvert slope (ADJ.S) should be established between a 2:1 and a 3:1 ratio. This transition slope is referred to as the FALL slope (S_f). The performance of this weir construction is evaluated in another program.

The adjusted slope value (ADJ.S), Label A, must be determined before the adjusted length (ADJ.L), Label B, can be calculated. No intermediate calculations should be performed between these calculations.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	D	STO 2	D
		S_o	STO 4	S_o
		FALL	STO 5	FALL
		S_{FU}	STO 6	S_{FU}
		L	STO 7	L
3	Calculate adjusted slope		A	ADJ.S
4	Calculate adjusted length		B	ADJ.L
5	For a change in any of the culvert properties, go to step #2 and change only the necessary data.			

EXAMPLE #1

A 6-foot pipe culvert has been designed for inlet control with a FALL of 6.52 feet. The normal channel slope is 5%, and the upstream fill slope is a 3:1 ratio. Early investigations showed that a 349.61 foot culvert should have worked if laid in the streambed. Find the adjusted slope and length of the culvert for the new design conditions.

KEYSTROKES	DISPLAY
6 STO 2	6.00
.05 STO 4	0.05
6.52 STO 5	6.52
3 STO 6	3.00

KEYSTROKES	DISPLAY	
349.61 STO 7	349.61	
A	0.029664	ADJ.S
B	368.91 ft.	ADJ.L

EXAMPLE #2

For a 3x5 box culvert on a 4% slope with 1½ foot of FALL, find the adjusted slope and length. The fill slope is 3:1 and the inlet elevation is 250.00 feet.

KEYSTROKES	DISPLAY	
5 STO 2	5.00	
.04 STO 4	0.04	
1.5 STO 5	1.50	
3 STO 6	3.00	
250 STO 7	250.00	
A	0.033393	ADJ.S
B	254.45 ft.	ADJ.L

LISTING - PROGRAM #9

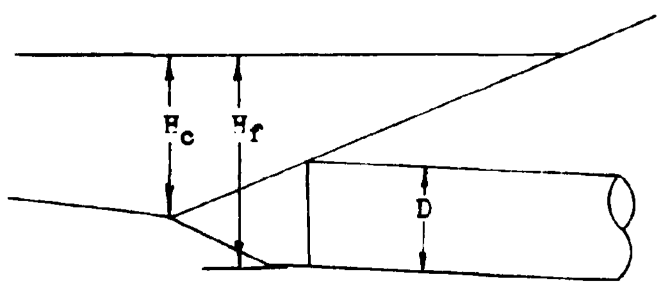
LBL A 1 STO 8 LBL 1 RCL 7 RCL 4 x RCL 4 E RCL 5 x - RCL 4 E RCL 1 x RCL 6 x RCL 7 + + ENTER E RCL 2 CHS x RCL 5 + RCL 4 E RCL 2 x + RCL 1 - 0 g x≷y g x=y GTO 2 RCL 3 g x≷y STO 3 - g x=y GTO 2 RCL 3 RCL 8 x g x≷y + STO 8 STO - 1 GTO 1 LBL B E g x≷y + RCL 7 RCL 4 x RCL 4 E + RCL 5 - x DSP . 2 RTN LBL E ENTER x 1 + f $\sqrt{x}$ RTN LBL 2 g R↓ g R↓ DSP . 6 RTN (95 STEPS)

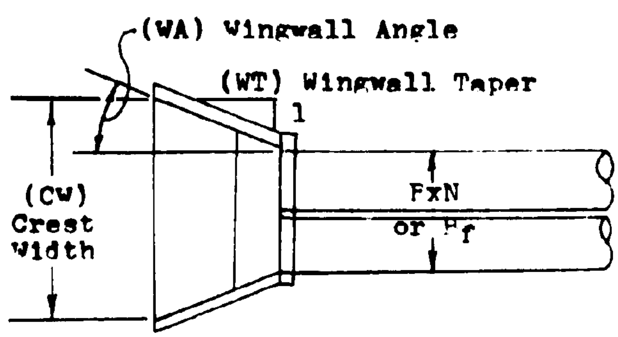
PROGRAM #10 - CREST CONTROL EVALUATION

If not properly designed, the transition section between the streambed and the culvert entrance could adversely affect the operation of the culvert. To insure that the culvert operates in the proper manner, this program computes the required inlet dimensions.

This program is designed to evaluate the crest control dimensions for both box and pipe culverts operating under inlet control and side-tapered throat control.

The diagrams below indicate the dimensions determined by the program.





EQUATIONS

$$H_c = \text{HW EL.} - \text{EL.OUTLET} - \frac{S_o(S_f - \text{ADJ.S})(\frac{1}{2}D + \text{ADJ.L})}{(S_f - S_o)\sqrt{\text{ADJ.S}^2+1}}$$

$$CW = Q/(2H_c)^{1.5}$$

$$WT = (L_o - L/\sqrt{\text{ADJ.S}^2+1})/((CW - BxN)/2)$$

$$WA = 90 - \arctan(WT)$$

The derivations of these equations are found in the appendix.

REMARKS

As mentioned before, this program may be used with either conventional or side-tapered inlet designs. For conventional inlets, the culvert width (B) and the number of barrels (N) are stored together as a product in register #3. When this program is used for side-tapered inlets, the face width (B_f) is stored in register #3 instead or the product BxN.

This program is written in such a manner that the labels must be pressed in an ascending order.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		B	ENTER	B
		N	x STO 3	BxN
		S_o	STO 4	S_o

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
2	Input register values	HW EL.	ENTER	HW EL.
		EL.OUT	- STO 5	HW EL.-EL.OUT
		S_f	STO 6	S_f
		ADJ.L	STO 7	ADJ.L
		ADJ.S	STO 8	ADJ.S
3	Calculate crest height		A	H_c
4	Calculate crest width		B	CW
5	Calculate wingwall taper		C	WT
6	Calculate wingwall angle		D	WA
7	For a change in any of these culvert properties, go to step #2 and reenter ADJ.S and the desired item.			

EXAMPLE #1

What is the recommended wingwall taper to insure inlet control for a flowrate of 850 cfs. through a twin 9x5 box culvert? The channel slope is 0.042 with an adjusted slope of 0.01. The culvert was originally 197 feet long but due to the applied FALL, it has been lengthened to 223 feet. The fill slopes of the roadway cross-section are 2:1 ratios. The outlet elevation is 473.00 feet and the headwater elevation at the face is 488.00 feet. The FALL slope is set at a 2:1 ratio.

KEYSTROKES	DISPLAY
850 STO 1	850.00

KEYSTROKES	DISPLAY		
5 STO 2	5.00		
9 ENTER 2 x STO 3 . . .	18.00		
.042 STO 4	0.04		
488 ENTER 473 - STO 5 .	15.00		
2 STO 6	2.00		
223 STO 7	223.00		
.01 STO 8	0.01		
A	5.37	ft.	H_c
B	24.12	ft.	CW
C	2.02		WT
D	26.32°		WA

Note: Labels A thru D must be used ascendingly for proper crest evaluation.

EXAMPLE #2

A 3-foot diameter pipe culvert with a side-tapered inlet is to be used under a city street. The outlet invert elevation is 115.32 feet and the headwater elevation is 121.85 feet. The side-tapered inlet section has a 4½ foot opening. The culvert is to be laid on a 1% slope where as the stream slope is 3½%. The total length of the culvert is 64 feet. The FALL slope has been chosen at a 3:1 ratio. A design flow-rate of 210 cfs. is expected. Evaluate this culvert and determine the necessary dimensions to insure inlet control.

KEYSTROKES	DISPLAY	
210 STO 1	210.00	
3 STO 2	3.00	
4.5 STO 3	4.50	
.035 STO 4	0.04	
121.85 ENTER 115.32 - STO 5	6.53	
3 STO 6	3.00	
64 STO 7	64.00 *	
.01 STO 8	0.01	
A	4.22 ft.	H_c
B	8.57 ft.	CW
C	1.01	WT
D	44.76°	WA

* Note: When the side-tapered inlet is evaluated with this program, the value stored in register #7 is the total length of the culvert. The total length is comprised of the adjusted length (ADJ.L) and the length of the side-tapered section (L_1).

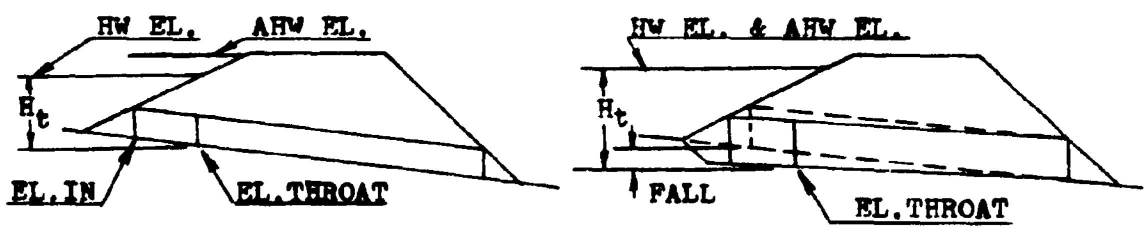
LISTING- PROGRAM #10

LBL A 0 STO 9 RCL 7 E + STO 9 RCL 2 2 + E + +
RCL 6 RCL 8 - x RCL 6 RCL 4 - + STO - 9 RCL 4 CHS
x RCL 5 + RTN LBL B RCL 1 g x≷y 2 x ENTER f √x x
+ RTN LBL C RCL 3 - 2 + RCL 9 CHS + g 1/x 0 g x≤y
g x≷y g NOP RTN LBL D f⁻¹ TAN 9 0 g x≷y - RTN LBL
E RCL 8 ENTER x 1 + f √x RTN (81 STEPS)

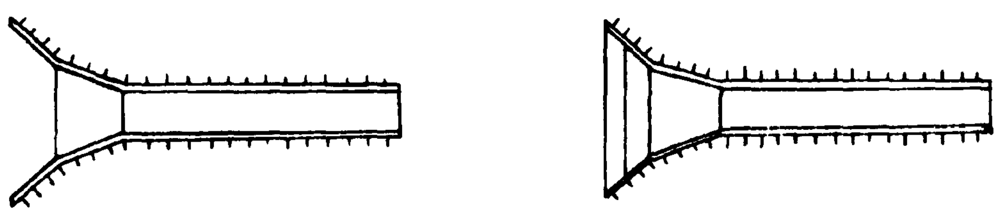
PROGRAM #11 - BOX CULVERT; THROAT CONTROL, TAPERED INLET

Besides improving the face configuration of an inlet, designing a new throat section will also increase a culverts performance.

This program evaluates the performance of a culvert operating in throat control. The formulas from this program can be applied to two different inlet shapes; side tapered and slope tapered. Like the improved inlet programs, throat inlet programs often can use FALL to increase the flow capacity of the culvert. The following diagrams describe the throat control inlets.

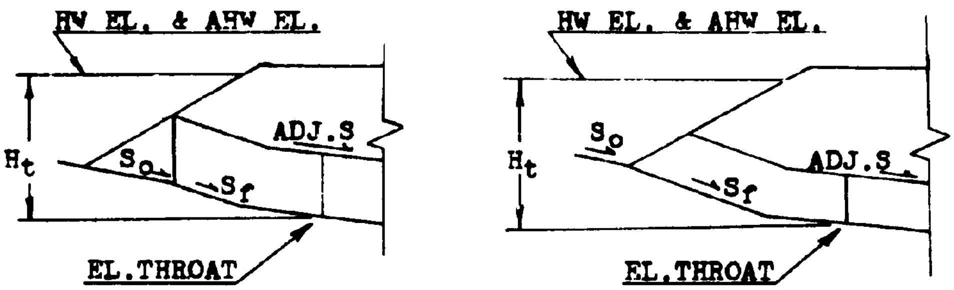


ELEVATION VIEW

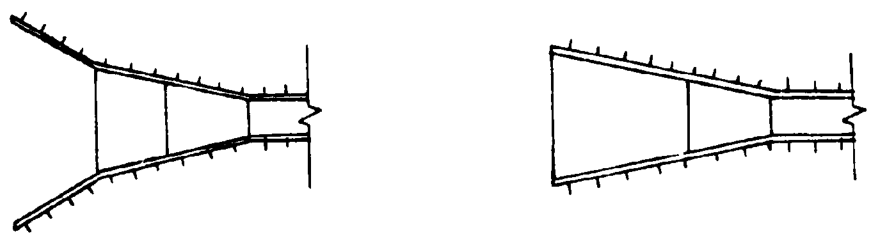


PLAN VIEW

SIDE-TAPERED INLET	SIDE-TAPERED INLET
NO FALL, AHW EL. > HW EL.	WITH FALL, AHW EL. ≤ HW EL.



ELEVATION VIEW



PLAN VIEW

SLOPE-TAPERED INLET VERTICAL FACE

SLOPE-TAPERED INLET MITERED FACE

EQUATIONS

EL.THROAT = AHW EL.$-H_t$ (With FALL)

= EL.INLET (Without FALL)

HW EL. = EL.THROAT$+H_t$

FALL = EL.INLET-EL.THROAT

$$H_t = D(0.1295033+0.3789445X-0.0437778X^2+0.00426329X^3-0.000106358X^4)$$

$$X = Q/(NBD^{1.5})$$

REMARKS

Label A is used during the culvert size determination part of the program. Once a culvert size has been selected, it is put into the calculator and Label A evaluates the appropriate throat elevation for the design flowrate. When using other flowrates during the performance curve evaluation, Label A must not be used.

Since the input registers have the same identity as the ones used for the inlet control programs (5-8), these programs can be run in succession. If all the inlet control programs exceed their maximum limit of FALL (1½D), the designer can immediately load this program and proceed with the culvert design without restoring any of the design values.

Due to the size limitations of this calculator, a small error results in the computation of the FALL. The program assumes that the elevation of the inlet and the elevation of the throat are equal before determining the value of the headwater elevation. This equality is false and a small difference, equal to the channel slope times the vertical distance between the inlet and the throat section ($S_o x L_1$), exists. This L_1 distance is an unknown in this program. It is determined by program #12. By understanding this error, a correction, if necessary, can be made.

The limits placed on the FALL value earlier, still apply. A minimum value of ¼D and a maximum value of 1½D. If the upper limit is exceeded, a larger culvert size should by tried. If the minimum value is exceeded, the presence of FALL will not increase the capacity of the culvert.

A polynomial best-fit equation is used to determine the headwater depths for these inlets. Since the equation is an approximation for the curves in HEC #13, it is subject to the same restrictions. The headwater depth (H_t) is limited to 4½D and not less than ½D. It is recommended that the value of H_t be kept around a value of 2D.

For the program to operate properly, the culvert width (B) and the number of barrels (N) are stored together as a product in register #3.

The number of barrels (N) is limited to a value of 1 or 2.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		B	Enter	B
		N	x STO 3	BxN
		EL.IN	STO 5	EL.IN
		AHW EL.	STO 6	AHW EL.
3	Calculate throat elevation		A	EL.THR
4	Calculate headwater elevation		B	HW EL.
5	Calculate the FALL		C	FALL
6	Calculate headwater depth		D	H_t
7	For a change in any of these culvert properties, go to step #2 and change only the necessary items.			

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
8	To obtain the performance curve coordinates, input the selected flowrates in register #1 and press Label B to obtain the headwater elevations. Note: Label A must not be used during the performance curve evaluation.			
9	To evaluate another inlet, load the required program card and go to step #3.			

EXAMPLE #1

Evaluate the throat control performance of a 3x3 box culvert with a flowrate of 150 cfs. The inlet elevation is 120 feet and the allowable headwater elevation is 124 feet.

KEYSTROKES	DISPLAY	
150 STO 1	150.00	
3 STO 2	3.00	
STO 3	3.00	
120 STO 5	120.00	
124 STO 6	124.00	
A	116.17 ft.	EL.THROAT
B	124.00 ft.	HW EL.
C	3.83 ft.	FALL
D	7.83 ft.	H_t

The culvert size is satisfactory since both the FALL and the headwater depth are within their allowable ranges.

A range of flowrates around the design value, are used to obtain the performance curve coordinates.

KEYSTROKES	DISPLAY	
90 STO 1	90.00	
B	120.85 ft.	HW EL. @ 0.6Q
120 STO 1	120.00	
B	122.24 ft.	HW EL. @ 0.8Q
180 STO 1	180.00	
B	126.20 ft.	HW EL. @ 1.2Q

LISTING - PROGRAM #11

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y - STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8 - RTN LBL D RCL 1 RCL 3 ÷ RCL 2 ENTER f √x x ÷ ENTER ENTER ENTER 1 0 6 3 . 5 8 CHS x 4 2 6 3 2 . 9 + x 4 3 7 7 7 8 - x 3 7 8 9 4 4 5 + x 1 2 9 5 0 3 3 + 7 f⁻¹ LOG ÷ RCL 2 x RTN

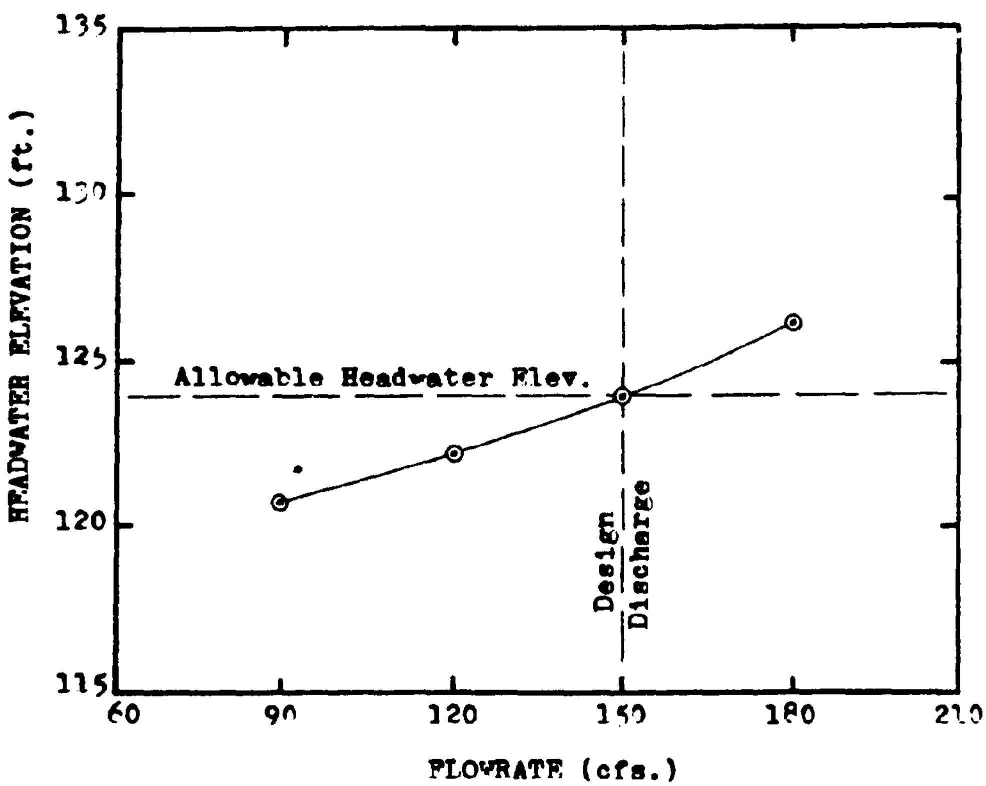
(90 STEPS)

Plot of the performance curve of a 3x3 box culvert operating in throat control.

Data taken from Example #1.

Plotting Coordinates

Q	90.00	120.00	150.00	180.00
HW EL.	120.85	122.24	124.00	126.20



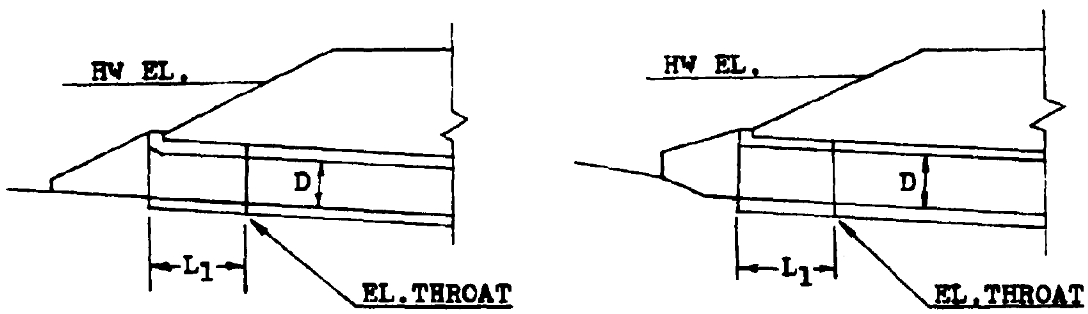
PROGRAMS #12 & #13 - BOX CULVERTS; FACE DIMENSIONS

SIDE-TAPERED INLET WITH SQUARE EDGES

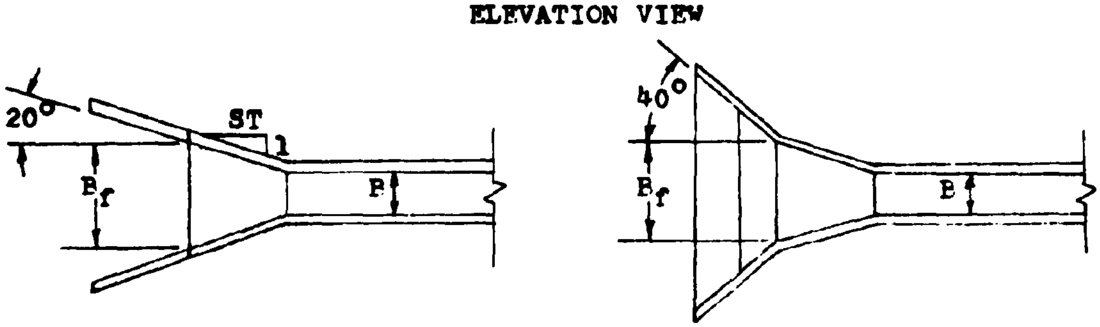
SIDE-TAPERED INLET WITH BEVELED EDGES

These programs continue with the design of a culvert operating in throat control. For a side-tapered entrance, these programs compute the face width (B_f) and the horizontal distance between the entrance and the throat control section (L_1).

Program #12 deals with square edged inlets. Inlets with wingwall flare angles from 15° to 26° with a top beveled edge, or inlets with wingwall flare angles from 26° to 90° with all edges squared. These inlets can be seen graphically below.



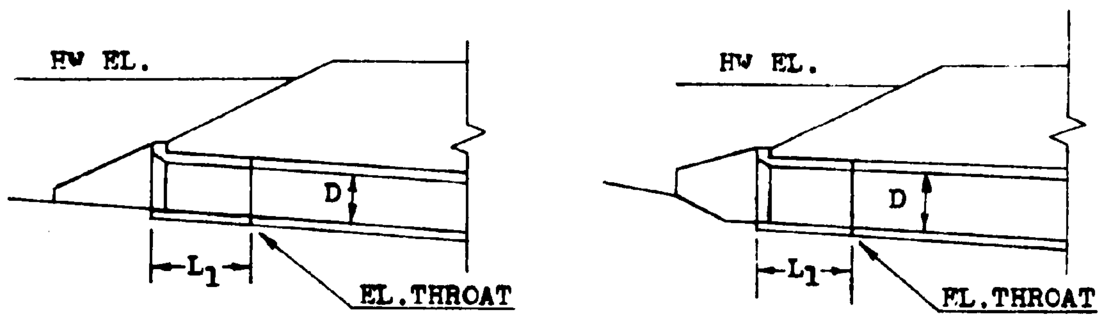
ELEVATION VIEW



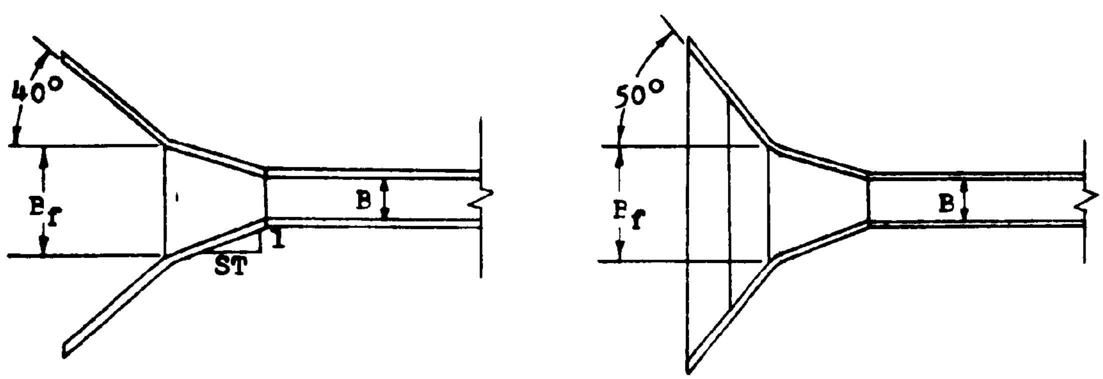
PLAN VIEW

15° to 26° Wingwall Flare	26° to 90° Wingwall Flare
Top Edge Beveled - No FALL	All Edges Square - With FALL

The bevel edged program, #13, pertains to inlets with wing-wall flare angles of 26° to 45° with top edges beveled, and to inlets with wingwall flare angles of 45° to 90° with both top and side edges beveled. For further details, refer to the diagrams below.



ELEVATION VIEW



PLAN VIEW

26° to 45° Wingwall Flare	45° to 90° Wingwall Flare
Top Edge Beveled - No FALL	Top and Sides Beveled - FALL

The determination of B_f and L_1 is a lengthy computation which exceeds the capacity of the HP-65 calculator. An extra program card is needed to complete these calculations. Programs #12 and #13 compute B_f and L_1 but one of the inputs for these calculations, the adjusted slope, is not determined until program #14. Correspondingly, program #14 needs the L_1 value of programs #12 and #13, to complete its evaluation of ADJ.S.

The method used to solve this dilemma is to alternately use either programs #12 and #14 or programs #13 and #14, several times until the values of B_f, L_1, and ADJ.S stabilize. This stabilization of values usually only takes two or three cycles.

For the initial calculation of B_f and L_1, the adjusted slope value is approximated by using the channel slope or a number slightly smaller.

Where prefabricated inlet sections are available, B_f and L_1 have usually been set by the manufacturing company. These values are normally fixed at 1½ times the culvert depth. If this type of design is desired, the given values of B_f and L_1 can be used in lieu of programs #12 and #13. The value of L_1 can be directly used in program #14.

EQUATIONS

$$L_1 = ((B_f - B \times N)/2)ST$$

$$H_f = \text{HW EL.} - \text{FL.THROAT} - L_1(\text{ADJ.S}) = H_t - L_1(\text{ADJ.S})$$

$$X = H_f/D$$

Program #12

$$B_f = Q/(D^{1.5}(-1.219+4.3X-0.6153X^2+0.0273X^3+0.0027X^4))$$

EQUATIONS (cont)

Program #13

$$B_f = Q/(D^{1.5}(-1.13607+3.69853X+0.12128X^2-0.205339X^3 +0.0256923X^4))$$

REMARKS

The product of the culvert width (B) and the number of barrels (N) is stored in register #3.

The number of culvert barrels (N), should be limited to a value of one or two.

As mentioned before, for the initial value of the adjusted slope (ADJ.S), the original channel slope (S_o) should be used as an approximation. This value is stored in register #4.

The sidewall taper (ST) chosen for the culvert inlet is limited to a value between a 4:1 and a 6:1 ratio. Values less than 4:1 are unacceptable and will not operate as side-tapered inlets. Values greater than 6:1 will perform better than the design will indicate. Therefore with this larger value, the design will be conservative.

The value for L_1 determined by these programs is a horizontal measurement. As compared with L or ADJ.L which are measured along the culvert barrel.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		B	ENTER	B
		N	x STO 3	BxN
	Initially use S_o	ADJ.S	STO 4	ADJ.S
		H_t	STO 5	H_t
		ST	STO 6	ST
3	Calculate the face width		A	B_f
4	Calculate the inlet length		B	L_1
5	Run program #14			
6	Repeat steps #2, #3, #4, and #5 until the values of B_f and L_1 stabilize.			

EXAMPLE #1

In designing a 7x6 box culvert for a Q_{50} of 1000 cfs., the throat elevation was determined to be 181.75 feet. The head-water elevation was 205 feet. If a 4:1 side taper is chosen, what is the face width and the length of the side-tapered inlet? The natural channel slope is 5%, and the inlet is to have square edges. The headwater depth at the throat section is 23.25 feet.

Load program #12

KEYSTROKES	DISPLAY
1000 STO 1	1000.00
6 STO 2	6.00

KEYSTROKES	DISPLAY
7 STO 3	7.00
.05 STO 4	0.05
23.25 STO 5	23.25
4 STO 6	4.00
A	8.12 ft. B_f
B	2.25 ft. L_1

Using L_1 in program #14, ADJ.S is calculated to be 0.029816

1000 STO 1	1000.00
6 STO 2	6.00
7 STO 3	7.00
.029816 STO 4	0.03
23.25 STO 5	23.25
4 STO 6	4.00
A	8.11 ft. B_f
B	2.23 ft. L_1

From program #14; the ADJ.S = 0.029814

1000 STO 1	1000.00
6 STO 2	6.00
7 STO 3	7.00
.029814 STO 4	0.03
23.25 STO 5	23.25
4 STO 6	4.00
A	8.11 ft. B_f
B	2.23 ft. L_1

B_f and L_1 stabilized after two trials.

EXAMPLE #2

Design the same inlet only using the bevel edged program.

Load program #13

KEYSTROKES	DISPLAY	
1000 STO 1	1000.00	
6 STO 2	6.00	
7 STO 3	7.00	
.029814 STO 4	0.03	
23.25 STO 5	23.25	
4 STO 6	4.00	
A	7.68 ft.	B_f
B	1.36 ft.	L_1

From program #14; the ADJ.S = 0.029734

1000 STO 1	1000.00	
6 STO 2	6.00	
7 STO 3	7.00	
.029734 STO 4	0.03	
23.25 STO 5	23.25	
4 STO 6	4.00	
A	7.68 ft.	B_f
B	1.36 ft.	L_1

As in the previous example, the values of B_f and L_1 stabilized rapidly.

LISTING - PROGRAM #12

LBL A 1 LBL 1 CHS RCL 5 + RCL 2 ÷ ENTER ENTER ENTER
. 0 0 2 7 x . 0 2 7 3 + x . 6 1 5 3 - x 4
. 3 + x 1 . 2 1 9 - RCL 1 g x≷y + RCL 2 ENTER f
$\sqrt{x}$ x + 3 f^{-1} LOG x f INT 3 f^{-1} LOG + RCL 9 g x≷y
g x=y GTO 2 RCL 3 - 2 + RCL 6 x STO 8 RCL 4 x GTO 1
LBL B RCL 8 RTN LBL 2 DSP . 2 RCL 3 g x≤y g x≷y
RTN 0 STO 8 RCL 3 RTN (97 STEPS)

LISTING - PROGRAM #13

LBL A 1 LBL 1 CHS RCL 5 + RCL 2 ÷ ENTER ENTER ENTER
. 0 2 5 6 9 x . 2 0 5 3 - x . 1 2 1 3 + x
3 . 6 9 9 + x 1 . 1 3 6 - RCL 1 g x≷y + RCL 2
ENTER f $\sqrt{x}$ x ÷ 3 f^{-1} LOG x f INT 3 f^{-1} LOG + RCL
9 g x≷y g x=y GTO 2 RCL 3 - 2 ÷ RCL 6 x STO 8 RCL 4
x GTO 1 LBL B RCL 8 RTN LBL 2 DSP . 2 RCL 3 g x≤y
g x≷y RTN 0 STO 8 RCL 3 RTN (100 STEPS)

PROGRAM #14 - SLOPE ADJUSTMENT FOR SIDE-TAPERED INLETS

This program calculates the adjusted slope of a culvert which has been designed with a side-tapered inlet with FALL. A complex equation results from solving the geometry of the culvert rotation. The calculator solves this equation by a trial and error method.

As mentioned in other programs, the computation of the adjusted slope (ADJ.S) requires the length of the side-tapered inlet. The small size of the HP-65's program storage, requires that this length be determined in other programs. For box culverts the side-tapered inlet length (L_1) is determined by programs #12 or #13. For pipe culverts, this length is calculated by programs #36, #37, or #38. By alternately using the values of ADJ.S and L_1, the correct values can be found.

The value of L_1 to be used in this program, must be a horizontal measurement. If a prefabricated inlet section is used, care must be taken to not use the manufactures inlet length. This length must be adjusted by setting the inlet on the channel slope and figuring the inplace horizontal length.

EQUATIONS

$$0 = (\text{FALL}+D(S_o^2+1)^{.5}-D(\text{ADJ.S}^2+1)^{.5}-\text{ADJ.S}L_1)(S_{FU}(S_o^2+1)^{.5}\text{ADJ.S})$$
$$-S_oL+\text{FALL}(S_o^2+1)^{.5}-L_1\text{ADJ.S}\,(S_o^2+1)^{.5}+L\text{ADJ.S}$$

ADJ.S is solved by a trial and error method.

The derivation of this equation is found in the appendix.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	D	STO 2	D
		S_o	STO 4	S_o
		FALL	STO 5	FALL
		S_{FU}	STO 6	S_{FU}
		L	STO 7	L
		L_1	STO 8	L_1
3	Calculate adjusted slope		A	ADJ.S
4	For a change in any of these properties after the program has been, the culvert height (D) must be restored along with the desired value to be changed.			
5	If necessary, reuse program #12, #13, #36, #37, or #38.			
6	Repeat steps #2, #3 and #5 until B_f, L_1, and ADJ.S stabilize.			

EXAMPLE #1

Find the adjusted slope for a side-tapered, 7x6 box culvert with 6.25 feet of FALL. The culvert is 325 feet long with an upstream fill slope of 2:1. The channel slope is 5% and the initial value of the horizontal inlet length is 2.25 feet.

KEYSTROKES	DISPLAY
6 STO 2	6.00

KEYSTROKES	DISPLAY
.05 STO 4	0.05
6.25 STO 5	6.25
2 STO 6	2.00
325 STO 7	325.00
2.25 STO 8	2.25
A	0.029816 ADJ.S

Using this value of ADJ.S in program #12, L_1 = 2.23 ft.

6 STO 2	6.00
.05 STO 4	0.05
6.25 STO 5	6.25
2 STO 6	2.00
325 STO 7	325.00
2.23 STO 8	2.23
A	0.029814 ADJ.S

LISTING - PROGRAM #14

LBL A RCL 2 1 STO 1 STO 3 DSP . 6 LBL 1 g R↓ RCL 4
F RCL 3 F - x RCL 5 + RCL 3 RCL 8 x - RCL 4 F
RCL 6 x x RCL 3 x RCL 4 RCL 7 x - RCL 4 F RCL 5
x + RCL 4 F RCL 3 x RCL 8 x - RCL 7 RCL 3 x +
0 g x≷y g x=y RCL 3 RTN RCL 1 g x≷y STO 1 - g x=y
RCL 3 RTN g R↑ g x≷y RCL 1 RCL 2 x g x≷y + 6 f^{-1}
LOG x f INT 6 f^{-1} LOG + STO 2 STO + 3 GTO 1 LBL
F ENTER x 1 + f $\sqrt{x}$ RTN (95 STEPS)

PROGRAM #15 - LENGTH ADJUSTMENT, SIDE-TAPERED INLETS

When a culvert is improved with a side-tapered inlet, the length of the culvert barrel is affected. If the new inlet is designed with FALL, the barrel length will increase due to the rotation of the culvert. It will also be shortened by the addition of the inlet section. If no FALL is applied, the original culvert length will be shortened by the length of the inlet. Program #15 computes these changes and corrects the culvert length accordingly.

With the change in culvert length, the elevation of the face of the improved inlet may also be affected. This calculation is also handled by program #15.

EQUATIONS

$$\text{ADJ.L} = (S_oL/(S_o^2+1)^{.5}-\text{FALL})((\text{ADJ.S}^2+1)^{.5}/\text{ADJ.S})-L_1(\text{ADJ.S}^2+1)^{.5}$$

$$\text{EL.FACE} = \text{EL.THROAT}+L_1\text{ADJ.S}$$

The derivations for these equations can be found in the appendix.

REMARKS

The length of the inlet (L_1) to be used by this program must be a horizontal distance.

The adjusted length, on the other hand, is measured along the culvert barrel. As mentioned in the paragraph above, the adjusted length does not include the length of the improved inlet.

This program can be used with either box or pipe culverts.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	FL.THR	STO 1	FL.THROAT
		ADJ.S	STO 3	ADJ.S
		S_o	STO 4	S_o
		FALL	STO 5	FALL
		L	STO 7	L
		L_1	STO 8	L_1
3	Calculate adjusted length		A	ADJ.L
4	Calculate face elevation		B	EL.FACE
5	For a change in any of these channel variables, go to step #2 and change the necessary data.			

EXAMPLE #1

Determine the adjusted length and the face invert elevation for a box culvert with the following conditions. The culvert slope has been adjusted from 3.2% to 1.79%. The required channel FALL is 4.23 feet and the horizontal length of the inlet is 9.8 feet. The elevation of the throat is 346.78 feet and the original culvert length is 352 feet.

KEYSTROKES	DISPLAY
346.78 STO 1	346.78
.0179 STO 3	0.02
.032 STO 4	0.03

KEYSTROKES	DISPLAY
4.23 STO 5	4.23
352 STO 7	352.00
9.8 STO 8	9.80
A	382.90 ft. ADJ.L
B	346.96 ft. EL.FACE

EXAMPLE #2

A larger side-tapered culvert is to be used in the previous example. This new size eliminates the FALL. Determine the adjusted length and the face elevation. Since there is no FALL, the adjusted slope value should be set equal to the original channel slope.

KEYSTROKES	DISPLAY
0 STO 5	0.00
RCL 4 STO 3	0.03
A	342.19 ft. ADJ.L
B	347.09 ft. EL.FACE

LISTING - PROGRAM #15

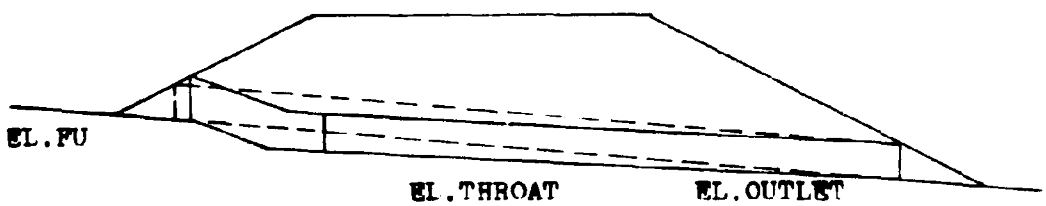
LBL A RCL 7 RCL 4 x RCL 4 E + RCL 5 - RCL 3 E x RCL 3 + RCL 3 F RCL 8 x - DSP . 2 RTN LBL B RCL 1 RCL 3 RCL 8 x + RTN LBL E ENTER x 1 + f $\sqrt{x}$ RTN (41 STEPS)

PROGRAMS #16 & #17 - SLOPE ADJUSTMENTS

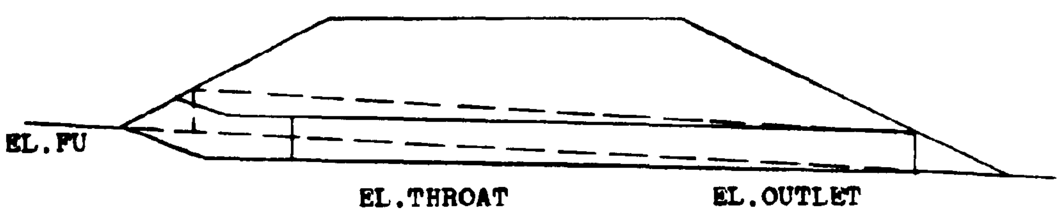
SLOPE-TAPERED INLET WITH VERTICAL FACE

SLOPE-TAPERED INLET WITH MITERED FACE

When an improved inlet incorporates FALL in the design, the culvert slope is altered and must be recalculated. Program #16 analyzes the inlet geometry and determines the adjusted slope for a slope-tapered, vertical face inlet. Program #17 solves for the adjusted slope of a slope-tapered, mitered face inlet. The diagrams below show the difference between these two inlet configurations.



SLOPE-TAPERED, VERTICAL FACE INLET



SLOPE-TAPERED, MITERED FACE INLET

These programs can be used with either box or pipe culverts.

EQUATIONS

PROGRAM #16

$$0 = EL.FU+(D(S_f^2+1)^{.5}(S_{FU}+S_f))/((S_{FU}S_o+1)(S_f^2))+L_3/S_f$$
$$+(EL.OUT-EL.FU)/(S_oS_f)+(EL.THR-EL.OUT)/(S_fADJ.S)$$
$$-L_3ADJ.S-D(ADJ.S^2+1)^{.5}-EL.THROAT$$

PROGRAM #17

$$0 = EL.FU+(D(S_f^2+1)^{.5}/S_f)+L_3/S_f+(EL.OUT-EL.FU)/(S_oS_f)$$
$$+(EL.THR-EL.OUT)/(S_fADJ.S)-L_3ADJ.S-D(ADJ.S^2+1)^{.5}$$
$$-EL.THROAT$$

These two equations are solved by a trial and error method.

Their derivations can be found in the appendix.

REMARKS

The value of L_3 is not calculated but is usually set equal to one-half the culvert width (B/2). Values slightly larger than B/2 may be used, but smaller values are not recommended.

In operating these programs, the values stored in registers #4, #6, #7, #8, and #9 are removed during the calculations of the adjusted slope. If the particular program is to be immediately reused, these register values must first be restored.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	D	STO 2	D
		L_3	STO 3	L_3

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
2	Input register values	S_o	STO 4	S_o
		EL.OUT	STO 5	EL.OUT
		S_{FU}	STO 6	S_{FU}
		EL.FU	STO 7	EL.FU
		S_f	STO 8	S_f
		EL.THR	STO 9	EL.THR
3	Calculate adjusted slope		A	ADJ.S
4	To change any of the channel variables go to step #2, reenter that value plus S_o, S_{FU}, EL.FU, S_f, and EL.THR.			

EXAMPLE #1

Determine the adjusted slope for a slope-tapered, vertical face inlet with the following site conditions. The culvert is a 5x4 box, with an outlet elevation of 102.00 feet, a throat elevation of 118.50 feet, and a channel slope of 5%. The upstream fill slope is on a 3:1 ratio and intersects the streambed at elevation 125.00 feet. The face slope has been set at a 3:1 ratio.

Load Program #16

KEYSTROKES	DISPLAY
4 STO 2	4.00
5 ENTER 2 + STO 3 . . .	2.50

KEYSTROKES	DISPLAY	
.05 STO 4	0.05	
102 STO 5	102.00	
3 STO 6	3.00	
125 STO 7	125.00	
3 STO 8	3.00	
118.5 STO 9	118.50	
A	0.038524	ADJ.S

EXAMPLE #2

Evaluate the same site conditions for a mitered face, 60-inch pipe culvert.

Load Program #17

KEYSTROKES	DISPLAY	
60 ENTER 12 ÷ STO 2 . .	5.00	
2 ÷ STO 3	2.50	
.05 STO 4	0.05	
102 STO 5	102.00	
3 STO 6	3.00	
STO 8	3.00	
125 STO 7	125.00	
118.5 STO 9	118.50	
A	0.037716	ADJ.S

LISTING - PROGRAM #16

```
LBL  A  RCL 2  RCL 8  ENTER  x  1  +  f  √x  x  RCL 8  RCL 6
RCL 4  x  1  +  x  +  RCL 6  RCL 8  +  RCL 8  +  x  RCL 7  +
RCL  9  -  RCL 3  RCL 8  +  +  RCL 5  RCL 7  -  RCL 8  +  RCL 4
STO 7  STO 1  STO 6  +  +  STO 4  RCL  9  RCL 5  -  RCL 8  ÷
STO 8  DSP  .  6  LBL  1  RCL 2  RCL 1  ENTER  x  1  +  f  √x
x  RCL 3  RCL 1  x  +  RCL 8  RCL 1  ÷  -  RCL 4  -  0  g x≷y
g x=y  RCL 1  RTN  RCL 7  g x≷y  STO 7  -  g x=y  RCL 1  RTN
RCL 7  RCL 6  x  g x≷y  +  STO 6  STO  +  1  GTO 1  (100 STEPS)
```

LISTING - PROGRAM #17

```
LBL  A  RCL 2  RCL 8  ENTER  x  1  +  f  √x  x  RCL 8  +  RCL 7
+  RCL  9  -  RCL 3  RCL 8  ÷  +  RCL 5  RCL 7  -  RCL 8  +
RCL 4  STO 7  STO 1  STO 6  +  +  STO 4  RCL  9  RCL 5  -  RCL 8
÷  STO 8  DSP  .  6  LBL  1  RCL 2  RCL 1  ENTER  x  1  +  f  √x
x  RCL 3  RCL 1  x  +  RCL 8  RCL 1  ÷  -  RCL 4  -  0  g x≷y
g x=y  RCL 1  RTN  RCL 7  g x≷y  STO 7  -  g x=y  RCL 1  RTN
RCL 7  RCL 6  x  g x≷y  +  STO 6  STO  +  1  GTO  1  (88 STEPS)
```

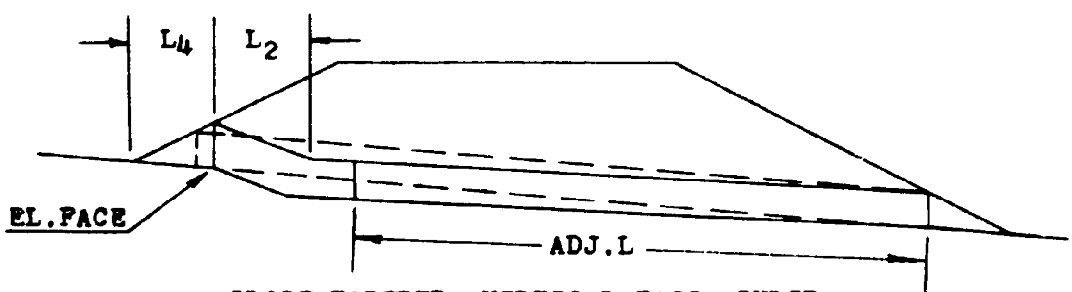
PROGRAMS #18 & #19 - INLET DIMENSIONS

SLOPE-TAPERED INLET WITH VERTICAL FACE

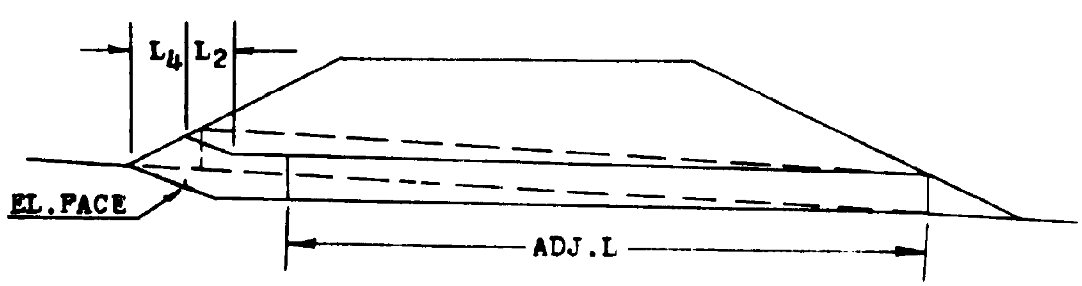
SLOPE-TAPERED INLET WITH MITERED FACE

In order to complete the design of the slope-tapered inlet, several inlet dimensions are required. Programs #18 and #19 calculate these values for the vertical face inlet and the mitered face inlet respectively.

Since the slope of the original culvert has been lowered, the original culvert length will be affected. The programs determine a new adjusted culvert length. The invert elevation of the face of the culvert is also determined by these programs. Two critical inlet lengths are also solved by these programs. The location of these values can be seen in the diagrams below.



SLOPE-TAPERED, VERTICAL FACE INLET



SLOPE-TAPERED, MITERED FACE INLET

These programs can be applied to either box or pipe culvert situations.

It should be noted that even though the face elevation is calculated by program #19, for the mitered face inlet, there is no break in the culvert slope to mark this elevation.

EQUATIONS

PROGRAM #18

$$EL.FACE = EL.FU - L_4 S_o$$

$$L_4 = S_{FU} D (S_f^2+1)^{.5} / (S_f (S_o S_{FU}+1))$$

PROGRAM #19

$$EL.FACE = EL.FU - L_4 / S_f$$

$$L_4 = S_{FU} D (S_f^2+1)^{.5} / (S_{FU}+S_f)$$

BOTH

$$L_2 = (EL.FU-EL.OUT)/S_o - L_4 - L_3 - (EL.THR-EL.OUT)/ADJ.S$$

$$ADJ.L = (EL.THR-EL.OUT)(ADJ.S^2+1)^{.5}/ADJ.S$$

The derivations of these equations can be found in the appendix.

REMARKS

The adjusted length value (ADJ.L) is measured along the culvert and does not include the length of the improved inlet.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
2	Input register values	ADJ.S	STO 1	ADJ.S
		D	STO 2	D
		L_3	STO 3	L_3
		S_o	STO 4	S_o
		EL.OUT	STO 5	EL.OUT
		S_{FU}	STO 6	S_{FU}
		EL.FU	STO 7	EL.FU
		S_f	STO 8	S_f
		EL.THR	STO 9	EL.THR
3	Calculate face elevation		A	EL.FACE
	Calculate L_4		B	L_4
	Calculate L_2		C	L_2
	Calculate adjusted length		D	ADJ.L
4	For a change in any of these values go to step #2 and reenter only the necessary value.			

EXAMPLE #1

Determine the inlet dimensions for a vertical face , slope-tapered culvert with the following characteristics. Original channel slope is 6.2% and after the improved inlet evaluation, the slope has been adjusted to 4.42%. The culvert is a 5x4 box, with an upstream fill slope of 3:1 and an inlet face slope of 2:1. The throat elevation is 117.00 feet, the outlet elevation is 105.40 feet, and the upstream fill catch-point elevation is 124.10 feet.

KEYSTROKES	DISPLAY
.0442 STO 1	0.04
4 STO 2	4.00
5 ENTER 2 ÷ STO 3 . . .	2.50
.062 STO 4	0.06
105.4 STO 5	105.40
3 STO 6	3.00
124.1 STO 7	124.10
2 STO 8	2.00
117 STO 9	117.00

Load Program #18

A	123.40	ft.	EL.FACE
B	11.31	ft.	L_4
C	25.36	ft.	L_2
D	262.70	ft.	ADJ.L

EXAMPLE 42

Evaluate the same site conditions for the mitered face inlet.

Load Program #19

A	121.42	ft.	EL.FACE
B	5.37	ft.	L_4
C	31.30	ft.	L_2
D	262.70	ft.	ADJ.L

LISTING - PROGRAM #18

LBL A DSP . 2 B RCL 4 x RCL 7 g x≷y - RTN LBL B
RCL 2 RCL 8 ENTER x 1 + f √x x RCL 8 + RCL 4 RCL 6
g 1/x + + RTN LBL C RCL 7 RCL 5 - RCL 4 + B -
RCL 3 - RCL 9 RCL 5 - RCL 1 + - RTN LBL D RCL 9
RCL 5 - RCL 1 ENTER x 1 + f √x x RCL 1 + RTN
(69 STEPS)

LISTING - PROGRAM #19

LBL A DSP . 2 B RCL 8 + RCL 7 g x≷y - RTN LBL B
RCL 2 RCL 6 x RCL 8 ENTER x 1 + f √x x RCL 6 RCL 8
+ + RTN LBL C RCL 7 RCL 5 - RCL 4 + B - RCL 3 -
RCL 9 RCL 5 - RCL 1 + - RTN LBL D RCL 9 RCL 5 -
RCL 1 ENTER x 1 + f √x x RCL 1 + RTN (66 STEPS)

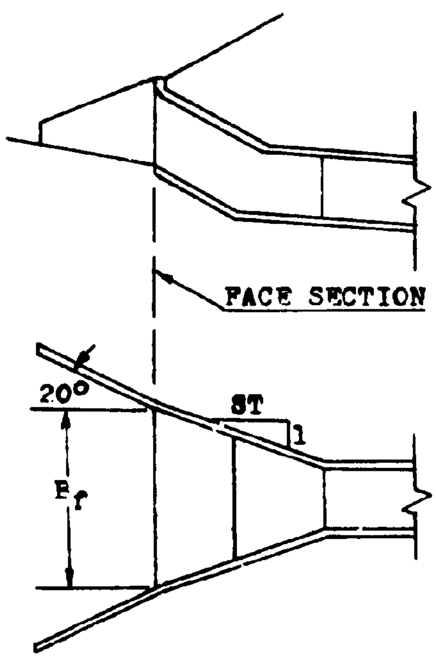
PROGRAMS #20 & #21 - FACE DIMENSIONS

SLOPE-TAPERED INLET WITH SQUARE EDGES

SLOPE-TAPERED INLET WITH BEVELED EDGES

These programs continue with the design of a culvert operating in throat control. For a slope-tapered inlet, these programs compute the face width of the improved inlet (B_f), and the taper of the inlet's sidewall (ST).

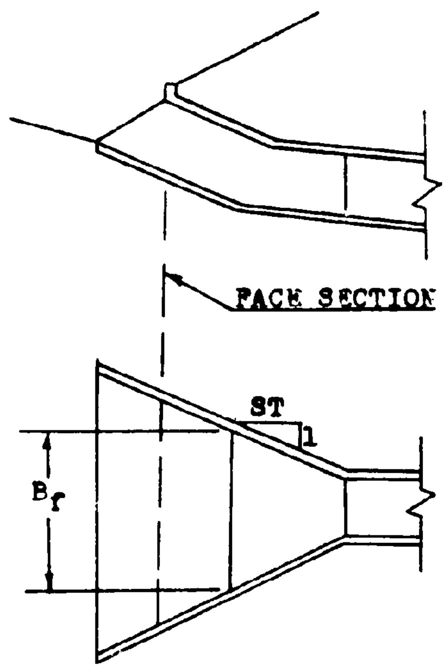
Program #20 deals with square edged inlets. Inlets in this catagory have wingwall flare angles from 15° to 26° with a top beveled edge, or inlets with wingwall flare angles from 26° to 90° with all squared edges. These inlets can be seen graphically below.



VERTICAL FACE

15° to 26° Wingwall Flare

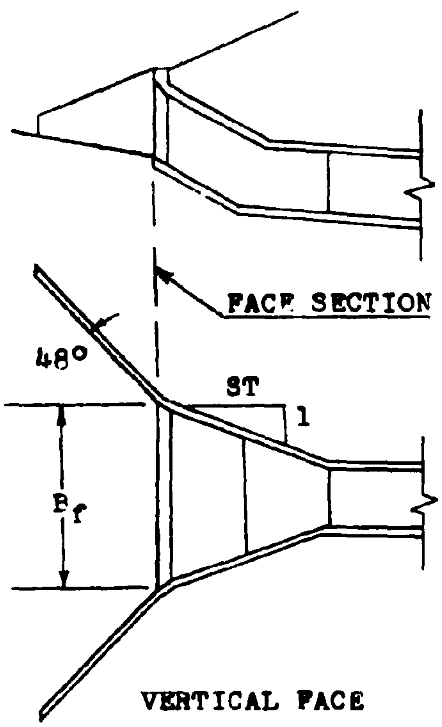
Top Edge Beveled



MITERED FACE

All Edges Squared

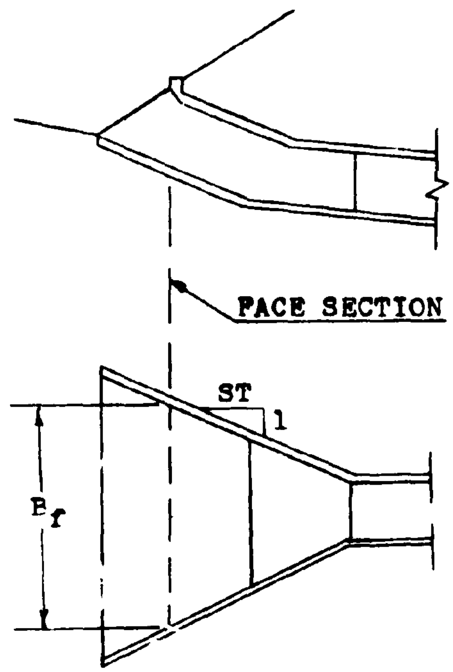
The bevel edged program, #21, pertains to inlets with wing-wall flare angles of 26° to 45° with their top edges beveled, and to inlets with wingwall flare angles from 45° to 90° with both top and side edges beveled. For further inlet descriptions refer to the diagrams below.



VERTICAL FACE

45° to 90° Wingwall Flare

Both Top and Side Edges Beveled



MITERED FACE

Top Edge Beveled

As can be noted from the diagrams, these programs can be applied to either vertical or mitered face inlets. Since the mitered face inlet generally has no wingwalls, the distinction between the use of these two programs as they pertain to the mitered inlet is whether the top edge is to be beveled or squared.

The bevel to be applied to the face section can be either a 1:1 bevel or a 1½:1 bevel.

These programs can be applied to either box or pipe culverts.

EQUATIONS

Program #20

$$B_f = Q/(D^{1.5}(-1.353+5.15X-1.131X^2+0.1578X^3-0.0144X^4 +0.0011X^5))$$

Program #21

$$B_f = Q/(D^{1.5}(-2.265863+7.942441X-4.0350294X^2+1.619481X^3 -0.3458214X^4+0.02846767X^5))$$

Both

$$X = (HW\ EL.-EL.FACE)/D$$

$$ST = (L_2+L_3)/((B_f-BxN)/2)$$

REMARKS

The value of L_3 is not calculated but is usually set equal to one-half the culvert width (B/2). Values slightly larger than B/2 may be used, but smaller values are not recommended.

The culvert width (B) and the number of culvert barrels (N), are stored together as a product in register #4.

Since the calculation of the sidewall taper (ST) uses the face width dimension (B_f), the B_f calculation should be performed first. Label 'A' before Label 'B'.

The headwater elevation (HW EL.) used in the program can be obtained from program #11 for box culverts and from programs #34 and #35 for pipe culverts.

To use the programs for the vertical face condition, the face elevation (EL.FACE) and the length L_2 should come from vertical face calculations from previous programs. For the mitered faced inlet, these two values should correspondingly come from mitered faced programs.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		L_3	STO 3	L_3
		B	ENTER	B
		N	x STO 4	BxN
		HW EL.	STO 5	HW EL.
		EL.FACE	STO 6	EL.FACE
		L_2	STO 7	L_2
3	Calculate face width		A	B_f
4	Calculate sidewall taper		B	ST
5	To change any of these variables go to step #2 and alter only the necessary data.			
6	To change from square edged to bevel edged inlet, or vice versa, load the appropriate program and go to step #3.			

EXAMPLE #1

For a 6x6 box culvert with a design flowrate of 800 cfs., determine the face width and sidewall taper. The headwater elevation is 180.00 feet and for a mitered faced inlet, the face elevation is 176.40 feet and a length of 23.70 feet is given to the dimension L_2. All edges are to be squared.

Load program #20.

KEYSTROKES	DISPLAY	
800 STO 1	800.00	
6 STO 2	6.00	
6 ENTER 2 ÷ STO 3 . . .	3.00	
6 ENTER 1 x STO 4 . . .	6.00	
180 STO 5	180.00	
176.4 STO 6	176.40	
23.7 STO 7	23.70	
A	39.96 ft.	B_f
B	1.57	ST

EXAMPLE #2

A 60-inch pipe culvert with a design flowrate of 480 cfs. is to be used with a slope-tapered inlet. The headwater elevation is set at 214.60 feet and the face elevation of 209.40 feet exists for the vertical faced situation. An L_2 length of 14.96 feet has been determined. Find the width of the face section and the sidewall taper. The pipe is to have a 90° wingwall flare. All edges are to be beveled.

Load program #21

KEYSTROKES	DISPLAY	
480 STO 1	480.00	
60 ENTER 12 ÷ STO 2 . .	5.00	
2 ÷ STO 3	2.50	
5 STO 4	5.00	
214.6 STO 5	214.60	
209.4 STO 6	209.40	
14.96 STO 7	14.96	
A	13.93 ft.	B_f
B	3.91	ST

LISTING - PROGRAM #20

LBL A RCL 5 RCL 6 - RCL 2 ÷ ENTER ENTER ENTER 1 . 1 x 1 4 . 4 - x 1 5 7 . 8 + x 1 1 3 1 - x 5 1 5 0 + x 1 3 5 3 - 3 f^{-1} LOG + RCL 2 ENTER f $\sqrt{x}$ x x RCL 1 g x≷y + STO 8 RTN LBL B RCL 8 RCL 4 - 2 ÷ g 1/x RCL 7 RCL 3 + x RTN (73 STEPS)

LISTING - PROGRAM #21

LBL A RCL 5 RCL 6 - RCL 2 ÷ ENTER ENTER ENTER 2 8 4 6 7 . 6 x 3 4 5 8 2 1 . 4 - x 1 6 1 9 4 8 1 + x 4 0 3 5 0 2 9 . 4 - x 7 9 4 2 4 4 1 + x 2 2 6 5 8 6 3 - 6 f^{-1} LOG + RCL 2 ENTER f $\sqrt{x}$ x x RCL 1 g x≷y + STO 8 RTN LBL B RCL 8 RCL 4 - 2 ÷ g 1/x RCL 7 RCL 3 + x RTN (94 STEPS)

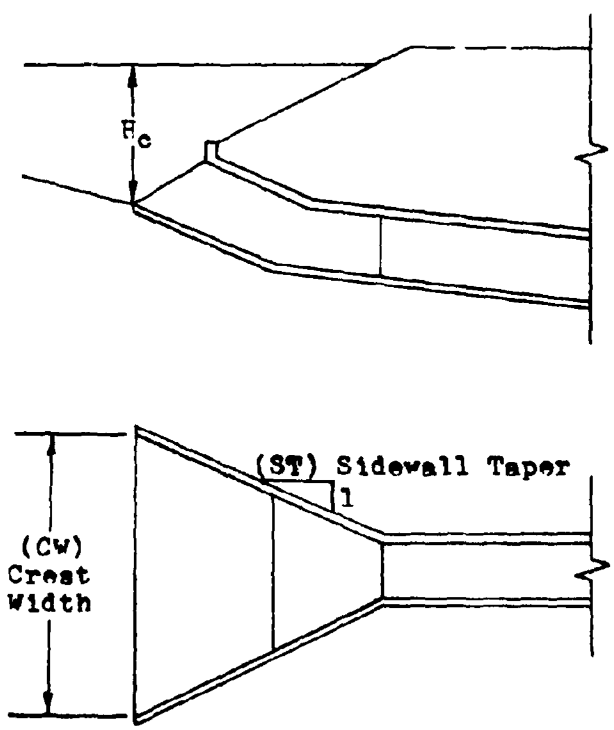
PROGRAM #22 - CREST CHECK EVALUATION

SLOPE-TAPERED MITERED INLET

In order for this inlet design to operate efficiently, the weir configuration at the inlet must be operating properly. This program establishes the width of the sidewall opening and the sidewall taper necessary to insure the appropriate hydraulic conditions.

This program can be used for either box or pipe culverts and for either square or bevel edged inlets.

The diagrams below indicate the locations of the dimensions determined by this program.



Slope-Tapered Mitered Faced Inlet

EQUATIONS

H_c = HW EL.-EL.FACE

$CW = Q/(2H_c)^{1.5}$

$ST = 2L_4/(CW-B_f)$

REMARKS

For the program to operate properly, the crest width (CW) must be calculated before the sidewall taper (ST) can be determined.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		L_4	STO 4	L_4
	(Throat)	HW EL.	STO 5	HW EL.
	(Mitered)	EL.FACE	STO 7	EL.FACE
	(Square or Beveled)	B_f	STO 8	B_f
3	Calculate crest height		A	H_c
4	Calculate crest width		B	CW
5	Calculate sidewall taper		C	ST
6	For a change in any of these culvert properties, go to step #2 and reenter the desired item plus the value of B_f.			

EXAMPLE #1

What is the recommended sidewall taper for a mitered face slope-tapered inlet to insure throat and not crest control of the hydraulic performance. The culvert is to handle 3000 cfs. and has a predetermined L_4 value of 10.0 feet. The headwater elevation is 98.4 feet and the elevation of the face section of the culvert is 83.2 feet. For a beveled edged inlet the face width is 8.12 feet.

KEYSTROKES	DISPLAY	
3000 STO 1	3000.00	
10 STO 4	10.00	
98.4 STO 5	98.40	
83.2 STO 7	83.20	
8.12 STO 8	8.12	
A	15.20 ft.	H_c
B	17.90 ft.	CW
C	2.05	ST

If the sidewalls are built on a 2:1 or larger taper, the culvert will operate in throat control.

LISTING - PROGRAM #22

LBL A RCL 5 RCL 7 - RTN LBL B RCL 1 A 2 x 1 . 5 g y^x ÷ STO 6 RTN LBL C RCL 4 2 x RCL 6 RCL 8 - ÷ 0 g x≤y g x≥y g NOP RTN (34 STEPS)

PROGRAMS #23 & #24 - BOX CULVERT; INLET CONTROL OUTLET VELOCITY

Due to the complexity of the calculations involved in computing this outlet velocity, the program has been divided into two parts, program #23 and program #24.

Together these programs contain polynomial equations which approximate the normal depth curve for a rectangular cross-sectional area. The set of curves involved were taken from "Open Channel Hydraulics" by Chow. See reference #4.

Program #23 determines the abscissa for the curves (called 'X' in the equation section), as well as one of the polynomial equations required. Program #24 compares the values produced by program #23 and completes the second polynomial expression if necessary.

To run these programs, the desired inputs are stored in their appropriate registers and then Label 'A' is pressed for program #23. The value of (X) is displayed. Program #24 is then loaded and Label A is immediately pressed again. The value of the outlet velocity for the culvert operating in inlet control is then displayed.

EQUATIONS

Program #23

$$X = (Qn/(1.486NS^{.5}))/B^{8/3}$$

If $X < 0.22$

$$d_n = B(0.036402+3.6483784X-15.152238X^2+64.991913X^3 -110.31635X^4)$$

EQUATIONS

Program #24

If $0.22 \leq X < 1.1$

$$d_n = B(0.084468+2.34061X-1.53643X^2+1.636594X^3 -0.677621X^4) \quad d_n \text{ is limited to } 2B$$

If $X \geq 1.1$

$$d_n = D$$

$$V = Q/(BNd_n)$$

REMARKS

Once the register values have been stored for program #23, they do not have to be restored for the running of program #24.

The calculators register values should not be tampered with between the running of the two programs.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program #23			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		B	STO 3	B
		N	STO 4	N
		n	STO 5	n
	(ADJ.S or S)	S	STO 6	S
3	Calculate 'X'		A	X
4	Load program #24			
5	Calculate outlet velocity		A	V
6	For a change in any data, goto step #1.			

EXAMPLE #1

Find the outlet velocity for a 6x5 box culvert operating in inlet control. The design discharge is 100 cfs, and the channel slope has been adjusted to 0.015. The box is to be constructed out of concrete making the value for Manning's n = 0.012.

KEYSTROKES	DISPLAY
100 STO 1	100.00
5 STO 2	5.00
6 STO 3	6.00
1 STO 4	1.00
.012 STO 5	0.01
.015 STO 6	0.02
Load program #23	
A	0.06
Load program #24	
A	13.74 fps. V_o

EXAMPLE #2

Evaluate the same culvert for a flowrate of 500 cfs.

KEYSTROKES	DISPLAY
500 STO 1	500.00
Load program #23	
A	0.28
Load program #24	
A	21.49 fps. V_o

LISTING - PROGRAM #23

```
LBL A RCL 1 RCL 5 x 1 . 4 8 6 + RCL 6 f √x +
RCL 4 + RCL 3 8 ENTER 3 + g y^x + STO 7 . 2 2
g x≤y RCL 7 RTN RCL 7 ENTER ENTER ENTER 1 1 0 3
1 6 4 CHS x 6 4 9 9 1 9 + x 1 5 1 5 2 2
- x 3 6 4 8 4 + x 3 6 4 . 0 2 + 4 f^-1 LOG
+ 2 g x>y g x≷y g NOP RCL 3 x RCL 2 g x≷y g x>y
g x≷y g NOP RCL 4 RCL 3 x x RCL 1 g x≷y + STO 8
RCL 7 RTN (100 STEPS)
```

LISTING - PROGRAM #24

```
LBL A . 2 2 RCL 7 g x≤y GTO 1 1 . 1 g x>y GTO 2
RCL 1 RCL 2 RCL 3 RCL 4 x x + RTN LBL 1 RCL 8 R/S
LBL 2 RCL 7 ENTER ENTER ENTER 6 7 7 6 2 1 CHS x
1 6 3 6 5 9 4 + x 1 5 3 6 4 3 0 - x 2 3 4
0 6 1 0 + x 8 4 4 6 8 + 6 f^-1 LOG + 2 g x>y
g x≷y g NOP RCL 3 x RCL 2 g x≷y g x>y g x≷y g NOP
RCL 4 RCL 3 x x RCL 1 g x≷y + R/S (97 STEPS)
```

PROGRAM #25 - PIPE CULVERT: CRITICAL DEPTH

The approach by this program to determine the critical depth for pipe culvert is to use polynomial best-fit equations of the critical depth curve given in, "Open Channel Hydraulics", by Chow. The program computes a 'Z' value which corresponds to the abscissa of the curve. This value is then applied to one of two equations which are used to approximate different reaches of the curve. Continuing through the calculations, the critical depth is determined.

EQUATIONS

$$Z = (Q/(N(32.2/\alpha)^{.5}))/D^{2.5}$$

$$X = \text{Log } Z$$

If $X \leq \text{Log } .7$

$$d_c = D(10)^Y$$

$$Y = (-0.0051657+0.407362X-0.1830236X^2-0.0915565X^3)$$

If $X > \text{Log } .7$

$$Y = (-.0244603+0.2017057X-0.640098 15X^2+0.695619X^3)$$

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		N	STO 3	N
		α	STO 4	α

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
3	Caloulate critical depth		A	d_c
4	To change any of the input data, go to step #2 and change only the necessary item.			

EXAMPLE #1

Find the critical depth for a corrigated metal pipe (CMP) of a 36-inch diameter. The flow through the pipe is 100 cfs. For a CMP the value for alpha is 1.12.

KEYSTROKES	DISPLAY
100 STO 1	100.00
36 ENTER 12 ÷ STO 2 . .	3.00
1 STO 3	1.00
1.12 STO 4	1.12
A	2.92 ft. d_c

EXAMPLE #2

How would the critical depth change if concrete was used instead of the corrigated metal. The value of alpha for concrete is 1.04.

KEYSTROKES	DISPLAY
1.04 STO 4	1.04
A	2.90 ft. d_c

Not much of a significant change results.

LISTING - PROGRAM #25

LBL A RCL 1 RCL 3 + 3 2 . 2 RCL 4 + RCL 2 x f √x

\+ RCL 2 RCL 2 x + f LOG ENTER ENTER ENTER . 7 f

LOG g x≤y g R↓ B g R↓ 9 1 5 6 CHS x 1 8 3 0 2

\- x 4 0 7 3 6 + x 5 1 7 - C LBL B 6 9 5 6

2 x 6 4 0 1 0 - x 2 0 1 7 1 + x 2 4 4 6 -

LBI C 5 f^{-1} LOG + f^{-1} LOG RCL 2 x RCL 2 g x>y

g x≥y g NOP R/S (100 STOPS)

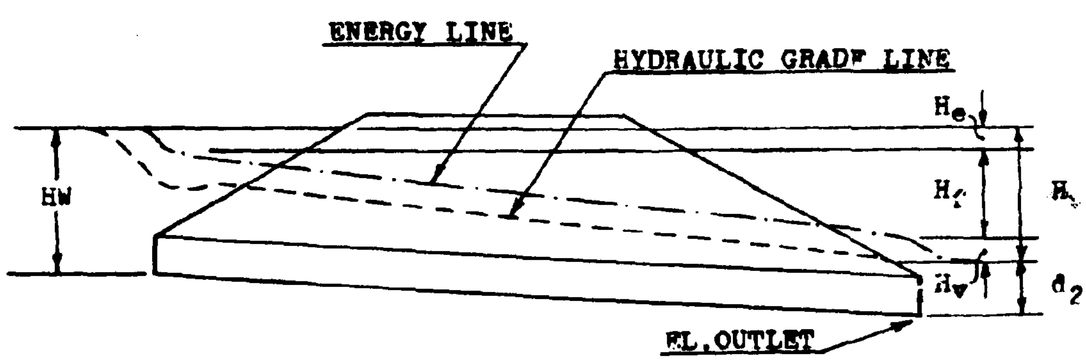
PROGRAM #26 - PIPE CULVERT; SIZE AND OUTLET CONTROL PERFORMANCE

This program has two functions. First, it can be used to select the appropriate pipe culvert size. Second, once this pipe size has been selected, the program will evaluate the performance of the culvert for various flowrates. The outlet control performance curve can be made by plotting these flowrates versus the generated headwater elevations (HW EL.).

In determining the best pipe culvert size, the designer must first select a trial diameter (D). For this value, the program computes the water surface elevation of the headwater pool at the culvert inlet. A visual comparison of this value to the allowable headwater elevation (AHW EL.) is made and the designer adjusts the diameter (D) accordingly.

Once the pipe size has been determined, various flowrate values can be used with the program to obtain a performance curve.

The following diagram indicates the location of the energy losses associated with the culvert design.



EQUATIONS

$$H_e = k_e V^2/2g$$

$$H_f = 29n^2LV^2/2gR^{1.33}$$

$$H_v = V^2/2g$$

$$H = H_e + H_f + H_v$$

$$= (1+k_e+29n^2L/(D/4)^{1.33})(4Q/ND^2\pi)^2/2g$$

$d_2 = (d_c+D)/2$ or the Tailwater depth, whichever is largest

HW EL. = $H+d_2$+EL.OUTLET

REMARKS

The critical depth (d_c) cannot be greater than the diameter of the pipe (D). The program includes a test for this situation.

Since the water at the inlet is considered to be a pool, the velocity at this point is assumed to be approximately zero. This allows the hydraulic grade line to be equated to the energy line.

For the program to operate properly, the number of barrels (N) and the barrel roughness value (n), must be stored together as a sum in register #3. The limitations on the equations above, require that the number of barrels (N), be limited to a value of either 1 or 2.

Label A (HW EL.) must be executed before Label C (d_2).

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		N	ENTER	N
		n	+ STO 8	N+n
		EL.OUT	STO 4	EL.OUTLET
		k_e	STO 5	k_e
		TW	STO 6	TW
		L	STO 7	L
		d_c	STO 8	d_c
3	Calculate headwater elevation		A	HW EL.
4	Calculate total head loss		B	H
5	Calculate depth of water at outlet		C	d_2
6	To evaluate another pipe size, reenter the new value and go to step #3. *			
7	To obtain outlet control performance curve coordinates, input various flowrates and calculate the corresponding headwater elevations. **			

* If the length, critical depth, and outlet elevation of the culvert change with the diameter, they must also be reentered.

** If the tailwater depth, and the critical depth change with the new flowrates, they must also be reentered.

EXAMPLE #1

For a flowrate of 420 cfs., and an entrance loss coefficient of 0.5, find the appropriate pipe culvert size. The tailwater depth for this flowrate is 3.61 feet. From the site conditions, it has been determined that for a twin 48-inch CMP, a 253.70 foot barrel is required. The outlet elevation for this size of pipe would be 119.43 feet. The corresponding critical depth is 3.90 feet. If a twin 54-inch CMP is selected for the site, the length would change to 248.56 feet, the outlet elevation would rise to 119.75 feet, and the critical depth would raise to 4.16 feet. For corrigated metal, Manning's n is 0.024. The allowable headwater elevation is set at 140.4 feet.

KEYSTROKES	DISPLAY
420 STO 1	420.00
2 ENTER .024 + STO 3 . .	2.02
.5 STO 5	0.50

Try the 48-inch culvert

48 ENTER 12 + STO 2 . .	4.00
119.43 STO 4	119.43
3.61 STO 6	3.61
253.7 STO 7	253.70
3.9 STO 8	3.90
A	148.26 ft. HW EL.

This HW EL. is larger than the allowable, try 54-inch pipes.

54 ENTER 12 + STO 2 . .	4.50
119.75 STO 4	119.75

KEYSTROKES	DISPLAY
248.56 STO 7	248.56
4.16 STO 8	4.16
A	137.75 ft. HW EL.

This HW EL. is below the allowable. Use it.

B	13.67 ft. H
C	4.33 ft. d_2

Use the twin 54-inch pipe culverts.

EXAMPLE #2

Evaluate the outlet performance curve for the pipe designed above. Plot the four points on the curve which correspond to the 0.6Q, 0.8Q, Q, and the 1.2Q. The tailwater depths are 3.42 feet, 3.55 feet, 3.61 feet, and 3.72 feet respectively. Similarly the critical depths are 3.39, 3.87, 4.16 and 4.32 feet.

KEYSTROKES	DISPLAY
420 ENTER .6 x STO 1 . .	252.00
54 ENTER 12 ÷ STO 2 . .	4.50
2 ENTER .024 + STO 3 . .	2.02
119.75 STO 4	119.75
.5 STO 5	0.50
3.42 STO 6	3.42
248.56 STO 7	248.56
3.39 STO 8	3.39
A	128.62 ft. HW EL. @ 0.6Q
420 ENTER .8 x STO 1 . .	336.00

KEYSTROKES	DISPLAY
3.55 STO 6	3.55
3.87 STO 8	3.87
A	132.68 ft. HW EL. @ 0.08Q
420 ENTER 1.2 x STO 1 .	504.00
3.72 STO 6	3.72
4.32 STO 8	4.32
A	143.84 ft. HW EL. @ 1.2Q

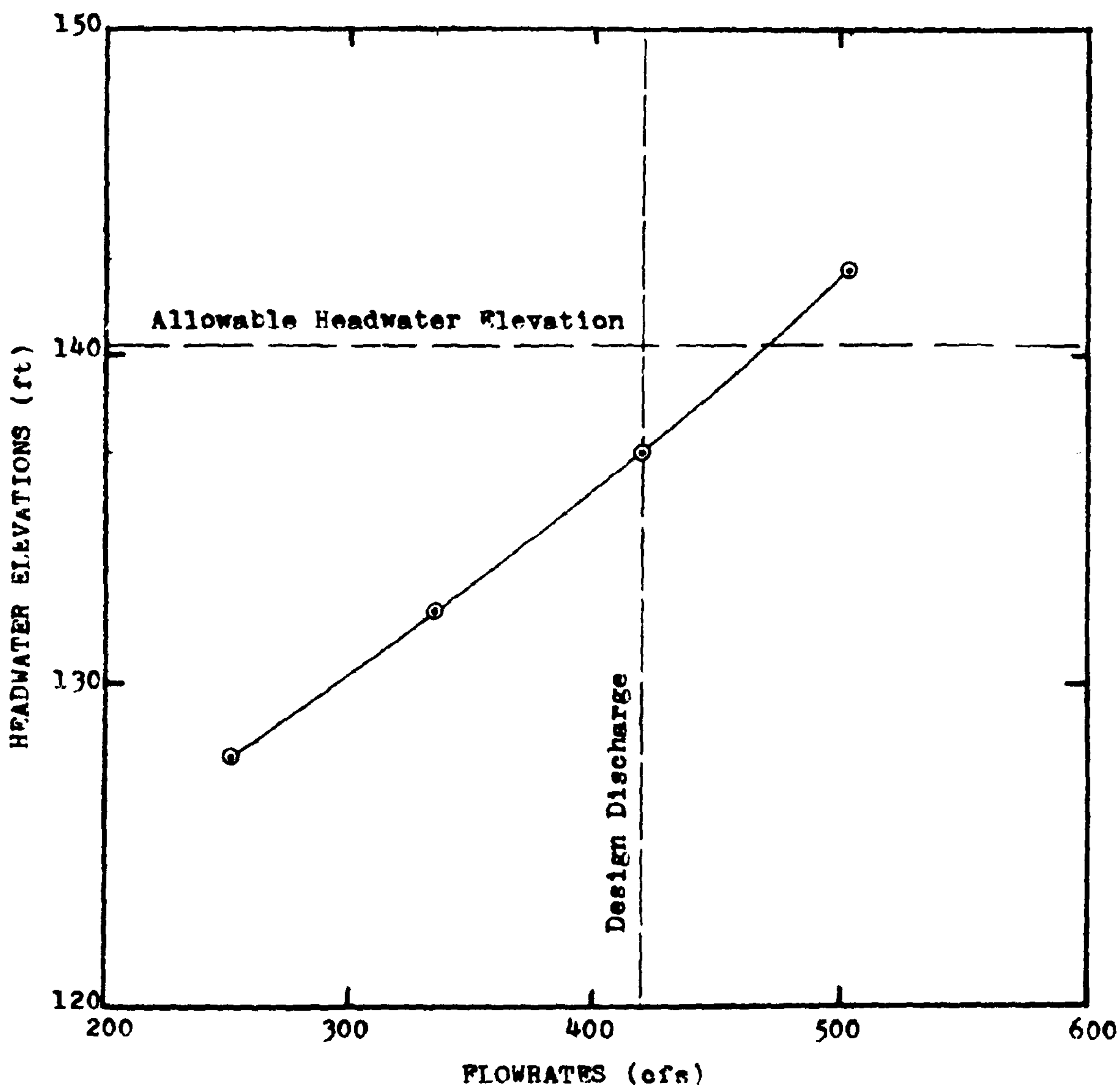
LISTING - PROGRAM #26

LBL A RCL 8 RCL 2 g x≤y RCL 2 g NOP + 2 + RCL 6 g x≤y g x≥y g NOP STO 9 B RCL 4 + RCL 9 + RTN LBL B 2 9 RCL 3 f^{-1} INT ENTER x x RCL 7 x RCL 2 4 + 4 ENTER 3 + g y^x + RCL 5 + 1 + 4 RCL 1 x RCI 3 f INT + RCL 2 ENTER x + g π + ENTER x 6 4 . 4 + x RTN LBL C RCL 9 RTN (77 STEPS)

Plot of the performance of a twin 54-inch pipe culvert operating in outlet control.

Plotting Coordinates

Q	252.00	336.00	420.00	504.00
HW EL.	128.62	132.68	137.75	143.84



PROGRAM #27 - PIPE CULVERT; OUTLET CONTROL OUTLET VELOCITY

This program determines the outlet velocity of a pipe culvert operating in outlet control.

The depth of flow used in the computation of the cross-sectional area of the flow through the culvert is equal to the critical depth or the tailwater depth, whichever is greater. However, if this depth is found to be larger than the diameter of the pipe culvert, the depth of flow is set equal to the diameter of the pipe.

EQUATIONS

$V = Q/AN$

$d_4 = d_c$ or TW, whichever is greater, not to exceed D

$R = D/2$

$r = ABS(R-d_4)$

If $d_4 < R$

$A = (\pi R^2 Cos^{-1}(r/R)/180)-r(R^2-r^2)^{.5}$

If $d_4 \geq R$

$A = \pi R^2-(\pi R^2 Cos^{-1}(r/R)/180)+r(R^2-r^2)^{.5}$

REMARKS

The calculator should be set in the degree mode for this program to operate properly.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		N	STO 3	N
		TW	STO 6	TW
		d_c	STO 8	d_c
3	Calculate outlet velocity		A	V
4	For a change in any of the culvert properties go to step #2 and change only the necessary item.			

EXAMPLE #1

What is the outlet velocity of a 48 inch pipe culvert with a discharge of 200 cfs.? The tailwater depth is 3.28 feet and the critical depth is 3.88 feet.

KEYSTROKES	DISPLAY
200 STO 1	200.00
48 ENTER 12 ÷ STO 2 . .	4.00
1 STO 3	1.00
3.28 STO 6	3.28
3.88 STO 8	3.88
A	16.06 fps V

LISTING - PROGRAM #27

LBL A RCL 8 RCL 6 g x≤y g x≷y g NOP RCL 2 g x>y g x≷y
g NOP RCL 2 2 + STO 4 g x≤y f SF 1 -- g ABS STO 5
RCL 4 + f^{-1} COS RCL 4 RCL 4 x x g π x 1 8 0 +
RCL 4 RCL 4 x RCL 5 RCL 5 x - f $\sqrt{x}$ RCL 5 x - f^{-1}
TF 1 GTO 1 RCL 4 RCL 4 x g π x g x≷y - f^{-1} SF 1
LBL 1 RCL 3 x RCL 1 g x≷y + RTN (71 STEPS)

PROGRAMS #28-33 PIPE CULVERTS: INLET CONTROL PERFORMANCE

Program #28: CMP with Projecting Edge

Program #29: CMP or Concrete with Standard End Section

Program #30: CMP or Concrete with Beveled Edges (Type A)

Program #31: Concrete with Square Edges in a Headwall

Program #32: Concrete with Projecting Socket Edge

Program #33: Concrete with Socket Edge in a Headwall

Information is also provided for the design of the following inlets.

CMP Mitered to Conform to Slope

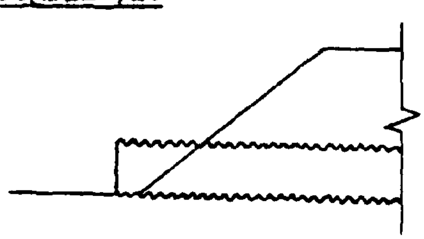
CMP in a Headwall

CMP or Concrete with Beveled Edges (Type B)

Concrete with Projecting Square Edges

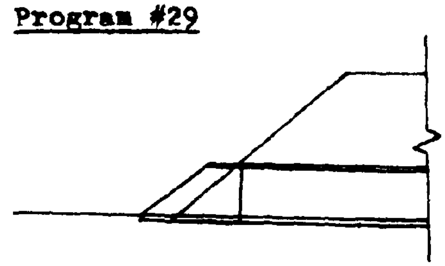
The programs named above evaluate the hydraulic performance for the described inlet configurations operating in inlet control. Although the shape of the inlet faces differ dramatically, the analysis formulas are very similar. For this reason, these programs are grouped together. A more detailed explanation of the geometry of these inlets is provided below:

Program #28

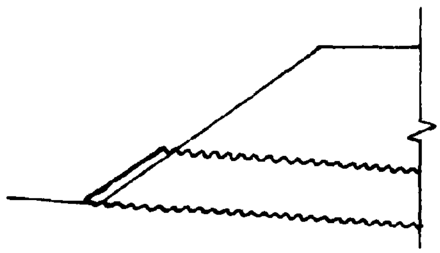


CMP - Projecting Edge

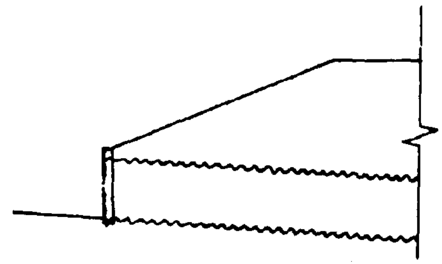
Program #29



CMP/Concrete - End Section

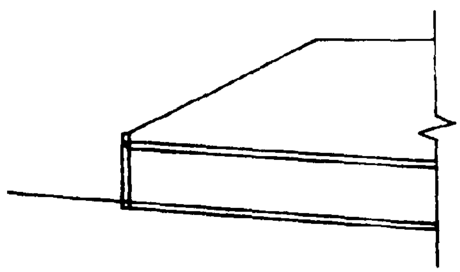


CMP - Mitered to Conform to Slope



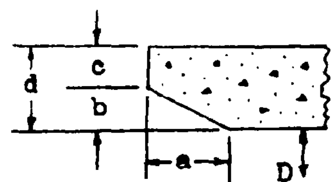
CMP - In a Headwall

Program #30



CMP/Concrete - Beveled Edges

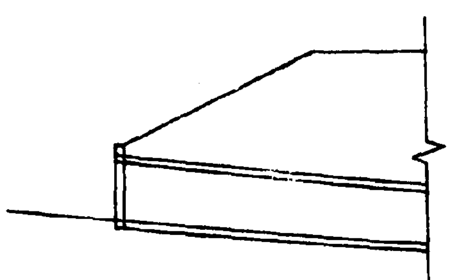
Type A and B



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

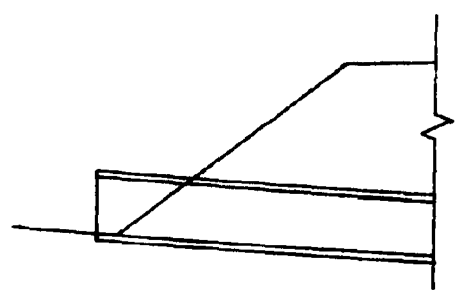
The beveled ring should extend a minimum of 300° around the face.

Program #31



Concrete - Square Edge

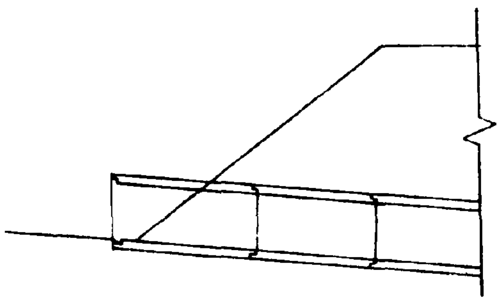
in Headwall



Concrete - Projecting

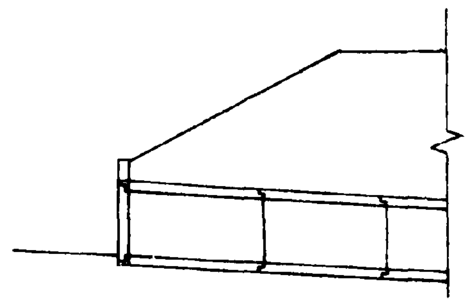
Square Edge

Program #32



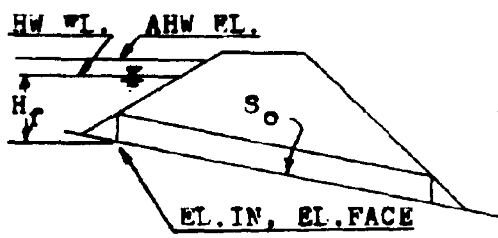
Concrete - Projecting Socket Edge

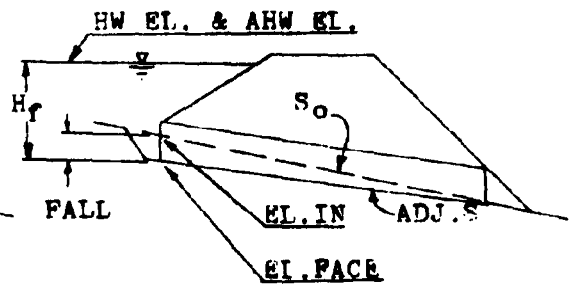
Program #33



Concrete - Socket Edge in Headwall

For each particular inlet, the program calculates the height of the water at the face of the culvert (H_f). This value is then added to the culvert inlet invert elevation (H_f + EL.IN). If this sum is less than the allowable headwater elevation (AHW EL.), then the inlet elevation becomes the elevation of the face (EL.FACE). However, if the sum of the height of the water at the face of the culvert plus the elevation of the inlet exceeds the allowable headwater elevation, the difference between this sum and the allowable headwater elevation is subtracted from the inlet invert elevation. This new elevation is now called the elevation of the face (EL.FACE). For the culvert to operate properly, the inlet invert must be reset to this elevation. The drop in elevation of the inlet invert is called the FALL. The diagrams on the following page graphically show this occurrence. It should be noted that as the inlet invert elevation drops, the culvert barrel rotates about the outlet invert.





No FALL Required

$EL.IN + H_f < AHW\ EL.$

FALL Required

$EL.IN + H_f \geq AHW\ EL.$

As indicated in the diagrams, when the calculated headwater elevation is above the allowable headwater elevation, the headwater elevation is set equal to the allowable value and the difference is taken up by the FALL.

The invert elevation of the culvert face can always be thought of as the elevation of the face (EL.FACE). The original elevation of the culvert inlet invert, before considering the affects of inlet control and possible FALL, can be taken as the elevation of the inlet (EL.INLET).

Once the culvert has been sized for the design flowrate conditions, the same program can be used to evaluate the performance of the culvert for other flowrate values. In this manner a performance curve for the culvert operating in inlet control can be drawn.

EQUATIONS

$$EL.FACE = AHW\ EL. - H_f \quad \text{(With FALL)}$$

$$= EL.INLET \quad \text{(Without FALL)}$$

HW EL. = EL.FACE+H_f

FALL = EL.FACE-EL.INLET

Note: The FALL is measured in a downward direction and therefore is always a positive value.

$X = Q/(ND^{2.5})$

<u>**Program #28**</u>

$$H_f = D(0.187321+0.567710X-0.156544X^2+0.0447052X^3 -0.00343602X^4+0.000089661X^5)$$

<u>**Program #29**</u>

$$H_f = D(0.120659+0.630768X-0.218423X^2+0.0591815X^3 -0.00599169X^4+0.000229287X^5)$$

<u>**Program #30**</u>

$$H_f = D(0.063343+0.766512X-0.316097X^2+0.0876701X^3 -0.00983695X^4+0.000416760X^5)$$

<u>**Program #31**</u>

$$H_f = D(0.087483+0.706578X-0.253295X^2+0.0667001X^3 -0.00661651X^4+0.000250619X^5)$$

<u>**Program #32**</u>

$$H_f = D(0.108786+0.662381X-0.233801X^2+0.0579585X^3 -0.00557890X^4+0.000205052X^5)$$

Program #33

$$H_f = D(0.114099+0.653562X-0.233615X^2+0.0597723X^3 -0.00616338X^4+0.000242832X^5)$$

CMP Mitered to Conform to Slope

$$H_f = D(0.107137+0.757789X-0.361462X^2+0.1233932X^3 -0.01606422X^4+0.000767390X^5)$$

CMP in a Headwall

$$H_f = D(0.167433+0.538595X-0.149374X^2+0.0391543X^3 -0.00343974X^4+0.000115882X^5)$$

CMP or Concrete with Beveled Edges (Type B)

$$H_f = D(0.081730+0.698353X-0.253683X^2+0.0651250X^3 -0.00719750X^4+0.000312451X^5)$$

Concrete with Projecting Square Edges

$$H_f = D(0.167287+0.558766X-0.159813X^2+0.0420069X^3 -0.00369252X^4+0.000125169X^5)$$

REMARKS

In evaluating these inlets, the pipe size must be determined before the culvert performance values can be generated. Once the pipe size has been fixed and the elevation of the face (EL.FACE) established using the design flowrate, the program can then be used for performance evaluations. In calculating the performance curve values, the elevation of the face must

remain a constant. To insure that this value is not altered, Label A on the calculator should <u>not</u> be used during the performance curve evaluation.

These programs have been written with the input values stored in the same registers for each program. This allows the designer to store the input data once and evaluate all of the inlet configurations by just loading another program card.

Whenever applicable, a bevel edged inlet is recommended for use in lieu of a square edged inlet. The large increase in hydraulic performance gained by using a beveled edged inlet over a square edged inlet, greatly outweighs the small additional cost.

To insure the proper operation of these inlets, the FALL value is limited to a minimum value of ¼D and a maximum value of 1½D. If the minimum value is exceeded, ie., FALL = 0.2D, one of three alternatives should be considered. First, since the FALL is so small, the culvert will operate as though no FALL is occurring. A side-tapered should be considered. Second, the pipe size could be reduced for the same inlet configuration. This would increase the amount of FALL required. And third, the same pipe size could be used with another inlet type.

If the maximum value for FALL, 1½D, is exceeded, either a larger pipe size or a more efficient inlet is required.

Polynomial best-fit equations are used to determine the headwater depths for these inlets. Since these equations are an approximation for the curves in HEC #13, they are subject to the same limitations. Therefore, the headwater depth (H_f) is limited to a maximum of 4½D and a minimum of ½D. To avoid the possibility of culvert failure due to buoyancy forces, it is recommended that H_f be limited to a value of around 2D.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		N	STO 3	N
		EL.IN	STO 5	EL.IN
		AHW EL.	STO 6	AHW EL.
3	Calculate the EL.FACE		A	EL.FACE
4	Calculate the headwater elev.		B	HW EL.
5	Calculate the FALI		C	FALI
6	Calcualte the headwater depth		D	H_f
7	To evaluate the same inlet with different design criteria, go to step #2.			
8	To evaluate another inlet, load the desired program card and go to step #3.			
9	To obtain the performance curve coordinates, input the selected flowrates in register #1 and press Label B to obtain the headwater elevations. Note: Label A must not be used during the performance curve evaluation.			

EXAMPLE #1

For a 50-year discharge of 200 cfs., an allowable headwater elevation of 72.00 feet, and an inlet elevation of 63.00 feet, determine the appropriate pipe culvert size. The design to be considered is a projecting CMP.

Load program #28

KEYSTROKES	DISPLAY	
200 STO 1	200.00	
1 STO 3	1.00	
63 STO 5	63.00	
72 STO 6	72.00	

Try a 42 inch pipe.

3.5 STO 2	3.50	
A	45.61 ft.	EL.FACE
C	17.39 ft.	FALL

This FALL value is larger than the allowable value of 5.25 feet.

Try a 48 inch pipe.

4 STO 2	4.00	
A	55.41 ft.	EL.FACE
C	7.59 ft.	FALL

This FALL is larger than the allowable (1½D) value of 6.00 feet.

Try a 54 inch pipe.

4.5 STO 2	4.50	
A	60.61 ft.	EL.FACE
C	2.39 ft.	FALL

This FALL value is within the limits (½D) and (1½D).

Check the limits of H_f.

D . . . . 11.39 ft. H_f

This value of H_f is below the maximum value of 20.25 = 4½D.

A 54 inch CMP culvert will work for the conditions specified.

EXAMPLE #2

Consider the same design criteria only change the pipe from a projecting inlet to a bevel edged inlet.

Load program #30.

KEYSTROKES	DISPLAY

With the design data already in the calculator from the previous example, just proceed with the calculations.

A	63.00 ft. FL.FACE
C	0.00 ft. FALL

This design uses the 54 inch diameter. With a bevel edged inlet no FALL is required. In order to maximize the design a smaller size of pipe will be evaluated. Try 48 inch diameter.

4 STO 2	4.00
A	60.50 ft. FL.FACE
C	2.50 ft. FALL

This FALL value is within the allowable range. Check H_f.

D . . . . 11.50 ft. H_f

This value is also within the allowable range.

Use 48 inch diameter pipe. The bevel edged inlet reduces the required diameter by one half of a foot.

EXAMPLE #3

Evaluate the performance of a twin 30 inch concrete pipe culvert entrance. The design flowrate is 100 cfs., and the allowable headwater elevation is 86.50 feet. The elevation of the inlet invert is 80.20 feet. Use program #31.

KEYSTROKES	DISPLAY		
100 STO 1	100.00		
2.5 STO 2	2.50		
2 STO 3	2.00		
80.2 STO 5	80.20		
86.5 STO 6	86.50		
A	80.20	ft.	EL.FACE
B	85.98	ft.	HW EL.
C	0.00	ft.	FALL
D	5.78	ft.	H_f

No excavation is required for this culvert design. The headwater elevation is just below the allowable value. For the performance curve coordinates use 0.6Q, 0.8Q, and 1.2Q.

60 STO 1	60.00		
B	83.37	ft.	HW EL. @ 0.6Q
80 STO 1	80.00		
B	84.49	ft.	HW EL. @ 0.8Q
120 STO 1	120.00		
B	87.81	ft.	HW EL. @ 1.2Q

Note: After the face elevation was originally determined, Label A, this button was not pressed again. To do so would produce an error in the calculation of the performance curve coordinates. Label A should only be used when the design flowrate is in register #1.

A plot of this performance is on the final page of this section.

<u>LISTING - PROGRAM #28</u>

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y
- STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8
- RTN LBL D RCL 1 RCL 3 ÷ RCL 2 2 . 5 g y^x ÷
ENTER ENTER ENTER 8 9 . 6 6 1 x 3 4 3 6 . 0 2
- x 4 4 7 0 5 . 2 + x 1 5 6 5 4 4 - x 5 6
7 7 1 0 + x 1 8 7 3 2 1 + 6 f^{-1} LOG + RCL 2
x RTN (96 STEPS)

<u>LISTING - PROGRAM #29</u>

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y
- STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8
- RTN LBL D RCL 1 RCL 3 + RCL 2 2 . 5 g y^x +
ENTER ENTER ENTER 2 2 9 . 2 8 7 x 5 9 9 1 . 6
9 - x 5 9 1 8 1 . 5 + x 2 1 8 4 2 3 - x 6
3 0 7 6 8 + x 1 2 0 6 5 9 + 6 f^{-1} LOG + RCL 2
x RTN (97 STEPS)

<u>LISTING - PROGRAM #30</u>

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y
- STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8
- RTN LBL D RCL 1 RCL 3 + RCL 2 2 . 5 g y^x +
ENTER ENTER ENTER 4 1 6 . 7 6 x 9 8 3 6 . 9 5

LISTING - PROGRAM #30 (cont)

- x 8 7 6 7 0 . 1 + x 3 1 6 0 9 7 - x 7 6
6 5 1 2 + x 6 3 3 4 3 + 6 f^{-1} LOG + RCL 2 x
RTN (95 STEPS)

LISTING - PROGRAM #31

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y
- STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8
- RTN LBL D RCL 1 RCL 3 + RCL 2 2 . 5 g y^x +
ENTER ENTER ENTER 2 5 0 . 6 1 9 X 6 6 1 6 . 5 1 - X
6 6 7 0 0 . 1 + X 2 5 3 2 9 5 - X 7 0 6 5 7 8 +
X 8 7 4 8 3 + 6 f^{-1} LOG + RCL2 X RTN (96 STEPS)

LISTING - PROGRAM #32

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y
- STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8
- RTN LBL D RCL 1 RCL 3 + RCL 2 2 . 5 g y^x +
ENTER ENTER ENTER 2 0 5 . 0 5 2 x 5 5 7 8 . 9
- x 5 7 9 5 8 . 5 + x 2 3 3 8 0 1 - x 6 6
2 3 8 1 + x 1 0 8 7 8 6 + 6 f^{-1} LOG + RCL 2
x RTN (96 STEPS)

LISTING - PROGRAM #33

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y
- STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8
- RTN LBL D RCL 1 RCL 3 + RCL 2 2 . 5 g y^x +

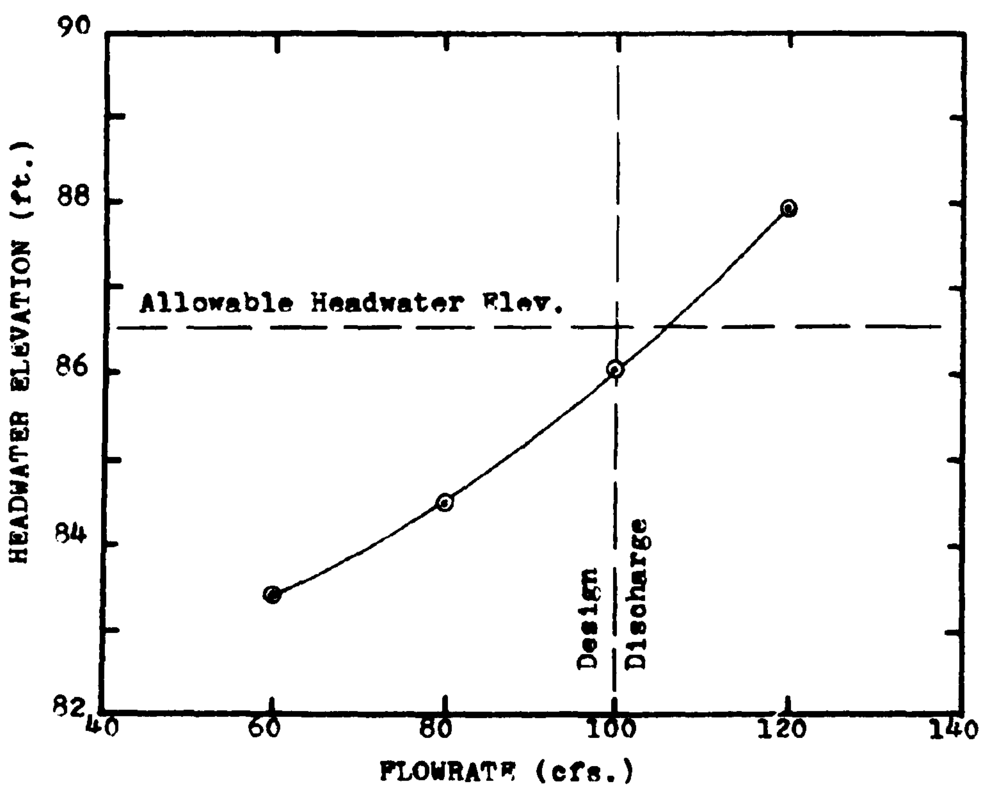
LISTING - PROGRAM #33 (cont)

ENTER ENTER ENTER 2 4 2 . 8 3 2 x 6 1 6 3 . 3 8 - x 5 9 7 7 2 3 + x 2 3 3 6 1 5 - x 6 5 3 5 6 2 + x 1 1 4 0 9 9 + 6 f^{-1} LOG ÷ RCL 2 x RTN (96 STEPS)

Plot of the performance of a twin 30 inch concrete pipe culvert operating in inlet control with square edges in a headwall.

Plotting Coordinates

Q	60.00	80.00	100.00	120.00
HW EL.	83.37	84.49	85.98	87.81



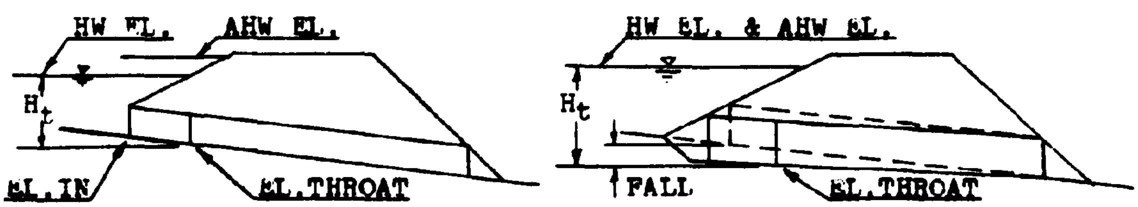
PROGRAMS #34 &35 - PIPE CULVERTS; SIDE-TAPERED THROAT CONTROL

SIDE-TAPERED WITH SMOOTH THROAT

SIDE-TAPERED WITH ROUGH THROAT

A culvert with a smooth throat pertains to pipe culverts made of concrete or of a smooth metal. Rough throated culverts apply to corrigated metal structures.

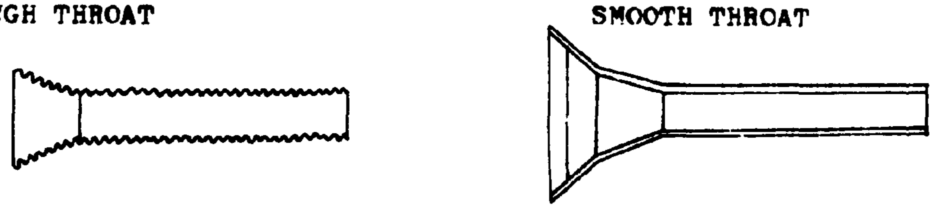
These programs evaluate the performance of a culvert operating in throat control. The formulas incorporated in these programs apply only to side-tapered inlets for pipe culverts. Like the inproved inlet programs, these throat control programs often can use FALL to increase the flow capacity of a culvert. The following diagrams describe the throat control inlets.



ELEVATION VIEW

ROUGH THROAT

SMOOTH THROAT



PLAN VIEW

SIDE-TAPERED INLET

NO FALL, HW EL. < AHW EL.

SIDE-TAPERED INLET

WITH FALL AND WINGWALLS

EQUATIONS

$$EL.THROAT = AHW\ EL.-H_t \quad \text{(With FALL)}$$

$$= EL.INLET \quad \text{(Without FALL)}$$

$$HW\ EL. = EL.THROAT+H_t$$

$$FALL = EL.INLET-EL.THROAT$$

$$X = LOG(Q/(ND^{2.5}))$$

Program #34

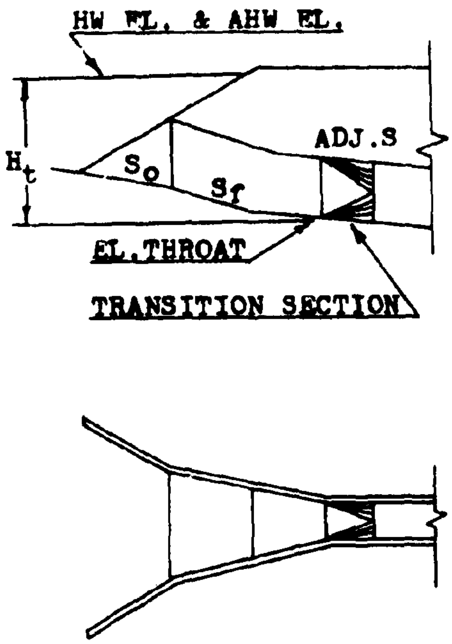
$$H_t = D\ 10^{(-0.237139+0.146792X+2.189321X^2-4.354114X^3+4.210539X^4-1.347032X^5)}$$

Program #35

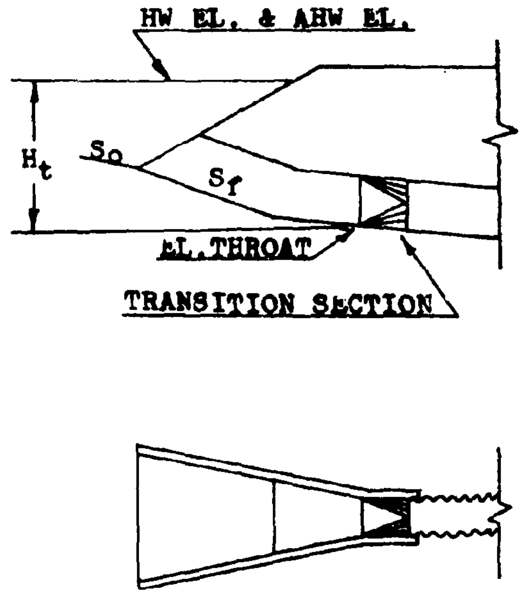
$$H_t = D\ 10^{(-0.233392+0.489125X+1.068638X^2-3.074435X^3+3.711165X^4-1.32836X^5)}$$

REMARKS

As mentioned before, these programs are only to be used with side-tapered pipe culverts. To evaluate the performance of a pipe culvert with a slope-tapered inlet, the designer should use program #11. This program evaluates the performance of box culverts with both side-tapered and slope-tapered inlets. The slope-tapered inlet for a pipe culvert is designed as if it were going to be used with a box culvert. A transition section is then fabricated to connect the box shaped inlet to the pipe culvert barrel. The diagrams on the next page will further explain this situation.



SLOPE-TAPERED INLET
VERTICAL FACE, WINGWALLS



SLOPE-TAPERED INLET
MITERED FACE

The width values (B) in program #11 will have to be translated into a diameter size. This can be accomplished by setting B equal to the diameter and then proceeding with the design as if the box culvert in question had a square cross-section.

Label A is used during the culvert size determination part of the program. Once a culvert size has been selected, it is stored in the calculator and Label A evaluates the appropriate throat elevation for the given design flowrate. When using flowrates other than the design value for the performance curve coordinates, Label A must <u>not</u> be pressed.

Since the input registers have the same identity as the ones used for the inlet control programs (#28-33), these two programs can be run in succession after the inlet control programs have been evaluated. If all of the inlet control programs have their calculated FALL values exceeding the maximum limit (1½D), the designer can immediately load these programs and proceed with the design of the culverts for throat control, without changing any of the register values.

Due to the size limitations of this calculator, a small error results in the computation of the FALL. The programs assume that the elevation of the inlet and the elevation of the throat are equal before determining the value of the headwater elevation. This equality is false and a small difference, equal to the channel slope times the vertical distance between the inlet and the throat section ($S_o x L_1$) exists. This L_1 distance is an unknown value in these programs. It is determined by the next programs. By understanding this error condition, a correction, if necessary, can be made.

The limits placed on the FALL value for the inlet control programs applies to the throat control designs also. A minimum value of ¼D and a maximum value of 1½D still apply. If the upper limit is exceeded, a larger culvert size should be tried. If the minimum value is exceeded, the culvert will essentially operate as if there was no FALL present. A larger or smaller culvert, or another inlet configuration should be considered.

Polynomial best-fit equations are used in determining the headwater depths for these inlets. Since the equations are an approximation for the curves in HEC #13, they are subject to the same restrictions. The headwater depth (H_t) is limited to $4\frac{1}{2}$D maximum and $\frac{1}{2}$D minimum. It is recommended that the value of H_t be kept below a value of 2D to protect the culvert from buoyancy forces.

The number of barrels (N) is limited to a value of 1 or 2.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Store register values	Q	STO 1	Q
		D	STO 2	D
		N	STO 3	N
		EL.IN	STO 5	EL.IN
		AHW EL.	STO 6	AHW EL.
3	Calculate throat elevation		A	EL.THROAT
4	Calculate headwater elevation		B	HW EL.
5	Calculate the FALL		C	FALL
6	Calculate headwater depth		D	H_t
7	For a change in any of these culvert properties, go to step #2 and change only the necessary items.			
8	To obtain the performance curve coordinates, input the selected flowrates in register #1 and press Label B to obtain the headwater elevations. Note: Label A must not be used during this calculation.			
9	To evaluate another inlet, load the desired program card and go to step #3.			

EXAMPLE #1

Size and evaluate the throat control performance of a CMP with a 300 cfs. flowrate. The inlet elevation is 135.00 feet and the allowable headwater elevation is 144.50 feet.

Load program #35

KEYSTROKES	DISPLAY
300 STO 1	300.00
1 STO 3	1.00
135 STO 5	135.00
144.5 STO 6	144.50

Try a 48 inch pipe.

4 STO 2	4.00
A	129.00 ft. EL.THROAT
C	6.00 ft. FALL

The FALL is within its allowable limits. Check H_t.

D	15.50 ft. H_t

This value is within the allowable but not the recommended range. Try a 54 inch diameter.

4.5 STO 2	4.50
A	133.02 ft. EL.THROAT
C	1.98 ft. FALL
D	11.48 ft. H_t

Both the FALL and H_t are within their allowable ranges. H_t equals 2.55 times the diameter. This value is above the recommended value of 2D but with proper anchoring it can be used.

The performance curve coordinates will be found for the 0.6Q, 0.8Q, and the 1.2Q values.

KEYSTROKES	DISPLAY
300 ENTER .6 x STO 1 . .	180.00
B	139.78 ft. HW EL. @ 0.6Q
300 ENTER .8 x STO 1 . .	240.00
B	141.87 ft. HW EL. @ 0.8Q
300 STO 1	300.00
B	144.50 ft. HW EL. @ Q
300 ENTER 1.2 x STO 1 .	360.00
B	147.75 ft. HW EL. @ 1.2Q

LISTING - PROGRAM #34

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y - STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8 - RTN LBL D RCL 1 RCL 3 + RCL 2 2 . 5 g y^x + f LOG ENTER ENTER ENTER 1 3 4 7 0 3 CHS x 4 2 1 0 5 4 + x 4 3 5 4 1 1 - x 2 1 8 9 3 2 + x 1 4 6 7 9 + x 2 3 7 1 4 - 5 f^{-1} LOG + f^{-1} LOG RCL 2 x RTN (97 STEPS)

LISTING - PROGRAM #35

LBL A D RCL 6 RCL 5 - g x≤y g x≷y g NOP RCL 6 g x≷y - STO 8 RTN LBL B D RCL 8 + RTN LBL C RCL 5 RCL 8 - RTN LBL D RCL 1 RCL 3 + RCL 2 2 . 5 g y^x + f LOG ENTER ENTER ENTER 1 3 2 8 3 6 CHS x 3 7 1 1 1 7 + x 3 0 7 4 4 4 - x 1 0 6 8 6 4 + x 4

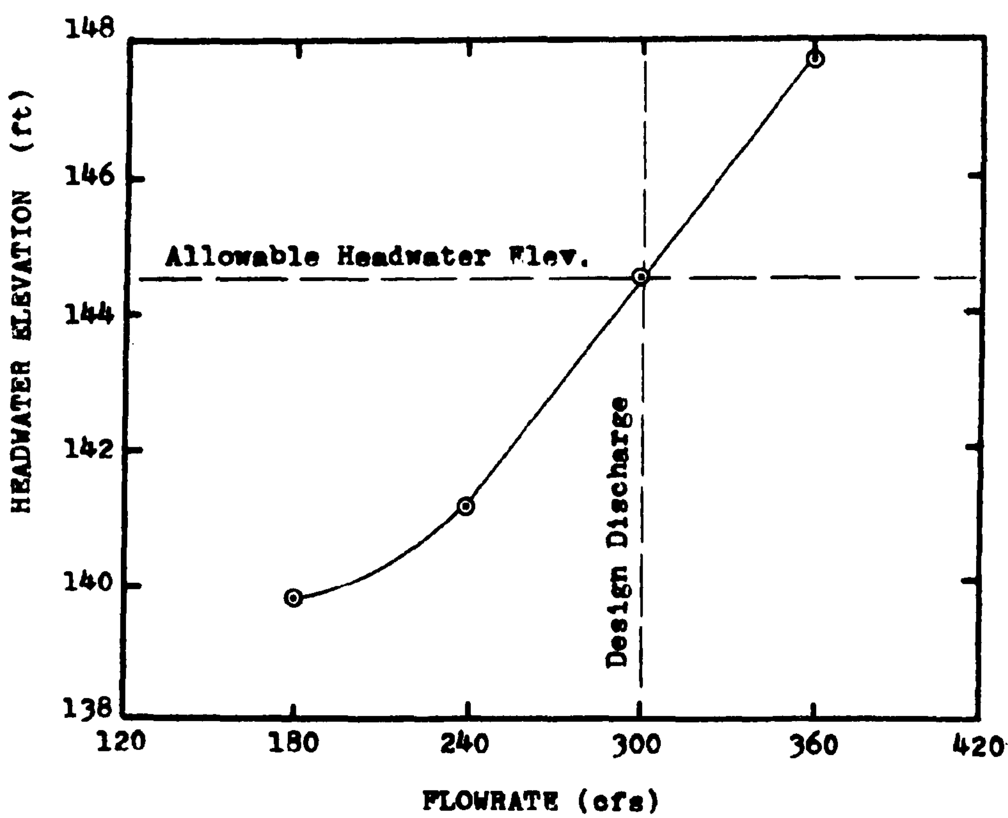
LISTING - PROGRAM #35 (cont)

8 9 1 3 + x 2 3 3 3 9 - 5 r^{-1} LOG + r^{-1} LOG RCL 2 x RTN (97 STEPS)

Plot of the performance curve of a 54 inch corrigated metal pipe culvert operating in throat control.

Plotting Coordinates

Q	180.00	240.00	300.00	360.00
HW EL.	139.78	141.87	144.50	147.75



PROGRAMS #36-38 PIPE CULVERTS; FACE DIMENSIONS

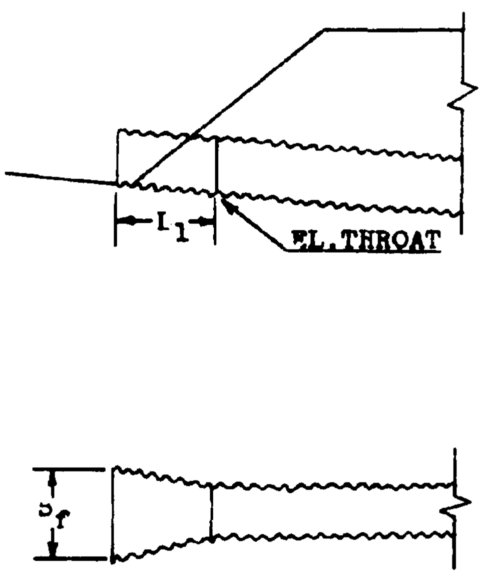
Program #36: Side-Tapered CMP with Projecting Edge

Program #37: Side-Tapered Square Edges in a Headwall

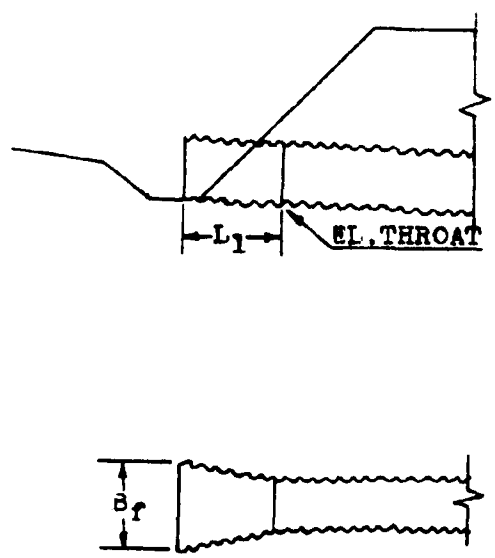
Program #38: Side-Tapered Beveled Edges in a Headwall

These programs continue with the design of a culvert operating in throat control. For the side-tapered entrance, these programs compute the face width (B_f) and the horizontal distance between the entrance and the throat control section (L_1). See the diagrams below for a further explanation.

Program #36

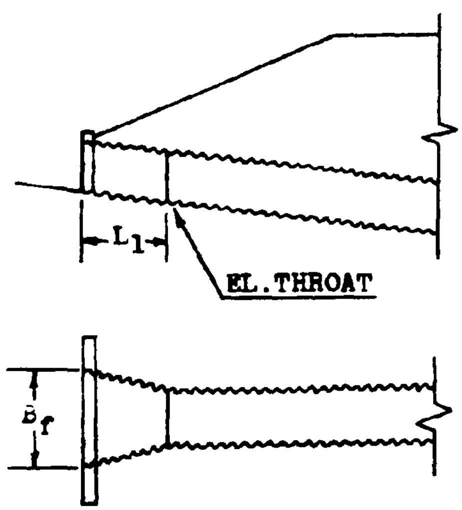


Side-Tapered, Projecting Edge
No FALL



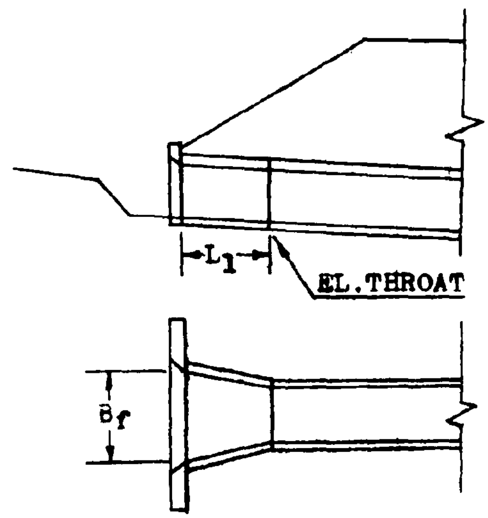
Side-Tapered, Projecting
Edge, With FALL

Program #37



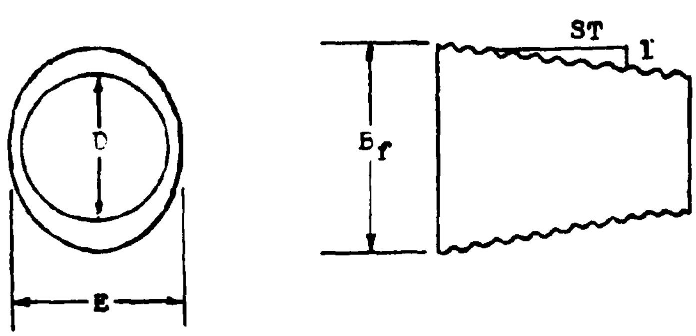
Side-Tapered, Square Edges
In a Headwall, CMP or Concrete
With or Without FALL

Program #38



Side-Tapered, Beveled Edges
In Headwall, CMP or Concrete
With or Without FALL

An additional dimension from the face of the side-tapered inlet is required as one of the program inputs. This is the value of the height of the side-tapered face. It is referred to as the value F in the diagram below.



The limitations on the value of W are a minimum of the diameter and a maximum of 1.1 times the diameter. The sidewall taper (ST) should be kept between a value of 4:1 to 6:1 for the program to operate properly.

The determination of B_f and L_1 is a lengthy computation which exceeds the capacity of the HP-65 calculator. An extra program card is needed to compute these values. This extra program, #14, computes the adjusted slope of a culvert which has FALL incorporated in its design. Program #14 uses the value L_1 in its computations. L_1 is determined by these programs, #36-38, but they need the value of the adjusted slope to compute L_1. The method used to solve this dilemma is to alternately use either programs #36 and #14, #37 and #14, or #38 and #14 in an alternating manner until the values of B_f, L_1 and ADJ.S stabilize. This process usually only requires two or three cycles.

For the initial calculation of B_f and L_1, the adjusted slope is approximated by using the original channel slope. A number slightly smaller than the original slope may be used to decrease the time of convergence.

Where prefabricated inlet sections are available, B_f and L_1 have generally been fixed by the manufacturing company. These values are normally set at 1½ times the culvert diameter. If this type of design is desired, the given values of B_f and L_1 can be used in lieu of programs #36-38. The value of L_1 can be directly used in program #14 to determine the adjusted slope.

EQUATIONS

$L_1 = ((B_f - DxN)/2)ST$

H_f = HW EL.-EL.THROAT-L_1ADJ.S = H_t - L_1ADJ.S

$X = H_f/D$

Program #36

$B_f = 4Q/((\pi E^{1.5})(0.0144+1.1505X+1.8167X^2-0.9642X^3$
$+0.1974X^4-0.0148X^5)$

Program #37

$B_f = 4Q/((\pi E^{1.5})(-0.0048+0.9426X+2.9784X^2-1.792X^3$
$+0.4228X^4-0.0357X^5)$

Program #38

$B_f = 4Q/((\pi E^{1.5})(0.73932X+3.2994X^2-1.746X^3$
$+0.3744X^4-0.0287X^5)$

REMARKS

The number of barrels (N) is limited to a value of 1 or 2.

As mentioned before, for the initial value of the adjusted slope (ADJ.S), the channel's original slope (S_o) should be used as an approximation. This value is stored in register #4.

Side taper values (ST) less than the specified value of 4:1 are unacceptable. Under this condition, the culvert would operate as if it were a regular culvert and there was no taper present. Side tapers in excess of the recommended value of 6:1 will perform better than the design will indicate. Therefore with this larger value, the programs will produce conservative results.

The value of L_1, determined by these programs is a horizontal measurement. This is in comparison with the adjusted length ADJ.L, which is measured along the slope of the culvert.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		N	STO 3	N
	Initially use S_o	ADJ.S	STO 4	ADJ.S
		H_t	STO 5	H_t
		ST	STO 6	ST
		E	STO 7	E
3	Calculate the face width		A	B_f
4	Calculate the inlet length		B	L_1
5	Run program #14			
6	Repeat steps #2, #3, #4, and #5 until the values of B_f, L_1, and ADJ.S stabilize.			

EXAMPLE #1

In the design of a 48 inch CMP culvert with a 25-year discharge of 190 cfs., the throat elevation was determined to be 79.30 ft.

EXAMPLE #1 (cont)

The headwater elevation for this site was 70.90 feet. This gives a headwater depth of 8.40 feet. The original channel slope was 5% and a side taper of 6:1 is to be used. The E value will be 1.05D or 4.2 feet. Find the face width and the inlet length. The culvert is not to have a headwall but to be projecting from the fill slope.

Load program #36

KEYSTROKES	DISPLAY
190 STO 1	190.00
4 STO 2	4.00
1 STO 3	1.00
.05 STO 4	0.05
8.4 STO 5	8.40
6 STO 6	6.00
4.2 STO 7	4.20
A	6.42 ft. B_f
B	7.26 ft. L_1

These are just two estimates of B_f and L_1 based on the approximation of ADJ.S by S_o. Using this L_1 value in program #14, a value of ADJ.S = 0.02495 is obtained. Using this value in program #36.

190 STO 1	190.00
4 STO 2	4.00
1 STO 3	1.00

KEYSTROKES	DISPLAY
.02495 STO 4	0.02
8.4 STO 5	8.40
6 STO 6	6.00
4.2 STO 7	4.20

Note: These values must be restored since the running of program #14 has altered their original values.

A	6.28 ft. B_f
B	6.84 ft. L_1

Again taking the value of L_1 to program #14. A value of 0.024907 for ADJ.S is obtained. Using this value in program #36.

190 STO 1	190.00
4 STO 2	4.00
1 STO 3	1.00
.024907 STO 4	0.02
8.4 STO 5	8.40
6 STO 6	6.00
4.2 STO 7	4.20
A	6.28 ft. B_f
B	6.84 ft. L_1

The face width is 6.28 feet and the inlet length is 6.84 feet.

The corresponding values used in program #14 are as follows:

S_o = 0.05, FALL = 6.0 feet, S_{FU} = 3:1, L = 250 feet, D = 4 feet.

LISTING - PROGRAM #36

LBL A 1 LBL 1 CHS RCL 5 + RCL 7 + ENTER ENTER ENTER
1 4 8 CHS x 1 9 7 4 + x 9 6 4 2 - x 1 8 1
6 7 + x 1 1 5 0 5 + x 1 4 4 + 4 f^{-1} LOG +
RCL 1 g x≷y + 4 x g π + RCL 7 ENTER f $\sqrt{x}$ x + RCL
9 g x≷y g x=y GTO 2 RCL 2 RCL 3 x - 2 + RCL 6 x
STO 8 RCL 4 x GTO 1 LBL B RCL 8 RTN LBL 2 DSP . 2
RCL 2 g x≤y g x≷y g NOP RTN (99 STEPS)

LISTING - PROGRAM #37

LBL A 1 LBL 1 CHS RCL 5 + RCL 7 + ENTER ENTER ENTER
3 5 7 CHS x 4 2 2 8 + x 1 7 9 2 0 - x 2 9
7 8 4 + x 9 4 2 6 + x 4 8 - 4 f^{-1} LOG + RCL 1
g x≷y + 4 x g π + RCL 7 ENTER f $\sqrt{x}$ x + RCL 9
g x≷y g x=y GTO 2 RCL 3 RCL 2 x - 2 + RCL 6 x
STO 8 RCL 4 x GTO 1 LBL B RCL 8 RTN LBL 2 DSP . 2
RCL 2 g x≤y g x≷y g NOP RTN (98 STEPS)

LISTING - PROGRAM #38

LBL A 1 LBL 1 CHS RCL 5 + RCL 7 + ENTER ENTER ENTER
2 8 7 CHS x 3 7 4 4 + x 1 7 6 4 0 - x 3 2
9 9 4 + x 7 3 9 3 . 2 + x 4 f^{-1} LOG + RCL 1
g x≷y + 4 x g π + RCL 7 ENTER f $\sqrt{x}$ x + RCL 9
g x≷y g x=y GTO 2 RCL 3 RCL 2 x - 2 + RCL 6 x STO 8
RCL 4 x GTO 1 LBL B RCL 8 RTN LBL 2 DSP . 2 RCL 2
g x≤y g x≷y G NOP RTN (97 STEPS)

PROGRAMS #39 & 40 - PIPE CULVERT; INLET CONTROL OUTLET VELOCITY

These two programs determine the outlet velocity for circular pipe culverts by first calculating the normal depth of flow within the barrel. Once this depth is determined, the waterway area is calculated and the velocity is found by dividing the discharge by the area.

Due to the length of the polynomial equations employed and the limited number of program steps of the HP-65 calculator, two programs must be used.

Normally as the depth of water within a pipe culvert increases, the discharge correspondingly increases. However, after the depth of flow reaches a little over 90 percent of the culvert height, the discharge begins to decrease as the depth increases. This decrease in flow is a result of the large increase in the wetted permeter (barrel roughness) with only a small increase in the waterway area. This decrease in discharge continues until the barrel flows full. For a given discharge requiring a flow depth greater than 82 percent of the pipe diameter, two depths of flow may exist. One value will be between 82 percent and 93 percent of the pipe diameter and the other depth will be between 93 percent and 100 percent full. Correspondingly there exist two values for the waterway area and two values for the flow velocity. The calculator programs determine the smaller flow depth. This action will produce the smaller areas and the higher outlet velocities.

The equations used in the programs are polynomial expressions which approximate the normal depth curve for circular cross sections as found in Figure 6-1 of reference #4.

To operate these programs, program #39 is loaded into the calculator and the input valves are stored in their appropriate registers. Label A is then pressed and an intermediate valve is displayed. This number will vary depending upon which subroutine the calculator has exited from. Program #40 is then loaded into the calculator and Label A is again pressed. The outlet velocity value for this particular pipe culvert operating in inlet control will then be displayed.

EQUATIONS

$$X = (Qn/(1.486NS^{.5}))/D^{8/3}$$

$$Z = LOG\ (X)$$

If $X < 0.06$

$$d_n = D \times 10^{(0.136525 + 0.57114Z + 0.023622Z^2)}$$

If $0.06 \leq X < 0.24$

$$d_n = D \times 10^{(0.3063639 + 0.907884Z + 0.192615Z^2)}$$

If $0.24 \leq X < 0.34$

$$d_n = D \times 10^{(0.685734 + 2.097532Z + 1.125836Z^2)}$$

If $X \geq 0.34$

$$d_n = D$$

θ = arc cosine (radians) $(1-2d_n/D)$

$A = (D/2)^2\ (\theta - \sin\theta \cos\theta)$

$V = Q/(NA)$

REMARKS

Once the input values have been stored for program #39, they do not have to be re-entered for program #40.

The calculator may be used between the running of programs as long as registers #1, #3, #4, and #7 and Flags #1 and #2 are not altered.

STEP	INSTRUCTIONS	INPUT	KEYS	DISPLAY
1	Load program #39			
2	Input register values	Q	STO 1	Q
		D	STO 2	D
		N	STO 3	N
		n	STO 5	n
		S	STO 6	S
3	Calculate "X"		A	X
4	Load program #40			
5	Calculate outlet velocity		A	V
6	For a change in any of the design data, go to step #1.			

EXAMPLES #1

Find the outlet velocity for a CMP of diameter 54 inches, with a slope of 0.032 and a flow rate of 100 cfs. Manning's n is 0.024.

Load program #39

KEYSTROKES	DISPLAY
100 STO 1	100.00
4.5 STO 2	4.50
1 STO 3	1.00
.024 STO 5	0.02
0.32 STO 6	0.03
A	0.24

EXAMPLE #1 (cont.)

Load program #40

KEYSTROKES	DISPLAY
A	12.12 fps.

EXAMPLE #2

What would be the outlet velocity for example #1 if the flow rate was 200 cfs?

Load program #39

200 STO 1	200.00
4.5 STO 2	4.50
1 STO 3	1.00
.024 STO 5	0.02
.032 STO 6	0.03
A	-0.07

Load program #40

A	13.78 fps.

LISTING - PROGRAM #39

```
LBL  A  RCL 1  RCL 3  DIV  STO 1  RCL 2  2  DIV  STO 3  g  x≤y  RCL 5
X  1  .  4  8  6  DIV  RCL 6  f  SRX  DIV  RCL 2  8  ENTER  3  DIV  g  y^x
DIV  f  LOG  STO 7  g  LST x  .  0  6  g  x>y  GTO  1  g  x≤y  .  2  4
g  x>y  GTO  2  g x≤y  .  3  4  g  x>y  RCL 7  E  0  STO  4  RTN  LBL
E  1  .  1  2  5  8  3  6  x  2  .  0  9  7  5  3  2  +  RCL 7  x  .  6  8
5  7  3  4  +  STO 4  R/S  LBL  1  f  SF 1  RTN  LBL  2  f  SF 2  RTN
(100 STEPS)
```

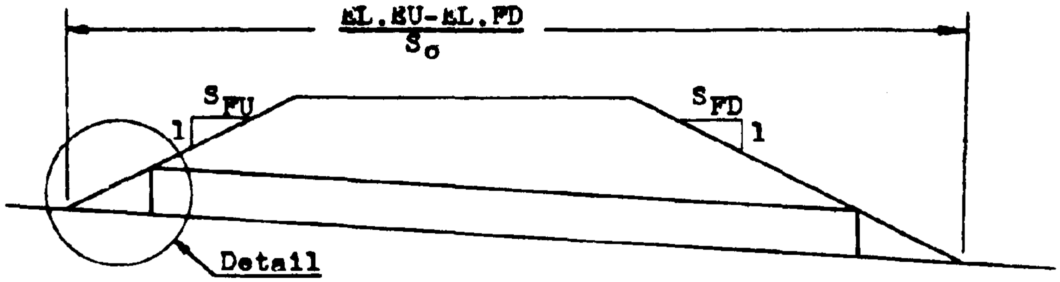
LISTING PROGRAM #40

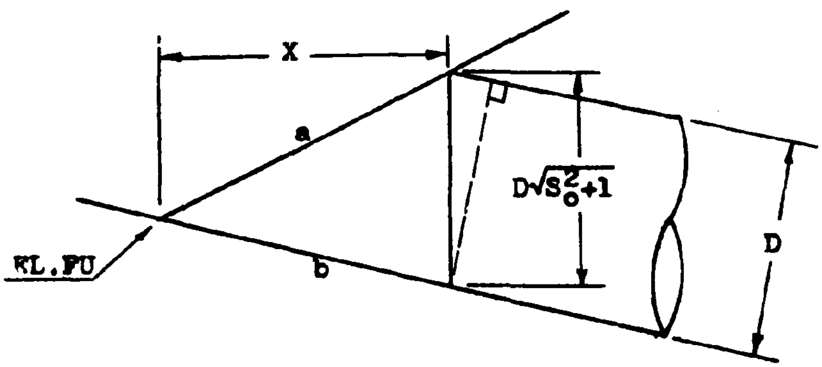
LBL A f TF 1 RCL 7 D f^{-1} TF 2 RCL 4 E RCL 7 . 1 9 2 6 1 5 X . 9 0 7 8 8 4 + RCL 7 X . 3 0 6 3 6 3 9 + E LBL D . 0 2 3 6 2 X . 5 7 1 1 4 + RCL 7 X . 1 3 6 2 5 + LBL E f^{-1} LOG 2 X 1 - CHS g RAD g COS^{-1} ENTER ENTER f COS g X⪌y f SIN X - RCL 3 ENTER X X RCL 1 g X⪌y DIV g DEG f^{-1} SF 1 f^{-1} SF 2 R/S (100 STEPS)

APPENDIX A

Derivations of Equations Used in Programs

PROGRAM #2





The equation for the fill slope (line a) is:

$$Y_a = \frac{X}{S_{FU}} + EL.FU$$

Similarly, the equation for the channel slope (line b) is:

$$Y_b = -S_o X + EL.FU$$

At the face of the culvert, the difference between these two equations equals the height of the culvert.

PROGRAM#2 (cont)

$$D\sqrt{S_o^2+1} = Y_a - Y_b = \frac{X}{S_{FU}} + EL.FU + S_oX - EL.FU = \frac{X}{S_{FU}} + S_oX$$

Solving for the unknown value X;

$$X = \frac{D\sqrt{S_o^2+1}}{(\frac{1}{S_{FU}} + S_o)} = \frac{S_{FU}D\sqrt{S_o^2+1}}{(1+S_oS_{FU})}$$

For the downstream condition, a similar value for X would be;

$$X = \frac{S_{FD}D\sqrt{S_o^2+1}}{(1-S_oS_{FD})}$$

Multiplying these values by the channel slope will give the change in elevation across the distance X. From this, the inlet and outlet elevations can be determined.

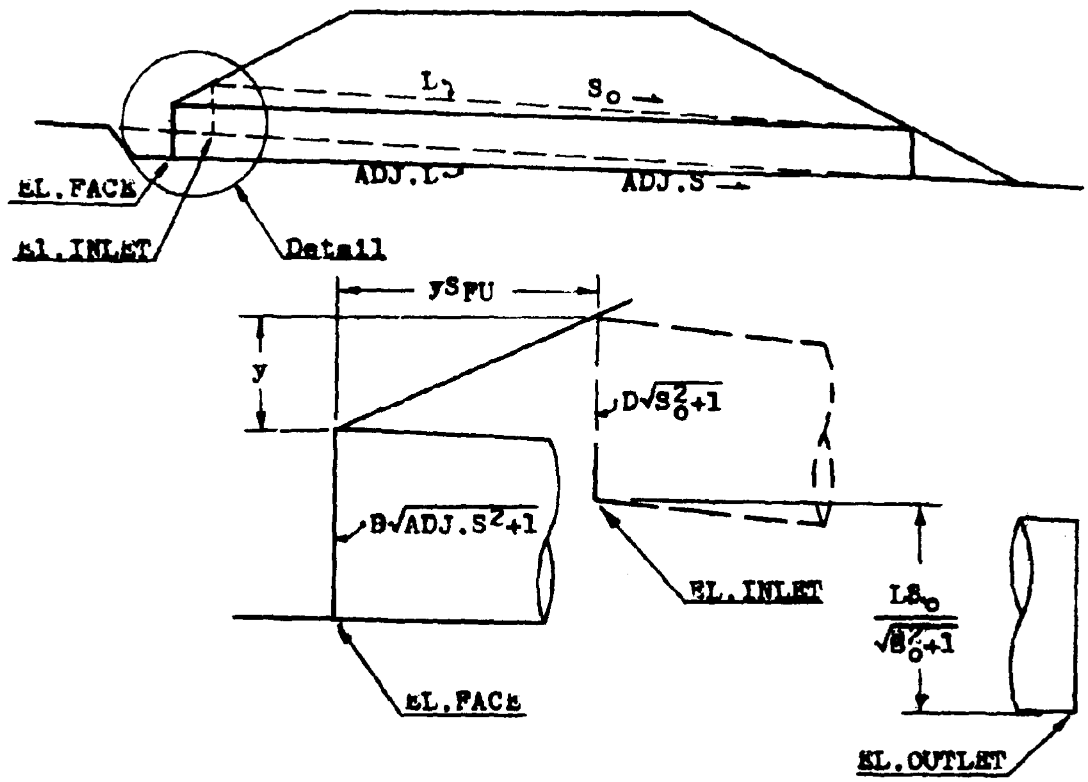
$$EL.INLET = EL.FU - \frac{S_oS_{FU}D\sqrt{S_o^2+1}}{(1+S_oS_{FU})}$$

$$EL.OUTLET = EL.FD + \frac{S_oS_{FD}D\sqrt{S_o^2+1}}{(1-S_oS_{FD})}$$

From these two values, the culvert length can be determined.

$$L = \frac{(EL.INLET-EL.OUTLET)\sqrt{S_o^2+1}}{S_o}$$

PROGRAM #9



There are three unknowns to be solved for in this program. ADJ.L, ADJ.S, and the vertical distance y. Knowing that the FALL is the difference between the inlet and face elevations, an expression for y can be obtained.

$$y = FALL + D\sqrt{S_o^2+1} - D\sqrt{ADJ.S^2+1}$$

Using a rise/run relationship, the value of ADJ.S becomes:

$$ADJ.S = \frac{(LS_o/\sqrt{S_o^2+1})-FALL}{(L/\sqrt{S_o^2+1})+yS_{FU}} = \frac{LS_o-FALL\sqrt{S_o^2+1}}{L+yS_{FU}\sqrt{S_o^2+1}}$$

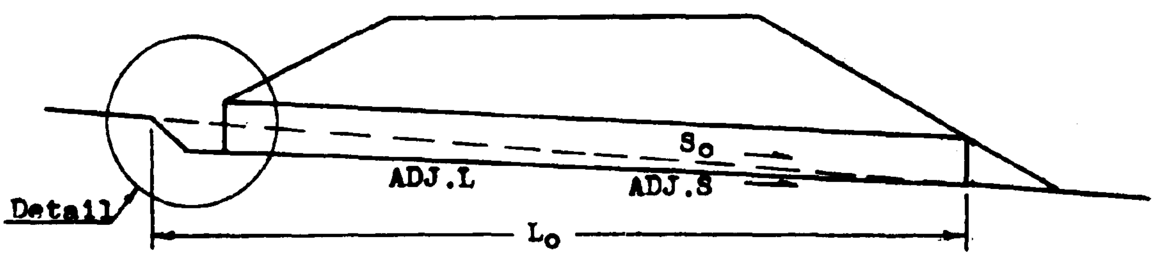
PROGRAM #9 (cont)

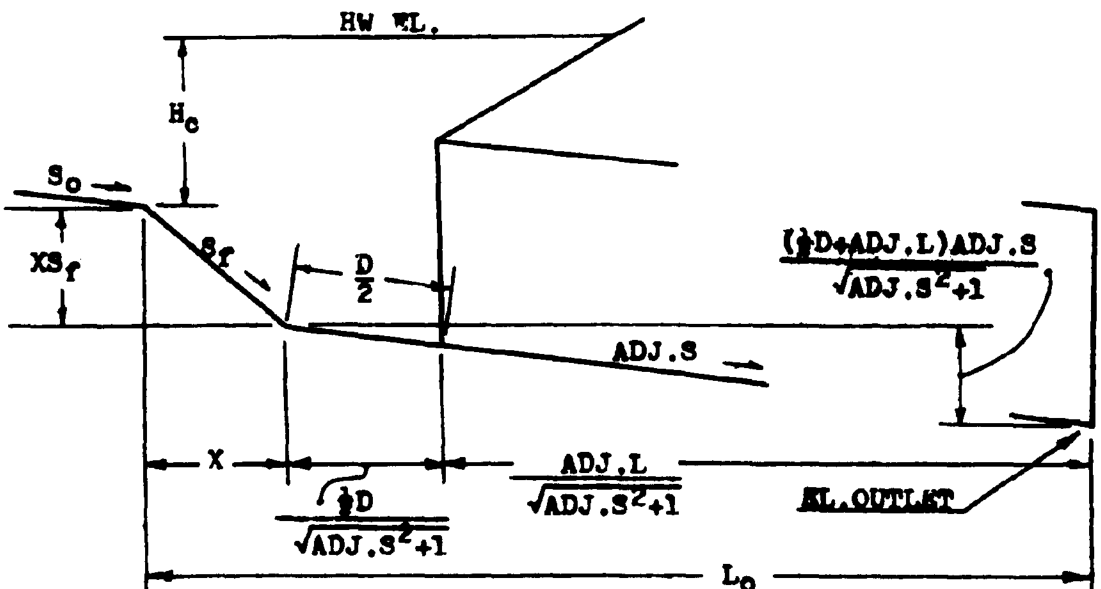
Due to the complexity of these two equations they are solved by a trial and error method by the calculator.

Once the adjusted slope is found the adjusted length can be obtained by multiplying the difference in elevation between the face invert and the outlet invert by the cosecant of the adjusted slope.

$$ADJ.L = \left(\frac{LS_o}{\sqrt{S_o^2+1}} - FALL\right)\left(\frac{\sqrt{ADJ.S^2+1}}{ADJ.S}\right)$$

PROGRAM #10





PROGRAM #10 (cont)

From the diagrams the value of L_o can be determined.

$$L_o = X + \frac{\frac{1}{2}D}{\sqrt{ADJ.S^2+1}} + \frac{ADJ.L}{\sqrt{ADJ.S^2+1}}$$

Since the value of X is also an unknown, an expression for it is also required. Summing vertical distances produces;

$$L_oS_o = XS_f + \frac{(\frac{1}{2}D+ADJ.L)ADJ.S}{\sqrt{ADJ.S^2+1}}$$

Combining these two equations, an expression for L_o without the value of X in it, is obtained.

$$L_o = \frac{(S_f-ADJ.S)(\frac{1}{2}D+ADJ.L)}{(S_f-S_o)\sqrt{ADJ.S^2+L}}$$

Substituting this value in an expression for H_c:

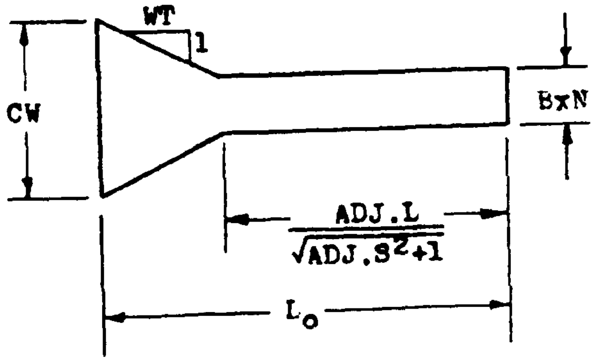
$$H_c = HW\ EL. - EL.OUTLET - L_oS_o$$

$$H_c = HW\ EL. - EL.OUTLET - \frac{S_o(S_f-ADJ.S)(\frac{1}{2}D+ADJ.L)}{(S_f-S_o)\sqrt{ADJ.S^2+1}}$$

The crest width can be calculated using this value of H_c. The formula relating crest width to the depth of water at the crest is taken from the references and is not derived here.

$$CW = \frac{Q}{(2H_c)^{1.5}}$$

PROGRAM #10 (cont)

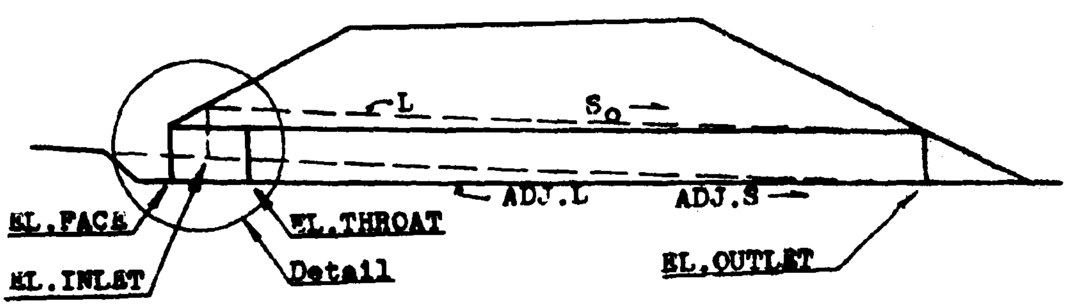


From this diagram, the wingwall taper is determined.

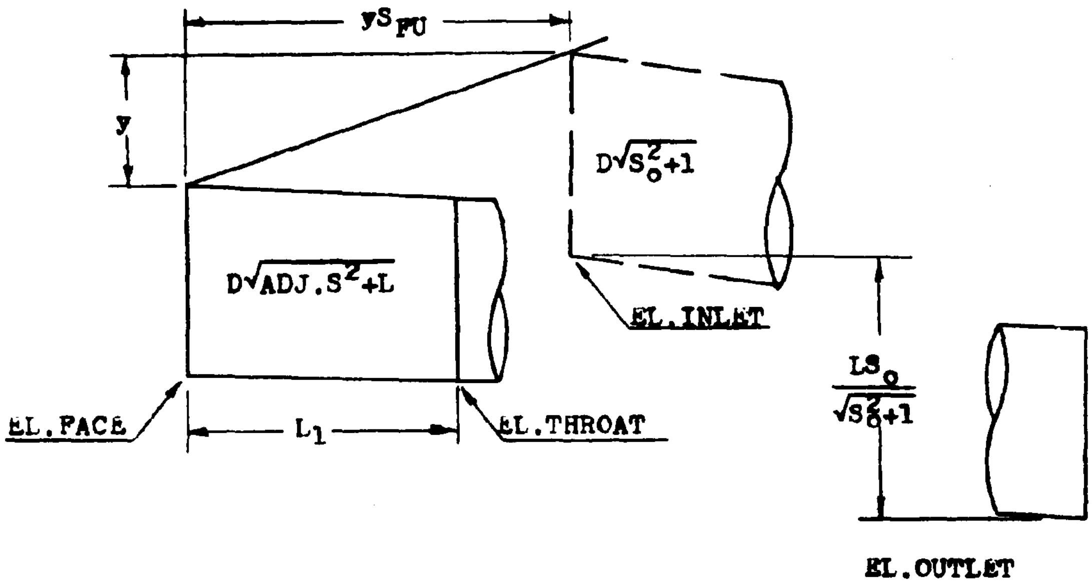
$$WT = \frac{(L_O - L/\sqrt{ADJ.S^2+1}}{(CW-BxN)/2}$$

The wingwall angle is just 90° - the arctangent of the wingwall taper.

PROGRAM #14



PROGRAM #14 (cont)



The formulas given here are similar to those given in program #9, except a new unknown L_1 has been introduced. The meaning of FALL has changed also. It now equals the difference between the elevation of the inlet and the elevation of the throat. The expressions for y and ADJ.S now equal;

$$y = FALL + D\sqrt{S_o^2+1} - D\sqrt{ADJ.S^2+1} - L_1 ADJ.S$$

$$ADJ.S = \frac{LS_o - FALL\sqrt{S_o^2+1} + L_1 ADJ.S\sqrt{S_o^2+1}}{L + yS_{PU}\sqrt{S_o^2+1}}$$

Substituting:

$$0 = (FALL + D\sqrt{S_o^2+1} - D\sqrt{ADJ.S^2+1})S_{PU}ADJ.S\sqrt{S_o^2+1} - LS_o$$
$$+ FALL\sqrt{S_o^2+1} - L_1 ADJ.S\sqrt{S_o^2+1} + LADJ.S - L_1 ADJ.S^2 S_{PU}\sqrt{S_o^2+1}$$

PROGRAM #15

The adjusted length computations used in program #15 can be derived using the diagrams of program#14. Once the adjusted slope is calculated by program #14, it is used by this program to find the new culvert length.

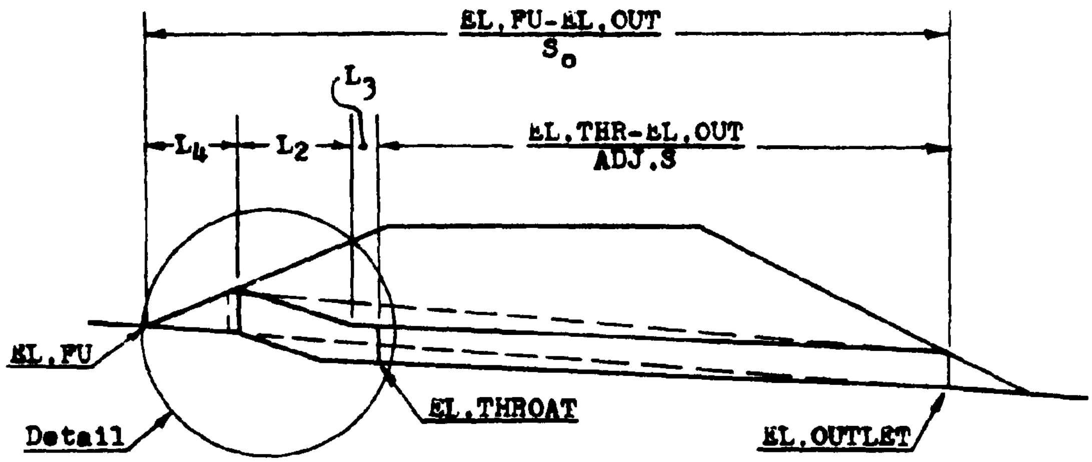
As was the case in program #9, the adjusted length is the product of the cosecant of the adjusted slope and a difference in elevations. In program #9, the difference was between the face invert elevation and the outlet invert elevation. For this program the difference is between the throat invert and the outlet invert. Although this difference in definition exists, it has little effect on the formula below. This differense is resolved by the two different definitions of the FALL. In program #9, the FALL is the difference in elevation between the inlet invert and the face invert. In program #15, it is the difference in elevation between the inlet invert and and the throat invert. After the culvert length is found, the length of the improved inlet is subtracted off.

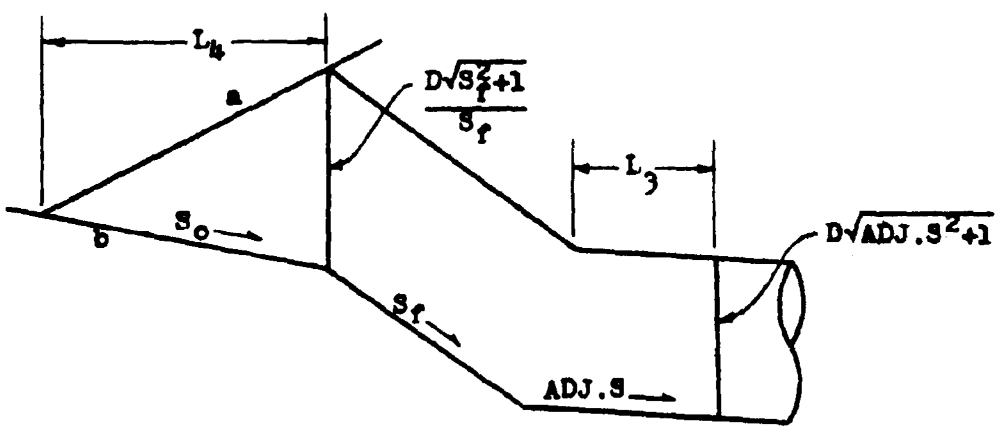
$$ADJ.L = \left(\frac{LS_o}{\sqrt{S_o^2+1}} - FALL\right)\left(\frac{\sqrt{ADJ.S^2+1}}{ADJ.S}\right) - L_1\sqrt{ADJ.S^2+1}$$

Sliding back up the adjusted slope from the throat section:

$$EL.FACE = EL.THROAT + L_1 ADJ.S$$

PROGRAM #16





The equation for the fill slope (line a) is:

$$Y_a = \frac{L_4}{S_{FU}} + EL.FU$$

Similarly, the equation for the channel slope (line b) is:

$$Y_b = -S_o L_4 + EL.FU$$

PROGRAM #16 (cont)

At the face of the culvert, the difference between these two equations equals the height of the culvert.

$$\frac{D\sqrt{S_f^2+1}}{S_f} = Y_a - Y_b = \frac{L_4}{S_{FU}} + EL.FU + S_oL_4 - EL.FU$$

Solving this expression for L_4:

$$L_4 = \frac{S_{FU}D\sqrt{S_f^2+1}}{S_f(1+S_oS_{FU})}$$

From the first diagram, it can be determined that;

$$L_2 = \frac{EL.FU-EL.OUT}{S_o} - L_4 - L_3 - \frac{EL.THR-EL.OUT}{ADJ.S}$$

By summing measurements in the vertical direction, the following expression was obtained.

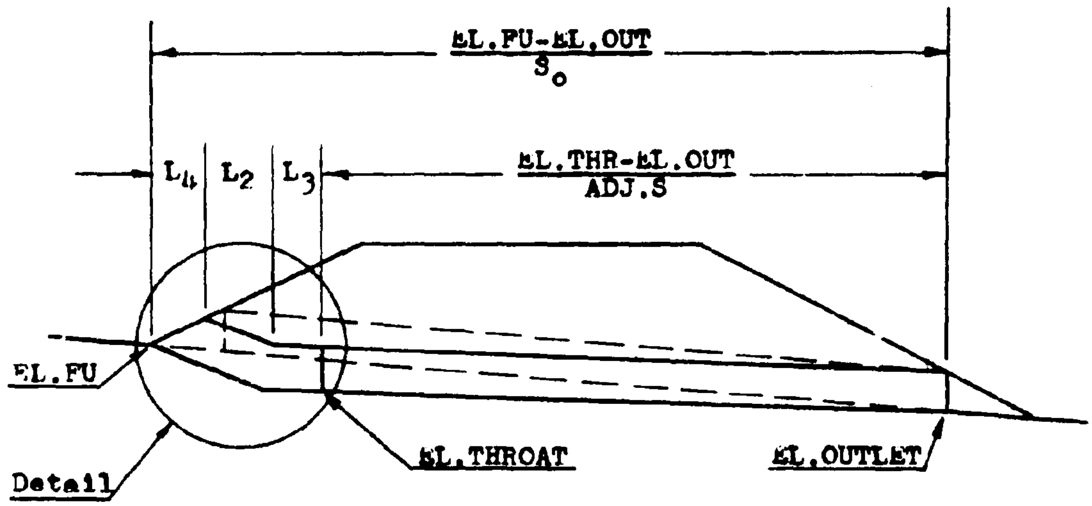
$$EL.THR = EL.FU + \frac{L_4}{S_{FU}} - \frac{L_2}{S_f} - L_3ADJ.S - D\sqrt{ADJ.S^2+1}$$

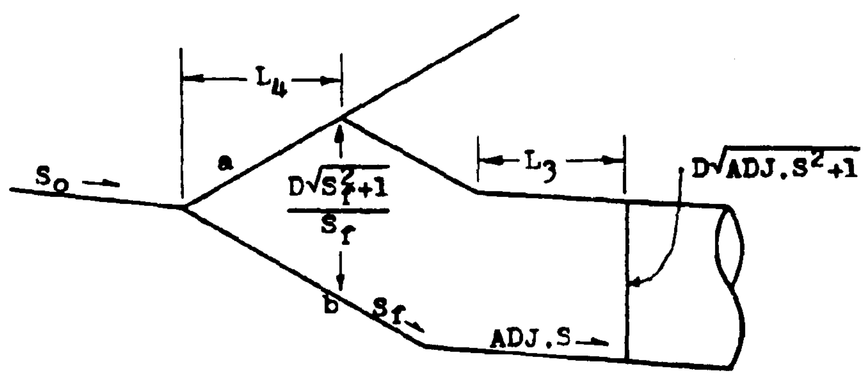
Combining these last three equations, an expression for the adjusted slope can be obtained.

$$0 = EL.FU + \frac{(S_f+S_{FU})D\sqrt{S_f^2+1}}{S_f^2(1+S_oS_{FU})} + \frac{L_3}{S_f} + \frac{EL.OUT-EL.FU}{S_oS_f} - L_3ADJ.S$$

$$+ \frac{EL.THR-EL.OUT}{S_fADJ.S} - D\sqrt{ADJ.S^2+1} - EL.THROUT$$

PROGRAM #17





The equation for the fill slope (line a) is:

$$Y_a = \frac{L_4}{S_{FU}} + EL.FU$$

Similarly, the equation for the fall slope (line b) is:

$$Y_b = \frac{-L_4}{S_f} + EL.FU$$

PROGRAM #17 (cont)

At the face of the culvert, the difference between these two equations equals the height of the culvert face.

$$\frac{D\sqrt{S_f^2+1}}{S_f} = Y_a - Y_b = \frac{L_4}{S_{FU}} + EL.FU + \frac{L_4}{S_f} - EL.FU$$

Solving this expression for L_4:

$$L_4 = \frac{S_{FU}D\sqrt{S_f^2+1}}{S_{FU}+S_f}$$

From the first diagram on the previous page:

$$L_2 = \frac{EL.FU-EL.OUT}{S_o} - L_4 - L_3 - \frac{EL.THR-EL.OUT}{ADJ.S}$$

By summing the measurements in the vertical direction, the following expression was obtained.

$$EL.THR = EL.FU + \frac{L_4}{S_{FU}} - \frac{L_2}{S_f} - L_3 ADJ.S - D\sqrt{ADJ.S^2+1}$$

Combining these last three equations, an expression for the adjusted slope can be obtained.

$$0 = EL.FU + \frac{D\sqrt{S_f^2+1}}{S_f} + \frac{L_3}{S_f} + \frac{EL.OUT-EL.FU}{S_o S_f} + \frac{EL.THR-EL.OUT}{S_f ADJ.S}$$

$$- L_3 ADJ.S - D\sqrt{ADJ.S^2+1} - EL.THROAT$$

PROGRAM #18

For the derivations of the equations for L_2 and L_4 refer to the derivations for program #16.

The WL.FACE equation can be taken from the diagrams of program #16. The ADJ.L is equal to the cosecant of the adjusted slope times the change in elevation between the throat section and the outlet section.

PROGRAM #19

Refer to the derivation equations for program #17 for an explanation of how L_2 and L_4 were obtained.

The WL.FACE equation can be taken from the diagrams of program #17. The ADJ.L is equal to the cosecant of the adjusted slope times the change in elevation between the throat invert and the outlet invert.

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4. "Open Channel Hydraulics," V. T. Chow, McGraw-Hill Book Company, Inc., New York, 1959.

5. "Open Channel Flow," F. M. Henderson, The MacMillan Company, New York, 1966.