U. S. Dept. of Agriculture
Soil Conservation Service
Engineering Division
Design Branch

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DESIGN NOTE NO. 8*

Subject: Entrance Head Losses in Drop Inlet Spillways

During the past several years, hydraulic model tests of drop inlet spillways have been in progress at St. Anthony Falls, Minnesota, and Stillwater, Oklahoma. New elbows and transitions have been tested at St. Anthony Falls, and inlets with trash racks and simulated trash have been tested on large-scale models at Stillwater. Although the tests have not been completed and reports are not yet available, considerable information on entrance losses has been obtained which can be used in design.

Table I is a summary of entrance head loss coefficients compiled from a recent review of all available data. The coefficients marked with asterisks were estimated from test data. The others are measured values. All are considered reliable for design purposes.

The nomenclature in this design note is the same as in Technical Release No. 29. The entrance head loss coefficient, K_e, multiplied by the velocity head in the conduit (barrel) gives the total entrance head loss from the reservoir to the conduit, including elbow and transition losses at the conduit entrance. For full pipe flow, as shown in TR 29,

$$H_o = \frac{v_b^2}{2g}(1 + K_e + K_p L_b) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where H_o = total head on the spillway
v_b = mean velocity of flow in the conduit
K_e = entrance head loss coefficient
K_p = friction loss coefficient for the conduit (see ES-42)
L_b = length of the conduit

Figure 1 illustrates how the quantities in Equation (1) are related. The hydraulic grade line usually is considered to intersect the plane of the conduit outlet 0.5D above the invert of the conduit or at the tailwater surface, whichever is higher. H_o is equal to the difference in elevation between the HGL at this point and the reservoir water surface.

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TABLE I

ENTRANCE LOSS COEFFICIENTS
IN DROP INLET SPILLWAYS

Description of Spillway	Minimum Clear Water K_e	Maximum With Debris K_e
1. Round conduit and Standard Covered Top Riser, except with special elbow and transition (Fig. 2 and ES-150)		
D x 1.5D Riser	0.65	0.75*
D x 2D Riser	0.41	0.50*
D x 3D Riser	0.25	0.35*
D x 5D Riser	0.17	0.30*
2. Round conduit and Standard Covered Top Riser, with round bottom and square-edged entrance to conduit (ES-150)		
D x 3D Riser	0.60*	0.70*
3. Round conduit and Standard Rectangular Open Top Riser, with round bottom and square-edged entrance to conduit (ES-151)		
D x 3D Riser	0.50*	0.90*
4. Round conduit and Standard Rectangular Open Top Riser, with flat bottom and square-edged entrance to conduit (ES-151)		
D x 3D Riser	0.60*	1.10*
5. Round conduit and Standard Square Open Top Riser, with flat bottom and square-edged entrance to conduit (ES-152)		
(D + 12) x (D + 12) Riser	1.20	2.00*
6. Rectangular conduit[1] with Standard Covered Top Riser, except with flat bottom, and with elbow as shown in Figure 4. Riser width equal to conduit width. D ≥ 4 ft.,		
B x 3D Riser, Rounded elbow	0.40*	
Special elbow	0.25*	
7. Rectangular conduit[1] with open top riser, no trash rack, and with elbow as shown in Figure 4. Riser width equal to conduit width, D ≥ 5 ft.,		
B x 3D Riser, Rounded elbow	0.35*	
Special elbow	0.20*	

*Estimated values
[1]Rectangular conduit B wide x D high with B x 3D riser.

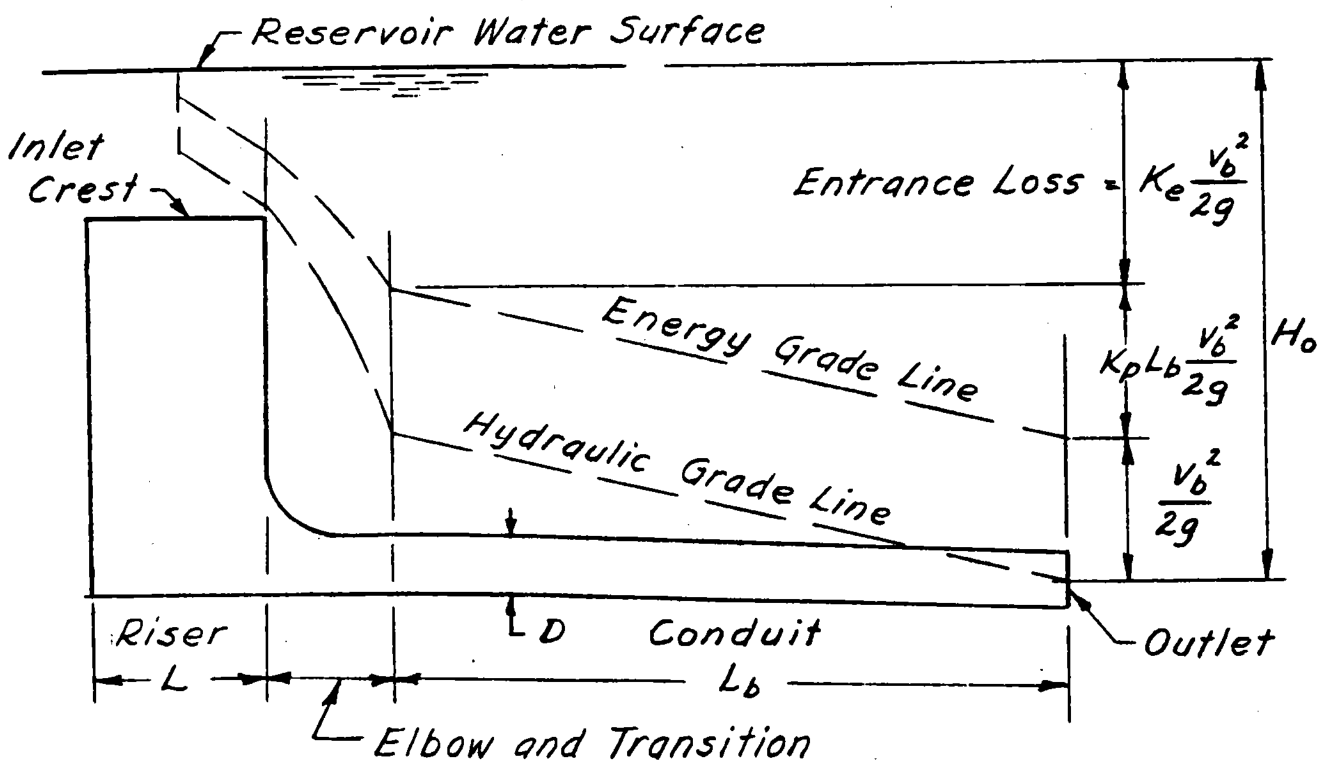

Figure 1. Full Pipe Flow

Special Elbow and Transition

Details of two elbows and a transition tested at St. Anthony Falls, for a rectangular riser and round pipe conduit, are shown in Figure 2 and Figure 3. Hydraulic performance of the two elbows is about the same.

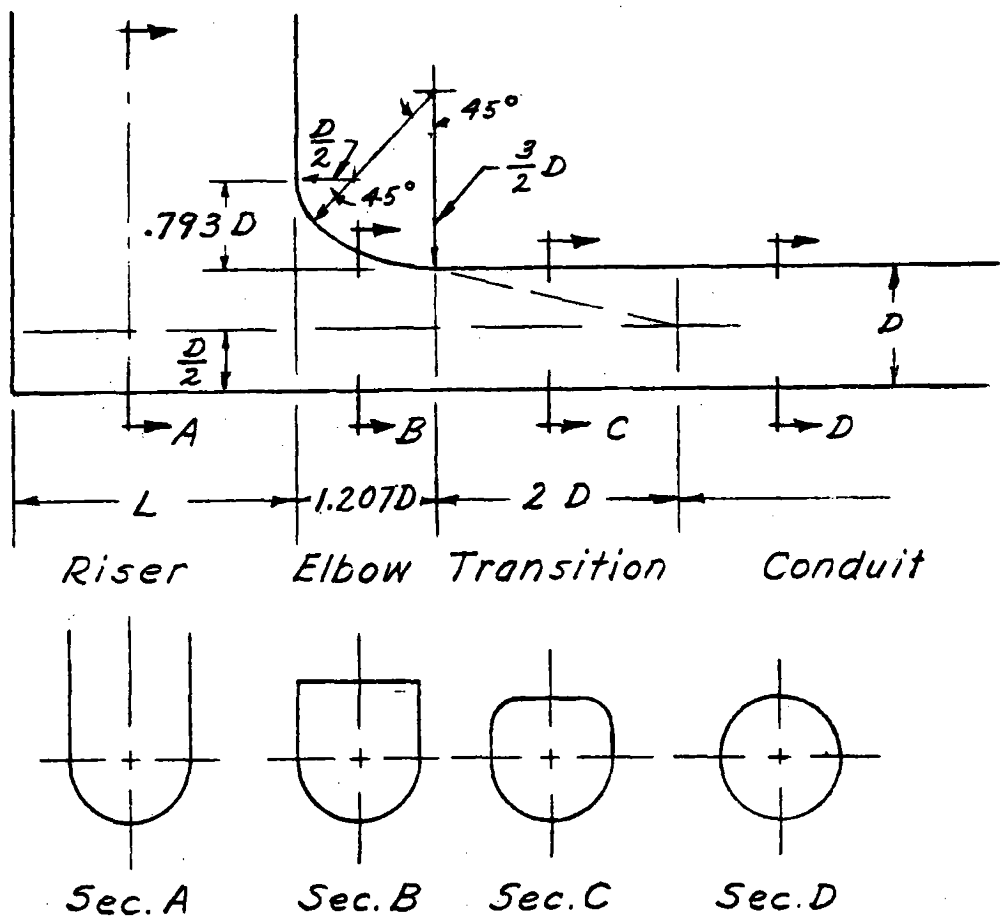

Figure 2. Special Elbow and Transition
(SAF Elbow 6 and Transition A)

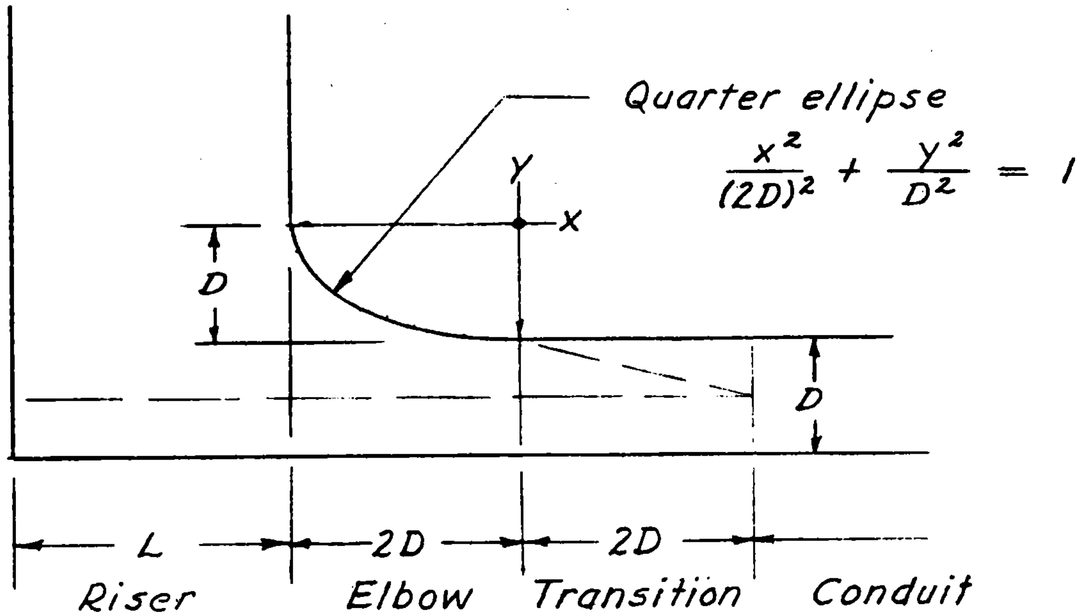

Figure 3. Alternative Special Elbow
(SAF Elbow 3 and Transition A)

The bottom of the riser and the invert of the elbow and transition are horizontal, and form a continuous half-cylinder of diameter D, matching the lower half of the round conduit. The change from horizontal at the outlet of the transition, to the conduit slope farther downstream is made by small angle changes at the first few pipe joints. The elbow is rectangular above the horizontal diameter. The upper half of the transition is rectangular at the upstream end and semicircular at the downstream end. Its surface consists of three plane triangles, on the top and sides, and two quarter-cones. The conical surfaces can be formed from flat sheet stock. Both the elbow and the transition were designed for ease of forming.

The special elbow and transition were developed to fill the need for a smooth transition from a rectangular riser to a round conduit. The standard square-edged conduit entrance is satisfactory in most cases. It is subject to flow separation and a substantial pressure drop just inside the conduit entrance, however, as indicated in TR 29. In large structures, especially high-head, high-velocity structures, the vibrations caused by the resulting turbulence may be intolerable. In some circumstances, the pressure drop may be sufficient to cause cavitation. Little, if any, separation occurs in the special elbow and transition, and the local pressure drop is essentially eliminated. An added advantage is that the energy loss is much less than in the square-edged entrance; enough to make a difference of several feet in the total head required for a given discharge in some cases.

Entrance Loss Coefficients

The "minimum, clear water" values of K_e in Table I represent the condition where minimum losses occur in the trash racks. The "maximum with debris" values are for trash racks partially blocked by debris. The susceptibility of the various types of inlets to clogging with debris was considered in estimating the coefficients.

Minimum coefficients will give the highest discharges and velocities. They should be used in appraising the downstream effects of maximum discharge and in determining the requirements for energy dissipation. Maximum coefficients should be used for establishing reservoir storage volume requirements and computing drawdown time. The relationship between friction loss in the conduit and local pressure deviations will indicate whether maximum or minimum velocities are more critical for cavitation potential.

Table I gives new values of K_e for the Standard Covered Top Riser. In TR 29, a test value of 0.687 is quoted and $K_e = 1.0$ is recommended for design. The tests were made with a flat bottom riser, however, while the standard riser has a round bottom. Losses at the conduit entrance probably are lower with the round bottom riser. Subsequent tests of the special elbow with a round bottom riser have given further support to lower values of K_e. The values in Table I (0.60 and 0.70), therefore, are believed to be the best estimates on the basis of data available thus far.

The coefficients for rectangular conduits are applicable to conduits not less than 4 feet deep having risers with the standard covered top and trash rack (ES-150), and to conduits not less than 5 feet deep having open top risers with no trash racks. Spillways of this size, detailed as indicated, are capable of passing most debris without danger of clogging. Hence, only "clear water" coefficients are applicable. The "rounded" and "special" elbows for which coefficients are given are illustrated in Figure 4.

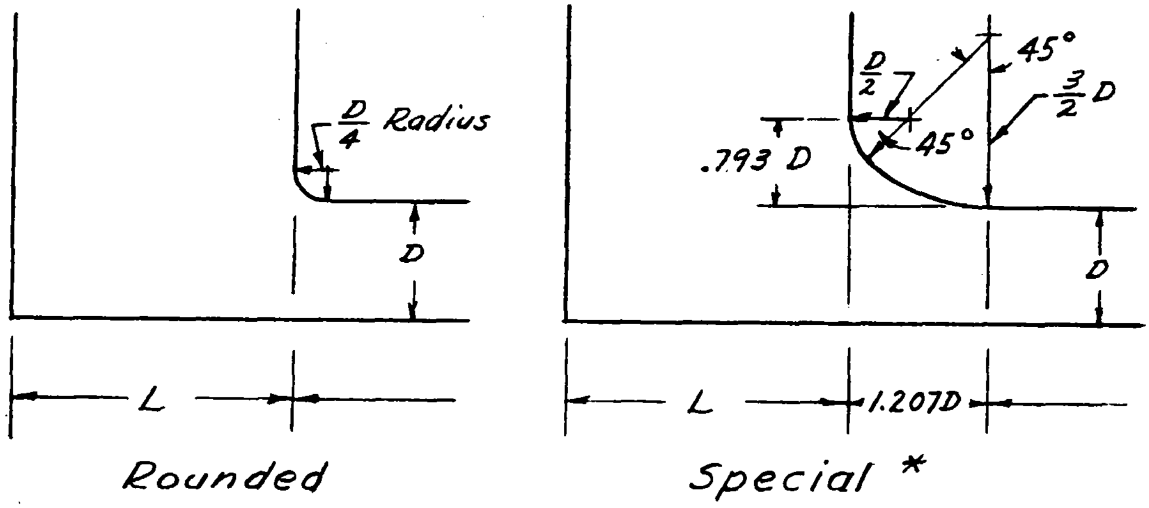

Figure 4. Elbows for Rectangular Conduit
*Elliptical curve may be used for special elbow, as in Fig. 3

Example:

A drop inlet spillway is required to discharge 470 cfs when the reservoir water surface is at the crest of the emergency spillway. Elevation of the hydraulic grade line at the conduit outlet is 100 (assumed datum). The emergency spillway crest elevation is to be approximately 170, and maximum pool level will be 6 feet above the crest. Crest of the principal spillway is to be at elevation 150.

Actual elevation of the structure is about 2000 feet above sea level.

The conduit is to be 380 feet long, on a slope of 6 feet per 100 feet. A 48-inch reinforced concrete pressure pipe conduit with a Standard Covered Top Riser (ES-150) will be tried. Estimated Manning's n for the conduit is .010, minimum, to .013, maximum.

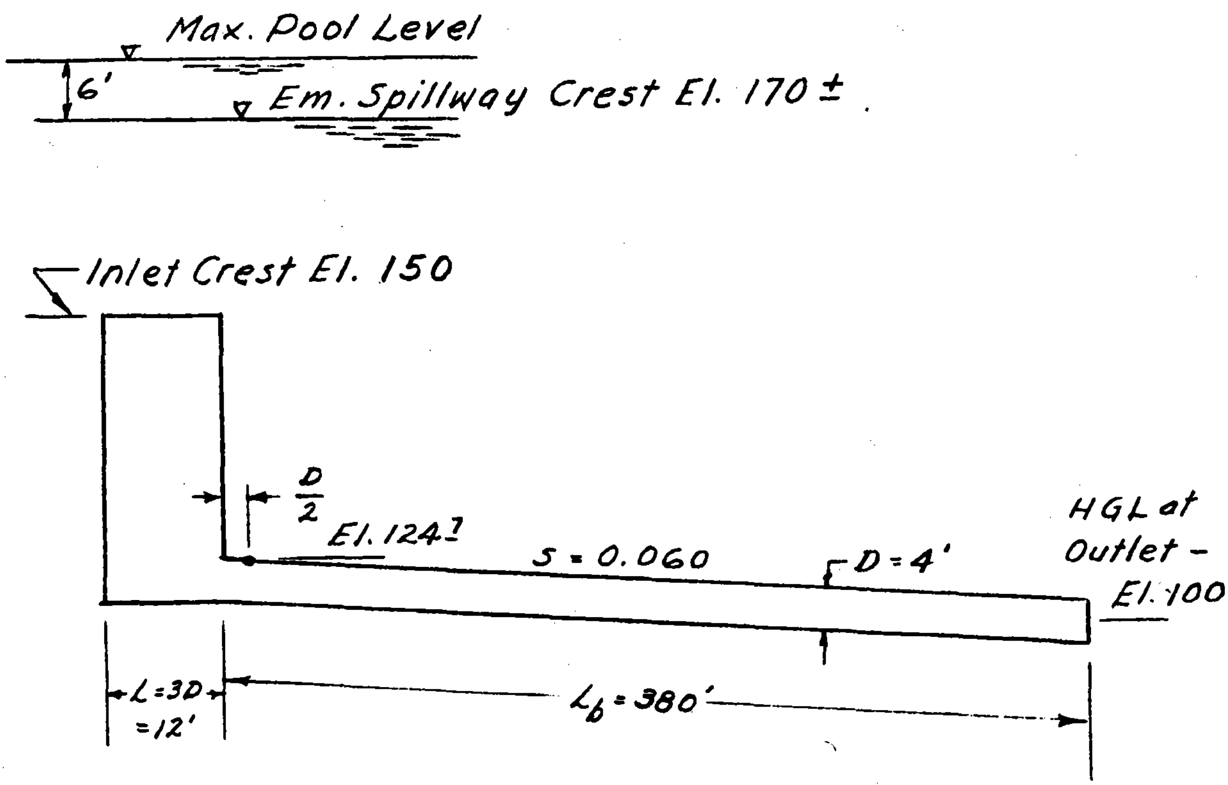

Figure 5. Example

I. Compute required head and emergency spillway crest elevation.

Conduit area $a_b = \pi(2.0)^2 = 12.6 \text{ ft.}^2$

Velocity $v_b = \frac{470}{12.6} = 37.3 \text{ fps}$

Velocity head $\frac{{v_b}^2}{2g} = \frac{(37.3)^2}{2(32.2)} = 21.6 \text{ ft.}$

If n = .013 $K_p = .00493$ (ES-42)

$K_p L_b = (.00493)(380) = 1.87$

With standard square-edged conduit entrance

Maximum $K_e = 0.70$ (Table I)

Total head $H_o = \frac{{v_b}^2}{2g}(1 + K_e + K_p L_b)$

$= (21.6)(1 + 0.70 + 1.87)$

$= 77.2 \text{ ft.}$

Emergency spillway crest elevation $= 100 + 77.2 = 177$

With special elbow and transition

Maximum $K_e = 0.35$ (Table I)

Total head $H_o = \frac{v_b^2}{2g}(1 + K_e + K_p L_b)$

$= (21.6)(1 + 0.35 + 1.87)$

$= 69.6$ ft.

Emergency spillway crest elevation $= 100 + 69.6 = 170$

II. Compute minimum pressure at conduit entrance

With standard square-edged conduit entrance

Maximum local deviation of hydraulic grade line $= 1.2 \frac{v_b^2}{2g}$ at crown of conduit $\frac{D}{2}$ downstream from entrance (Ref. TR 29).

Elevation of crown of conduit $\frac{D}{2}$ downstream from entrance

$$Z_c = 100 + 0.06\left(L_b - \frac{D}{2}\right) + \frac{D}{2}$$

$$= 100 + 0.06\,(378) + 2.0 = 124.7$$

Elevation of hydraulic grade line $\frac{D}{2}$ downstream from conduit entrance

$$HGL = 100\ K_p\left(L_b - \frac{D}{2}\right)\frac{v_b^2}{2g} - 1.2\,\frac{v_b^2}{2g}$$

If $n = .010$ $K_p = .00292$

$K_p L_b = .00292(380) = 1.11$

$K_p\left(L_b - \frac{D}{2}\right) = .00292(378) = 1.10$

$$HGL = 100 + 1.10 \frac{v_b^2}{2g} - 1.2 \frac{v_b^2}{2g} = 100 - 0.1 \frac{v_b^2}{2g} \quad . \quad . \quad (a)$$

Here, the coefficient applied to velocity head for the local negative deviation of the hydraulic grade line is larger than the positive coefficient for friction head. Therefore, as shown by Equation (a), the low point on the HGL at the conduit entrance will be lowest when the velocity is highest.

∴ To find the lowest pressure, use conditions giving the highest velocity.

Maximum pool elevation = 177 + 6 = 183 ft.

Maximum H_b = 183 - 100 = 83 ft.

Minimum K_e = 0.60 (Table I)

$$H_b = \frac{v_b^2}{2g} (1 + K_e + K_p L_b) = \frac{v_b^2}{2g} (1 + 0.60 + 1.11) = 2.71 \frac{v_b^2}{2g}$$

$$\frac{v_b^2}{2g} = \frac{H_b}{2.71} = \frac{83}{2.71} = 30.6 \text{ ft.}$$

$$HGL = 100 - 0.1 \frac{v_b^2}{2g} = 100 - 0.1 (30.6) = 96.9 \text{ ft.}$$

Pressure head at crown of conduit

h_{pc} = HGL - Z_c = 96.9 - 124.7 = -27.8 ft.

Probable minimum atmospheric pressure at elevation 2000 (TR 4, Table II)

= 1876 psf

= 30.0 ft. H_2O

Absolute pressure head at crown of conduit

= 30.0 - 27.8 = 2.2 ft.

This is higher than the vapor pressure of water at usual temperatures, but pulsations could easily produce momentary cavitation pressures locally when the average pressure is this low.

With special elbow and transition

Local deviation of hydraulic grade line is essentially zero.

Elevation of crown of conduit at entrance (downstream end of transition, Figure 2)

$$Z_c = 100 + 0.06\ (L_b - 3.207D) + \frac{D}{2}$$

$$= 100 + 0.06\ (367.2) + 2.0 = 124.0$$

Elevation of hydraulic grade line at conduit entrance

$$HGL = 100 + K_p\,(L_b - 3.207D)\ \frac{v_b^2}{2g}$$

If $n = .010 \quad K_p = .00292$

$$K_p L_b = (.00292)(380) = 1.11$$

$$K_p\,(L_b - 3.207D) = (.00292)(367.2) = 1.07$$

$$HGL = 100 + 1.07\ \frac{v_b^2}{2g} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (b)$$

In this case, there is no local drop in the hydraulic grade line. The friction head coefficient is positive. Therefore, as shown by Equation (b), the HGL is lowest at the conduit entrance when the velocity is lowest.

$\therefore$ To find the lowest pressure, use conditions giving the lowest velocity (with full pipe flow).

Minimum pool elevation for pipe flow

$$= 150 + \frac{D}{2} = 150 + 2.0 = 152 \qquad \text{(TR 29)}$$

Minimum $H_b = 152 - 100 = 52$ ft.

Maximum $K_e = 0.35$ (Table I)

$$H_b = \frac{v_b^2}{2g}\,(1 + K_e + K_p L_b) = \frac{v_b^2}{2g}\,(1 + 0.35 + 1.11) = 2.46\ \frac{v_b^2}{2g}$$

$$\frac{v_b^2}{2g} = \frac{H_b}{2.46} = \frac{52}{2.46} = 21.1 \text{ ft.}$$

$$HGL = 100 + 1.07 \frac{v_b^2}{2g} = 100 + 1.07\ (21.1) = 122.6$$

Pressure head at crown of conduit

$$h_{p\,c} = HGL - Z_c = 122.6 - 124.0 = -1.4 \text{ ft.}$$

Absolute pressure head at crown of conduit (see page 10)

$$= 30.0 - 1.4 = 28.6 \text{ ft.}$$