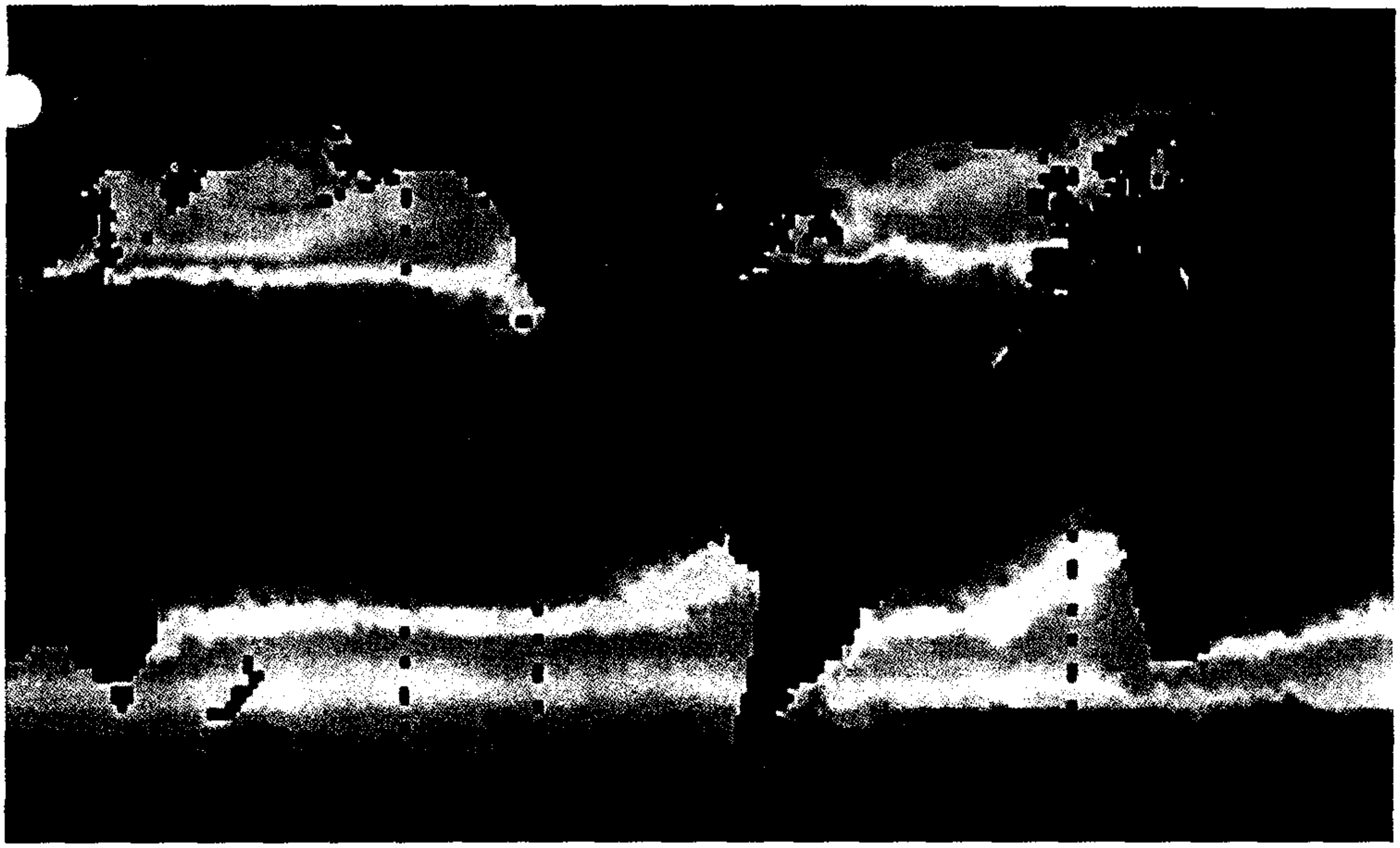

(image courtesy of FEMA El Nino Loss Reduction Center/ http://www.fema.gov/nwz97/elnino.htm)

Winter '97/'98: Year of the Great El Niño?

San Diego, CA

March 11-13, 1998

Floodplain Management Association

Technical Program Chair: Lisa Vomero Inouye
A & M Engineering Consultants of California

Chair: Clark Farr, County of Kern, CA

Executive Director: Laura Hromadka

Floodplain Management Association Conference
San Diego
March 13 &14, 1998

Closed Conduit Profile Calculations Using HEC-RAS

J. J. DeVries and T. V. Hromadka

Abstract

HEC-RAS can be used to model free surface mixed flows (subcritical and supercritical flow) and pressure flow in closed conduits. Computer program HEC-RAS was developed to model gradually varied steady flow in open channels; however, the energy equation as used in the program (which includes friction loss plus expansion and contraction loss) is also applicable to flow in closed conduits. The program checks to see if the calculated water surface is on the "right" side of critical depth and can determine if the flow goes through critical depth or if there is a hydraulic in the profile. The momentum equation is used by HEC-RAS to determine depths on each side of the jump when it occurs. In modeling a closed conduit, the lower half of the conduit is modeled by using the x-y coordinates for the basic cross section; the upper part of the conduit is modeled using the program option which adds a lid to the cross section. The section interpolation feature of the program provides an easy way to add multiple cross sections to the model. An example of an application of HEC-RAS for the calculation of hydraulic grade lines in closed conduits is given and some modeling guidelines are provided.

Introduction

There are few computer programs which are easy to apply to situations where both free-surface and pressure flows exist in a closed conduit. The HEC-RAS program is a computer program that can accomplish this. There is an optional calculation procedure in the HEC-RAS computer program which permits the calculation of closed conduit flow conditions as long as there is no part of the cross section which is lower than the computed hydraulic grade line elevation. HEC-RAS (HEC 1997a) was recently released by the Hydrologic Engineering Center of the U. S. Army Corps of Engineers to replace computer program HEC-2. The program was developed to model gradually varied steady flow in open channels, and it solves the one-dimensional energy equation between two cross sections accounting for energy loss between the sections as boundary resistance loss (friction loss) plus an expansion or a contraction loss. The geometry of the cross section is defined by x-y coordinates to define the section area normal to the flow path. Friction losses are computed using Manning's equation to compute the slope of the energy grade line at the section (S_f) and the head loss due to friction is computed using the "average" conveyance of the two sections.

HEC-RAS can be used to model free surface mixed flows (subcritical and supercritical flow) and pressure flow in closed conduits. If the flow is entirely free-surface flow the program uses the standard-step procedures in the same way as for river profile calculations. HEC-RAS has an option which permits a "lid" to be put on the cross section. The lid is defined by a set of lower coordinates and upper coordinates. The area, wetted perimeter, top width, etc. at a cross section in HEC-RAS are computed by assuming an elevation for the water surface and determining the area between the water surface and the solid boundary of the section. The energy equation is solved iteratively to determine the appropriate water surface elevation. If the water surface is below the highest elevation on the lower set of coordinates for the lid the flow is open channel flow. If the computed water surface elevation is above the highest of the set of lower coordinates but below the lowest of the higher coordinates pressure flow exists and the value that is supplied by the program as the water surface elevation is the elevation of the hydraulic gradeline. The energy equation solved by HEC-RAS, although in terms of the water surface elevation, is exactly equivalent to the energy equation if were written for pipe flow. For open channel flow the equation is written as

$$(\mathrm{WSEL} + \alpha\, V^2/2g)_{\mathrm{upstream}} = (\mathrm{WSEL} + \alpha\, V^2/2g)_{\mathrm{downstream}} + \Sigma\, h_L$$

where WSEL is the elevation of the water surface, $\alpha\, V^2/2g$ is the velocity head, and $\Sigma\, h_L$ is the summation of the energy losses between the upstream and downstream sections (HEC 1997b). The water surface elevation WSEL is the hydraulic grade line elevation, so the energy equation as used in the program is also applicable to closed conduit flow (i.e., the case when the lid on the cross section defines the flow area).

$$\mathrm{HGL} = p/\gamma + z = Z + y = \mathrm{WSEL}$$

where Z is the elevation of the channel bed, y is flow depth, p/γ is the pressure head in the flow, z is the elevation at the point the pressure head is evaluated, and HGL is the hydraulic grade line elevation.

However, the flow will not be correctly modeled by HEC-RAS if the computed water surface is above the lowest elevation on the upper set of coordinates for the lid because HEC-RAS will assume that the upper part of the section can also carry water, and the energy gradeline calculations will be based on the area defined by the lid plus additional open channel flow area above the lid. If this situation occurs, either the upper elevations for the lid must be raised above the computed water surface elevation WSEL, or the discharge at the section where water is "lost" to the closed conduit section must be changed to so that the calculations are based on only the actual amount of water passing through the closed conduit section.

HEC-RAS will determine hydraulic gradelines for the following conditions: for open channel flow in the conduit, for the condition where the water surface touches the crown of the closed conduit and becomes pressure flow, and for conditions where the flow changes from pressure flow to free-surface flow. The accuracy of the open channel profile calculations depends in large part on the spacing of the cross sections—as is the case for any profile calculation. The cross sections should be closely spaced when the flow area changes from cross section to cross section, and close spacing should be used when the profile is changing from full conduit flow to partially-full flow. Of course, when the conduit is flowing full, there is no increase in accuracy in the calculation of the profile when the flow area is not changing.

Adjustment of cross section spacing is very easy in HEC-RAS since the program makes it very easy to copy and adjust elevations of cross sections. Adding cross sections for reaches where the conduit dimensions are constant is also easy to do by using the option of the program which provides interpolated cross sections between specified cross sections.

Description of the Cross Section

HEC-RAS requires the cross section geometry to be defined in terms of x-y coordinates which are linked by straight-line segments. For a simple, but curved section, such as a circle, multiple coordinates must be used to specify the section. The section data need to be entered only once, and then the geometric data can be copied from section to section at each grade break point. Intermediate sections can be supplied using the cross section interpolation option of HEC-RAS.

For the example used here the x-y coordinates were computed for the section in a Excel spreadsheet. The flow top width for a circular section can be calculated from the depth by the following equation (ASCE 1992):

$$T = 2[y(D - y)]^{1/2}$$

Figure 1 shows the x-y coordinates used to represent the 6-ft diameter circular conduit section.

	x	lower y	upper y
1	0.00	3.00	3.00
2	0.04	2.50	3.50
3	0.17	2.00	4.00
4	0.40	1.50	4.50
5	0.76	1.00	5.00
6	1.34	0.50	5.50
7	1.80	0.25	5.75
8	2.14	0.13	5.86
9	3.00	0.00	6.00
10	3.86	0.13	5.88
11	4.20	0.25	5.75
12	4.66	0.50	5.50
13	5.24	1.00	5.00
14	5.60	1.50	4.50
15	5.83	2.00	4.00
16	5.96	2.50	3.50
17	6.00	3.00	3.00

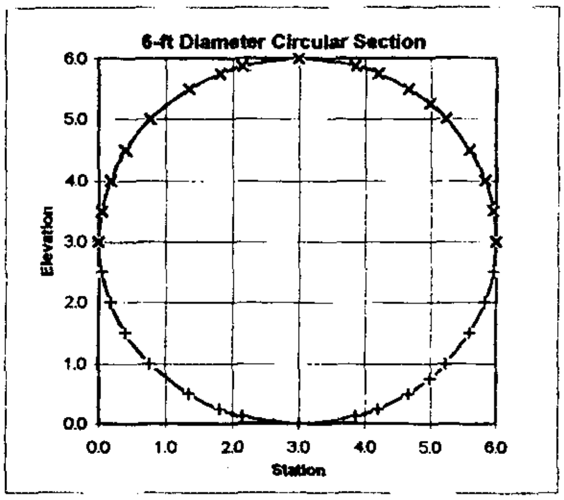

Figure 1. x-y Coordinates for Conduit Section

Conduit Profile

The conduit being modeled has a steep section at the upstream and downstream ends of the profile and a flatter slope section in the middle. The cross section is constant through out the length of the conduit. The profile can be specified by elevations of the conduit invert at the upstream and downstream ends and at the grade change points. The HEC-RAS geometric model is defined by entering the x-y geometry (Stations and Elevations) for the lower portion of the cross section as defined in the spreadsheet table. The top of the conduit is defined using the "Add a Lid to the Cross Section" Option. The "low coordinates" for the lid define the upper part of the conduit. "High coordinates" are needed to completely block out the area above the top of the conduit. Ordinarily the same value will be used for all high coordinates. The elevation of this section can then be adjusted to match the correct invert elevation and all of the coordinates (the lid as well as the section) will be adjusted.

This cross section can then be copied to grade break and upstream-most locations, and the section can be adjusted to provide the correct elevations of the coordinate points. If the ground surface as represented by the upper coordinates of the lid need to be adjusted this must be done after the other elevation adjustments are made.

If the conduit is flowing full at all points, not additional cross sections are needed for the hydraulic calculations. However, for most storm drainage systems the discharge varies over a wide range of flows and open channel flow may occur at various points in the system. The properly calculate a gradually-varied open-channel-flow profile the cross section spacing must be close enough so that the change in depth and velocity is reasonably small.

Additional cross sections can now be added using HEC-RAS' cross section interpolation option. Figure 2 shows the basic geometry of the example conduit without the interpolated cross sections; Figure 3 is a plot of a representative cross section showing the lid.

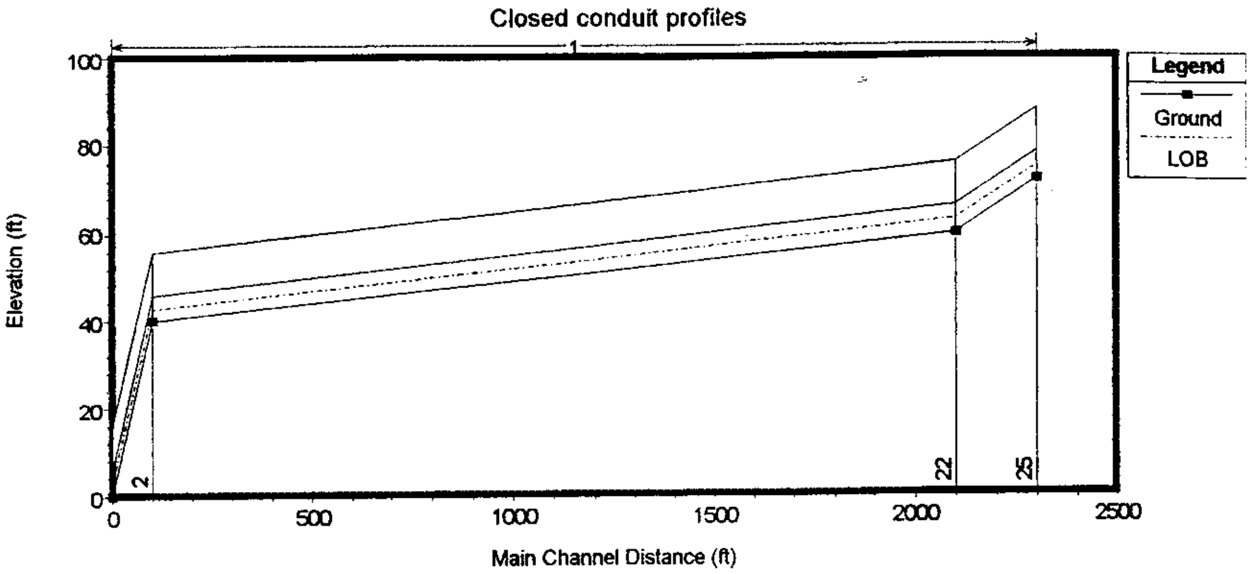

Figure 2. Basic Profile of Conduit

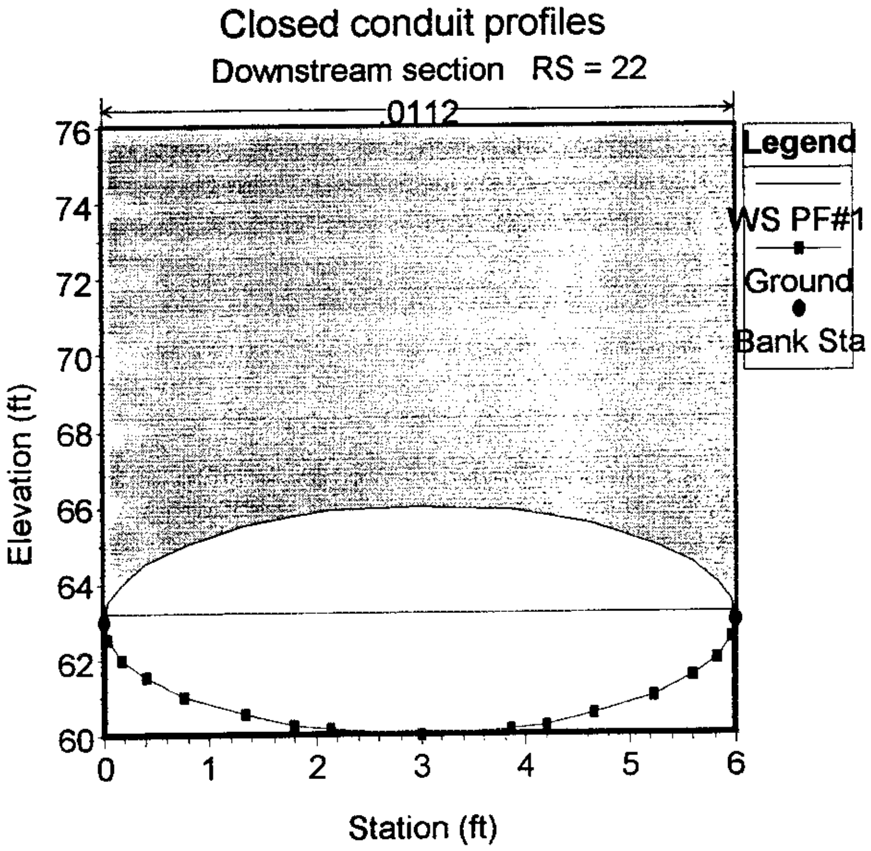

Figure 2. HEC-RAS Section with Lid

Profile Calculations

Discharge and boundary condition data are specified next, and the steady-flow simulation is made. Because hydraulically steep slopes exist in this model the Mixed Flow regime option is specified for the simulation. The program will calculate both subcritical and supercritical flow conditions where they exist in the system. The transition from supercritical to subcritical conditions (i.e., where a hydraulic jump occurs) is determined by solving the momentum equation between two adjacent cross sections. Simulated water surface profiles are shown in Figure 4.

Two profiles are simulated: one for a discharge of 400 cfs and the second for a discharge of 460 cfs. In both cases the upstream boundary condition is set as critical depth and the downstream boundary condition as a depth at the outlet which is 4 feet above the crown of the pipe.

The lower of the two profiles (Q = 400 cfs) corresponds to a profile that is supercritical flow throughout the entire conduit. No hydraulic jump occurs in the conduit for this profile; there is not sufficient tailwater at the downstream end to produce a hydraulic jump at the outlet. The momentum equation (which is used to calculate the jump location) is discussed in the next section.

The upper profile (Q = 460 cfs) has pressure flow through much of the conduit length. because the discharge is greater than the full flow capacity of the pipe. Critical depth occurs a relatively short distance above the very steep lower leg of the conduit system. There a jump in the conduit which occurs in the upper steep leg fairly close to the upstream end of the system.

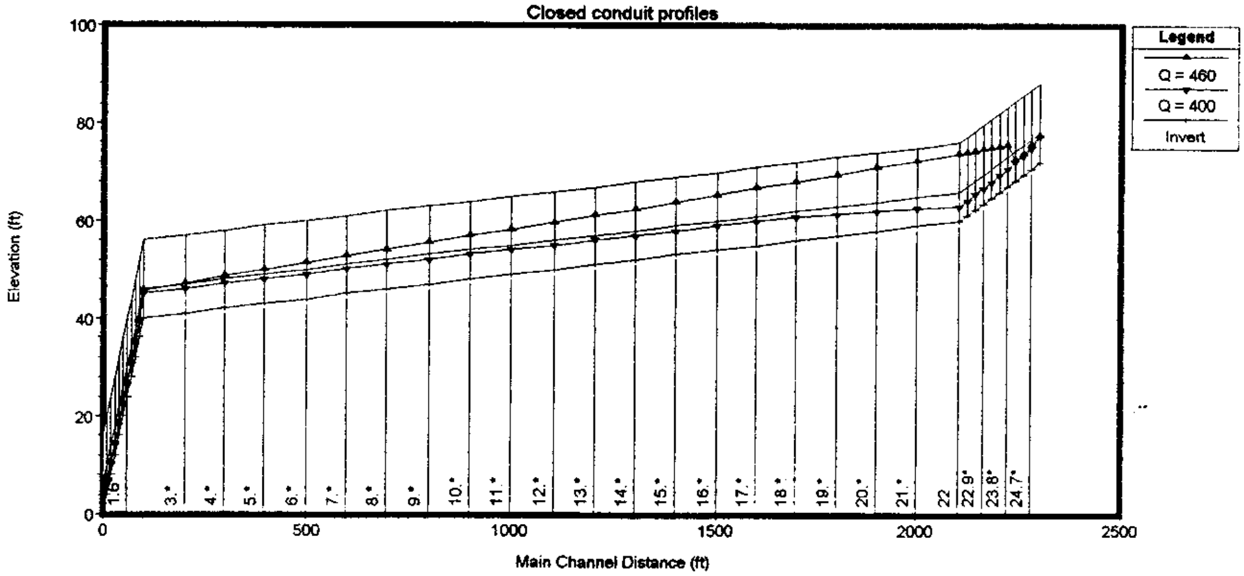

Figure 4. Calculated Water Surface Profiles

Momentum Equation Calculations

When there is a possibility of either supercritical or subcritical flow depth at a particular cross section, the HEC-RAS program checks to see if the calculated water surface is on the "correct" side of critical depth. It uses the momentum equation to determine if the flow goes through critical depth or if there is a hydraulic jump in the profile, and the momentum equation is used to determine the depths on each side of the jump when it occurs. The form of the momentum equation used by HEC-RAS (HEC 1997b) accounts for forces related to a weight component of the flow free body between cross section plus a boundary friction force. The equation is

$$Q_2^2\beta_2/gA_2 + A_2Y_2 + L\ S_o(A_1 + A_2)/2 - L\ S_f(A_1 + A_2)/2 = Q_1^2\beta_1/gA_1 + A_1Y_1$$

In this equation the subscripts 1 and 2 represent the downstream and upstream sections respectively, Q is discharge, β is a moment correction coefficient, A is cross sectional area, Y is the depth from the water surface to the centroid of A, L is distance between cross sections, S_o is the bed slope, and S_f is the average friction slope between the two sections A_1 and A_2.

Two things should be kept in mind relative to momentum balance calculations by HEC-RAS: 1) HEC-RAS does not account for the length of the jump. The upstream (supercritical) depth location is correctly located, but the downstream end of the jump will be farther downstream than indicated by the program. 2) The flow depths upstream and downstream from the jump are directly related to the actual channel roughness. Often for design a Manning's n-value that is on the higher side of possible n-values is selected to produce a " conservative design." For flow depth calculations this is appropriate. For hydraulic jump calculations this may lead to an erroneous calculation of the jump location. If the actual Manning's n-value is actually lower than assumed the momentum force for the flow entering the jump may actually be significantly higher then the calculated value and the required depth after the jump will be correspondingly higher making the location where the momentum balance occurs actually at a different point than is calculated.

Design standards for hydraulic jump basins used by various agencies—for example, the US Bureau of Reclamation (USBR 1974)—require two sets of Manning's n-values to be used in the hydraulic jump analysis so that the range of possible jump locations is bracketed. A 20 percent reduction in Manning's n is recommended by the USBR for the analysis of hydraulic jumps to make sure tailwater depths are adequate to ensure that the jump is not swept downstream by a higher upstream velocity (momentum force) than expected. A run with the Manning's n value reduced by 20 percent is shown in Figure 5.

Figure 5 shows a run made using the same discharge (Q = 460 cfs) and boundary conditions as the profile with the jump, but the Manning's n-value is reduced to 80 percent of the value used in the other run. For this condition there is no hydraulic jump, but supercritical flow exists through the entire profile.

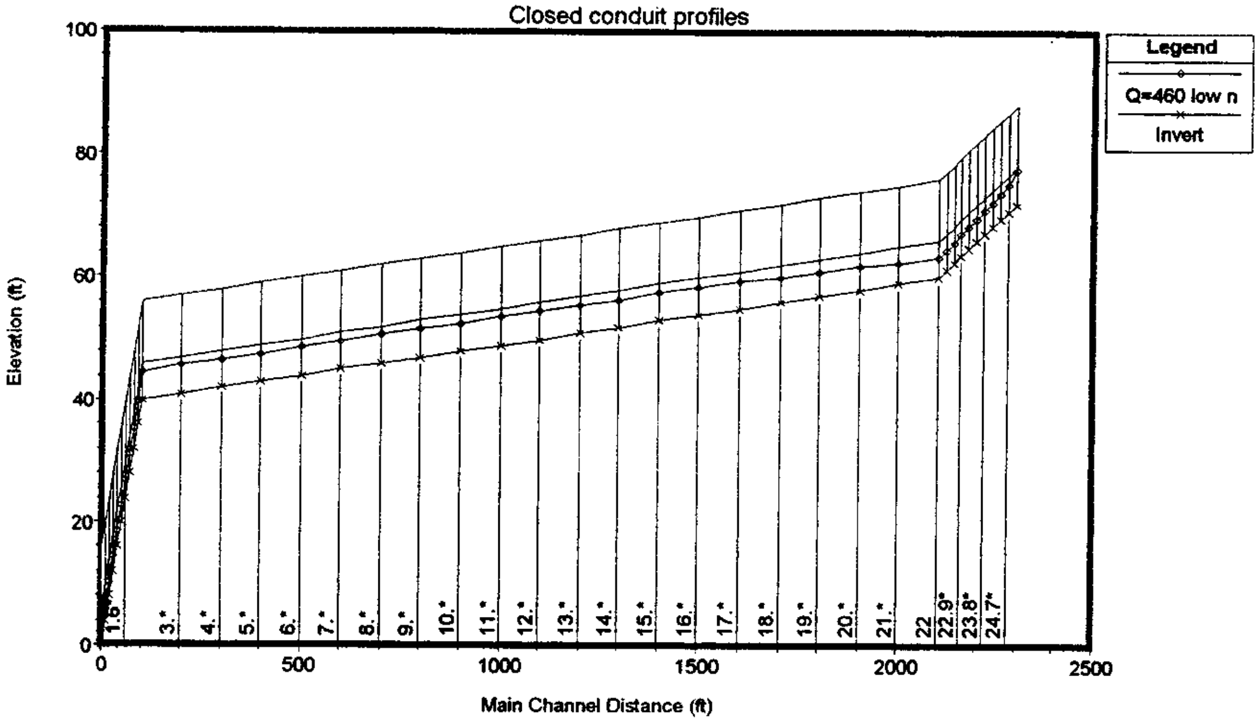

Figure 5. Profile with Low n-Value

Conclusions

HEC-RAS is a very useful tool for the analysis of mixed flows (subcritical and supercritical flows) in closed conduits using the program option which adds a lid to the cross section and adds interpolated sections between specified sections. The program variable labeled WSEL is equivalent to the hydraulic gradeline elevation in the pipe. Care must be taken if the computed WSEL value is above the ground line (upper elevation for the lid) because the program will assume that open channel flow can occur in this part of the cross section.

References

1. ASCE (1992) Design and Construction of Urban Stormwater Management Systems, American Society of Civil Engineers, NY.
2. Chaudhry, M. H. (1993) *Open-Channel Flow*, Prentice-Hall, Englewood Cliffs, NJ.
3. HEC (1997) "User's Manual - HEC-RAS River Analysis System", Hydrologic Engineering Center, US Army Corps of Engineers, Davis, CA.
4. HEC (1997b) "Hydraulic Reference Manual - HEC-RAS River Analysis System, Hydrologic Engineering Center, US Army Corps of Engineers, Davis, CA.
5. USBR (1974) *Design of Small Canal Structures*, US Bureau of Reclamation Denver