

Culvert Design

By

Pete Peterson, PE

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CULVERT DESIGN

Culverts are very commonly used to convey drainages across roadways, both in rural environments and sometimes in more urban environments. Proper sizing of these culverts requires an understanding of the hydraulics of a culvert, which involves more than just a simple solution of Manning's equation. An understanding of the importance of determine inlet control for a culvert is also important. Sometimes a steeper pipe will provide more capacity, but more often a steeper pipe has very limited impacts on capacity and a larger pipe is required. The use of FHWA software HY8 will allow the designer to properly select all of the important parameters for a culvert installation. Further review of the design is required, though, to appropriately limit the depth of water on the upstream side of the culvert and provide an appropriate design service life for a culvert.

IMPORTANT PARAMETERS

Design Flow and Return Period

Determining the appropriate design flow for a culvert is a function of several parameters. The hydrology of the upstream basin is the most important, but not the only factor. The hydrology is a function of the size of the drainage area, the slope of the drainage area, the land use upstream (the extent of development that creates more impervious surface) and potentially the soils. Hydrology is a separate topic and is not addressed in this course.

Some of the other factors include the amount of traffic, the available detours and the acceptable risk. The acceptable risk is partially a function of the amount of traffic and the available detours. If the roadway carries a high volume of traffic, it is more important to reduce the potential for flooding of this roadway, so a higher design flow, associated with a longer return period, is appropriate. If multiple nearby, high-capacity detour routes are available around a specific culvert crossing location, it is less important to reduce the potential for flooding at this specific location. In other words, the design flow for a specific location depends not only on the hydrology of the site, but also the risk associated with flooding at the location.

Overtopping elevation, location and frequency

Another important parameter to determine in selecting an appropriate culvert is overtopping. Overtopping occurs when water that reaches the upstream end of the culvert does not go through the culvert, but rather is diverted somewhere else. Normally when water does not go through the culvert, it overtops the roadway at or near the culvert. However, water can also be diverted over a low point upstream from the culvert and directed into a separate drainage. The condition that has the lower elevation will be the controlling condition.

The location of overtopping can also impact the risk associated with overtopping. If the roadway overtops at the culvert, there is a high probability the culvert itself will be dislodged and damaged. Repair of this situation involves not only repair of the roadway, but also acquisition and installation of a new culvert. If the overtopping occurs at a location away from the culvert, it is much less likely the culvert will be damaged.

The depth of overtopping also becomes an important factor, although depth of overtopping can't be determined until the hydraulic analysis is complete. At very shallow depths, there is little damage to a paved roadway. However, at depths even as small as 6 inches, erosion of the downstream embankment can become an issue. As the downstream embankment continues to erode, a head cut is formed which can start to erode the roadway.

The acceptable frequency of overtopping is also important. This factor is often considered In conjunction with the depth of overtopping. If water overtops the road in a relatively frequent event (such as a 5-year or 10-year event), but the depth of water is very shallow, the risk of culvert failure could still be low. In this situation, frequent overtopping could be acceptable. On the other hand, if the roadway has a significant sag curve at or near the culvert, the depth of overtopping could become large even at relatively low overtopping flows, so frequent overtopping would not be acceptable.

Allowable upstream headwater elevation

Another potentially important parameter in the design of a culvert is the allowable upstream headwater elevation. As noted above, when the roadway overtops, there can be significant damage to the roadway. However, even before the roadway overtops, there can be damage to buildings or other infrastructure upstream from the culvert. If there is not develop upstream from the culvert, then the allowable upstream elevation is not an important parameter.

Pipe invert elevations

In most situations, the pipe inverts are established to match the channel invert elevations and this is the default condition. There are several situations where this might not be the case, however. Sometimes it is desirable to set the invert of the culvert below the channel invert. This is usually done to promote passage of aquatic organisms or, with large culverts, allow the passage of wildlife. Sometimes a culvert is set below the channel invert with the intent to increase the capacity of the culvert. However, there is often a high risk of the bottom of the culvert filling with sediment to an elevation that approximately matches the existing channel inverts.

The other situation where pipe inverts might not match the channel invert is in situations where multiple culverts are used. In this case, one culvert should be set in the center of the channel and the second culvert set at an elevation that matches the overbank elevation at the center of the second culvert. If the natural channel is wide enough that both culverts can be installed in the width of the natural channel, both culverts can be set at the same elevation. In many cases, the design will provide for an artificially widened channel constructed upstream and downstream from the multiple culvert installation, with the intent to keep both culverts open. Most channels will carry sufficient sediment that the wider channel is only a temporary condition and either one of the culverts becomes blocked with sediment, or both culverts become partially blocked. In either case, the multiple culverts do not have the anticipated flow capacity.

Installation conditions

There are a number of considerations related to the installation of the culvert that can impact the selection of an appropriate culvert. The first consideration is the loading conditions the culvert will need to support. Culverts are most commonly located under roadways, so they can be subjected to significant live loads. Culverts carry flows from drainages and in some situations it is necessary to place a significant amount of fill to construct the roadway. In these conditions, the dead load associated with the fill material must be supported by the culvert.

The desired life expectancy of the culvert is also an important parameter. Many agencies have guidelines on the desired life expectancy, but many of them do not have any guidance on how to calculate the expected life. The corrosion conditions of the specific site can have a

significant impact on life expectancy, but these conditions are not always evaluated appropriately.

The foundation for the culvert is another important parameter. If the material under the culvert is soft, appropriate foundation material under the culvert will be required. The bedding material under and around the culvert is also important, especially if a flexible pipe material is used.

PIPE MATERIAL OPTIONS

A number of different materials are commonly used for culverts. The most common are reinforced concrete pipe (RCP) and Corrugated Steel Pipe (CSP). Other options include Corrugated Aluminum Pipe CAP), Corrugated High Density Polyethylene (HDPE), Corrugated Polypropylene (PPE) and Steel Reinforced Polyethylene (SRPE).

Reinforced Concrete Pipe (RCP)

There are many specifications that govern the manufacturer of reinforced concrete pipe. Some of the most common include:

ASTM C 76 – Reinforced Concrete Culvert, Storm Drain and Sewer Pipe
ASTM C 443 – Joints for Circular Concrete Sewer and Culvert Pipe, Using rubber Gaskets
ASTM C 478 – Precast Reinforced Concrete Manhole Sections

Reinforced concrete pipe is generally available in sizes from 12 inches in diameter up to 120 inches in diameter. It is commonly available with diameters of 12, 15, 18, 24, 30, 36, 42, 48, 60, 72, 84, 96, 108 and 120 inches. It is less commonly available with diameters of 21, 27, 33, 54, 66, 78 and 90 inches. With these less common sizes, it's very important to contact the local pipe supplier early in the design process, and maintain contact throughout the design to verify the less common sizes will still be available. Even then, it's possible the supplier will indicate during or after the bid these sizes aren't available and will want to discuss alternative sizes. The sizes of RCP are the inside diameter.

Reinforced concrete pipe is also available in arch sizes, where the span of the pipe is greater than the height of the pipe. Arch pipes are especially useful when the available cover at a particular site is limited. The flow area of an arch pipe is slightly smaller than the flow area of an equivalent round pipe. For an example, an arch pipe equivalent to a 54-inch diameter round pipe has a span of 65 inches and a rise of 40 inches. The arch pipe has a flow area of about 90% of the flow area of a 54-inch diameter round pipe.

Reinforced concrete pipe is manufactured in a variety of different strengths It is commonly constructed in Class 1 through Class 5. Class 1 pipe has a strength of 800 pounds per foot per foot, while Class 5 has a strength of 3000 pounds per foot per foot. These strengths refer to the force, per foot of diameter and per foot of length, that is required to create a crack with a thickness of 0.01 inches in the pipe. The inside and outside diameters of different strengths of concrete pipe are the same. The increased strength of Class 5 pipe, compared to Class 1 pipe, is achieved by the use of more reinforcing steel in the pipe, not by increasing the thickness of the concrete wall. If pipe strengths greater than 3000 pounds per foot per foot are required, special pipe can be manufactured with higher strengths. Early coordination with the local pipe supplier is necessary in these special cases.

The manufacture of reinforced concrete pipe involves only a few steps. First, a “cage” of reinforcing mesh is shaped (see Figure 1). The mesh is set on a casting platform, then the form (see Figure 2) is placed over the mesh. The concrete is centrifugally cast inside the form and the inside is finished with rotating trowels. The concrete used in this process is typically very stiff, zero slump concrete. Once all of the concrete is cast, the form and pipe are lifted from the casting platform to a curing platform. The forms for the pipe can then be immediately removed. Once the curing platform is full of pipe, it can be moved into a curing room, where the pipe is steam cured at a controlled temperature. The concrete used in this process is generally also very early, high strength concrete, so that within 24 hours after casting, the concrete has reached the required 28-day strength. At that point, it can be loaded onto a truck, shipped to the site and installed.



Figure 1 – RCP reinforcing mesh.



Figure 2 – RCP Form

There are two different joint configurations used for reinforced concrete pipe. The first joint configuration is a tongue and groove joint. See Figure 3 for the tongue end and Figure 4 for the groove end. The pipes in Figures 3 and 4 are arch pipes. The second joint configuration is a bell and spigot joint. See Figure 5 for the bell end and Figure 6 for the spigot end.



Figure 3 – Tongue end of tongue and groove pipe



Figure 4 - Groove end of tongue and groove pipe

With tongue and groove pipe, sometimes the tongue is simply inserted into the groove, with no joint material. This provides a joint that allows only a small amount of fine material to pass through the joint and is sometimes considered an adequate seal, depending on the site conditions. As an alternative, a bituminous material (such as Ram-nek®) is used in this joint. This bituminous material provides a better seal and essentially eliminates the potential for any sediment to enter the pipe. It is not generally considered to be a watertight seal, however.



Figure 5 – Bell end of bell and spigot pipe



Figure 6 – Spigot end of bell and spigot pipe

Bell and spigot pipe is used primarily when a better joint seal is desired. The spigot end of the pipe is provided with a slot (see Figure 6) for a rubber gasket. When the spigot end is inserted into the bell end, this gasket provides an excellent seal between the two pieces of pipe. This joint is generally considered to be a water-tight joint and will withstand small amounts of pressure (in the range of 10 psi) without leaking.

One special shape of reinforced concrete pipe is a concrete box (see Figure 7). The primary standard specification that applies to concrete boxes is ASTM C 1433, "Standard Specification for Precast Reinforced Concrete Monolithic Box Sections for Culverts, Storm Drains, and Sewers." Concrete boxes are used in locations where high flows need to be conveyed, but there is limited headroom. The joints on a concrete box are essentially tongue and groove joints, very similar to those use on reinforced concrete pipe. These joints can be assembled either with or without the bituminous sealant material.



Figure 7 – Groove end of a reinforced concrete box

Corrugated Metal Pipe (CMP)

There are two different kinds of corrugated metal pipe – corrugated steel pipe (CSP) and corrugated aluminum pipe (CAP). More size options are available in CSP than CAP, but the hydraulics of the two materials are essentially the same, so they will be addressed together. The primary applicable specifications for corrugated metal pipe include:

- AASHTO M36 – "Corrugated Steel Pipe, Metallic-Coated, for Sewers and Drains"
- AASHTO M190 – "Bituminous-Coated Corrugated Metal Culvert Pipe and Pipe-Arches"
- AASHTO M245 – "Corrugated Steel Pipe, Polymer Precoated, for Sewers and Drains"
- AASHTO M196 – "Corrugated Aluminum Pipe for Sewers and Drains"

Corrugated steel pipe and corrugated aluminum pipe are generally available in sizes from 12 inches in diameter up to 120 inches in diameter. It is commonly available with diameters of 12, 15, 18, 24, 30, 36, 42, 48, 54, 60, 72, 84, 96, 108 and 120 inches. It is less commonly available with diameters of 21, 27, 33, 66, 78 and 90 inches. With these less common sizes, it's very important to contact the local pipe supplier early in the design process, and maintain contact throughout the design to verify the less common

sizes will still be available. The sizes of CSP and CAP are the inside diameter. Sizes larger than 120 inches are available as structural plate pipes. The corrugations for small diameter metal pipes are generally 2-2/3" x ½". This means that the height of the corrugation is ½ inch and the distance between the top of corrugations is 2-2/3 inches. As the diameter of the corrugated metal pipe gets larger, the size of the corrugations gets larger. Larger pipes can have corrugations of 3" x 1" or 5" x 1". With structural plate pipes, the corrugations are 6" x 2" for most sizes and very large structural plate pipes have corrugations of 9" x 3".



Figure 8 – Corrugated Steel Pipe

Corrugated High Density Polyethylene Pipe (HDPE)

Corrugated High Density Polyethylene Pipe is sometimes used for culverts. Corrugated HDPE is generally available in either single wall or double wall pipe. Single wall pipe has a corrugated interior along with the corrugated exterior. Double wall pipe has a corrugated exterior, but the interior is constructed with a second, smooth wall pipe heat-welded to the corrugated exterior pipe. The primary applicable specifications for corrugated high density polyethylene pipe include:

- ASTM F667 – "Standard Specification for Large Diameter Corrugated Polyethylene Tubing and Fittings"
- AASHTO M252 – "Corrugated Polyethylene Drainage Tubing"
- AASHTO M294 – "Corrugated Polyethylene Pipe, 12 in. to 60 in. Diameter

One of the challenges of corrugated HDPE is it is a very flexible product. This requires better bedding around the pipe to provide adequate structural support. HDPE pipe has several different joint types. Figure 9 shows the bell end of a gasketed joint, which can provide a watertight connection, but some other joints are not watertight.



Figure 9 – Corrugated High Density Polyethylene Pipe

Another option with corrugated HDPE is to provide a steel reinforcing center to the pipe. Several manufacturers provide this option. This steel center provides a stiffer, stronger pipe. The interior of this pipe is smooth wall HDPE.

Corrugated Polypropylene Pipe (PPE)

Corrugated High Density Polyethylene Pipe is sometimes used for culverts. It is similar to HDPE pipe and is available in sizes from 12 inches up to 60 inches. The primary applicable specifications include:

- ASTM F2736 – “Standard Specification for 6 to 30 in. Polypropylene (PP) Corrugated Single Wall Pipe And Double Wall Pipe”
- ASTM F2764 – “Standard Specification for 30 to 60 in. Polypropylene (PP) Triple Wall Pipe and Fittings for Non-Pressure Sanitary Sewer Applications”
- ASTM F2881 – “Standard Specification for 12 to 60 in. Polypropylene (PP) Dual Wall Pipe and Fittings for Non-Pressure Storm Sewer Applications”

Steel Reinforced Corrugated Polyethylene Pipe (SRPE)

A more recent option for culverts is Steel Reinforced Polyethylene Pipe. It is similar to HDPE pipe but has a steel interior core. It is available in sizes from 12 inches up to 120 inches. The primary applicable specifications include:

- ASTM F2435 – “Standard Specification for Steel Reinforced Polyethylene Corrugated Pipe”
- ASTM D2321 – “Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications”

It has a smooth interior and a corrugated exterior, very similar to corrugated HDPE. It is available with a bell and spigot joint with a gasket that is a watertight joint and a bell and spigot joint without a gasket that is soil tight, but not watertight.

DATA FOR HYDRAULIC ANALYSIS USING HY8

The hydraulic analysis of culverts is most easily completed using computer software. Early engineering designs for culverts were completed using a series of nomographs (charts) developed by the Bureau of Public Roads (a predecessor of the Federal Highway Administration). The simplest software to use is HY-8, which was developed by FHWA in the late 1980s. This software is public domain software and is available for free download from FHWA.

Culvert Data Input for HY8

The start window for HY8 is shown in Figure 10. This window provides the opportunity to Create a New Project or to Open an Existing File.

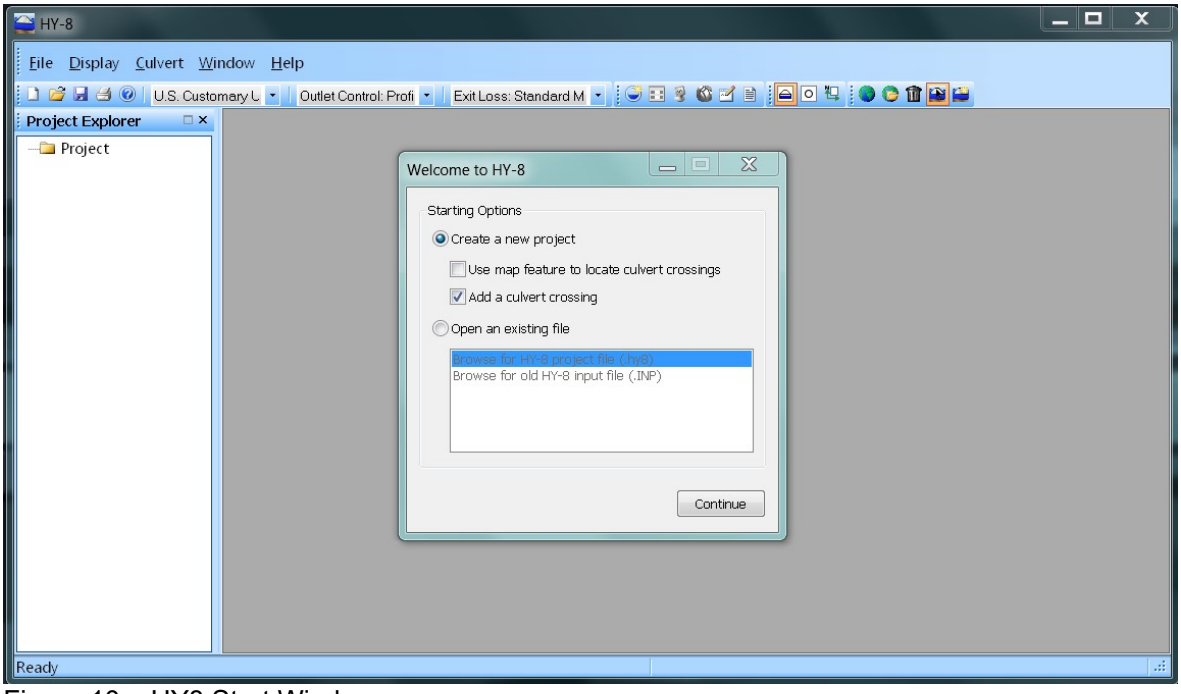


Figure 10 – HY8 Start Window

Clicking on “Create a New Project” will open the Culvert Data Input window in Figure 11. This window provides all the data necessary to analyze a culvert. Each section of this window is described below.

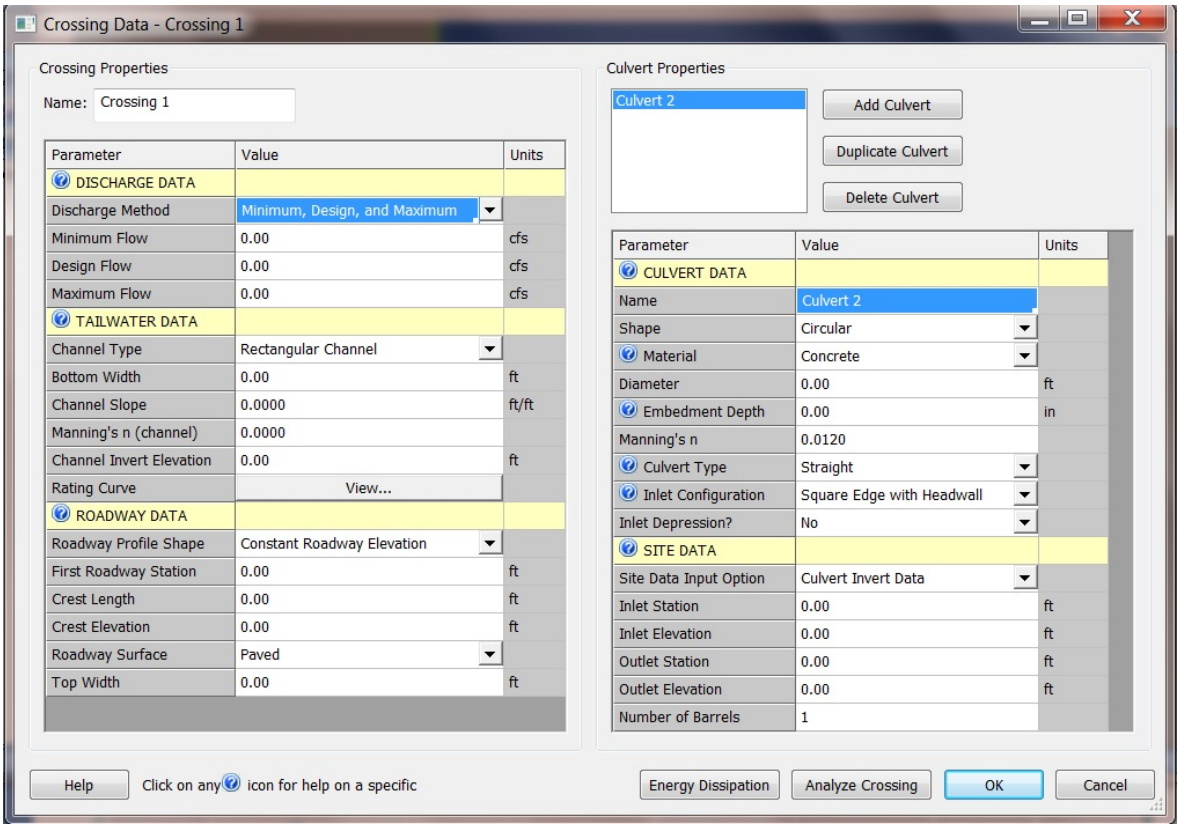


Figure 11 – HY8 Culvert Data Input Window

In the upper right-hand side of this window is a section titled “Culvert Data” (see Figure 12 for an enlargement of this portion of this window. This data should be entered from top to bottom since the selection of some options will change the available options below that entry. Each line will be addressed individually.

Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Concrete	
Diameter	0.000	ft
Embedment Depth	0.000	in
Manning's n	0.012	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall	
Inlet Depression?	No	

Figure 12 – Culvert Data

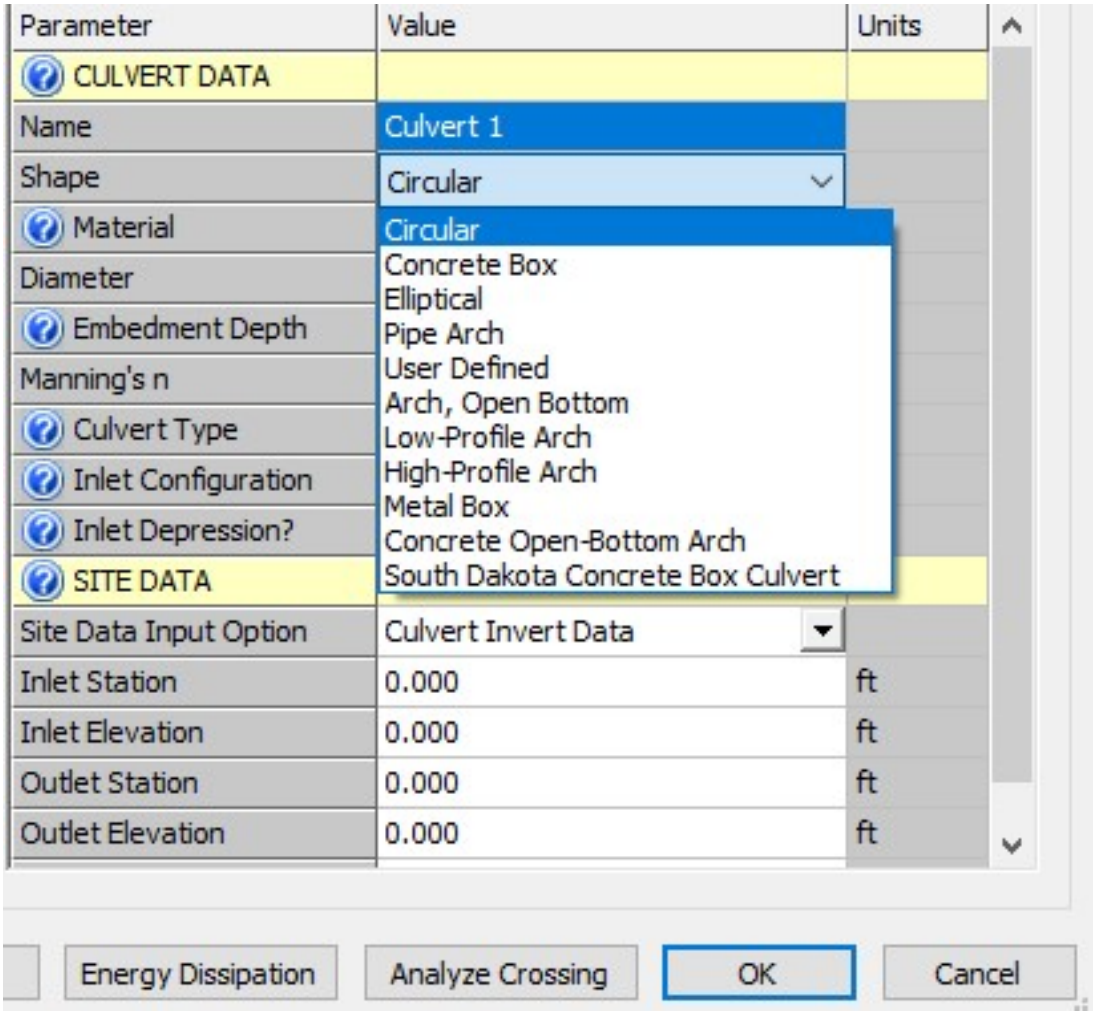


Figure 13 – Culvert Shape

Clicking on the drop-down box adjacent to the culvert shape brings up the choices for shape of the culvert (see Figure 13). These options include:

- Circular – This is the most common shape and is therefore the default value for the software.
- Concrete Box – This is for a rectangular concrete box.
- Elliptical – Reinforced Concrete Pipe is also available in some elliptical shapes (which are different than pipe arches).
- Pipe Arch – As noted in the section above on materials, both reinforced concrete pipe and corrugation metal pipe (steel and aluminum) are available as arch pipes.
- User Defined – When none of the normal pipe shapes are appropriate, it is possible to define an existing (or proposed) shape by a series of x-y coordinates.
- Arch, Open Bottom – Another material option is Corrugated Steel or Corrugated Aluminum pipe that has an arch shape but doesn't have a bottom. These pipes require a footing on each side of the opening to provide structural support. With an open bottom pipe, the bottom is the natural channel.
- Low-Profile Arch, High-Profile Arch – These are two additional specialty shapes available in corrugated steel or corrugated aluminum.

- Metal Box – The corrugated pipe industry makes a metal box, similar to a concrete box. The top corners of a metal box are rounded however, to provide better strength than a square corner, so the geometry of a metal box is somewhat different than the geometry of a concrete box.
- Concrete Open-Bottom Arch – Similar to a metal open bottom arch, this is an arch shape without a bottom.
- South Dakota Concrete Box Culvert – The conduit portion of a South Dakota Concrete Box Culvert is the same as the conduit portion of a standard concrete box. However, the South Dakota Concrete Box Culvert provides a number of different inlet configurations, which provides a more efficient inlet.

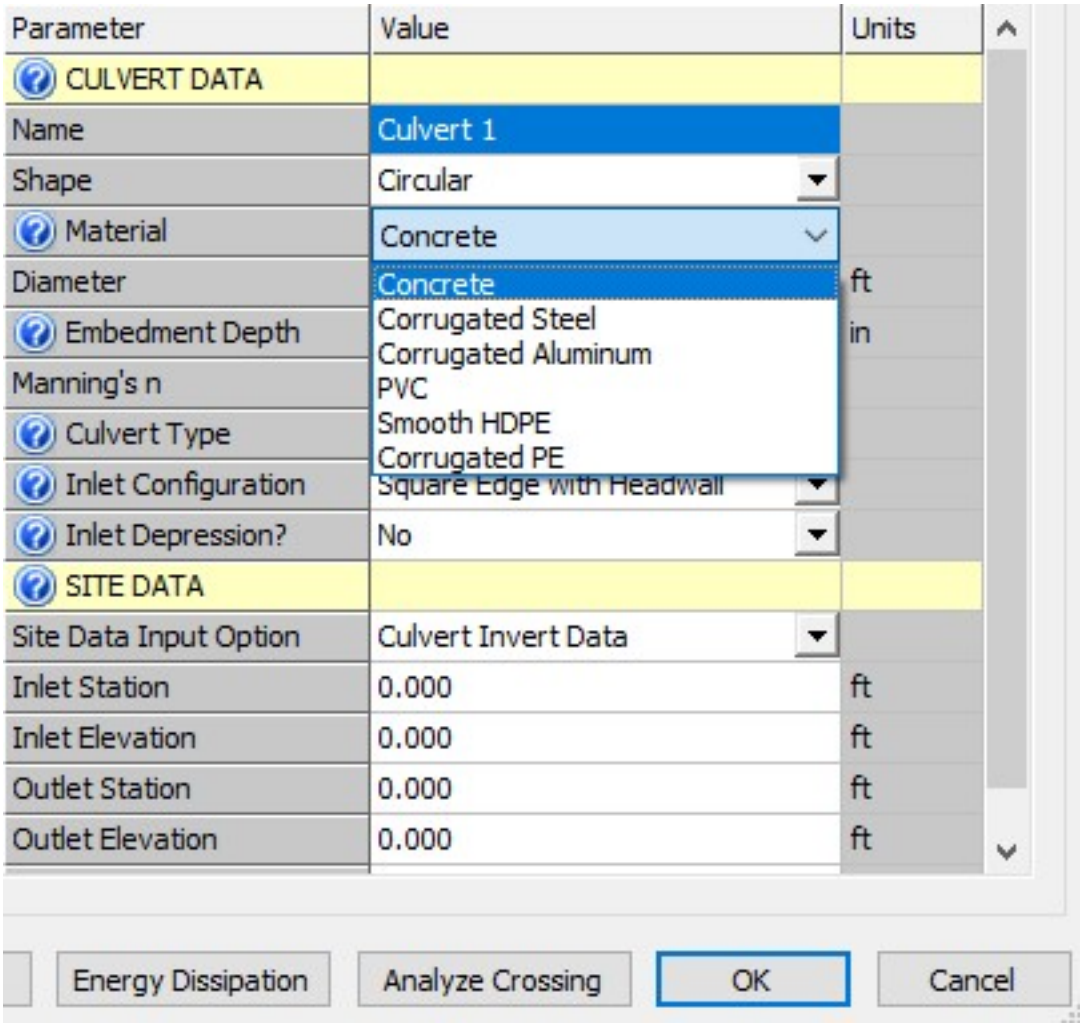


Figure 14 – Culvert Material

Clicking on the drop-down box adjacent to the culvert material brings up the choices for material (see Figure 14). These options include:

- Concrete
- Corrugated Steel

- Corrugated Aluminum
- PVC
- Smooth HDPE – This selection can be used for double wall HDPE or double wall PPE, where the interior of the pipe is smooth.
- Corrugated HDPE – This selection can be used for single wall HDPE where the interior of the pipe is corrugated.

The next parameter to be entered is the diameter for a circular culvert. Note the default value for this parameter is zero, so a positive value needs to be entered. If a shape other than circular is selected (such as an arch or a box), this window changes to require input of the span and rise of the culvert. This will be shown in more detail in an example later in this course.

After the diameter is entered, it is necessary to enter the embedment depth. In some cases it is desirable to place the invert of the culvert below the invert of the natural channel and fill the bottom of the culvert. This is usually done to accommodate fish passage or passage of other aquatic animals or small mammals. If a culvert is set one foot below the channel invert and one foot of fill is placed, a value of 12 is entered (note the units on embedment are inches). If this is done for an 8-foot wide by 4-foot-high concrete box, only 3 feet of the height is available to convey the flow. A separate Manning's n value is required for the fill material. The default value for this embedment depth is zero and this value is appropriate when the culvert invert matches the channel invert.

The Manning's n value for the culvert should be entered, or at least verified. Depending on the selection of pipe shape and material, a default value of Manning's n is provided. For concrete pipe, this value is 0.012. While this is a reasonable value, some jurisdictions require use of an n value of 0.013 for analysis, so the default value would need to be changed. In addition, when circular corrugated steel or corrugated aluminum are selected, the default value is 0.024 regardless of the size of the pipe. Use of 0.024 is appropriate for small diameter pipes where the corrugations are 2-2/3" x ½". However, for larger pipes (usually larger than 48-inch diameter), the typical corrugations are 3" x 1" and the use of an n value of 0.026-0.028 is more appropriate. For large steel structural plate pipes, appropriate n values are in the range of 0.033 to 0.036.

Clicking on the drop-down box adjacent to Culvert Type brings up the choices for this parameter (see Figure 15).

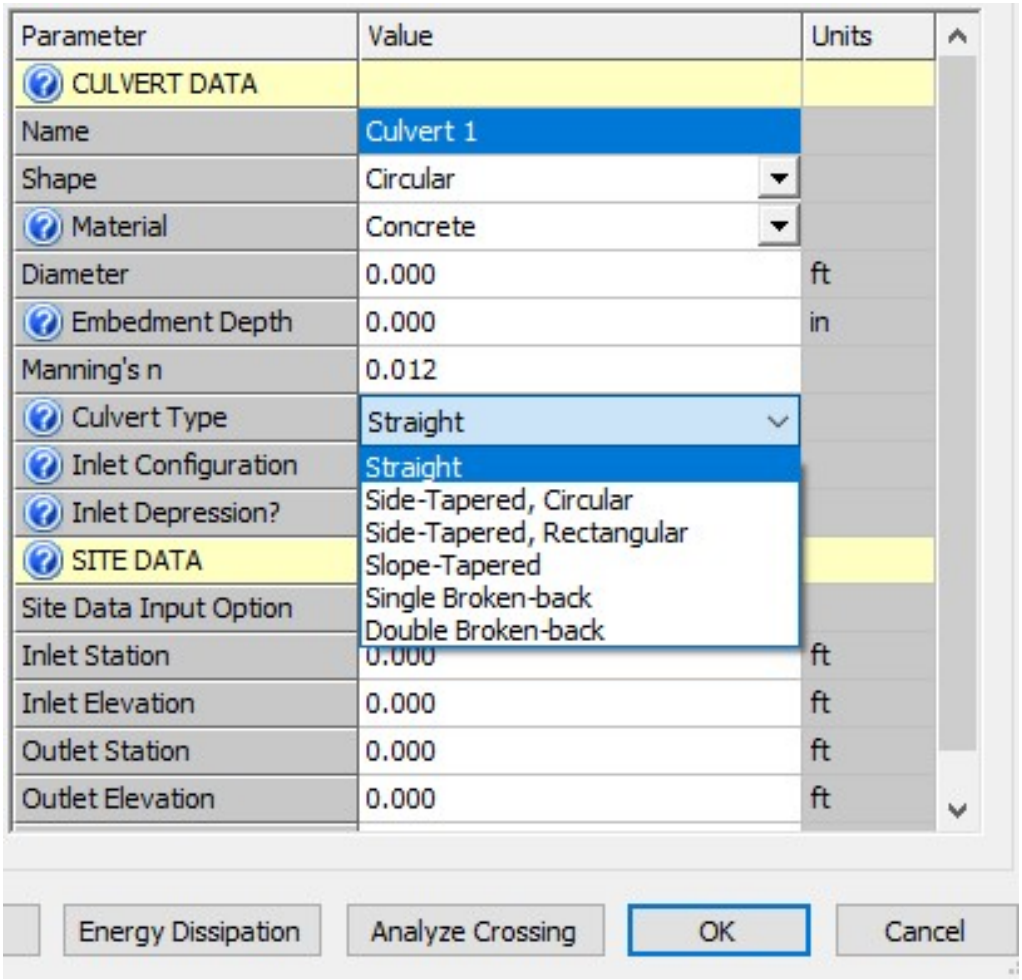


Figure 15 – Culvert Type

By far the most common culvert type is a straight culvert. All of the other options are for very unique situations. The side-tapered and slope-tapered options relate to unique inlet characteristics (see Figures 16 and 17). Broken-back culverts have a very unique profile. A single broken-back culvert (see Figure 18) is sometimes used in a situation where a consistent slope would create a hydraulic jump at the downstream end of the culvert. With a single broken-back configuration, the hydraulic jump is contained within the culvert. This configuration can be effective, but great care needs to be taken to ensure the culvert can handle the increased erosive forces associated with the hydraulic jump and to ensure that adequate air is provided to the area of the hydraulic jump so that pulsating flow does not occur. A double broken-back culvert (see Figure 19) is sometimes used in areas of large fill to reduce the amount of fill over the pipe near the center of the roadway. Again, this vertical alignment often results in a hydraulic jump and the precautions noted above need to be addressed.

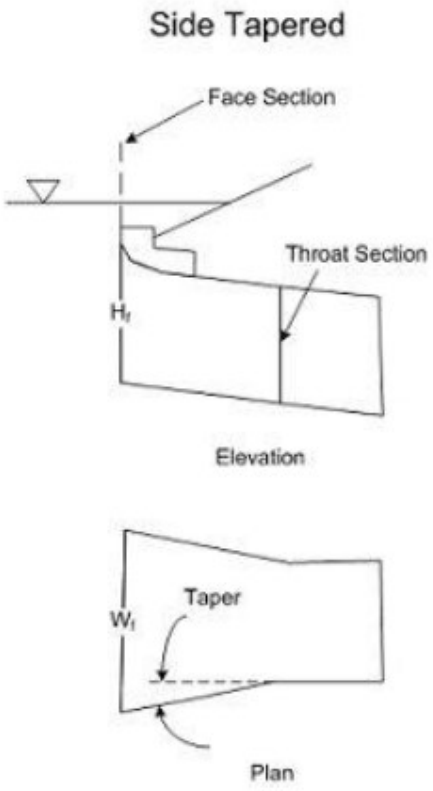


Figure 16 – Side Tapered Inlet

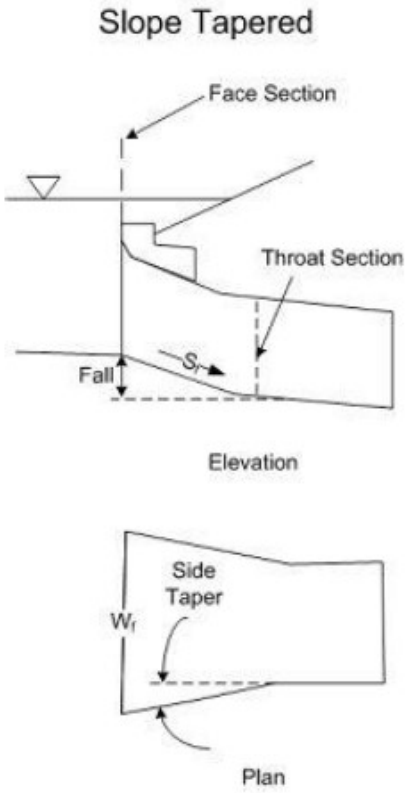


Figure 17 – Slope Tapered Inlet

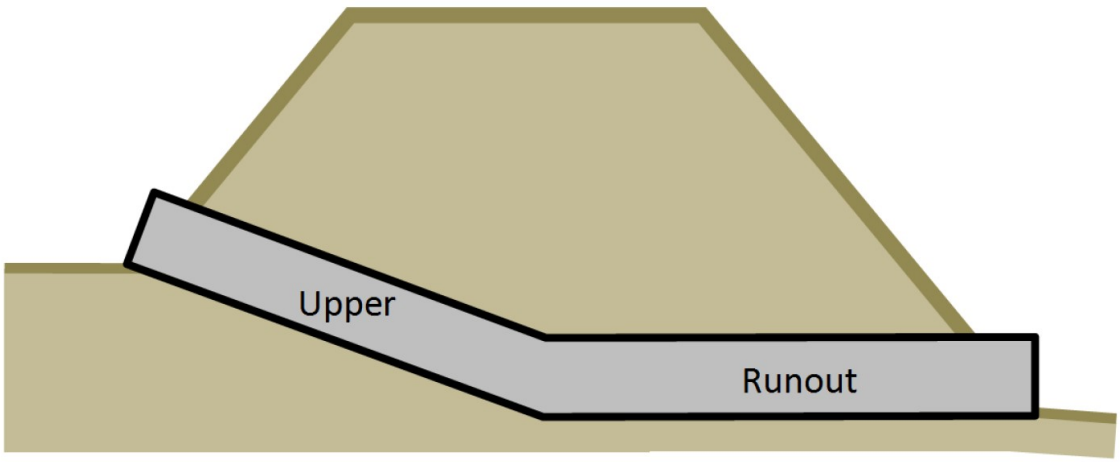


Figure 18 – Single Broken-Back Culvert

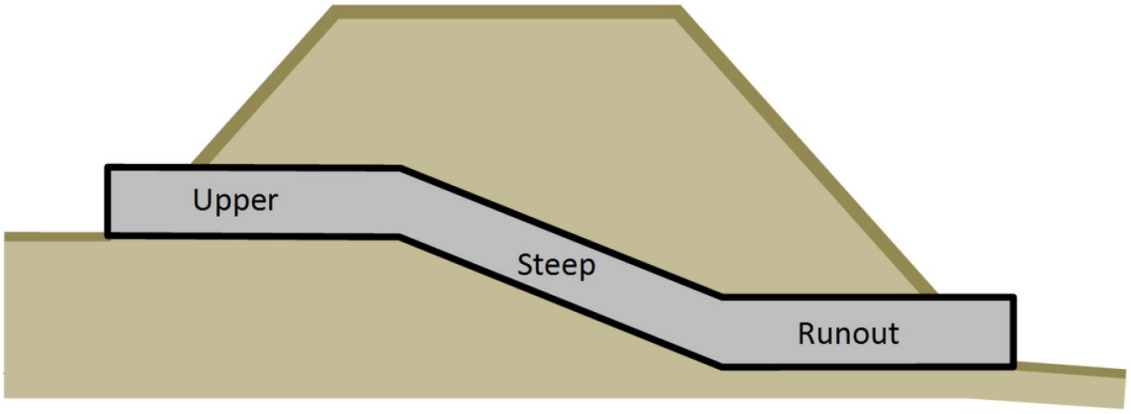


Figure 19 – Double Broken-Back Culvert

The next parameter to define is the inlet configuration. The choices vary slightly depending on the type of pipe. For circular concrete pipe (see Figure 20) they include:

- Square Edge with Headwall – This configuration provides a vertical headwall at the inlet of the pipe with a square pipe end.
- Grooved End Projecting – This configuration provides a grooved end of the pipe (see Figure 4 and Figure 21) extending upstream into the natural channel.
- Grooved End in Headwall – This configuration provides a vertical headwall at the inlet, but with a grooved end of the pipe (see Figure 4)
- Beveled Edge (1:1 or 1.5:1) – These two configurations provide a vertical headwall with a chamfer at the pipe inlet.
- Mitered to Conform to Slope – This configuration provides a pipe cut (mitered) to the same angle as the upstream embankment slope. This configuration is not used for a standard flared end section.

Flared end sections made of either metal or concrete (see Figure 22), are the sections commonly available from manufacturers. Information from FHWA indicates that from limited hydraulic tests they are equivalent in operation to a headwall in both inlet and outlet control.

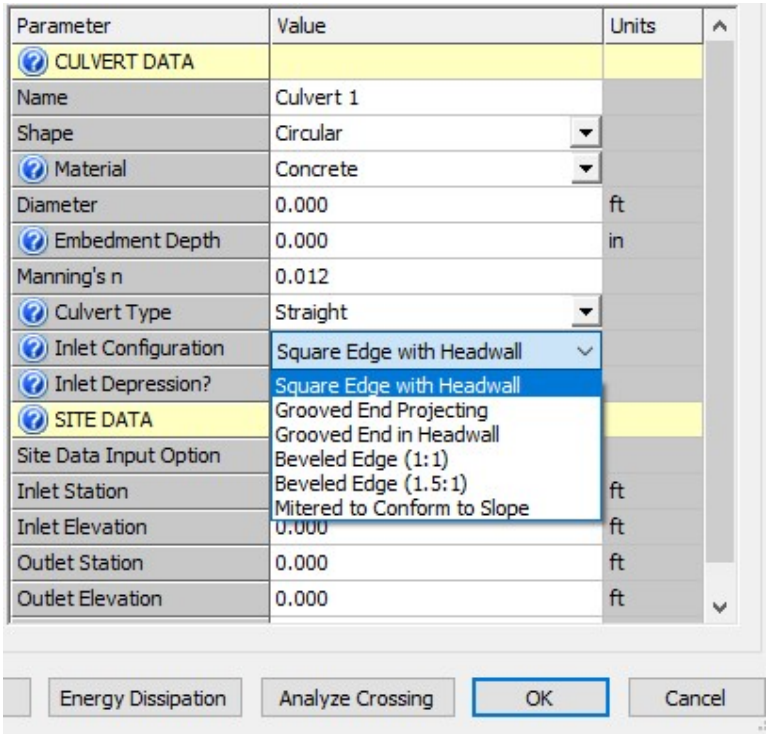


Figure 20 – Inlet Configuration for Concrete Pipe



Figure 21 – Grooved End of Concrete Pipe in Headwall (with trashrack)



Figure 22 – Flared End Section of Concrete Pipe (with trashrack)

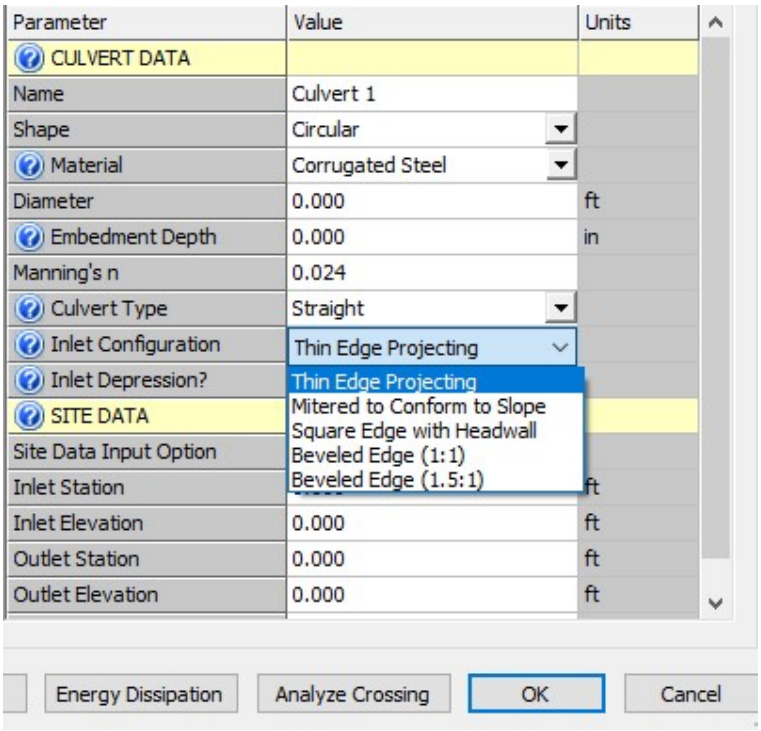


Figure 23 – Inlet Configuration for Corrugated Steel Pipe

The next parameter to define is the inlet configuration. The choices vary slightly depending on the type of pipe. For circular steel pipe (see Figure 23) they include:

- Thin Edge Projecting – This configuration provides a square end of the metal pipe extending upstream into the natural channel.
- Mitered to Conform to Slope – This configuration provides a pipe cut (mitered) to the same angle as the upstream embankment slope. This configuration is not used for a standard flared end section.
- Square Edge with Headwall – This configuration provides a vertical headwall at the inlet of the pipe with a square pipe end.
- Beveled Edge (1:1 or 1.5:1) – These two configurations provide a vertical headwall with a chamfer at the pipe inlet.

The final parameter in the culvert data window is Inlet Depression. The depression of a culvert is the vertical drop of the inlet control section below the stream bed. An inlet depression is defined by entering a value for each of the following items:

Depression – The vertical drop of inlet control section below the stream bed.

Depression Slope – The slope between the stream bed and the invert at the face of the culvert. The depression slope must be set between 2:1 and 3:1.

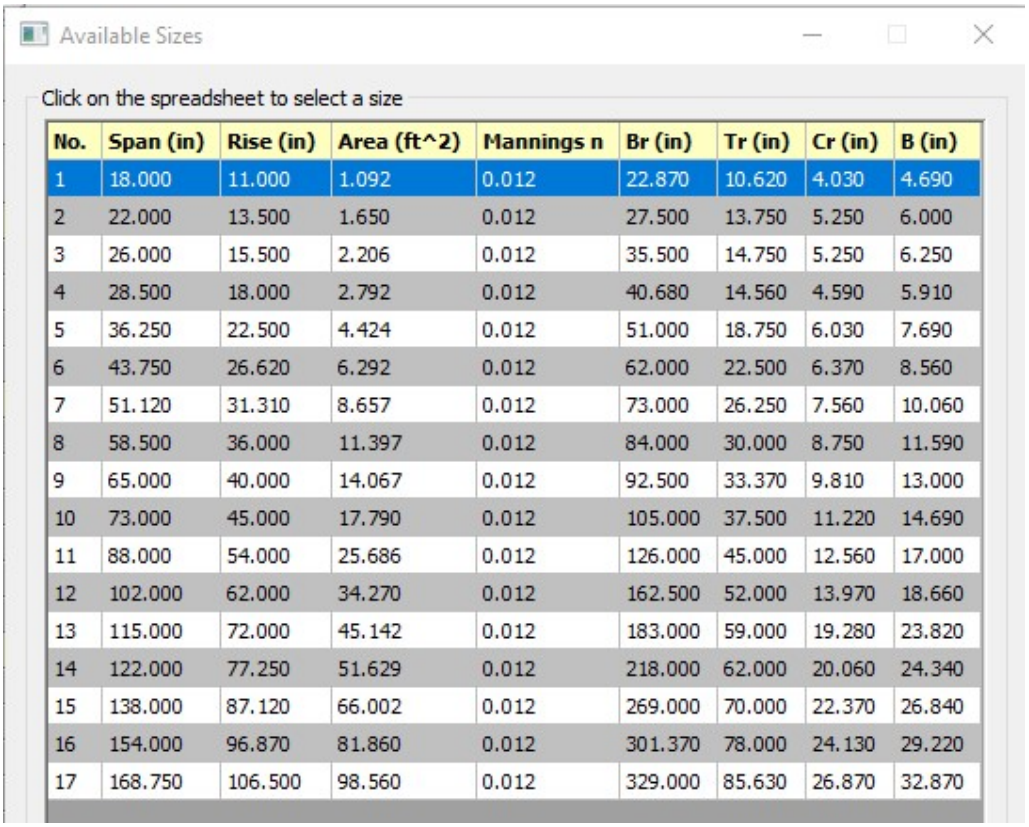
Crest Width – The length of weir crest at the top of the depression slope. Designing the crest width becomes an iterative process in HY-8 as the user must select a crest width wide

enough so that it does not control the headwater calculations. If the selected crest width is not wide enough the crest section will produce a higher headwater elevation than the culvert throat. The user must continue to increase the crest width and run the analysis until the headwater depth ceases to change with increasing crest width. Once this occurs the crest section no longer controls and may be used in analysis and construction.

If the selected culvert shape is a pipe arch, instead of circular, different options will be available. If Pipe Arch is selected as the shape and concrete is selected as material, the window is modified as shown in Figure 24. Below the Material line, a new line titled “Define” is shown along with Span and Rise. The default values for span and rise are 18 inches and 11 inches respectively, which represent the smallest concrete arch pipe. When the define button is selected, a new window, shown in Figure 25 is presented. The table in Figure 25 represents all of the available concrete arch pipes, including span, rise and other necessary geometric parameters.

Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Pipe Arch	
Material	Concrete	
Size	Define...	
Span	18.000	in
Rise	11.000	in
Embedment Depth	0.000	in
Manning's n	0.012	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	ft
Inlet Elevation	0.000	ft

Figure 24 – Concrete Pipe Arch Material



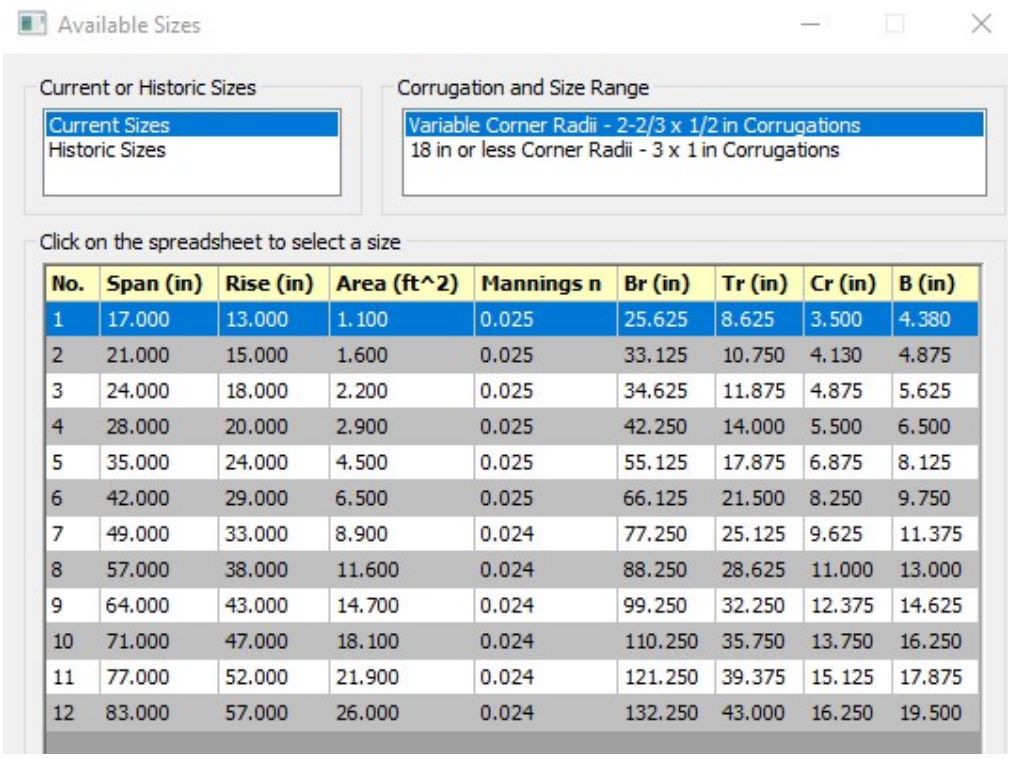
No.	Span (in)	Rise (in)	Area (ft^2)	Mannings n	Br (in)	Tr (in)	Cr (in)	B (in)
1	18.000	11.000	1.092	0.012	22.870	10.620	4.030	4.690
2	22.000	13.500	1.650	0.012	27.500	13.750	5.250	6.000
3	26.000	15.500	2.206	0.012	35.500	14.750	5.250	6.250
4	28.500	18.000	2.792	0.012	40.680	14.560	4.590	5.910
5	36.250	22.500	4.424	0.012	51.000	18.750	6.030	7.690
6	43.750	26.620	6.292	0.012	62.000	22.500	6.370	8.560
7	51.120	31.310	8.657	0.012	73.000	26.250	7.560	10.060
8	58.500	36.000	11.397	0.012	84.000	30.000	8.750	11.590
9	65.000	40.000	14.067	0.012	92.500	33.370	9.810	13.000
10	73.000	45.000	17.790	0.012	105.000	37.500	11.220	14.690
11	88.000	54.000	25.686	0.012	126.000	45.000	12.560	17.000
12	102.000	62.000	34.270	0.012	162.500	52.000	13.970	18.660
13	115.000	72.000	45.142	0.012	183.000	59.000	19.280	23.820
14	122.000	77.250	51.629	0.012	218.000	62.000	20.060	24.340
15	138.000	87.120	66.002	0.012	269.000	70.000	22.370	26.840
16	154.000	96.870	81.860	0.012	301.370	78.000	24.130	29.220
17	168.750	106.500	98.560	0.012	329.000	85.630	26.870	32.870

Figure 25 – Concrete Pipe Arch Size Options

If Pipe Arch is selected as the shape and steel is selected as material, the window is modified as shown in Figure 26. Below the Material line, a new line titled “Define” is shown along with Span and Rise. The default values for span and rise are 17 inches and 13 inches respectively, which represent the smallest steel arch pipe. When the define button is selected, a new window, shown in Figure 27 is presented. The table in Figure 27 represents some of the available steel arch pipes, including span, rise and other necessary geometric parameters. The sizes in Figure 27 represent the current sizes available with 2-2/3” x ½” corrugations, as indicated in the box in the upper right-hand side. These are the smaller steel arch pipes. If the line “18 in or less Corner Radii – 3 x 1 in corrugations” is highlighted, this will show the larger steel arch sizes, which have 3” x 1” corrugations (see Figure 28). Note in the box in the upper left of this window, the line “Current Sizes” is highlighted. If historic sizes are selected in this window, a table of all of the historic sizes of arch pipes will be shown. This information can be valuable when trying to analyze an existing arch pipe that is old, since the shape of arch pipes has changed over time.

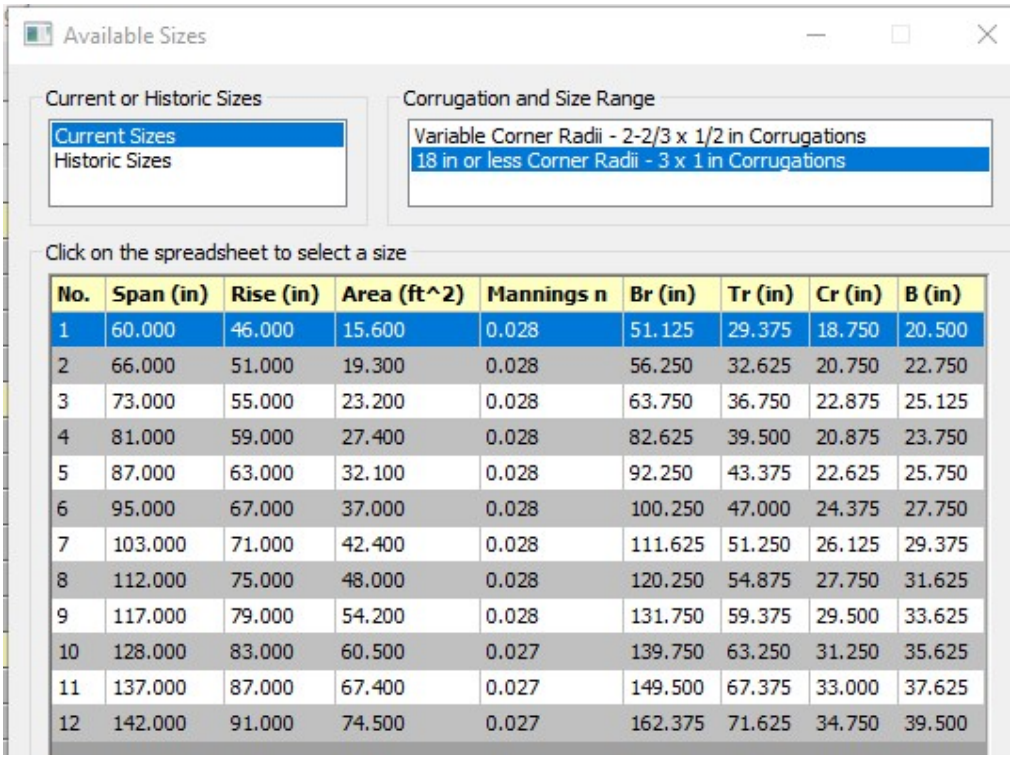
Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Pipe Arch	
Material	Steel or Aluminum	
Size	Define...	
Span	17.000	in
Rise	13.000	in
Embedment Depth	0.000	in
Manning's n	0.025	
Culvert Type	Straight	
Inlet Configuration	Projecting	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	ft
Inlet Elevation	0.000	ft

Figure 26 – Steel Pipe Arch Material



No.	Span (in)	Rise (in)	Area (ft^2)	Mannings n	Br (in)	Tr (in)	Cr (in)	B (in)
1	17.000	13.000	1.100	0.025	25.625	8.625	3.500	4.380
2	21.000	15.000	1.600	0.025	33.125	10.750	4.130	4.875
3	24.000	18.000	2.200	0.025	34.625	11.875	4.875	5.625
4	28.000	20.000	2.900	0.025	42.250	14.000	5.500	6.500
5	35.000	24.000	4.500	0.025	55.125	17.875	6.875	8.125
6	42.000	29.000	6.500	0.025	66.125	21.500	8.250	9.750
7	49.000	33.000	8.900	0.024	77.250	25.125	9.625	11.375
8	57.000	38.000	11.600	0.024	88.250	28.625	11.000	13.000
9	64.000	43.000	14.700	0.024	99.250	32.250	12.375	14.625
10	71.000	47.000	18.100	0.024	110.250	35.750	13.750	16.250
11	77.000	52.000	21.900	0.024	121.250	39.375	15.125	17.875
12	83.000	57.000	26.000	0.024	132.250	43.000	16.250	19.500

Figure 27 – Steel Pipe Arch Size Options (small)



No.	Span (in)	Rise (in)	Area (ft^2)	Mannings n	Br (in)	Tr (in)	Cr (in)	B (in)
1	60.000	46.000	15.600	0.028	51.125	29.375	18.750	20.500
2	66.000	51.000	19.300	0.028	56.250	32.625	20.750	22.750
3	73.000	55.000	23.200	0.028	63.750	36.750	22.875	25.125
4	81.000	59.000	27.400	0.028	82.625	39.500	20.875	23.750
5	87.000	63.000	32.100	0.028	92.250	43.375	22.625	25.750
6	95.000	67.000	37.000	0.028	100.250	47.000	24.375	27.750
7	103.000	71.000	42.400	0.028	111.625	51.250	26.125	29.375
8	112.000	75.000	48.000	0.028	120.250	54.875	27.750	31.625
9	117.000	79.000	54.200	0.028	131.750	59.375	29.500	33.625
10	128.000	83.000	60.500	0.027	139.750	63.250	31.250	35.625
11	137.000	87.000	67.400	0.027	149.500	67.375	33.000	37.625
12	142.000	91.000	74.500	0.027	162.375	71.625	34.750	39.500

Figure 28 – Steel Pipe Arch Size Options (large)

In addition to the steel pipe arch sizes shown in Figures 27 and 28, much larger steel pipe arches are available. These arches are constructed using corrugated structural steel plates, bolted together, rather than a continuous sheet of corrugated steel. The radius of the bottom corner of these larger pipes falls into one of three sizes – 18 inches (see Figure 29), 31 inches (see Figure 30) or 47 inches (see Figure 31). The maximum size shown in these tables is a 31'-4" span by 18'-10" rise.

Click on the spreadsheet to select a size

No.	Span (in)	Rise (in)	Area (ft^2)	Mannings n	Br (in)	Tr (in)	Cr (in)	B (in)
1	73.000	55.000	22.090	0.035	76.300	36.800	18.000	21.000
2	76.000	57.100	24.100	0.035	98.600	38.100	18.000	20.500
3	81.200	58.900	26.160	0.035	83.500	41.000	18.000	22.000
4	84.200	61.100	28.400	0.035	104.200	42.300	18.000	21.400
5	87.000	63.200	30.620	0.034	136.200	43.500	18.000	20.800
6	92.400	65.000	32.910	0.034	109.800	46.500	18.000	22.400
7	95.200	67.200	35.390	0.034	137.900	47.700	18.000	21.700
8	97.800	69.400	37.960	0.034	182.900	48.900	18.000	20.900
9	103.400	71.700	40.460	0.034	141.000	51.900	18.000	22.700
10	106.000	73.300	43.100	0.034	178.700	53.000	18.000	21.900
11	111.800	75.100	45.830	0.034	144.600	56.200	18.000	23.800
12	114.200	77.300	48.690	0.034	177.500	57.300	18.000	22.900
13	116.600	79.500	51.670	0.034	227.700	58.300	18.000	21.900
14	122.600	81.200	54.510	0.034	178.300	61.500	18.000	24.000
15	128.400	82.900	57.460	0.034	153.200	64.900	18.000	26.100
16	131.000	85.100	60.720	0.034	180.400	65.900	18.000	25.100
17	136.800	86.900	63.860	0.034	157.900	69.400	18.000	27.400
18	139.400	89.100	76.240	0.034	183.200	70.200	18.000	26.300
19	141.800	91.300	70.700	0.033	216.400	71.100	18.000	25.200
20	147.800	93.000	74.080	0.033	186.500	74.700	18.000	27.500
21	150.200	95.200	77.640	0.033	216.800	75.500	18.000	26.400
22	152.400	97.400	81.370	0.033	257.400	76.400	18.000	25.200
23	154.400	99.700	85.200	0.033	314.700	77.300	18.000	24.000
24	160.800	101.300	88.780	0.033	254.800	80.700	18.000	26.400
25	167.200	103.000	92.580	0.033	220.700	84.400	18.000	28.900
26	169.400	105.200	96.560	0.033	254.100	85.100	18.000	27.600

Figure 29 – SSPPA Table for 18-inch radius

Click on the spreadsheet to select a size

No.	Span (in)	Rise (in)	Area (ft^2)	Mannings n	Br (in)	Tr (in)	Cr (in)	B (in)
1	159.400	112.300	98.130	0.034	192.600	80.100	31.000	38.600
2	162.200	114.400	102.300	0.034	220.800	81.300	31.000	37.800
3	167.600	116.200	106.410	0.034	197.900	84.400	31.000	39.600
4	170.600	118.400	110.880	0.034	222.600	85.600	31.000	38.900
5	172.800	120.500	115.130	0.034	256.600	86.600	31.000	38.000
6	178.600	122.300	119.530	0.034	227.700	89.800	31.000	39.900
7	184.200	124.100	124.050	0.034	208.500	93.100	31.000	41.900
8	187.000	126.300	128.780	0.034	232.100	94.100	31.000	41.000
9	189.600	128.500	133.660	0.034	260.600	95.200	31.000	40.100
10	195.400	130.200	138.290	0.034	236.000	98.500	31.000	42.200
11	198.000	132.400	143.290	0.034	263.200	99.500	31.000	41.200
12	203.600	134.200	148.060	0.034	241.000	102.900	31.000	43.400
13	206.200	136.300	153.040	0.034	266.800	103.800	31.000	42.400
14	208.800	138.500	158.290	0.034	297.900	104.800	31.000	41.400
15	214.600	140.300	163.730	0.034	270.600	108.200	31.000	43.600
16	217.200	142.400	168.730	0.034	299.700	109.100	31.000	42.500
17	223.000	144.200	173.980	0.034	274.500	112.600	31.000	44.800
18	225.400	146.400	179.540	0.034	302.300	113.500	31.000	43.700
19	231.400	148.100	184.790	0.034	278.600	117.000	31.000	46.000
20	234.000	150.300	190.610	0.034	305.100	117.900	31.000	44.900
21	236.400	152.500	196.340	0.034	336.500	118.800	31.000	43.800
22	238.600	154.700	202.230	0.034	374.300	119.700	31.000	42.600
23	224.800	156.400	207.920	0.034	338.100	123.200	31.000	45.000
24	247.000	158.600	213.820	0.034	373.500	124.000	31.000	43.800

Figure 30 – SSPPA Table for 31-inch radius

Click on the spreadsheet to select a size

No.	Span (in)	Rise (in)	Area (ft^2)	Mannings n	Br (in)	Tr (in)	Cr (in)	B (in)
1	240.000	167.000	216.590	0.033	223.600	122.500	47.000	62.800
2	246.000	171.000	228.680	0.033	255.700	124.700	47.000	61.400
3	257.000	174.000	240.060	0.033	236.700	131.400	47.000	65.300
4	263.000	179.000	254.540	0.033	268.100	133.500	47.000	63.700
5	269.000	183.000	267.480	0.033	307.100	135.500	47.000	62.100
6	280.000	187.000	281.730	0.033	280.200	142.400	47.000	66.200
7	290.000	191.000	295.890	0.033	262.100	149.700	47.000	70.700
8	296.000	194.000	307.800	0.033	292.200	151.400	47.000	68.800
9	302.000	199.000	324.160	0.033	328.600	153.200	47.000	66.900
10	307.000	203.000	338.460	0.033	373.300	155.000	47.000	64.800
11	319.000	207.000	354.570	0.033	339.400	162.100	47.000	69.400
12	330.000	210.000	368.430	0.033	315.800	169.600	47.000	74.200
13	336.000	214.000	383.930	0.033	350.200	171.100	47.000	72.100
14	341.000	219.000	401.840	0.033	392.300	172.700	47.000	69.900
15	352.000	222.000	416.480	0.033	361.100	180.200	47.000	74.800
16	364.000	226.000	434.310	0.033	339.100	188.200	47.000	80.000

Figure 31 – SSPPA Table for 47-inch radius

Site Data Input for HY8

In the lower right side of the overall window is the location to enter the appropriate site data for the HY8 analysis. The Site Data Input Option provides two options for input. Figure 32 shows the input based on Culvert Invert Data. This is the easiest approach to input for site data and is the recommended approach. The necessary parameters include:

- Inlet Station – This can be any value, but 0 is the simplest number to use.
- Inlet Elevation – This is the elevation of the culvert at the inlet, which is typically set to equal the elevation of the natural channel at the inlet.
- Outlet Station – This value must be larger than the Inlet Station value. The difference between the Outlet Station and the Inlet Station is the length. If the Inlet Station Value is set to 0, the Outlet Station Value is simply the pipe length.
- Outlet Elevation – This is the elevation of the culvert at the outlet, which is typically set to equal the elevation of the natural channel at the outlet.
- Number of Barrels – This is the number of parallel culverts with the identical geometry. Normally this value is set to 1 if only one culvert is analyzed. If there are two culverts, with identical geometry (size, material type, length and inverts), this value can be set to 2. When analyzing existing crossings with two culverts, field survey will often indicate small differences in invert elevations or lengths. This can be addressed by adding a second culvert in the analysis, rather than assuming the two culverts are identical. This will be addressed further in an example.

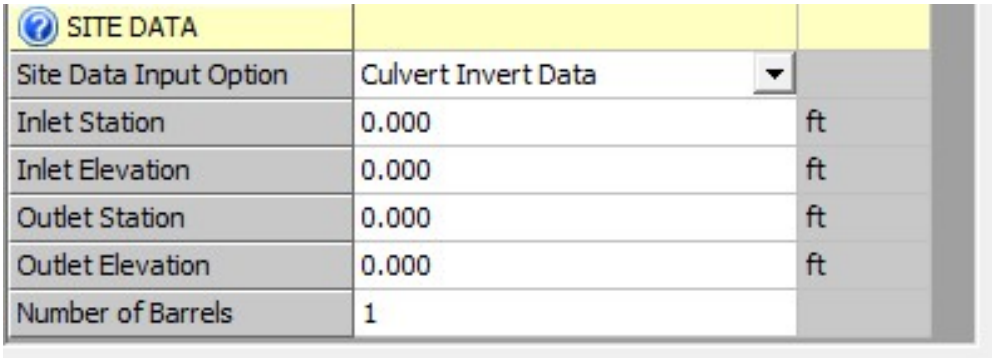


Figure 32 – Site Data using Culvert Invert Data

The second approach to site data input is to use the embankment toe data. Figure 33 shows the input based on Embankment Toe Data. The primary difference is the pipe length is a calculated value rather than a known value. The upstream and downstream stations are where the roadway embankment intersects the channel bottom. The pipe length is shorter than the difference between these stations, since the embankment intersects the pipe at a location closer to centerline than the place where the embankment intersects the channel.

SITE DATA		
Site Data Input Option	Embankment Toe Data	
Upstream Station	0.000	ft
Upstream Elevation	0.000	ft
Upstream Embankment Slope (H:V)	0.000	_:1
Downstream Station	0.000	ft
Downstream Elevation	0.000	ft
Downstream Embankment Slope (...	0.000	_:1
Number of Barrels	1	

Figure 33 – Site Data using Embankment Toe Data

Flow Data Input for HY8

In the upper left side of the overall window is the location to enter the appropriate flow data for the HY8 analysis. HY8 is hydraulic software, not hydrologic software, therefore determining appropriate design flows must be completed independently of HY8. There are three options in entering the discharge method used by HY8 (see Figure 34).

Parameter	Value	Units
DISCHARGE DATA		
Discharge Method	Minimum, Design, and Maximum	
Minimum Flow	Minimum, Design, and Maximum	cfs
Design Flow	User-Defined	cfs
Maximum Flow	Recurrence	cfs
	0.000	

Figure 34 – Discharge Data

The options include:

Minimum, Design, and Maximum – This is the original option provided in HY8. This allows the user to enter three flows – the minimum flow for analysis purposes, the design flow, and the maximum flow for analysis purposes. These numbers do not have to be all different, but the minimum flow must be the smallest number and the maximum flow must the largest number (or they all have to be the same).

User-Defined – This option allows the user to enter any number of specific flows (up to at least 100 different values) and provide a specific user defined name for each flow. See Figure 35 for an example.

Recurrence – This option allows the user to enter nine specific return period values (see Figure 36). All nine values are required, which is the reason the user-defined option is

sometimes preferred, since all nine flow values are not always available or necessary for the analysis.

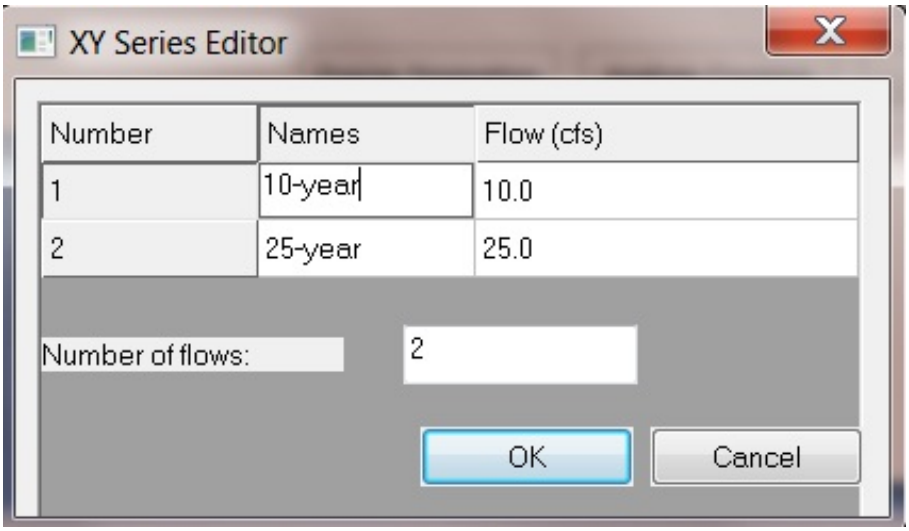


Figure 35 – User-Defined Flows

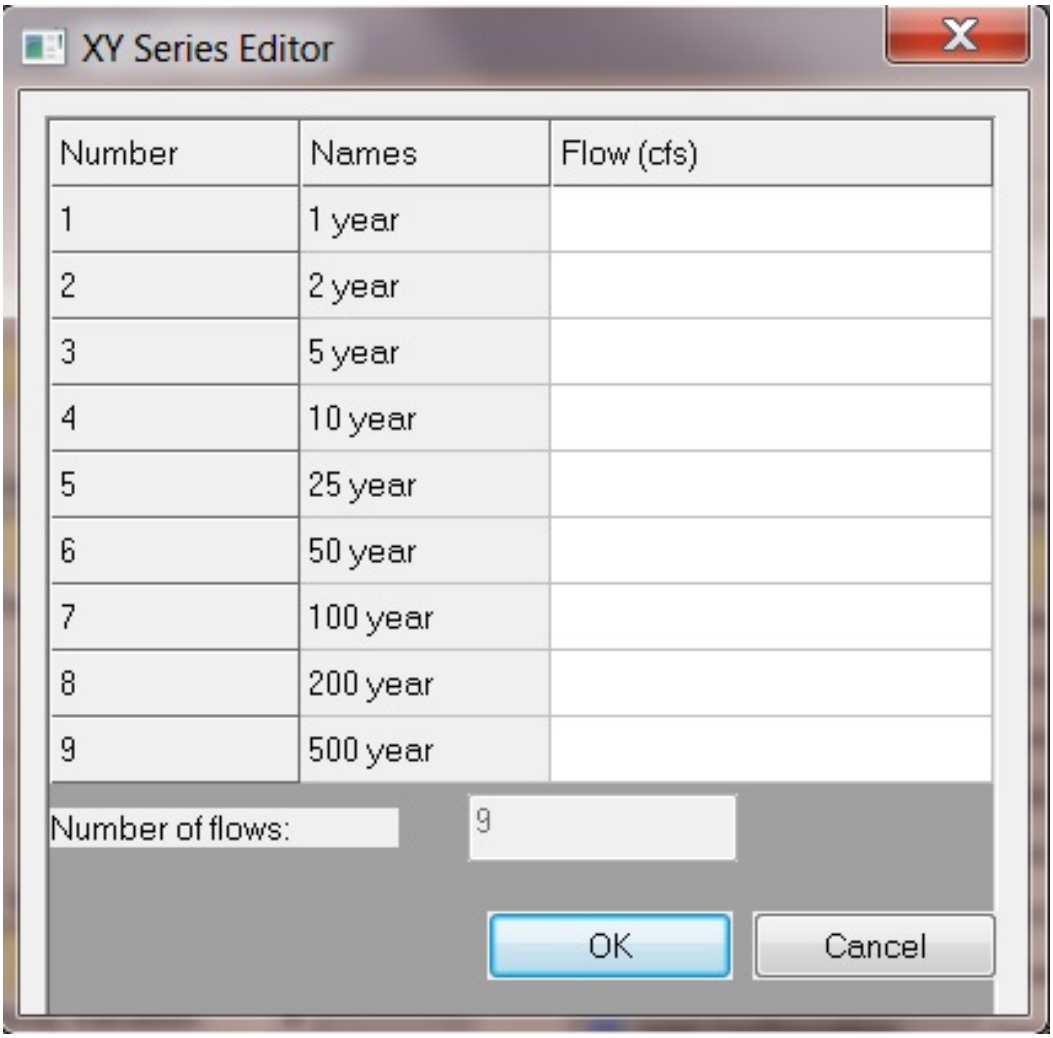


Figure 36 – Recurrence Interval Flows

Tailwater Data Input for HY8

In the center of the left side of the overall window is the location to enter the appropriate tailwater data for the HY8 analysis (see Figure 37). The tailwater data will define the water surface elevation at the downstream end of the culvert. The water surface elevation at the downstream end of the culvert may restrict the overall capacity of the culvert, depending on a variety of other factors.

The options channel type include:

- Rectangular Channel – Enter the Bottom Width, Channel Slope (of downstream channel), Manning's n of the channel and Channel Invert Elevation.
- Trapezoidal Channel – Enter the Bottom Width, Side Slope of the Channel, Channel Slope (of downstream channel), Manning's n of the channel and Channel Invert Elevation

- Triangular Channel – Enter the Side Slope of the Channel, Channel Slope (of downstream channel), Manning's n of the channel and Channel Invert Elevation.
- Irregular Channel – If the downstream channel cannot be reasonably approximated by a rectangular, trapezoidal or triangular channel, a series of x-y coordinates can be entered to define the shape of the downstream channel.
- Enter Rating Curve – The rating curve option represents flow rate versus tailwater elevation for the downstream channel. When this option is selected, the user is prompted to define 11 increasing flow and elevation values, as shown below. When using this option a channel invert elevation (generally the same as the downstream invert of the culvert) is required so that a tailwater depth can be computed from the rating curve.
- Enter Constant Tailwater Elevation – A constant tailwater elevation means that the tailwater elevation entered remains constant for all flows. When using this option a channel invert elevation (generally the same as the downstream invert of the culvert) is required so that a tailwater depth can be computed. A constant tailwater elevation may represent, for example, the design elevation of a lake, bay, or estuary into which the culvert(s) discharge.

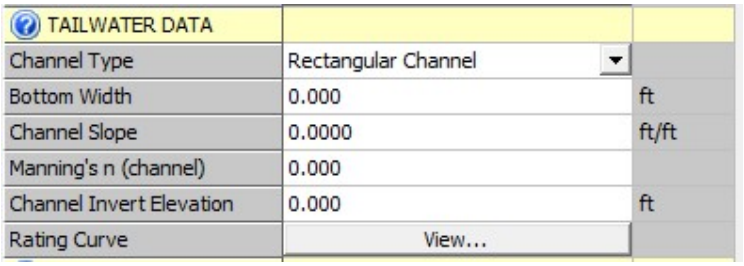


Figure 37 – Tailwater Data

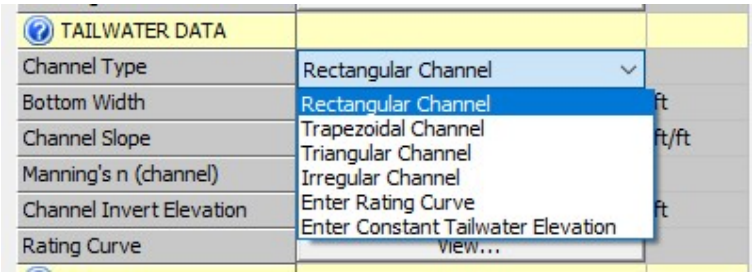


Figure 38 – Tailwater Data, Channel Type

Roadway Data Input for HY8

In the center of the left side of the overall window is the location to enter the appropriate roadway data for the HY8 analysis (see Figure 39). While this section is titled Roadway Data, it is actually the overtopping data for the site. In most cases, the critical overtopping to be analyzed will be the roadway, usually near the culvert. Sometimes the roadway is designed so the overtopping location is a few hundred feet away from the culvert. In certain

situations, it is possible that the roadway ditch overtops before the roadway itself, and water is directed into an adjacent drainage. In this situation, it is necessary to define the divide overtopping information rather than the roadway overtopping information.

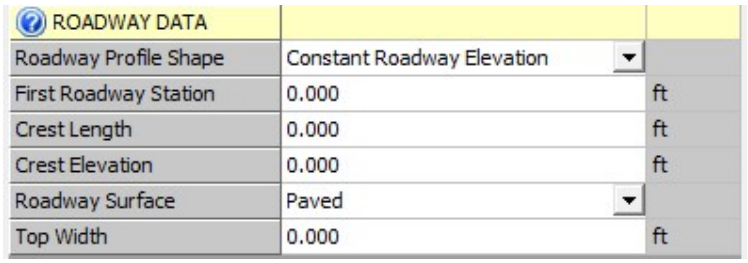


Figure 39 – Roadway Data

The required data input includes:

- Roadway Profile Shape – The roadway profile can be entered as a single, constant roadway elevation or as a series of x-y coordinates. For locations where overtopping is not anticipated or acceptable, a constant elevation is acceptable. In other locations, the x-y profile of the roadway should be defined. This information will allow the software to more accurately determine the depth of overtopping and the width of the roadway inundated at varies flows.
- First Roadway Station – This value corresponds to the first point in the roadway profile if a profile is provided. This is important only in that it allows the software to create a better visual representation of the culvert in relation to the overtopping location.
- Crest Length – When the constant roadway elevation option is used, this is the length perpendicular to the flow direction. This value is used as the length of the broad-crested weir when calculating overflow.
- Roadway Surface – Options are either Paved or Gravel, or the user is allowed to input an appropriate weir discharge coefficient if the overflow isn't a paved or gravel roadway.
- Top Width – This is the width of the roadway (parallel to the direction of overflow). This parameter allows the software to select an appropriate weir coefficient for the roadway, which functions as a broad-crested weir.

Once all of the necessary parameters are entered, the Analyze Crossing button at the bottom can be selected and results reviewed. The discussion of interpretation of results will be provided by means of a series of examples.

HYDRAULIC ANALYSIS USING HY8

This section provides a number of examples of the results of the hydraulic analysis using HY8. The overall input table will be provided, along with a description of the site conditions, and the output results will be shown. Each example is included to point out one or more particular aspects of culvert analysis that can be important.

Example 1

Determine the required culvert size. The design criteria include the culvert is capable of passing the design flow without overtopping the roadway.

Culvert and Site Data:

60-foot length

1% slope

Invert elevation at inlet = 120.2

Invert elevation at outlet = 119.6

Flow Data

Minimum = 0 cfs

Design = 15 cfs

Maximum = 20 cfs

Tailwater Data

Trapezoidal Channel

2-foot-wide bottom

4:1 side slopes

Channel slope = 1%

Manning's n value = 0.035

Channel invert (at pipe outlet) = 119.6 (matches the pipe invert)

Roadway Data

Constant Roadway Elevation

Crest Length = 100 ft

Crest Elevation = 125.2

Paved Roadway, 24-feet wide

The data above are shown in Figure 40, along with a preliminary pipe selection of 24” CSP, with the edge of the pipe projecting into the upstream channel.

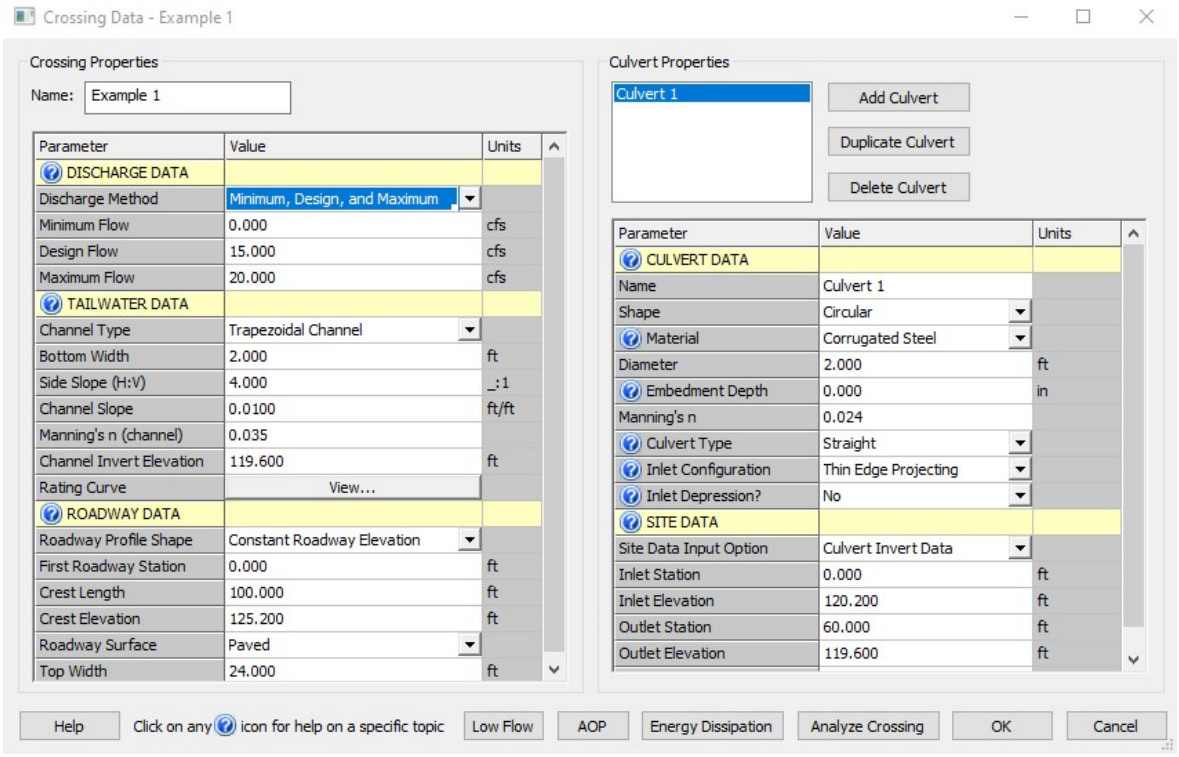
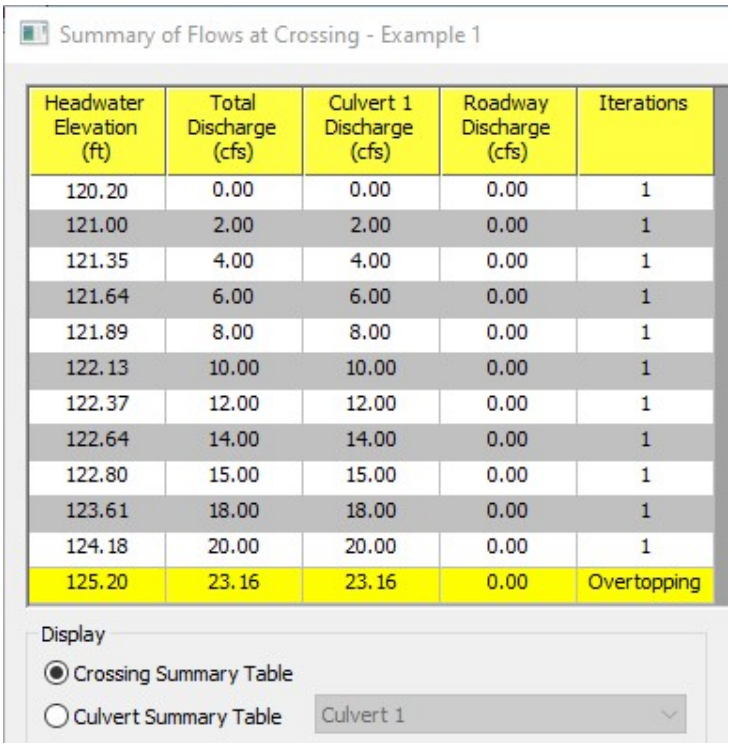


Figure 40 – Example 1 Data

Clicking on the “Analyze Crossing” button at the bottom of the Data Window will calculate the hydraulics of this culvert. The Crossing Table Summary (Figure 41) will be displayed.



Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
120.20	0.00	0.00	0.00	1
121.00	2.00	2.00	0.00	1
121.35	4.00	4.00	0.00	1
121.64	6.00	6.00	0.00	1
121.89	8.00	8.00	0.00	1
122.13	10.00	10.00	0.00	1
122.37	12.00	12.00	0.00	1
122.64	14.00	14.00	0.00	1
122.80	15.00	15.00	0.00	1
123.61	18.00	18.00	0.00	1
124.18	20.00	20.00	0.00	1
125.20	23.16	23.16	0.00	Overtopping

Figure 41 – Example 1 Crossing Table Summary

The Crossing Table Summary shows the headwater elevation (water surface elevation at the culvert inlet) at ten different flows. The flow increment is equal to Maximum Flow – Minimum Flow/10. In this case, 20 cfs – 0 cfs/10 = 2.0 cfs. There is one exception to this general rule – the design flow is always shown. The ninth line in this table should be 16 cfs, based on the general rule, but because the design flow is 15.0 cfs, the design flow is shown instead of the flow at 16 cfs. The last line in the Crossing Table Summary shows the Overtopping Flow. In this case a flow of 23.16 cfs is necessary to reach the overtopping elevation of 125.2. The design flow is 15 cfs and the calculated water surface elevation at that flow is 122.80, or 2.6 feet above the invert of the 2-foot diameter culvert. This culvert is therefore large enough to pass the design flow without overtopping.

If the radio button titled Culvert Summary Table, near the bottom of Figure 41, is clicked, it will bring up a summary of the culvert (see Figure 42).

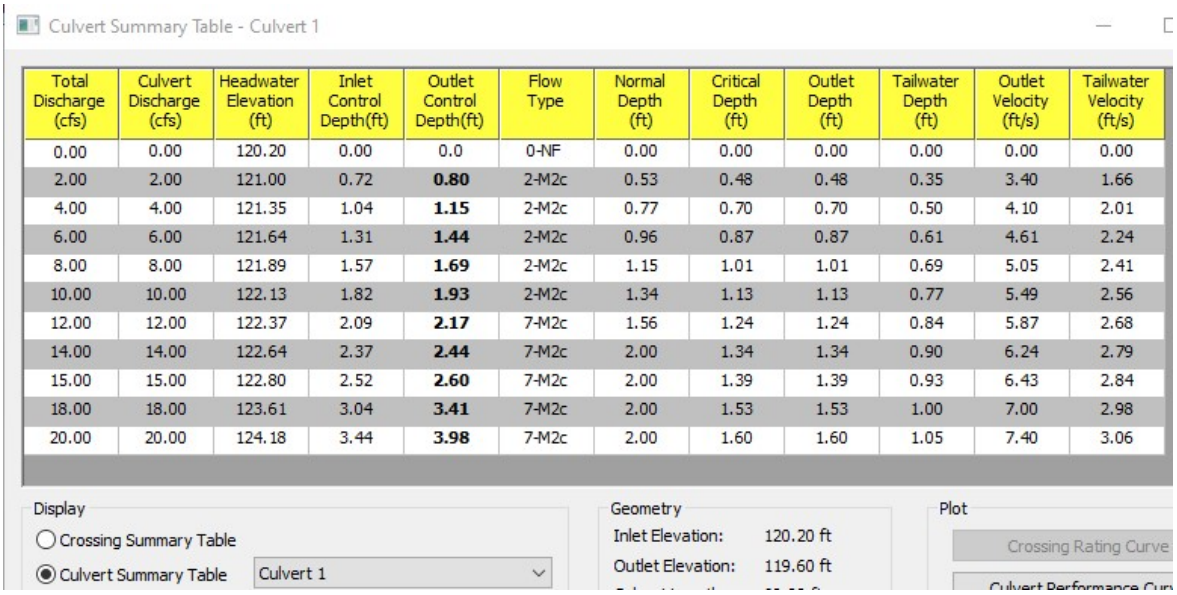


Figure 42 – Example 1 Culvert Summary Table

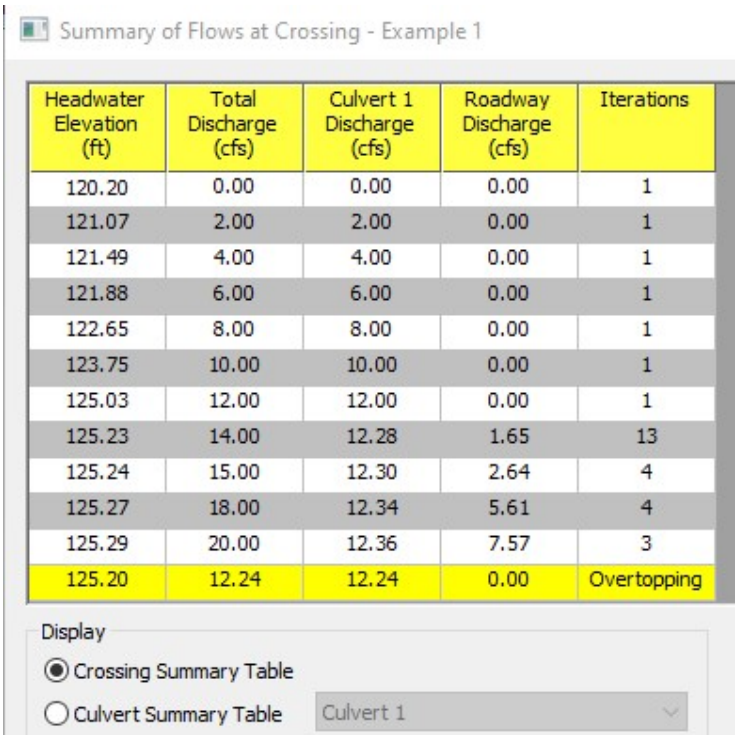
The Culvert Summary Table provides a more detailed look at the conditions which impact the headwater elevation at each flow. The Culvert Summary Table shows the Total Discharge, the Culvert Discharge (which is the same as the total discharge when there is only one culvert and overtopping is not reached) and the Headwater Elevation, similar to what is presented in the Crossing Summary Table. The next two columns are the Inlet Control Depth and the Outlet Control Depth.

For each flow, the inlet control depth and the outlet control depth are calculated. Outlet control is impacted by the parameters most often associated with culvert flow capacity – the tailwater depth, the pipe size, the pipe slope, the pipe friction, and the head losses at the pipe inlet and outlet. Inlet control is not as clear to many designers as outlet control and is sometimes ignored in pipe sizing analysis. Inlet control is impacted primarily by the size of the inlet opening and to a lesser extent by the head losses at the pipe inlet. Inlet control will be demonstrated in more detail in later examples. Either the Inlet Control Depth or the Outlet Control Depth is in bold for each flow rate. The bold indicates the controlling value (the controlling value is the larger of the two values). While Figure 42 shows this pipe is in outlet control throughout the flow range analyzed, that is not always the case.

Example 1A

Example 1 indicates a 24-inch diameter CSP is adequate to convey the design flow. When the first selection indicates a culvert is large enough, another analysis should be completed to determine if the selected culvert is too large. Therefore, this example changes the pipe

size from a 24” CSP to an 18” CSP. The Crossing Summary Table for this analysis is shown in Figure 43. The results in Figure 43 indicate the headwater elevation at 15 cfs is 125.24 (0.04 feet above the overtopping elevation) and the overtopping flow is 12.24 cfs (less than the design flow of 15 cfs). Therefore an 18” CSP is not large enough to pass the design flow without overtopping.


Summary of Flows at Crossing - Example 1

Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
120.20	0.00	0.00	0.00	1
121.07	2.00	2.00	0.00	1
121.49	4.00	4.00	0.00	1
121.88	6.00	6.00	0.00	1
122.65	8.00	8.00	0.00	1
123.75	10.00	10.00	0.00	1
125.03	12.00	12.00	0.00	1
125.23	14.00	12.28	1.65	13
125.24	15.00	12.30	2.64	4
125.27	18.00	12.34	5.61	4
125.29	20.00	12.36	7.57	3
125.20	12.24	12.24	0.00	Overtopping

Display
Crossing Summary Table
Culvert Summary Table
Culvert 1

Figure 43 – Example 1A Crossing Summary Table

Example 1B

Example 1 indicates a 24-inch diameter CSP is adequate to convey the design flow and Example 1A indicates an 18-inch diameter CSP is not adequate. Example 1 included a thin-edge projecting inlet configuration for this culvert. This is one of several relatively common inlet configurations. This example will look at the impact of changing this inlet configuration to a common flared end section. The other common inlet configuration is a concrete headwall which is hydraulically the same as a flared end section. This change reduces the inlet head loss coefficient from 0.9 for a thin edge projecting to 0.5 for a concrete headwall. The data window is shown in Figure 44 and the Crossing Summary Table is shown in Figure 45.

Figure 45 shows the overtopping flow is 24.21 cfs and the headwater elevation at the design flow of 15 cfs is 122.66 feet. These values compare to 23.16 cfs and 122.80 feet for the same pipe without the flared end section.

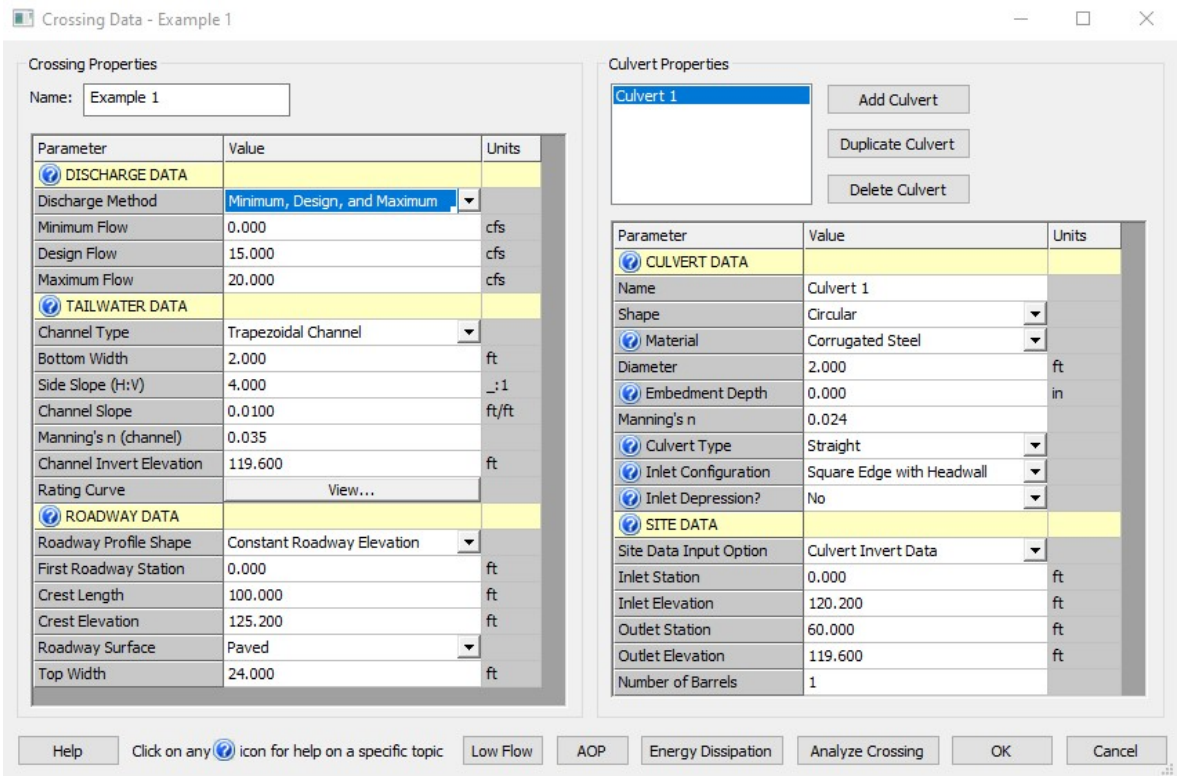


Figure 44 – Example 1B Data

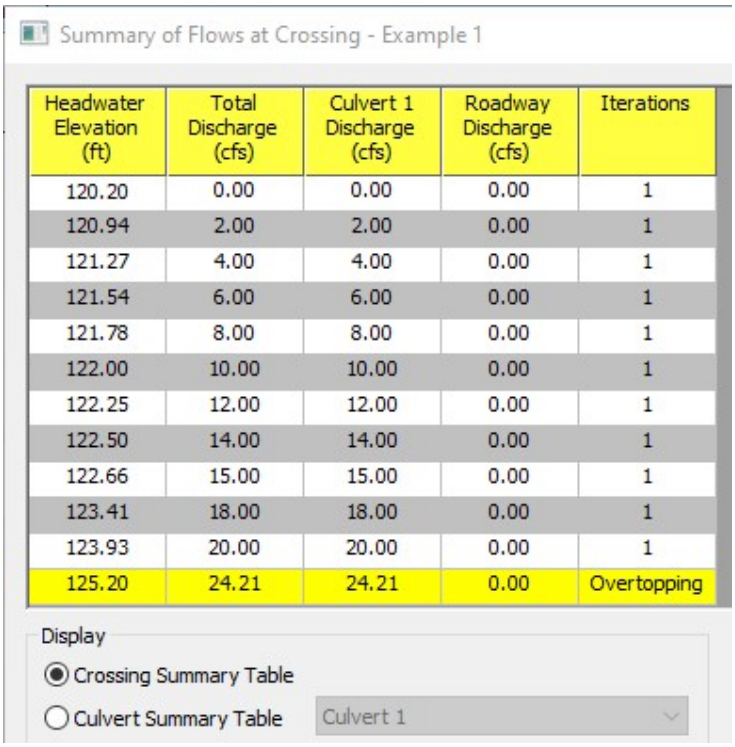


Figure 45 – Example 1B Crossing Summary Table

Example 1C

Example 1B showed the impact of changing the inlet end from a thin edge projecting to a standard flared end. Another option to consider for this crossing is the use of RCP instead of CSP. Example 1 showed this pipe was in outlet control, so providing a smoother conduit should provide better flow conditions. The data window is shown in Figure 46, the Crossing Summary Table is shown in Figure 47 and the Culvert Summary Table is shown in Figure 48.

Figure 47 shows the overtopping flow is 30.23 cfs and the headwater elevation at the design flow of 15 cfs is 122.45 feet. These values compare to 24.21 cfs and 122.66 feet for the CSP pipe with the flared end section.

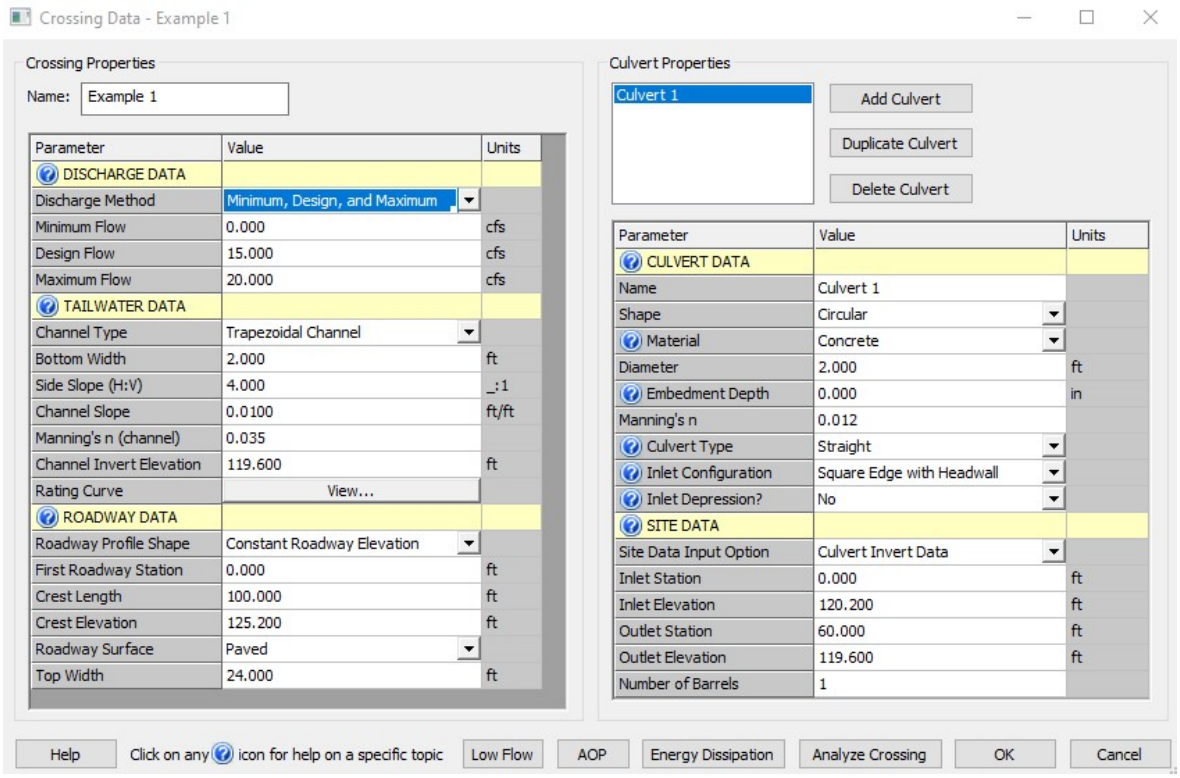


Figure 46 – Example 1C Data

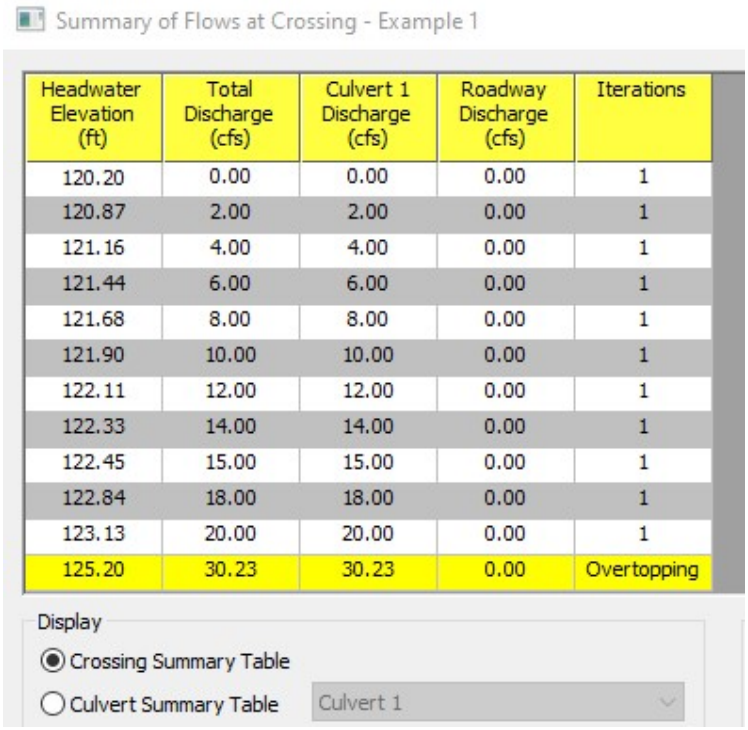


Figure 47 – Example 1C Crossing Summary Table

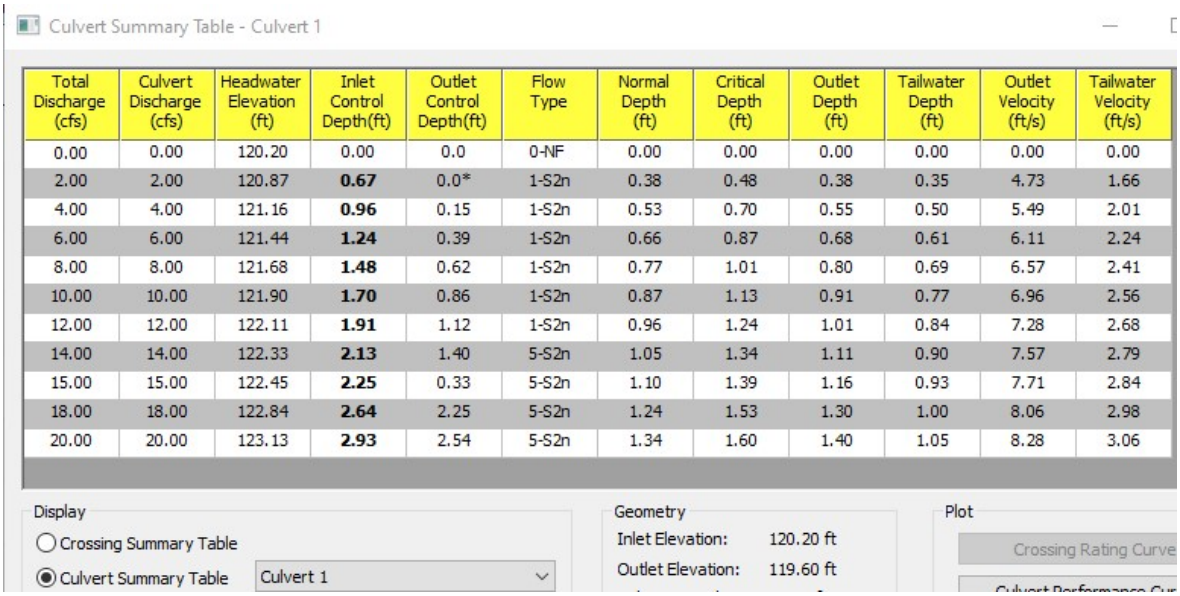


Figure 48 – Example 1C Culvert Summary Table

Example 1D

Example 1C showed the impact of changing the pipe material from CSP to RCP. The overtopping capacity of the pipe increased from 24.21 cfs to 30.23 cfs, an increase of about 25%. A review of Figure 48 shows this culvert is now in inlet control. As previously noted, for a culvert in inlet control, the capacity of the culvert is almost exclusively a function of pipe diameter and inlet conditions. To demonstrate this, Example 1D will analyze this same culvert, but change the slope of the culvert from 1% to 4%. Based on Manning's Equation, the flow capacity of a pipe is a function of the slope to the one-half power. Therefore, if the slope is increased by a factor of four (from 1% to 4%), the capacity of the culvert should double. The Crossing Summary Table for an RCP with a slope of 4% is shown in Figure 49. Note the culvert is still in inlet control and the overtopping capacity is 30.35 cfs, compared to 30.23 cfs for the culvert on a 1% slope, an increase of only about 0.4%. This example clearly illustrates the importance of properly evaluating the culvert to determine both outlet control and inlet control. Once a proposed culvert is shown to be operating in inlet control, increasing the slope of that culvert (or reducing the friction factor) will have very nominal impact on the flow capacity of the culvert. Figure 50 shows the Culvert Summary Table for this example. Note the culvert is in inlet control throughout the range of flows, just as it was at a slope of 1%, as illustrated in Figure 48.

Summary of Flows at Crossing - Example 1D

Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
120.20	0.00	0.00	0.00	1
120.85	2.00	2.00	0.00	1
121.14	4.00	4.00	0.00	1
121.41	6.00	6.00	0.00	1
121.65	8.00	8.00	0.00	1
121.87	10.00	10.00	0.00	1
122.08	12.00	12.00	0.00	1
122.30	14.00	14.00	0.00	1
122.42	15.00	15.00	0.00	1
122.81	18.00	18.00	0.00	1
123.10	20.00	20.00	0.00	1
125.20	30.35	30.35	0.00	Overtopping

Display

(•) Crossing Summary Table

( ) Culvert Summary Table Culvert 1

Figure 49 - Example 1D Crossing Summary Table

Culvert Summary Table - Culvert 1

Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth(ft)	Outlet Control Depth(ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
0.00	0.00	120.20	0.00	0.0	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
2.00	2.00	120.85	**0.65**	0.0*	1-S2n	0.27	0.48	0.28	0.35	7.30	1.66
4.00	4.00	121.14	**0.94**	0.0*	1-S2n	0.38	0.70	0.40	0.50	8.80	2.01
6.00	6.00	121.41	**1.21**	0.0*	1-S2n	0.46	0.87	0.49	0.61	9.75	2.24
8.00	8.00	121.65	**1.45**	0.0*	1-S2n	0.53	1.01	0.58	0.69	10.28	2.41
10.00	10.00	121.87	**1.67**	0.0*	1-S2n	0.60	1.13	0.65	0.77	10.81	2.56
12.00	12.00	122.08	**1.88**	0.0*	1-S2n	0.66	1.24	0.73	0.84	11.25	2.68
14.00	14.00	122.30	**2.10**	0.0*	5-S2n	0.71	1.34	0.79	0.90	11.71	2.79
15.00	15.00	122.42	**2.22**	0.0*	5-S2n	0.74	1.39	0.83	0.93	11.83	2.84
18.00	18.00	122.81	**2.61**	0.45	5-S2n	0.82	1.53	0.92	1.00	12.34	2.98
20.00	20.00	123.10	**2.90**	0.74	5-S2n	0.87	1.60	0.98	1.05	12.59	3.06

Display

( ) Crossing Summary Table

(•) Culvert Summary Table Culvert 1

Geometry

Inlet Elevation: 120.20 ft

Outlet Elevation: 117.80 ft

Plot

Crossing Rating Curve

Culvert Performance Cur

Figure 50 – Example 1D Culvert Summary Table



Figure 51 – Culverts Operating in Inlet Control, Upstream Side of Culvert



Figure 52 – Culverts Operating in Inlet Control, Downstream Side of Culvert

Figures 51 and 52 show an example of inlet control. Water is flowing from right to left in each photo. The water is almost at the top of the culvert at the inlet end, but close to the centerline of the culvert at the outlet end. This is a primary indication that the flow capacity is limited by the inlet, not by the outlet.

Example 2

Determine the required culvert size. The design criteria include the culvert is capable of passing the design flow without overtopping the roadway. This example includes higher flow but all of the other parameters as Example 1. This will result in very limited cover over the top of the pipe, to describe some of the options available.

Culvert and Site Data:

60-foot length

1% slope

Invert elevation at inlet = 120.2

Invert elevation at outlet = 119.6

Flow Data

Minimum = 0 cfs

Design = 70 cfs

Maximum = 100 cfs

Tailwater Data

Trapezoidal Channel

2-foot-wide bottom

4:1 side slopes

Channel slope = 1%

Manning's n value = 0.035

Channel invert (at pipe outlet) = 119.6 (matches the pipe invert)

Roadway Data

Constant Roadway Elevation

Crest Length = 100 ft

Crest Elevation = 125.2

Paved Roadway, 24-feet wide

The data above are shown in Figure 53, along with a preliminary pipe selection of 36" RCP, with a standard flared end section. The Crossing Summary Table is shown in Figure 54 and the Culvert Summary Table is shown in Figure 55.

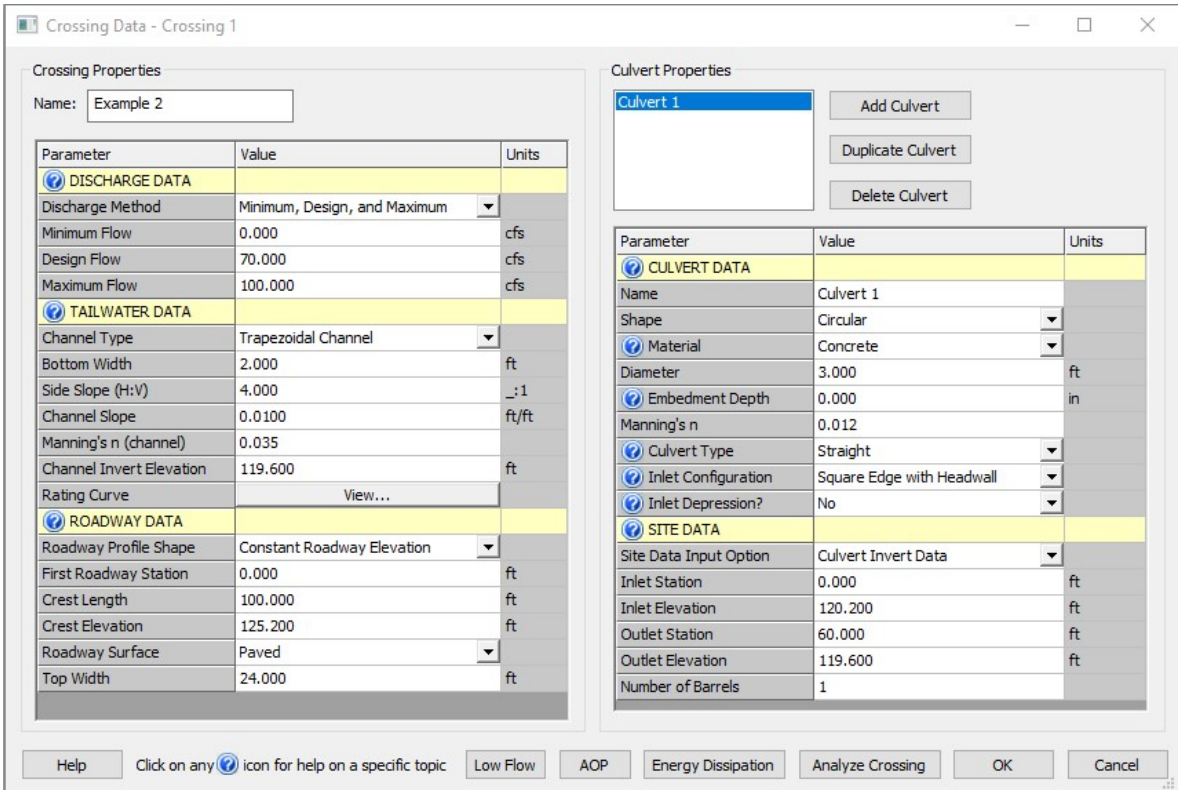
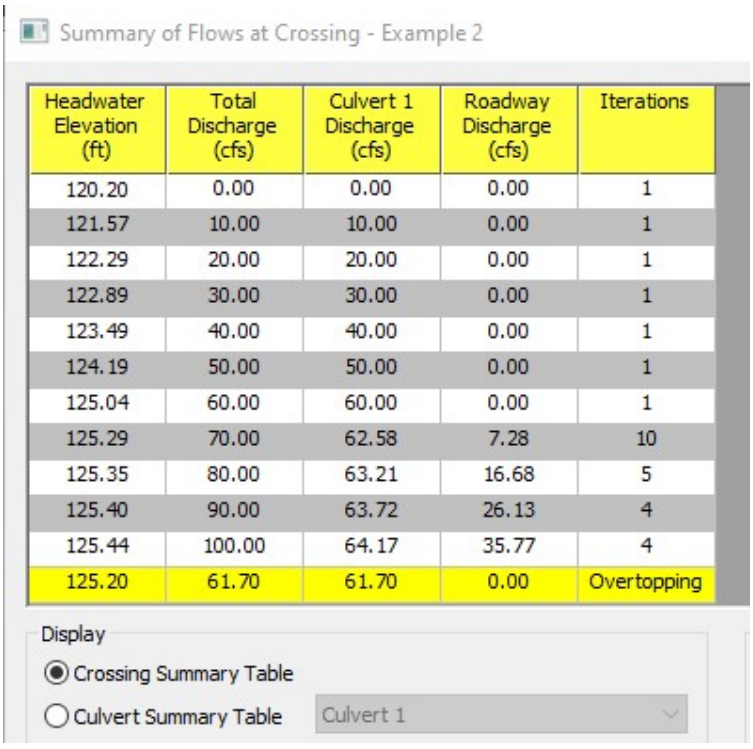


Figure 53 – Example 2 Data



Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
120.20	0.00	0.00	0.00	1
121.57	10.00	10.00	0.00	1
122.29	20.00	20.00	0.00	1
122.89	30.00	30.00	0.00	1
123.49	40.00	40.00	0.00	1
124.19	50.00	50.00	0.00	1
125.04	60.00	60.00	0.00	1
125.29	70.00	62.58	7.28	10
125.35	80.00	63.21	16.68	5
125.40	90.00	63.72	26.13	4
125.44	100.00	64.17	35.77	4
125.20	61.70	61.70	0.00	Overtopping

Figure 54 – Example 2 Crossing Summary Table

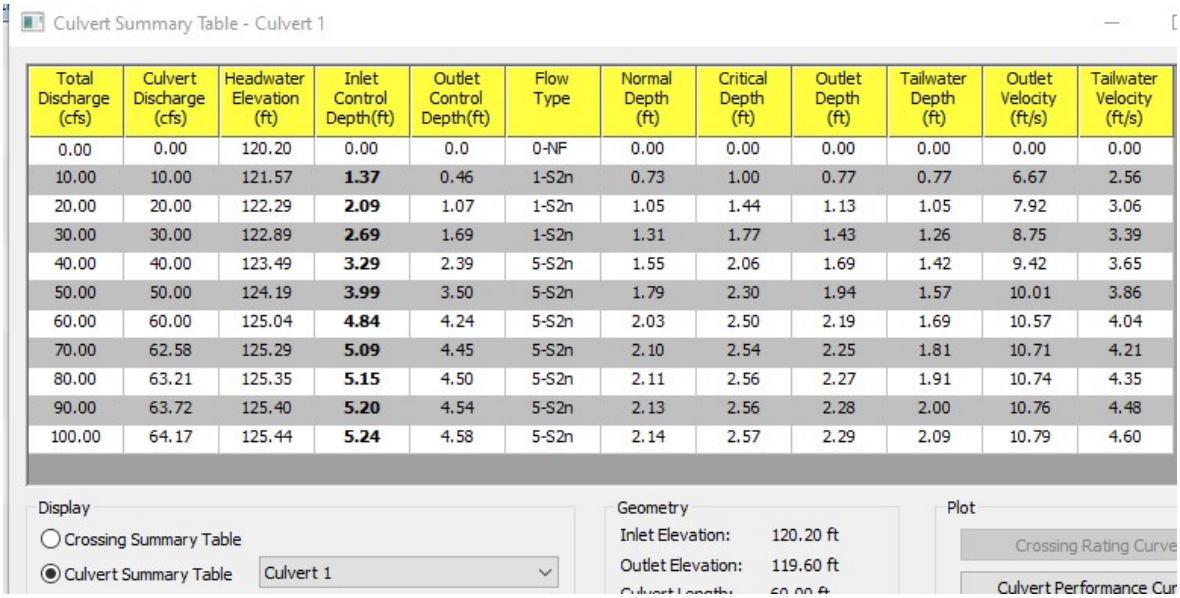


Figure 55 – Example 2 Culvert Summary Table

Based on Figure 54, the overtopping flow for this culvert is 61.70 cfs and at the design flow of 70 cfs, 62.58 cfs goes through the culvert and the remaining flow goes over the roadway. Figure 54 shows the flow over the roadway to be 7.28 cfs, yielding a total of 69.86 cfs. The individual flow values will not always add up to the total flow, due to slight rounding errors. Based on the results in Figure 54, the 36-inch RCP is not large enough to pass the design flow of 70 cfs without roadway overtopping. Based on Figure 55, this culvert is in inlet control, so increasing the pipe slope is not a viable option to increasing the culvert capacity.

Example 2A

Example 2 shows a 36-inch RCP is too small to convey the design flow. The next step is to select a larger culvert. There is one additional consideration at this crossing with a larger pipe however. The roadway overtopping has been established at elevation 125.2. If this low spot in the roadway occurs at (or near) the culvert, minimum cover for the culvert will be an issue. Minimum and maximum cover will be addressed later in this course, but for the purposes of this example, a minimum cover of 2 feet will be assumed. The invert of the pipe inlet is 120.2, the pipe is on a 1% slope and is 60 feet long. Therefore, the invert of the pipe at the roadway centerline is approximately 120.2 – (30 8 1%) = 119.9, indicating about 5.3 feet of cover to the pipe invert. The wall thickness for a 36-inch RCP is about 0.3 ft, so the top of the pipe is at 119.9 + (36/12) + 0.3 = 123.2, leaving just 2 feet of cover from the top of the pipe to the centerline of the roadway.

In order to increase the capacity of the proposed culvert without increasing the height of the culvert, an arch pipe can be used. To continue this example, a reinforced concrete pipe arch

(RCPA) will be used. Figure 56 shows the data summary for the largest RCPA that has a rise of 36 inches or less. This pipe has a span of 51.12 inches and a rise of 31.31 inches. Arch pipes are often referenced to their equivalent round pipe. It is simple to determine the equivalent round pipe for any arch pipe (concrete or steel) – simply add the span and rise and divide by 2. In this case 51.12 + 31.31 = 82.43 inches / 2 = 41.21 inches. This calculation will yield a size just slightly smaller than the equivalent round pipe, so in this case, the arch pipe is equivalent to a 42-inch round pipe. The flow area of a round pipe will be slightly smaller (about 5% to 10%) than the equivalent round pipe. However, an arch pipe has greater area near the bottom of the culvert, so it can have better hydraulic characteristics at lower flows. Figure 57 shows the Crossing Summary Table for this arch pipe and Figure 58 shows the Culvert Summary Table.

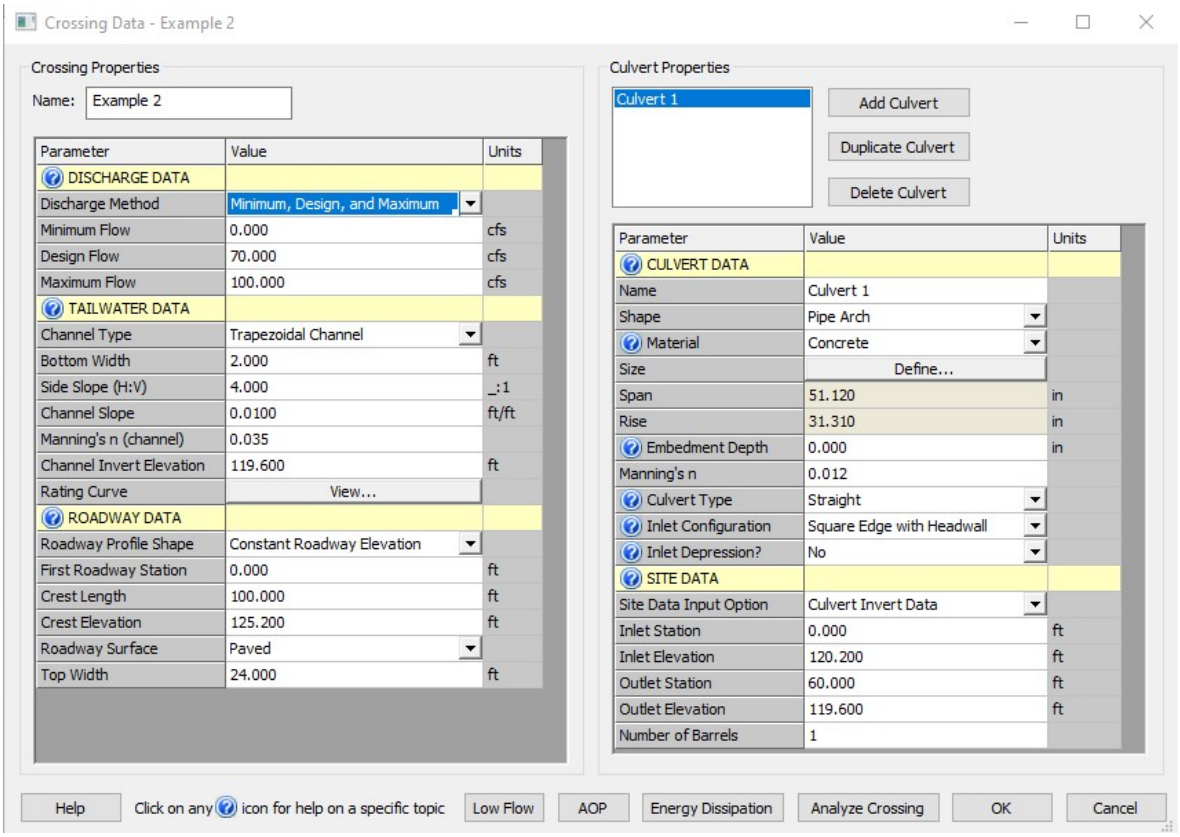
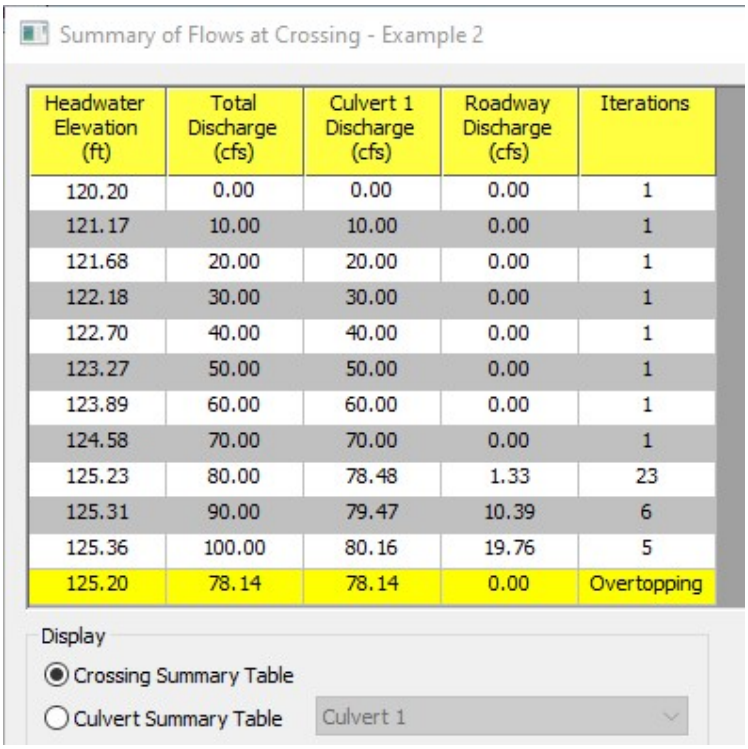


Figure 56 – Example 2A RCPA Culvert Data



Summary of Flows at Crossing - Example 2

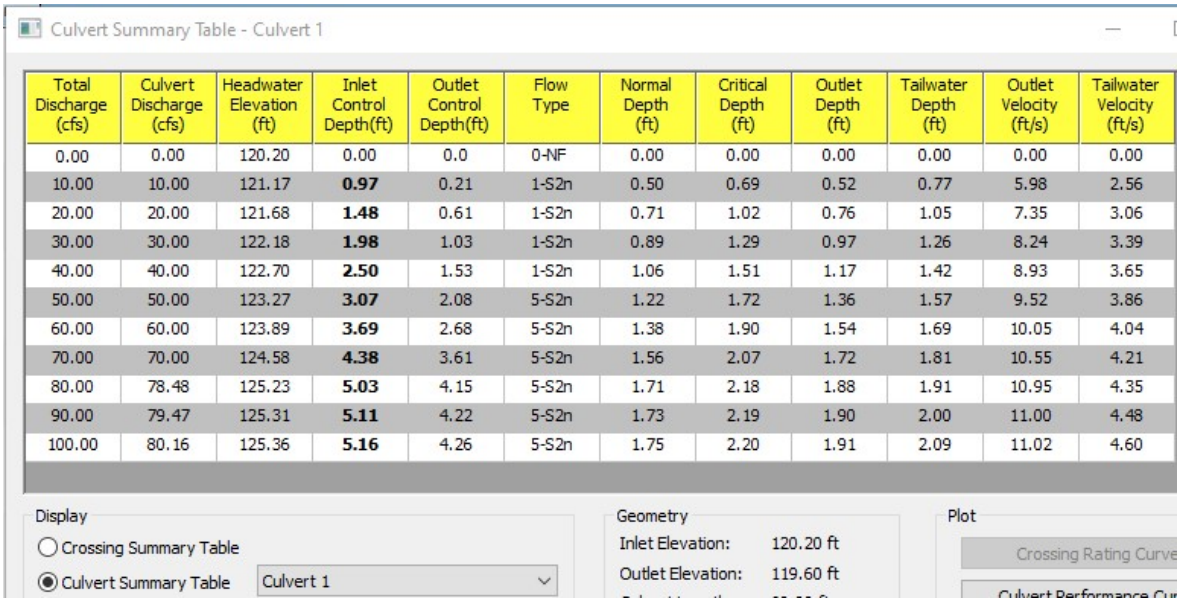
Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
120.20	0.00	0.00	0.00	1
121.17	10.00	10.00	0.00	1
121.68	20.00	20.00	0.00	1
122.18	30.00	30.00	0.00	1
122.70	40.00	40.00	0.00	1
123.27	50.00	50.00	0.00	1
123.89	60.00	60.00	0.00	1
124.58	70.00	70.00	0.00	1
125.23	80.00	78.48	1.33	23
125.31	90.00	79.47	10.39	6
125.36	100.00	80.16	19.76	5
125.20	78.14	78.14	0.00	Overtopping

Display

Crossing Summary Table

Culvert Summary Table — Culvert 1

Figure 57 – Example 2A RCPA Crossing Summary Table



Culvert Summary Table - Culvert 1

Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth(ft)	Outlet Control Depth(ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
0.00	0.00	120.20	0.00	0.0	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
10.00	10.00	121.17	**0.97**	0.21	1-S2n	0.50	0.69	0.52	0.77	5.98	2.56
20.00	20.00	121.68	**1.48**	0.61	1-S2n	0.71	1.02	0.76	1.05	7.35	3.06
30.00	30.00	122.18	**1.98**	1.03	1-S2n	0.89	1.29	0.97	1.26	8.24	3.39
40.00	40.00	122.70	**2.50**	1.53	1-S2n	1.06	1.51	1.17	1.42	8.93	3.65
50.00	50.00	123.27	**3.07**	2.08	5-S2n	1.22	1.72	1.36	1.57	9.52	3.86
60.00	60.00	123.89	**3.69**	2.68	5-S2n	1.38	1.90	1.54	1.69	10.05	4.04
70.00	70.00	124.58	**4.38**	3.61	5-S2n	1.56	2.07	1.72	1.81	10.55	4.21
80.00	78.48	125.23	**5.03**	4.15	5-S2n	1.71	2.18	1.88	1.91	10.95	4.35
90.00	79.47	125.31	**5.11**	4.22	5-S2n	1.73	2.19	1.90	2.00	11.00	4.48
100.00	80.16	125.36	**5.16**	4.26	5-S2n	1.75	2.20	1.91	2.09	11.02	4.60

Display

Crossing Summary Table

Culvert Summary Table — Culvert 1

Geometry

Inlet Elevation: 120.20 ft

Outlet Elevation: 119.60 ft

Plot

Crossing Rating Curve

Figure 58 – Example 2A RCPA Culvert Summary Table

Figure 57 shows the overtopping flow is 78.14 cfs and the headwater elevation at the design flow of 70 cfs is 124.58 feet. These values compare to 61.7 cfs and 125.29 feet for the 36-inch round RCP. Figure 38 shows this culvert is still in inlet control. Based on the results in Figure 57, the 42-inch equivalent reinforced concrete arch pipe will meet the design conditions.

Example 2B

Example 2A shows a 42-inch equivalent RCPA is adequate to convey the design flow. It is also possible that a steel arch culvert (CSPA) could be adequate. In order to approximately match the RCPA size, the CSPA would be a 49” x 33” arch pipe. Steel arch pipes generally have a slightly wider span and shorter rise than the equivalent RCPA, so it is sometimes possible to get a slightly larger CSPA in the same location. The culvert data is shown in Figure 59. The Crossing Summary Table is shown in Figure 60 and the Culvert Summary Table is shown in Figure 61.

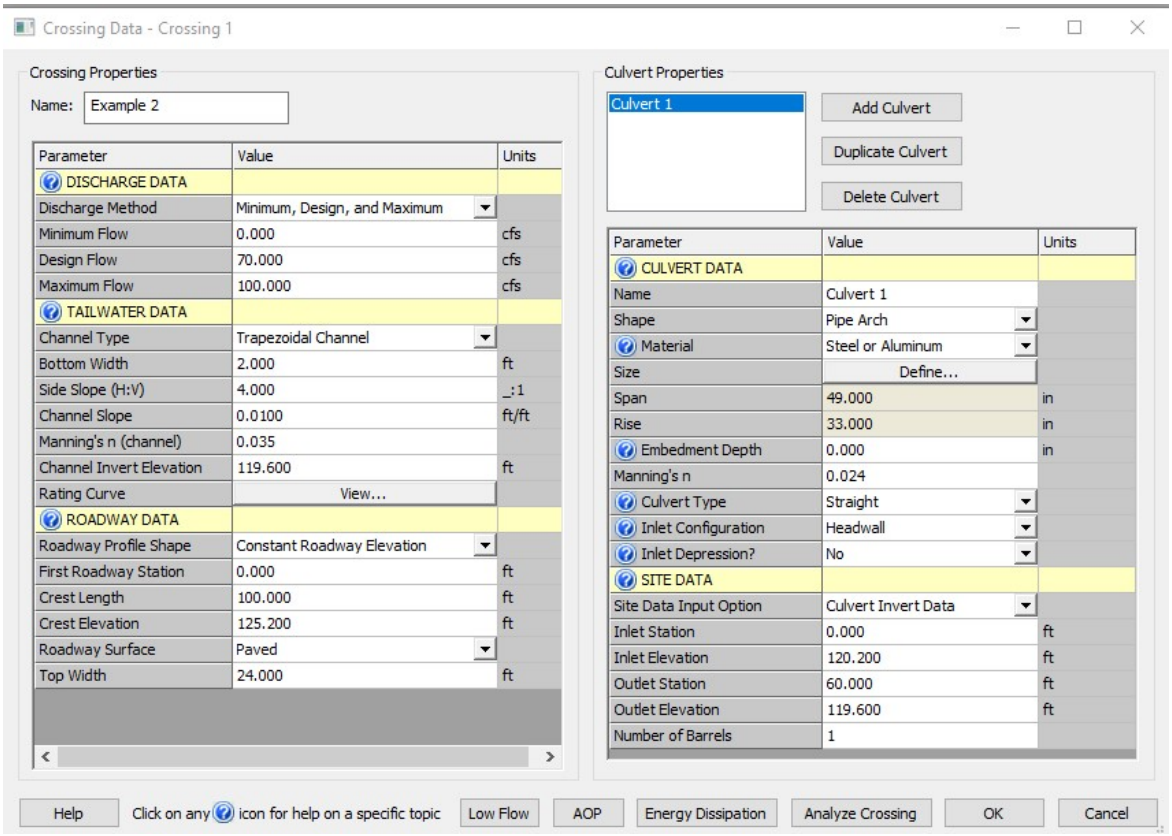


Figure 59 – Example 2B Culvert Data

Summary of Flows at Crossing - Example 2

Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
120.20	0.00	0.00	0.00	1
121.34	10.00	10.00	0.00	1
121.92	20.00	20.00	0.00	1
122.41	30.00	30.00	0.00	1
122.86	40.00	40.00	0.00	1
123.34	50.00	50.00	0.00	1
123.88	60.00	60.00	0.00	1
124.72	70.00	70.00	0.00	1
125.26	80.00	75.95	3.81	17
125.33	90.00	76.51	13.28	5
125.38	100.00	77.16	22.64	4
125.20	75.36	75.36	0.00	Overtopping

Display
(•) Crossing Summary Table
( ) Culvert Summary Table Culvert 1

Figure 60 – Example 2B Crossing Summary Data

Culvert Summary Table - Culvert 1

Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth(ft)	Outlet Control Depth(ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
0.00	0.00	120.20	0.00	0.0	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
10.00	10.00	121.34	1.08	**1.14**	3-M1t	0.73	0.71	0.77	0.77	3.94	2.56
20.00	20.00	121.92	1.64	**1.72**	2-M2c	1.09	1.06	1.06	1.05	5.39	3.06
30.00	30.00	122.41	2.11	**2.21**	2-M2c	1.42	1.33	1.33	1.26	6.24	3.39
40.00	40.00	122.86	2.56	**2.66**	2-M2c	1.77	1.56	1.56	1.42	7.02	3.65
50.00	50.00	123.34	3.04	**3.14**	7-M2c	2.75	1.78	1.78	1.57	7.71	3.86
60.00	60.00	123.88	3.59	**3.68**	7-M2c	2.75	1.96	1.96	1.69	8.42	4.04
70.00	70.00	124.72	4.23	**4.52**	7-M2c	2.75	2.13	2.13	1.81	9.15	4.21
80.00	75.95	125.26	4.66	**5.06**	7-M2c	2.75	2.22	2.22	1.91	9.59	4.35
90.00	76.51	125.33	4.70	**5.13**	7-M2c	2.75	2.23	2.23	2.00	9.64	4.48
100.00	77.16	125.38	4.75	**5.18**	7-M2c	2.75	2.24	2.24	2.09	9.69	4.60

Display
( ) Crossing Summary Table
(•) Culvert Summary Table Culvert 1

Geometry
Inlet Elevation: 120.20 ft
Outlet Elevation: 119.60 ft
Culvert Length: 60.00 ft

Plot
Crossing Rating Curve
Culvert Performance Cu

Figure 61 – Example 2B Culvert Summary Data

Figure 60 shows the overtopping flow is 75.36 cfs and the headwater elevation at the design flow of 70 cfs is 124.72 feet. These values compare to 61.7 cfs and 125.29 feet for the 36-inch round RCP and 78.14 cfs and 124.58 feet for the 51” x 31” RCPA. Figure 61 shows this culvert is now in outlet control. Based on the results in Figure 60, the 42-inch equivalent corrugated steel arch pipe will also meet the design conditions.

Example 2C

Example 2A shows a 42-inch equivalent RCPA is adequate to convey the design flow and Example 2B shows a 42-inch equivalent CSPA is also adequate to convey the design flow. One option that is often considered when a single round pipe is not adequate to convey the design flow is to install two round pipes, or a double culvert. There are several problems associated with the use of a double culvert, especially when the use of a double culvert is to address minimum cover issues. The first issue with use of double culverts is the natural channel is often much narrower than the overall width of the culvert installation. In order to get adequate compaction in the material between the two culverts, the distance between the outside edges of the two culverts is usually at least three or four feet. In conjunction with the culvert size, this often results in an overall width substantially wider than the channel. While it is possible to excavate the channel to create a transition to this wider opening, this wider channel is frequently subject to sedimentation that fills it in back to a width resembling the original channel. The second issue with double culverts is in many such installations, one culvert becomes the dominant culvert. It is difficult to install two culverts so the upstream hydraulic conditions are identical, so one culvert becomes slightly (or significantly) more efficient than the other. The culvert with the less efficient entrance conditions will tend to allow some sediment to settle at the inlet (see Figure 62).



Figure 62 – Double Culvert Installation

The culvert data for a double 30-inch round RCP is shown in Figure 63. The Crossing Summary Table is shown in Figure 64 and the Culvert Summary Table is shown in Figure 65.

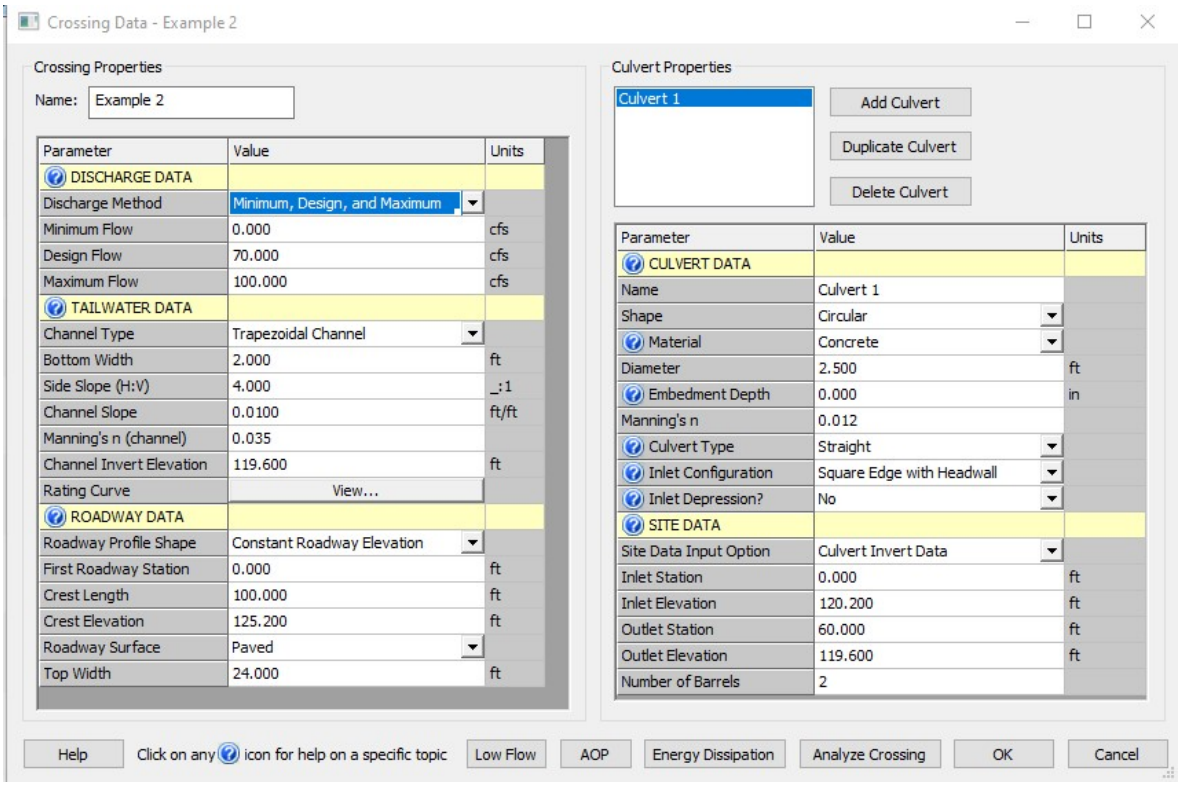


Figure 63 – Example 2C Culvert Data

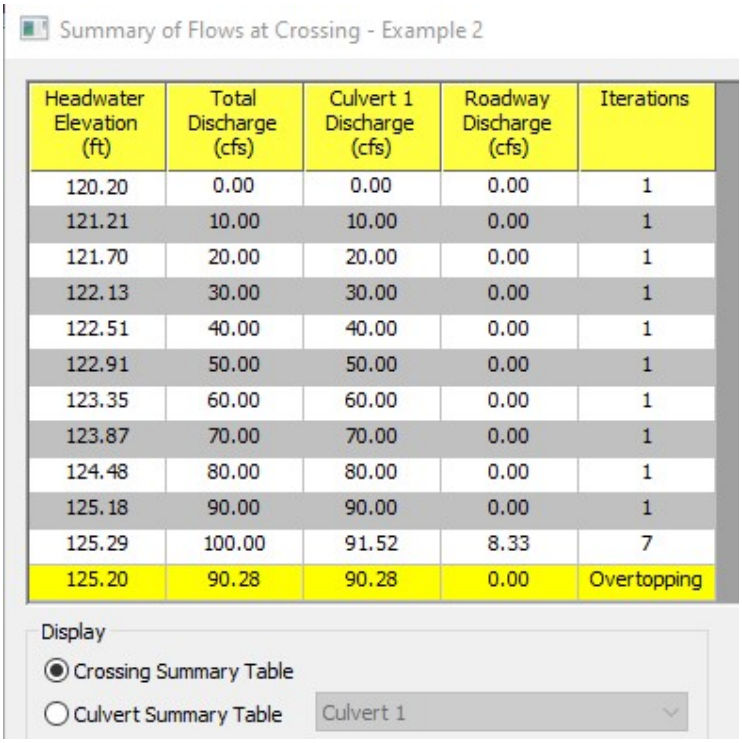


Figure 64 – Example 2C Crossing Summary Table

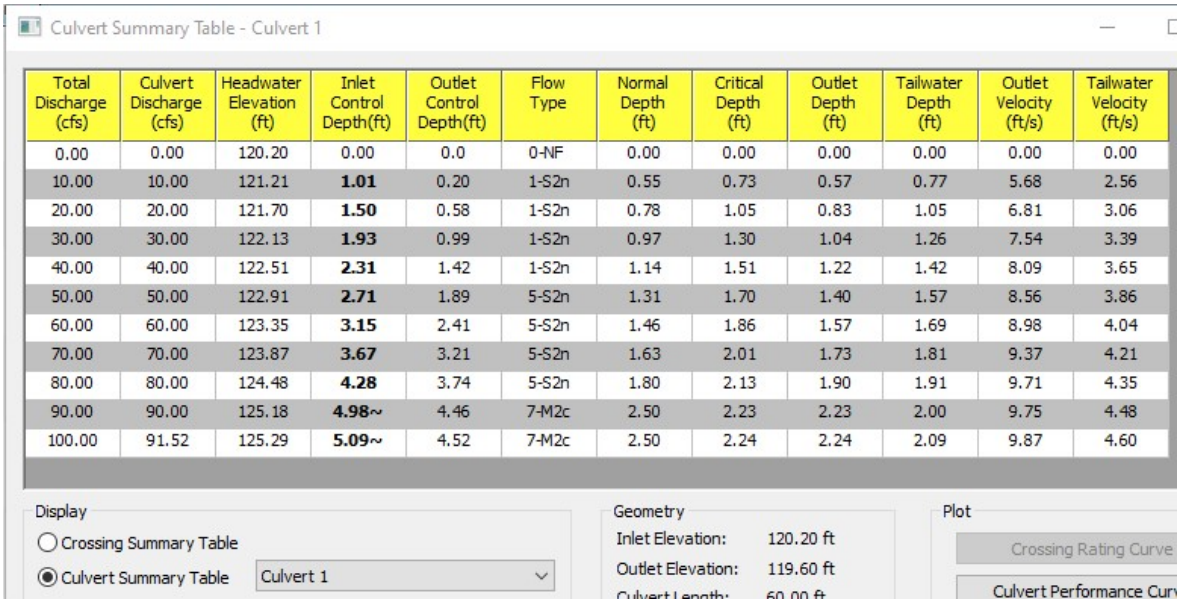


Figure 65 – Example 2C Culvert Summary Table

Figure 64 shows the overtopping flow is 90.28 cfs and the headwater elevation at the design flow of 70 cfs is 123.87 feet. These values compare to 61.7 cfs and 125.29 feet for the 36-inch round RCP, 78.14 cfs and 124.58 feet for the 51" x 31" RCPA, and 75.36 cfs and 124.72 feet for the 49" x 33" CSPA. Figure 64 shows the double culvert installation is back in inlet control. Based on the results in Figure 64, the double 30-inch round reinforced concrete pipes will also meet the design conditions. This result assumes that both round concrete pipes remain completely open, which is often not the case.

Example 2D

One way to address the issue of one pipe becoming the dominant pipe in a double pipe installation is to intentionally set the second culvert invert at a higher elevation. When this is done the most common configuration is to set one culvert as close to the centerline of the main channel as possible and the second culvert is set off to one side, in the larger of the overbank areas. To demonstrate the hydraulic impact of this, Example 2C will be modified to set the inlet of one of the 30-inch diameter culverts 6 inches above the channel invert. The outlet of this culvert is still set at the channel invert. In Example 2C, it was just necessary to change the number of barrels from 1 to 2 and leave all of the other culvert data the same. For Example 2D it is necessary to add a second culvert. Figure 66 shows the culvert data for the first culvert (at the channel invert) and Figure 67 shows the culvert data for the second culvert. Figure 68 shows the Crossing Summary Table. Note that there are separate columns for Culvert 1 and Culvert 2 since each culvert carries a different flow. Figure 69 shows the Culvert Summary Table for Culvert 1 and Figure 70 shows the Culvert Summary Table for Culvert 2.

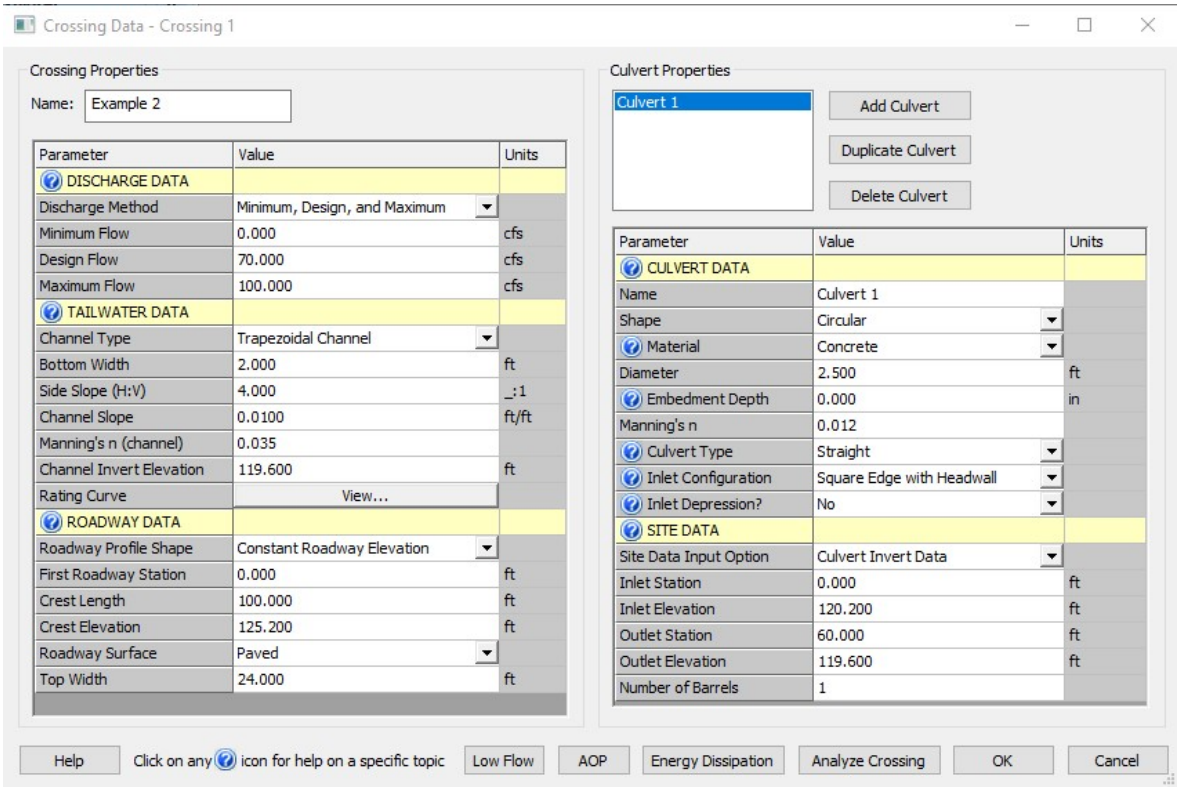


Figure 66 – Example 2D Culvert 1 Data

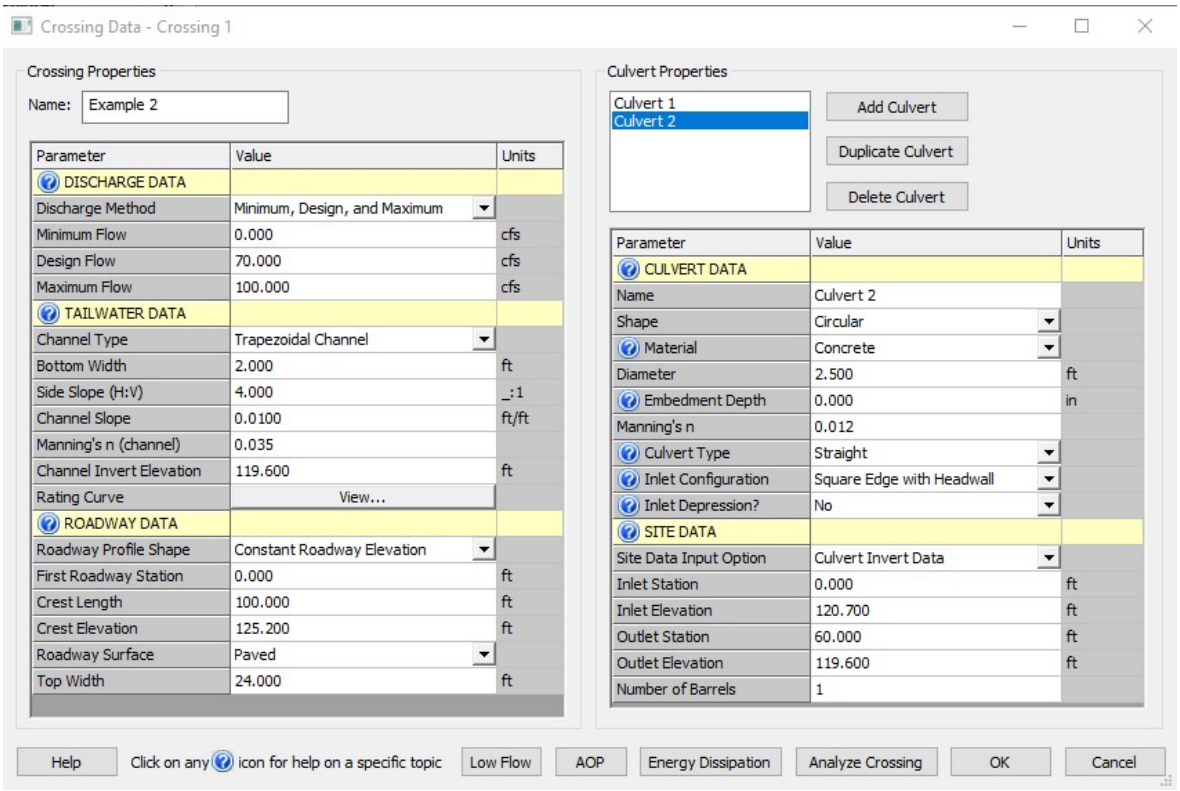


Figure 67 – Example 2D Culvert 2 Data

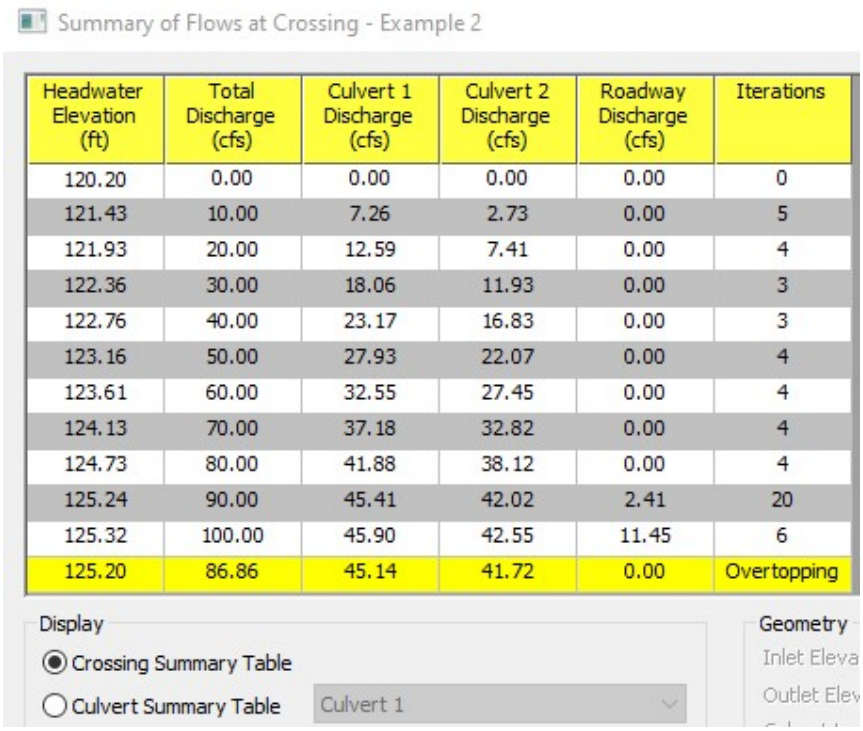


Figure 68 – Example 2D Crossing Summary Table

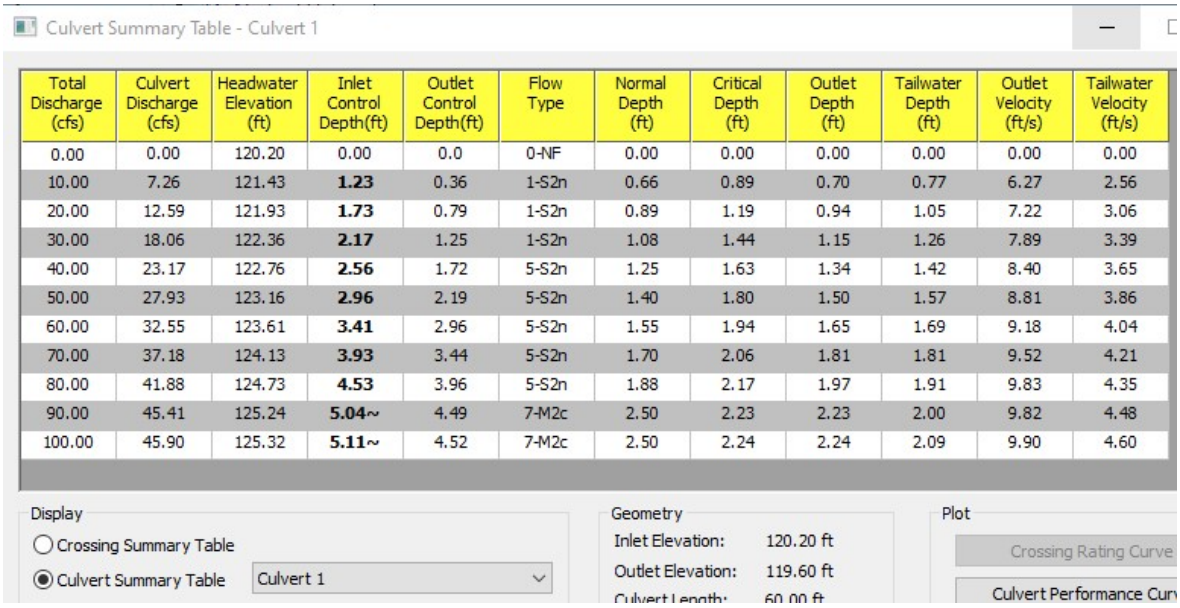


Figure 69 – Example 2D Culvert 1 Summary Table

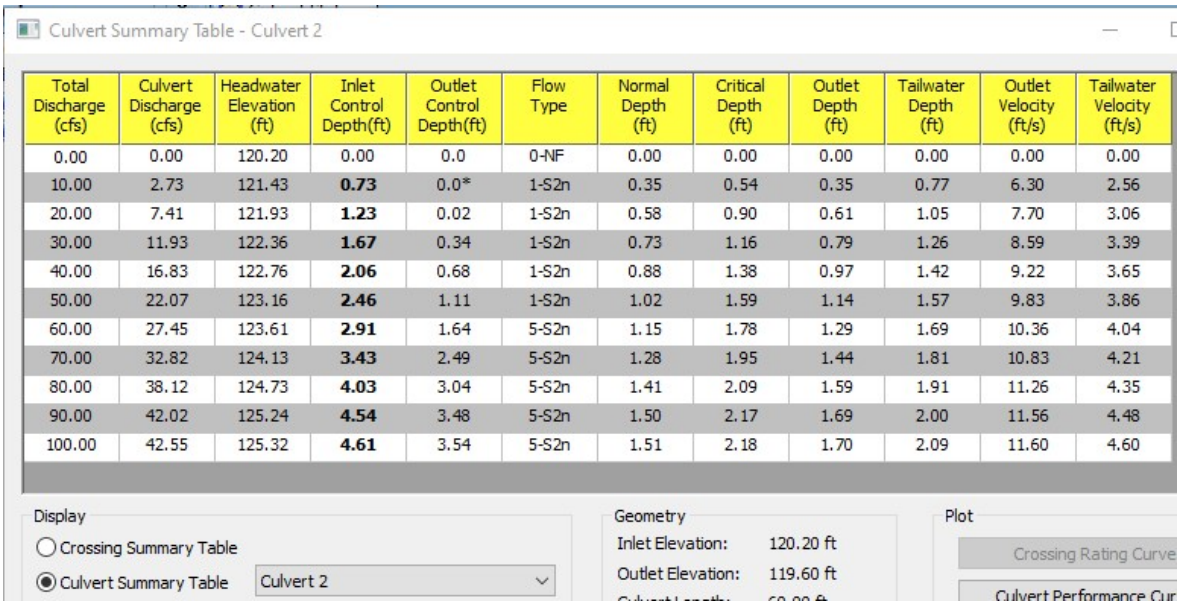


Figure 70 – Example 2D Culvert 2 Summary Table

Figure 68 shows the overtopping flow is 86.86 cfs and the headwater elevation at the design flow of 70 cfs is 124.13 feet. These values compare to 90.28 cfs and 123.87 feet for the double 30-inch round RCP with the inverts set at the same elevation and 78.14 cfs and 124.58 feet for the 51" x 31" RCPA. Figure 68 also shows at the design flow of 70 cfs, the pipe set at the channel invert (Culvert 1) carries about 37.2 cfs and the pipe set 6 inches above the channel invert (Culvert 2) carries about 32.8 cfs. This indicates setting one culvert invert slightly higher than the other does have some impact on the capacity of the higher culvert, but there is still substantial capacity available. Note at low flows like 10 cfs, the Culvert 1 carries 7.3 cfs and the Culvert 2 only carries about 2.7 cfs. This would be expected from the description of the culvert configuration. Figures 69 and 70 show both culverts are in inlet control. Based on the results in Figure 68, the double 30-inch round reinforced concrete pipes, with one invert set 6 inches above the channel bottom, will also meet the design conditions. This result assumes that both round concrete pipes remain completely open, which is more likely with the different inlet invert elevations.

Example 2E

Rather than set the second culvert up 6 inches, we can also analyze it assuming that 6 inches of sediment accumulates in the pipe. The data for the two culverts still needs to be entered separately, but the data for Culvert 2 is changed as shown in Figure 71. The change shows in the Culvert Data, with the value of embedment depth shown at 6 inches. The inlet elevation is changed back to match Culvert 1, but all other data remains the same.

Figure 72 shows the Crossing Summary Table. Note that there are separate columns for Culvert 1 and Culvert 2 since each culvert carries a different flow. Figure 73 shows the Culvert Summary Table for Culvert 1 and Figure 74 shows the Culvert Summary Table for Culvert 2.

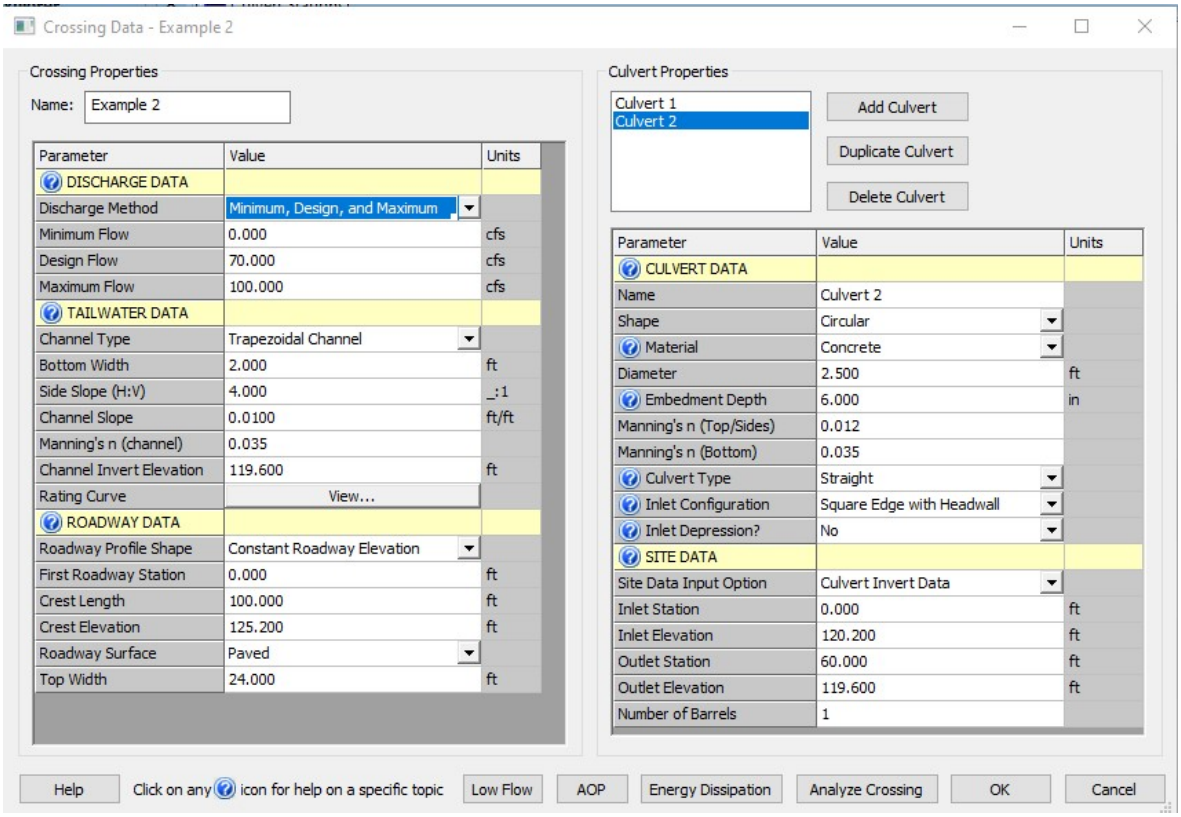


Figure 71 – Example 2E Culvert 2 Data

Summary of Flows at Crossing - Example 2

Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Culvert 2 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
120.20	0.00	0.00	0.00	0.00	0
121.40	10.00	6.94	3.05	0.00	5
121.93	20.00	12.52	7.47	0.00	4
122.37	30.00	18.09	11.91	0.00	3
122.80	40.00	23.63	16.36	0.00	4
123.26	50.00	28.95	20.57	0.00	8
123.58	60.00	32.23	27.79	0.00	6
124.12	70.00	37.09	32.91	0.00	4
124.76	80.00	42.10	37.90	0.00	4
125.25	90.00	45.47	41.23	3.15	18
125.32	100.00	45.93	41.69	12.14	5
125.20	86.05	45.14	40.91	0.00	Overtopping

Display
Crossing Summary Table
Culvert Summary Table
Culvert 1

Geometry
Inlet Elevati
Outlet Eleva

Figure 72 – Example 2E Crossing Summary Table

Culvert Summary Table - Culvert 1

Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth(ft)	Outlet Control Depth(ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
0.00	0.00	120.20	0.00	0.0	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
10.00	6.94	121.40	**1.20**	0.33	1-S2n	0.65	0.87	0.68	0.77	6.22	2.56
20.00	12.52	121.93	**1.73**	0.79	1-S2n	0.88	1.19	0.94	1.05	7.21	3.06
30.00	18.09	122.37	**2.17**	1.25	1-S2n	1.08	1.44	1.15	1.26	7.90	3.39
40.00	23.63	122.80	**2.60**	1.76	5-S2n	1.26	1.65	1.35	1.42	8.44	3.65
50.00	28.95	123.26	**3.06**	2.30	5-S2n	1.43	1.83	1.53	1.57	8.90	3.86
60.00	32.23	123.58	**3.38**	2.93	5-S2n	1.54	1.93	1.64	1.69	9.15	4.04
70.00	37.09	124.12	**3.92**	3.43	5-S2n	1.70	2.06	1.80	1.81	9.52	4.21
80.00	42.10	124.76	**4.56**	3.98	5-S2n	1.89	2.17	1.98	1.91	9.85	4.35
90.00	45.47	125.25	**5.05~**	4.50	7-M2c	2.50	2.23	2.23	2.00	9.82	4.48
100.00	45.93	125.32	**5.12~**	4.52	7-M2c	2.50	2.24	2.24	2.09	9.90	4.60

Display
Crossing Summary Table
Culvert Summary Table
Culvert 1

Geometry
Inlet Elevation: 120.20 ft
Outlet Elevation: 119.60 ft

Plot
Crossing Rating Curve
Culvert Performance Curv

Figure 73 – Example 2E Culvert 1 Summary Table

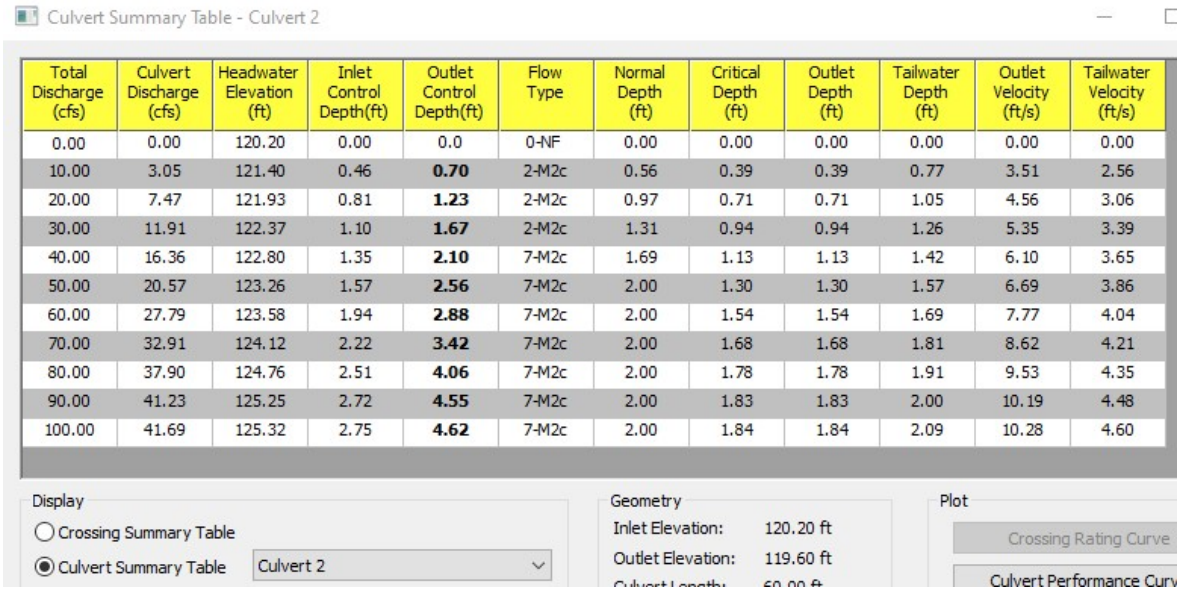


Figure 74 – Example 2E Culvert 2 Summary Table

Figure 72 shows the overtopping flow is 86.05 cfs compared to 86.86 cfs when Culvert 2 is set 6 inches about the channel bottom, and the headwater elevation is 124.12 feet compared to 124.13 feet, so there is very little difference in the hydraulics of these two configurations.

Example 3

Sometimes the drainage area and design flows are relatively small, but a large amount of fill is placed over the culvert due to the design of the vertical alignment of the roadway. This can create some additional issues that need to be properly addressed.

Determine the required culvert size. The design criteria include the culvert is capable of passing the design flow without overtopping the roadway. In higher fill situations, the end of a corrugated steel pipe is often just a thin edge projecting, so that condition will be analyzed first.

Culvert and Site Data:

100-foot length

1% slope

Invert elevation at inlet = 120.2

Invert elevation at outlet = 119.2

Flow Data

Minimum = 0 cfs

Design = 30 cfs

Maximum = 50 cfs

Tailwater Data

Trapezoidal Channel

2-foot-wide bottom

4:1 side slopes

Channel slope = 1%

Manning's n value = 0.035

Channel invert (at pipe outlet) = 119.2 (matches the pipe invert)

Roadway Data

Constant Roadway Elevation

Crest Length = 100 ft

Crest Elevation = 132.2

Paved Roadway, 24-feet wide

The data above are shown in Figure 75, along with a preliminary pipe selection of 24" CSP, with a standard flared end section. The Crossing Summary Table is shown in Figure 76 and the Culvert Summary Table is shown in Figure 77.

Many jurisdictions have minimum pipe size requirements. These are often 18-inch or 24-inch diameter pipes for mainline crossings, and sometimes a smaller minimum size for pipes that cross approach roads. There are several reasons for establishing a minimum size. For very small drainages, the engineering time spent deciding between two very small pipes can be more expensive than the potential construction cost savings. Oftentimes more importantly, it is difficult to keep very small pipes in rural areas clean of debris. A relatively large minimum diameter reduces the potential for small debris to plug the pipe.

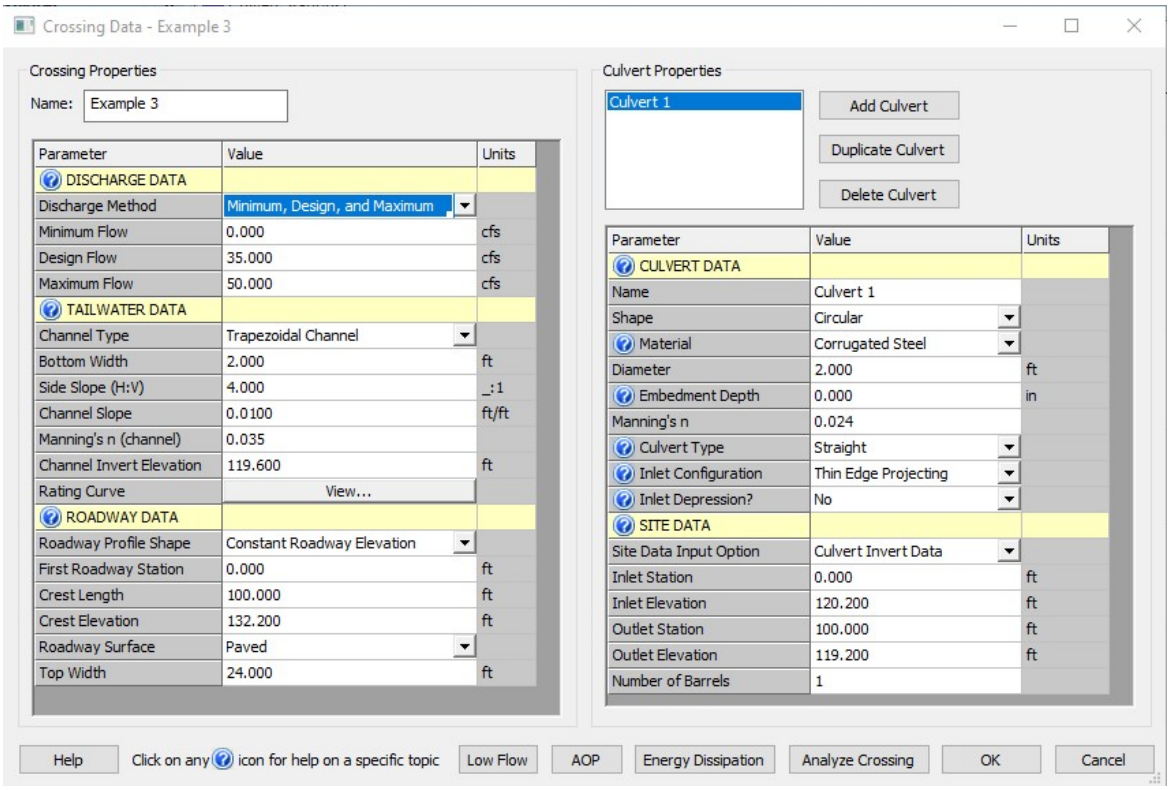


Figure 75 – Example 3 Culvert Data

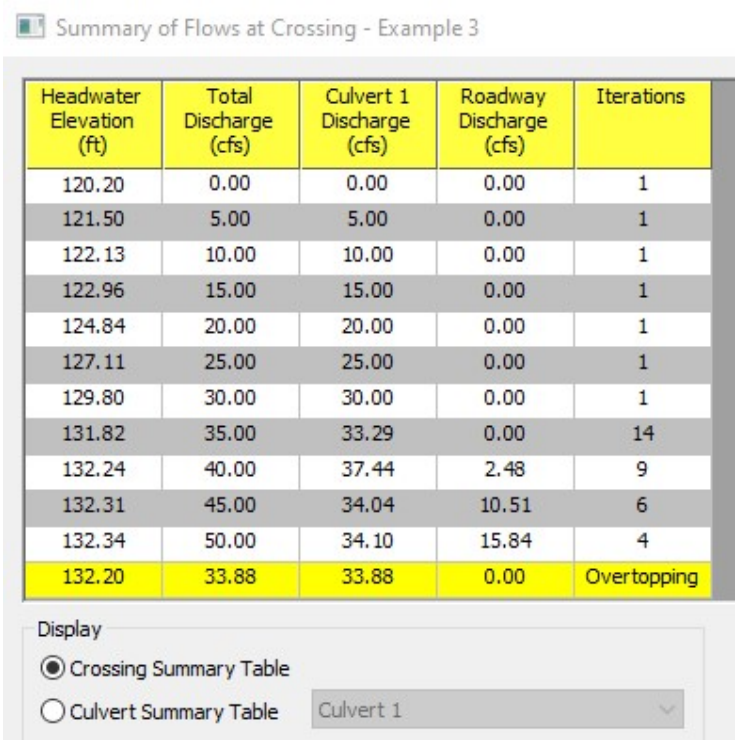


Figure 76 – Example 3 Crossing Summary Table

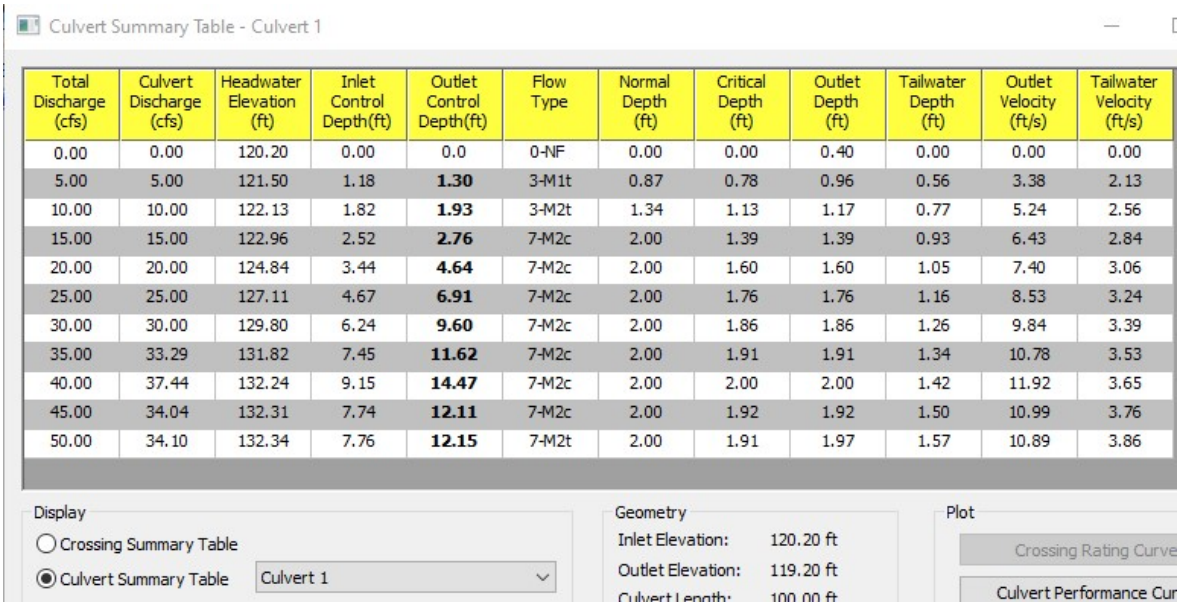


Figure 77 – Example 3 Culvert Summary Table

Based on Figure 76, the overtopping flow for this culvert is 33.8 cfs and at the design flow of 30 cfs, the upstream water surface elevation is 129.8, which is more than 2 feet below the roadway overtopping. This culvert meets the basic requirement of passing the design flow without overtopping the roadway.

There is another consideration for this pipe, however. This consideration is often referred to as the HW/D ratio, or the ratio of upstream headwater (depth) to the pipe diameter. The water depth at the upstream end of the culvert is 9.6 feet above the culvert invert. For a 24-inch diameter CSP, this means the HW/D ratio is 4.8. When the water at the inlet of the culvert gets above the top of the pipe, significant buoyant forces start to develop. When these forces get large enough, the bottom of the pipe starts to bend upward. If the forces are large enough, they can permanently deform the inlet end of the pipe. This is a particular problem with steel and aluminum pipes which don't have the same structural strength as reinforced concrete pipe.

Figure 78 shows an example of what can happen to steel pipe subject to high headwater conditions. This Figure shows two relatively large steel pipes that have step-bevel ends. A step bevel end has a portion of the top of the pipe cut away to better match the fill slope. An example of a step bevel end with a concrete headwall is shown in Figure 79. The shape of the culverts in Figure 78 was initially similar to the culvert in Figure 79, but a headwall was not provided. In Figure 78, the original bottom of each culvert has been bent upward and is shown in the red oval. Because the culvert inverts have been bent upward, there is now a

standing pool of water on the upstream side of these culverts and the flow capacity of these culverts has been severely compromised.



Figure 78 – Upstream end of culvert subject to high headwater



Figure 79 – Steel pipe with step bevel end and concrete headwall

In order to reduce the potential for culvert failure such as that shown in Figure 78, many transportation agencies have established limits for allowable HW/D for culverts. There is no universal guidance provided by the Federal Highway Administration, however. Many state DOT's have established guidance, but there is no consensus. Three examples are shown below to illustrate some of the differences.

Vermont DOT

- If the culvert rise is less than or equal to 36 inches, the HW/D ratio should be less than 1.5 at the design flow.
- If the culvert rise is greater than 36 inches, the HW/D ratio should be less than 1.2 at the design flow
- If the culvert rise is greater than 60 inches, not only should the HW/D ratio be less than 1.2 at the design flow, the HW/D ratio should also be less than 1.5 at the 100-year event.

Colorado DOT

- If the culvert rise is less than 36 inches, the HW/D ratio should be less than 2.0 at the design flow.

- If the culvert rise is between 36 inches and 60 inches, the HW/D ratio should be less than 1.7 at the design flow
- If the culvert rise is between 60 inches and 84 inches, the HW/D ratio should be less than 1.5 at the design flow.
- If the culvert rise is between 84 inches and 120 inches, the HW/D ratio should be less than 1.2 at the design flow.
- If the culvert rise is greater than 120 inches, the HW/D ratio should be less than 1.0 at the design flow.

Washington DOT

- HW/D ratio should be less than 1.25 at the 25-year event

If the location in Example 3 is located in Vermont, the allowable HW/D ratio is 1.5, while the calculated HW/D ratio is 4.8. Therefore, even though the basic design requirement of the design flow not overtopping the roadway, a 24-inch CSP is not large enough.

Example 3A

Since a 24-inch diameter CSP does not meet the HW/D requirements, a 30-inch diameter CSP will be analyzed. All of the other parameters remain the same. The Crossing Summary Table is shown in Figure 80. Based on Figure 80, the headwater elevation at the design flow of 30 cfs is 124.23 feet and the headwater depth is 4.03 feet. For a 30-inch diameter culvert, this yields an HW/D ratio of 1.61. While this is much smaller than the 4.8 ratio for a 24-inch diameter CSP, it's still higher than the allowable ratio of 1.5.

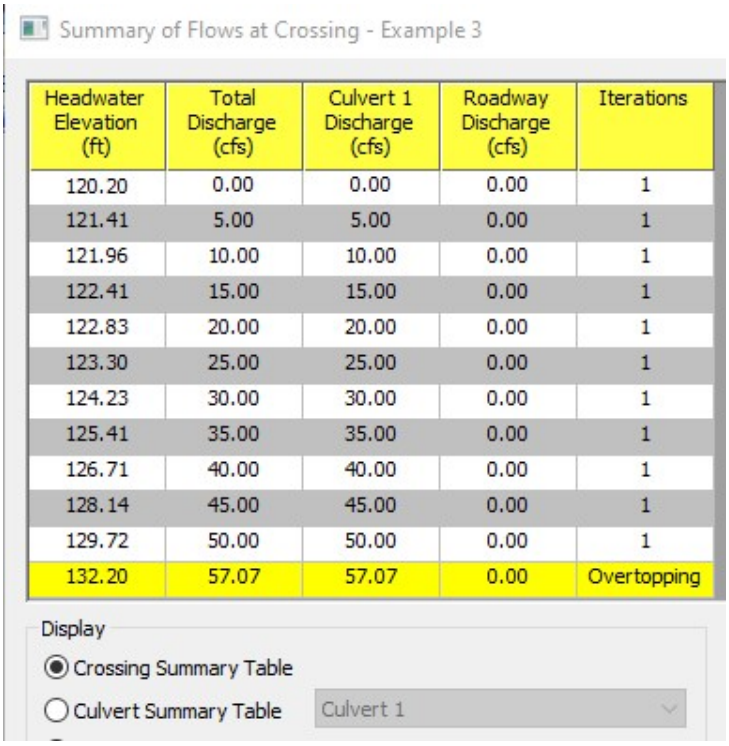
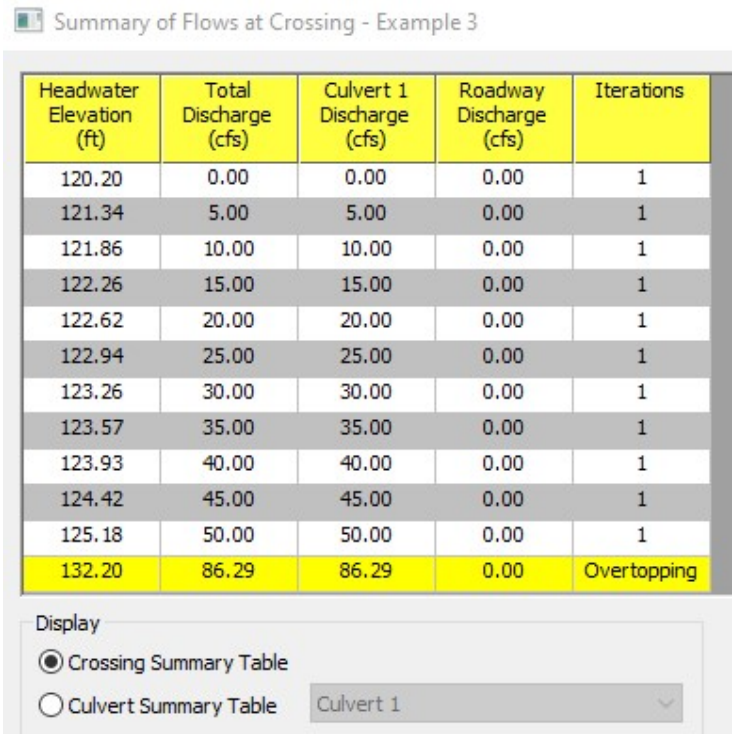


Figure 80 – Example 3A Crossing Summary Table

Example 3B

Since a 30-inch diameter CSP does not meet the HW/D requirements, a 36-inch diameter CSP will be analyzed. All of the other parameters remain the same. The Crossing Summary Table is shown in Figure 81. Based on Figure 81, the headwater elevation at the design flow of 35 cfs is 123.26 feet and the headwater depth is 3.06 feet. For a 36-inch diameter culvert, this yields an HW/D ratio of 1.02. This is below the allowable ratio of 1.5, so a 36-inch diameter CSP meets the HW/D requirement.


Summary of Flows at Crossing - Example 3

Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
120.20	0.00	0.00	0.00	1
121.34	5.00	5.00	0.00	1
121.86	10.00	10.00	0.00	1
122.26	15.00	15.00	0.00	1
122.62	20.00	20.00	0.00	1
122.94	25.00	25.00	0.00	1
123.26	30.00	30.00	0.00	1
123.57	35.00	35.00	0.00	1
123.93	40.00	40.00	0.00	1
124.42	45.00	45.00	0.00	1
125.18	50.00	50.00	0.00	1
132.20	86.29	86.29	0.00	Overtopping

Display
Crossing Summary Table
Culvert Summary Table
Culvert 1

Figure 81 – Example 3B Crossing Summary Table

Summary of HY8 Considerations

HY8 is a very useful software package for hydraulic analysis of culverts. As shown in this course, data input is quite simple. The software calculates both inlet control and outlet control which is extremely important. The software was developed by a Federal Agency, is generally recognized by both design engineers and review engineers, and the software is non-proprietary, so it is easy to obtain.

There are a couple of cautions when using HY8. The available inlet types do not include standard flared end sections, which are very common. This can be overcome by selecting a concrete headwall as the inlet configuration, since this is hydraulically similar to a standard flared end section. The default values for Manning's n for culverts are not always correct. The default values include:

- 0.012 for RCP. Some jurisdictions require 0.13.
- 0.024 for all circular steel pipes. Larger pipes, with 3”x 1”, 5” x 1” and 6” x 2” corrugations will have higher values, between 0.027 and 0.034.
- 0.011 for PVC. This is a pretty optimistic value where sediment is present.

In general, the use of HY8 is recommended for hydraulic analysis of a single culvert crossing, although this can include multiple culverts at one location. It not as useful in locations where there are multiple crossings along a single stream, when the crossings are close together. The crossings would be considered close together when the backwater from the downstream culvert raises the water surface elevation on the downstream end of the upstream culvert. In this situation, use of software such as HEC-RAS should be considered. The use of vendor software is also appropriate in situations where the simplified output tables in HY8 are inadequate for presentation purposes.

MINIMUM AND MAXIMUM COVER FOR CULVERTS

In selecting an appropriate size and material for a culvert, it is important to consider the minimum and maximum cover for each pipe. Factors that impact allowable cover include:

- Live loads from highways, airports and railroads
- Live loads from construction equipment
- Pipe material and thickness
- Bedding material soil type (granular vs. fines)
- Bedding material compaction
- Fill material around pipe
- Dead loads (weight of soil over the pipe)

Table 1 shows the live loads imposed on a culvert, with varying depths of cover, for highway, railroad and airport loading conditions. Note that railroad loads are substantially higher than airport loads, which are substantially higher than highway loads.

Height of Cover (ft)	Live Load Transferred to Pipe, psi		
	Highway	Railroad	Airport
1	12.5		
2	5.56	26.39	13.14
3	4.17	23.61	12.28
4	2.78	18.49	11.27
5	1.74	16.67	10.09
6	1.39	15.63	8.79

7	1.22	12.15	7.85
8	0.69	11.11	6.93
10	*	7.64	6.09
12	*	5.56	4.76

* Negligible Live Load Influence

Table 1

Live loads from construction equipment can be substantially higher than normal highway loads. During construction of a roadway, loaded scrapers are often moving soils around the site to construct the roadway and this often occurs right after culverts are installed and sometimes before even minimum cover is placed over the culverts. It is important to protect culverts during the construction process and to examine all culverts, especially flexible pipes such as corrugated metal and corrugated plastic pipes, immediately after construction. Because flexible pipes are designed to deform slightly to transfer the load from the pipe to the adjacent soil, if the construction loads are excessive, these pipes can be permanently deformed, which can damage the pipes and shorten the expected life span.

Proper bedding and backfill are important parts of the design and installation of a culvert. With a reinforced concrete pipe, most of the structure for the culvert is the pipe itself. All of the other pipe materials – corrugated steel, corrugated aluminum, corrugated HDPE, corrugated PPE, and corrugated steel reinforced HDPE – are flexible pipes. With flexible pipes, the pipe mostly functions as a form for the structure and the contractor is required to build the structure using the bedding and backfill materials. Poor quality bedding and backfill will result in a poor-quality structure which can fail prematurely.

In general, the best bedding and backfill materials are non-plastic sands and gravels. They are easy to place and compact and generally don't form large voids in the backfill. Highly plastic and organic materials are unsuitable for bedding and backfill. Materials with some plasticity (like a sandy silt) can be used in some instances. However, soils with more plasticity are more likely to be corrosive, so pipe life needs to be evaluated carefully.

Backfill must be placed and compacted around the pipe without distorting the shape of the pipe. This is particularly critical with arch pipes, which are already "deformed" to a predetermined shape. As pipes get larger and more flexible, the choice of backfill materials becomes even more important.

Cover for Reinforced Concrete Pipe

The manufacturer's recommended maximum cover for concrete pipes is shown in Table 2. These values are based on a Type 1 Installation (see manufacturer's recommendations for more details on this installation) and an embankment weight of 120 pounds per cubic foot. For deeper installations than those shown, it is possible to obtain concrete pipe stronger than Class V. A conversation with the local concrete pipe supplier will provide the design engineer with information on the availability of stronger pipe. The manufacturer's recommended minimum cover for concrete pipes is shown in Table 3. Minimum cover is typically measured to the bottom of flexible pavements (such as asphalt) and to the top of rigid pavements (such as concrete).

Pipe Size	Class I (800 psf)	Class II (1000 psf)	Class III (1350 psf)	Class IV (2000 psf)	Class V (3000 psf)
12"	16	20	27	40	60
18"	16	20	27	41	60
24"	16	20	27	41	60
30"	16	20	27	40	60
36"	15	19	27	40	60
42"	15	19	26	40	60
48"	15	19	26	40	59
54"	15	19	26	40	59
60"	15	19	26	40	59
72"	14	19	25	38	58
84"	14	18	25	38	57
96"	14	18	25	38	57

Table 2 – Maximum Cover for Reinforced Concrete Pipe

Pipe Size	Class I (800 psf)	Class II (1000 psf)	Class III (1350 psf)	Class IV (2000 psf)	Class V (3000 psf)
12”	2	2	1	1	1
18”	2	1	1	1	1
24”	2	1	1	1	1
30”-96”	1	1	1	1	1

Table 3 – Minimum Cover for Reinforced Concrete Pipe

Cover for Corrugated Steel Pipe

For circular corrugated steel pipe, the manufacturer’s recommended minimum cover for pipe with 2-2/3” x ½” corrugations is generally one foot. For 3” x 1” and 5” x 1” corrugations, the minimum cover is one foot for pipes up to 96 inches in diameter and 1.5 feet for pipe up to 144 inches in diameter. For pipe with 6” x 2” corrugations, the minimum cover is one foot up to 8 feet in diameter, 1.5 feet up to 12 feet in diameter and 2 feet up to 16 feet in diameter. While these values represent the manufacturer’s recommendations, they should be used with caution. Providing another 1-2 feet of cover can be sound engineering practice in many situations.

For corrugated steel pipe arches, the manufacturer’s recommendations are similar to those for circular pipes. One foot is the minimum for 2-2/3” x ½” corrugations. Fifteen inches is the recommended minimum for 3” x 1” and 5” x 1” corrugations up to equivalent 60-inch diameter and 18 inches up to equivalent 90-inch diameter. For 6” x 2” corrugations, one foot is the minimum requirement up to 6.5-foot equivalent diameter, 1.5 feet up to the equivalent 10-foot diameter and 2 feet up to the equivalent 13-foot diameter. For corrugated steel pipe arches, proper material and compaction is very important at the corners of the arch so this should be well-covered in the construction specifications.

For corrugated steel pipes, the manufacturer’s recommended maximum cover depends on the pipe diameter and the pipe thickness. For 2-2/3” x ½” corrugations under highway loads, 16 gage material (with a thickness of 0.064”) up to four feet in diameter is generally acceptable for depths up to 62 feet. For 3” x 1” and 5” x 1” corrugations, 16 gage material up to 102 inches in diameter is generally acceptable for depth up to about 30 feet. For 6” x 2” corrugations, pipe is only available in 12-gage and thicker, but up to 15-feet in diameter, 12 gage material is generally acceptable for depths up to about 27 feet.

Note these are manufacturer's recommendations. Specific agencies often have requirements limiting the minimum and maximum cover to a narrower range, to allow for a more conservative design, based on specific experience of that agency.

Cover for Plastic Pipe

The strength of plastic pipe is generally measured by the pipe stiffness. The pipe stiffness is the force required to deflect the pipe (make it egg-shaped) by 5% of its inside diameter. Because PVC gravity sewer pipe has been available for many years, the pipe stiffness of this material is often used as a comparison or benchmark for other materials. In many jurisdictions, SDR 35 PVC is the standard material used for gravity sewer pipes. It has a pipe stiffness of 46 psi. In some jurisdictions, SDR 35 has been determined to be too flexible for the installation challenges, so SDR 26 PVC pipe is the standard for gravity sewers. SDR 26 PVC has a pipe stiffness of 115 psi.

The strength of corrugated HDPE pipe varies from about 50 psi for 12-inch diameter pipe to about 14 psi for 60-inch diameter pipe. For steel reinforced corrugated HDPE, the stiffness ranges from about 80 psi for 12-inch diameter pipe to between 15 psi and 58 psi for 60-inch diameter pipe. The large difference for the larger diameter pipe is a function of the different steel content options available for the larger pipe.

For corrugated HDPE the manufacturer's recommended minimum cover is generally one foot. Maximum cover is at least 20 feet, but greater cover can potentially be accommodated. For minimum cover installations it's important to remember this pipe is very flexible and will deflect slightly when loading conditions are changed. This means when a heavily loaded truck crosses this pipe, the increase in live load may cause the pipe to deflect. While this does not create any significant problems for the pipe, the flexible pavement above the pipe is typically not designed for this much flexibility, and cracks can occur over flexible pipes with very shallow cover.

EROSION PROTECTION FOR CULVERTS

As part of the design of culverts, appropriate consideration of erosive forces needs to be included. It is fairly common practice to include erosion protection at the downstream end of a culvert, but less common to include erosion protection at the upstream end.

At the upstream end of a culvert, the flow is transitioned from a relatively wide channel into a very narrow, well-defined culvert section. This results in some major changes in direction of flow vectors in the vicinity of the culvert, especially along the embankment. This can result in significant erosion on the upstream side of the culvert (see Figure 82).



Figure 82 – Erosion on Upstream Side of Corrugated Steel Pipe

There are a couple different approaches used to resist erosion on the upstream side of a culvert. One approach is to provide a concrete cut-off wall at the bottom of the pipe and then a concrete slab along the embankment, to above the top of the pipe. This concrete slab is commonly called concrete edge protection. An example of this type of installation is shown in Figure 83. The concrete edge protection serves two important functions. It obviously reduces the potential for erosion of embankment material immediately adjacent to the pipe. It also

substantially increases the weight of the installation at the inlet, which substantially reduces the potential for the type of culvert failure noted in Figure 78.

A second approach to erosion protection at the inlet of a culvert is the use of a concrete cutoff with riprap for edge protection. An example of this type of installation is shown in Figure 84. This type of installation is typically less expensive than concrete edge protection while still providing fairly significant protection against erosion of the embankment material adjacent to the culvert. It does not provide as much protection against buoyant uplift as concrete edge protection, however. Edge protection is important for reinforced concrete pipes as well as for corrugated steel pipes.



Figure 83 – Concrete Edge Protection on Upstream Side of Corrugated Steel Pipe



Figure 84 – Riprap Edge Protection on Upstream Side of Corrugated Steel Pipe

At the downstream end of the culvert, flow is transitioned from the narrow, well-defined geometry of a culvert to the wider, less well-defined geometry of a natural channel. The flow velocity coming out of the culvert is typically much higher than the velocity in the natural channel. One of the advantages of using the HY8 software is this information in readily available. In the Culvert Crossing Table for each culvert, the last four columns are:

- Outlet Depth – this is the depth of flow in the culvert, at the end of the culvert.
- Tailwater Depth – this is the depth of flow in the natural channel, just downstream from the end of the culvert.
- Outlet Velocity – this is the flow velocity in the culvert, at the end of the culvert.
- Tailwater Velocity – this is the flow velocity in the natural channel, just downstream from the end of the culvert.

The information from HY8 can be used to help identify and design solutions for erosion protection on the downstream side of a culvert. The extent of the erosion protection depends on the flow, the velocity in the culvert, the change in velocity between the culvert and the natural channel, the frequency of high flows and the risk associated with failure. Options for outlet protection include:

- Concrete energy dissipation structure, followed by a riprap channel (see Figure 85)
- Cabled concrete blocks (see Figure 86)
- Riprap apron and cabled concrete blocks (see Figure 87)
- Riprap apron (see Figure 88).



Figure 85 – Concrete energy dissipation structure and riprap



Figure 86 – Cabled concrete blocks



Figure 87 – Riprap apron and cabled concrete blocks



Figure 88 – Riprap Apron

The design of concrete energy dissipation structures is a specialty design and best addressed in FHWA document HEC-14, “Hydraulic Design of Energy Dissipators for Culverts and Channels.” The extent of cabled concrete blocks should be similar to the recommended footprint of a riprap apron. The design of a riprap apron should generally follow Equation 10.4 from HEC-14:

Riprap Size, $D_{50} = 0.2 * D * (Q/(g^{0.5}*D^{2.5}))^{4/3} * (D/TW)$

Where

- D_{50} is median size of the riprap required (ft)
- D is the diameter of the pipe (ft)
- Q is the flow rate (cfs)
- TW is the tailwater depth (ft), but not less than 0.4 * D
- Valid only for sub-critical flow (which we should always try to achieve at pipe outlets)

Riprap Apron Design Example:

- 48-inch diameter culvert, Q = 156 cfs
- $D_{50} = 0.2 * D * (Q/(g^{0.5}*D^{2.5}))^{4/3} * (D/TW)$
- TW = 4 ft * 0.4 = 1.6 ft (could be more or less in a pond, but this is the minimum to use in the equation)
- $D_{50} = 0.2 * 4 * (156/(32.2^{0.5}*4^{2.5}))^{4/3} * (4/1.6)$
- D_{50} = 1.63 ft (about 20 inches)

There are many different designations for riprap classes. Table 4 shows the riprap class and apron dimensions based on HEC-14. However, Class 1 riprap has different sizes in different jurisdictions and it is important to use the local size requirements for riprap.

Class	D_{50} (inches)	Apron Length[1]	Apron Depth
1	5	4D	3.5 D_{50}
2	6	4D	3.3 D_{50}
3	10	5D	2.4 D_{50}
4	14	6D	2.2 D_{50}
5	20	7D	2.0 D_{50}
6	22	8D	2.0 D_{50}

[1]D is the culvert rise

Table 4 – Riprap Sizes from HEC-14

Continuing Riprap Apron Example: With D_{50} = 20 inches (Class 5), apron length is 7D or 7*4 = 28 ft, apron depth is 2.0 D_{50} or 2.0 * 1.67 = 3.34 ft. Figure 89 shows a standard detail for the plan view of a riprap apron. Figure 90 shows a standard detail for the ross-section of a riprap apron. While this detail shows a minimum depth of 24 inches, Table 4 indicates the apron depth could be less than this value and in some instances this thickness of riprap is not necessary.

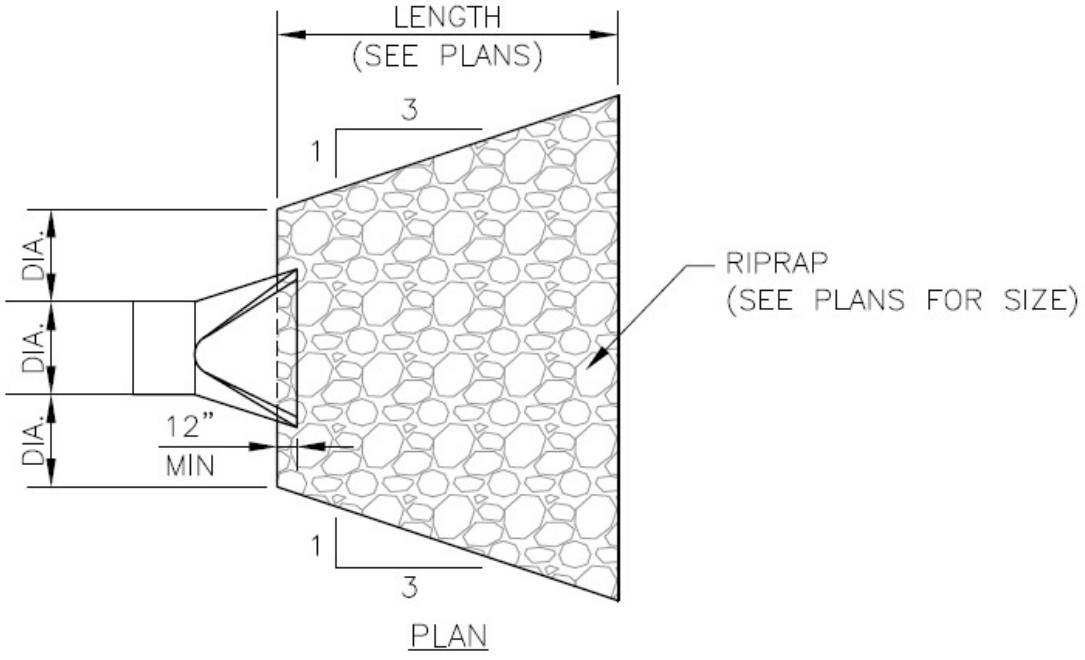


Figure 89 – FHWA Standard Plan View Detail for Riprap Apron

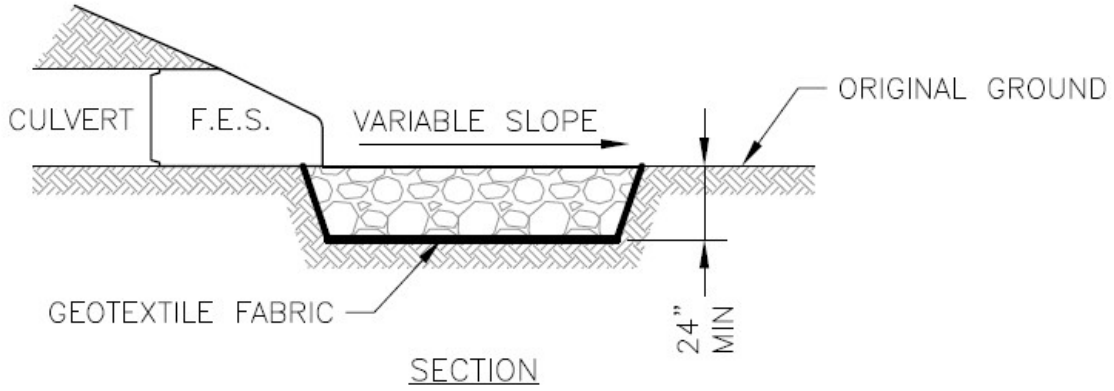


Figure 90 – FHWA Standard Cross-Section Detail for Riprap Apron

Some limitations on riprap aprons include:

- Generally recommended for pipes 60-inches in diameter and smaller. A more robust design is usually required for larger pipes.
- Aprons can require relatively large riprap, which can be difficult to obtain in some locales.
- The width of the apron can exceed the downstream channel width.
- Exceeding any of these requirements could require going to a concrete structure, but these are more expensive to design and build.

PIPE LIFE FOR CULVERTS

In most installations a very long service life is desirable. The desired service life could be 50, 75 or 100 years. The most controversial material to determine pipe life is corrugated steel. The controversy includes how service life is defined and how it is calculated.

Based on Caltrans criteria, concrete pipe will provide a 50-year service life (which meets Caltrans requirements) under the conditions noted in Table 5. The primary concern with concrete pipe is susceptibility to attack by sulfates. This can be offset to some extent by using more cement in the mix. Note that it is necessary to test both the soil and the water. In some situations, the soils may be relatively non-corrosive, but the water can be very corrosive. This is particularly true in areas where acid mine drainage is present.

Soil or Water pH	Sulfate concentration of Soil or Water (ppm)	Cement Requirements
7.1 to 14.0	0 to 1499	Standard
5.6 to 7.0	1500 to 1999	Standard
3.0 to 5.5	2000 to 15,000	675 pounds/cubic yard, plus other requirements

Table 5 – Cement requirements for RCP based on sulfate concentration

The corrugated steel pipe industry defines the end of service life when 25% of the material is corroded. Many DOTs, however, define the end of service life when the first perforation (the first hole in the pipe) occurs. The time to first perforation is about half the time to when 25% of the material is corroded.

The pipe life for corrugated steel pipe is a function of:

- Soil Resistivity (R) measured in ohm-cm
- pH
- Pipe Thickness
- Pipe Coatings

The American Iron and Steel Institute (AISI) publishes the following equations for Service Life for galvanized corrugated steel pipe:

- Life (years) = 2.94 $R^{0.41}$ for pH > 7.3
  Equation 1
- Life (years) = 27.58 [log R – log 2160 – 2490 * log R] for pH <7.3
  Equation 2

Caltrans publishes the following equations for Service Life for galvanized corrugated steel pipe. Note these equations are exactly half of the AISI equations.

- Life (years) = 1.47 $R^{0.41}$ for pH > 7.3
  Equation 3
- Life (years) = 13.79 [log R – log 2160 – 2490 * log R] for pH <7.3
  Equation 4

Equations 1-4 incorporate the impact of soil resistivity and pH, but do not directly account for the pipe thickness. Table 6 shows the appropriate adjustment factors for different

thicknesses. Note the adjustment factors for AISI are based on a minimum thickness of 18-gage, which relates to a thickness of 0.052 inches (1.3 mm). The adjustment factors for Caltrans are based on a minimum thickness of 16-gage, which relates to a thickness of 0.064 inches (1.6 mm). Note not all pipe sizes are available in all thicknesses.

Thickness, mm	Thickness, in	Gage	AISI multiplier	Caltrans multiplier
1.3	0.052	18	1	0.8
1.6	0.064	16	1.3	1
2.0	0.079	14	1.6	1.3
2.8	0.109	12	2.2	1.8
3.5	0.138	10	2.8	2.3
4.3	0.168	8	3.4	2.8

Table 6 – Adjustment factors for CSP thickness

Example 4 – Pipe life for CSP

Calculate the pipe life for a 12-gage corrugated steel pipe with pH = 7.5 and R = 3000, using both AISI and Caltrans equations.

For AISI, use Equation 1:
Base Service Life = $2.94\ (3000)^{0.41}$ = 78.3 years

The base service life is for 18 gage pipe. From Table 6, the AISI adjustment factor for 12-gage pipe is 2.2.

Pipe Service Life = 78.3 * 2.2/1.0 = 172 years

For Caltrans, use Equation 3:
Base Service Life = $1.47\ (3000)^{0.41}$ = 39.2 years

The base service life is for 16-gage pipe. From Table 6, the Caltrans adjustment factor for 12-gage pipe is 1.8.

Pipe Service Life = 39.2 * 1.8/1.0 = 70.5 years

This example indicates the difference between the AISI equations and Caltrans equation is more than a factor of 2. It will also vary depending on the pipe thickness, since the adjustment factors for pipe thickness are different for the two methods. Different DOTs will have different approaches to pipe service life. In most cases, the correct method to use is the one that meets the standards of the particular state DOT.

A study by the Colorado DOT suggests the thickness coefficient is overestimated, yielding a longer calculated pipe life than is appropriate. This study indicates the thickness multiplier should be:

$$\text{Multiplier} = (\text{thickness, mm}/\ 1.3\ \text{mm})^{0.16} \qquad \text{Equation 5}$$

Using Equation 5 for the 12-gage pipe in Example 4, the thickness multiplier should be $(2.8\ \text{mm}/1.3\ \text{mm})^{0.16} = 1.13$, not 1.8 as indicated by Caltrans or 2.2 as indicated by AISI. For Example 4, if the basic service life is 39.2 years (per Caltrans), the Pipe Service Life is 39.2 * 1.13 = 44.3 years.

Corrugated Steel Pipe often has a coating which may extend the life of the pipe. The standard coating is galvanized which is the basis for the calculations. The coating options include:

- Bituminous coating – Caltrans indicates this provides additional life of 0-6 years in abrasive conditions and 8 years in non-abrasive conditions
- Polymeric coating – Caltrans indicates this provides additional life of 0-30 years in abrasive conditions and exceeds the required 50-year design life in non-abrasive conditions.
- Type II Aluminized coating – This pipe is manufactured to provide a layer of aluminum on the interior and exterior of the steel, providing a coating that is integral to the pipe. Caltrans indicates this coating provides a design life in excess of the required 50 years in both abrasive and non-abrasive conditions.

To determine the corrosivity of soils, sample of the soils must be taken. However, the location of the sample can have a significant impact on the result. It is common to take the soil sample from the soils in the bottom of the channel. This is likely the soil adjacent to the bottom of the pipe so a sample in this location is useful. However, this soil does not necessarily represent all of the soils around the pipe. Because culverts are in drainages, which are the low spot in the landscape, fill material is imported to raise this low spot to create a smoother roadway profile. The source of this fill material is not always known, so it can be difficult to sample the material during the design process. One way to address this is to require the contractor to sample the borrow source prior to approving the material and require specific minimum Resistivity values. This can add to the cost of the project but can ensure the desired service life for the pipe. Another approach is to specify a minimum corrosivity for the fill material and require corrosivity testing on site during the fill operation. As an alternative to these methods, the use of good quality granular material around the culvert can significantly reduce the potential for corrosion and will also increase the structural performance of the culvert installation.

Based on Caltrans criteria, aluminum pipe and Type II Aluminized steel pipe will provide the required 50-year design life with pH between 5.5 and 8.5 and Resistivity values greater than 1500, without additional thickness for service life. Caltrans generally considers HDPE pipe to meet the 50-year design life.

Abrasion can also reduce pipe life. Caltrans has some valuable guidance on the impacts of abrasion as it relates to material selection and pipe life.

CONCLUSIONS

When selecting a culvert size and material, the most important consideration is the selection must meet the design requirements, including:

- Adequate flow carrying capacity
- Adequate structural strength for the depth of cover
- Appropriate joint type (for example, watertight if that is necessary for the site)

The second most important consideration is cost. In some cases, the client might think cost is the most important consideration, but that's not the case, even for them. However, material cost is only one factor. Installation cost may be as much as one-half the total cost and contractors are the only ones that can reasonably determine installation cost. Even then, the only real answer to installation cost is obtained when bids are opened.

When more than one material choice will meet the design requirements, there is significant value in allowing all material types that will meet the design requirements and let the contractor's bid determine the most cost effective. When bidding multiple materials however, it is important that all components of each installation are included in the unit price. For example, more flexible pipe materials (such as CSP of HDPE) may require more bedding or high quality bedding, compared with RCP. If the pay item is "pipe in place, complete" then a fair comparison of total cost can be completed. However, if bedding or backfill material is bid as a separate pay item, then all of the material quantities associated with the culvert installation need to be included as alternate bids.

Inlet considerations include:

- Does the inlet type meet the hydraulic requirements?
- Is an improved inlet cost effective?
- Is the inlet configuration structurally adequate?
- Are appropriate erosion control measures included?
- Does the inlet match the embankment slope?

Outlet considerations include:

- Does the outlet match the embankment slope?
- Are appropriate erosion control measures included?

REFERENCES

HEC- 22, Urban Drainage Design Manual, FHWA
HDS-5, Hydraulic Design of Highway Culverts, FHWA
"Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials," Colorado DOT Report CDOT-2009-11.

Culvert Design - Quiz

Updated: 5/15/2022

1. The design return period for a culvert is a function of:
    a. The amount of traffic
    b. The available detours
    c. The acceptable risk at the site
    d. All of the above

2. The overtopping location will be which of the following?
    a. The roadway right at the culvert location
    b. A roadway sag near the culvert location
    c. A basin divide upstream of the culvert location that is lower than the roadway sag.
    d. It could be any of the above locations.

3. The allowable headwater elevation will be which of the following?
    a. The roadway overtopping elevation
    b. The floor elevation of upstream buildings that are lower than the roadway overtopping
    c. It could be either of the above
    d. None of the above

4. Which of the following is not a flexible pipe?
    a. Corrugated steel pipe
    b. Corrugated high density polyethylene
    c. Reinforced concrete pipe
    d. Steel reinforced polyethylene

5. A 65-inch by 40-inch reinforced concrete arch pipe is approximately equivalent to what size round concrete pipe?
    a. 42 inch
    b. 48 inch
    c. 54 inch
    d. 60 inch

6. Class 5 reinforced concrete pipe has a strength of 3000 pounds per foot per foot. This represents the force required to create what size crack in the pipe?
    a. 0.001”
    b. 0.01”
    c. 0.1”
    d. 1.0”

7. Which of the following joints is the most watertight joint for reinforced concrete pipe?
    a. Bell and spigot with o-ring gasket
    b. Tongue and groove with bituminous gasket
    c. Tongue and groove with no gasket
    d. All of the above are very watertight joints

8. What is the corrugation size for the smallest corrugated steel pipes?
    a. 2-2/3" x ½"
    b. 3" x 1"
    c. 5" x 1"
    d. 6" x 2"

9. Which Federal Agency developed the HY8 software?
    a. Environmental Protection Agency
    b. Federal Highway Administration
    c. Army Corps of Engineers
    d. Bureau of Reclamation

10. Which of the following culvert shapes can be analyzed using HY8?
    a. Circular
    b. Concrete Box
    c. Metal Box
    d. All of the above

11. What is the default value for Manning's n for concrete pipe in HY8?
    a. 0.011
    b. 0.012
    c. 0.013
    d. 0.024

12. Flared end sections are often provided by pipe manufacturers. What type of inlet configuration is selected in HY8 to model these end sections?
    a. Mitered to conform to slope
    b. Thin edge projecting
    c. Square edge with headwall
    d. None of the above

13. What is the rise of a reinforced concrete arch pipe with a span of 51.12 inches?
    a. 18.0 inches
    b. 22.5 inches
    c. 26.62 inches
    d. 31.31 inches

14. How is pipe length determined in HY8?
    a. It is entered directly
    b. It is entered as the Inlet Station
    c. It is entered as the Outlet Station
    d. It is calculated as the difference between the Outlet Station and the Inlet Station.

15. Which of the following is an available channel type for Tailwater Data in HY8?
    a. Rectangular Channel
    b. Trapezoidal Channel
    c. Irregular Channel
    d. All of the above

16. In Example 1 in this course, which pipe option had the highest overtopping flow?
    a. CSP with a thin edge projecting
    b. CSP with a standard flared end section
    c. RCP with a standard flared end section
    d. The overtopping flow was the same for all three of the above options.

17. In Example 1, when the slope of the 24" RCP is increased from 1% to 4%, what is the change in overtopping flow?
    a. Less than 1%
    b. 20%
    c. 50%
    d. Almost 100%

18. In Example 2, which of the following pipe options has the largest overtopping flow?
    a. 36-inch round RCP
    b. 51" x 31" RCPA
    c. 49" x 33" CSPA
    d. They all had the same overtopping flow.

19. For a 42-inch diameter culvert designed in accordance with the Colorado DOT standards noted, what is the maximum allowable HWD ratio at the design flow?
    a. 2.0
    b. 1.7
    c. 1.5
    d. 1.2

20. Which of the following conditions will have the largest live loads on a culvert, for a given depth?
    a. Highway
    b. Airport
    c. Railroad
    d. They are all the same.

21. What is the recommended maximum cover for a 48-inch diameter Class III reinforced concrete pipe?
    a. 19 feet
    b. 26 feet
    c. 40 feet
    d. 59 feet

22. What is the pipe stiffness for SDR 35 PVC gravity pipe?
    a. 15 psi
    b. 46 psi
    c. 80 psi
    d. 115 psi

23. Where is erosion protection typically necessary for a culvert?
    a. At the outlet end
    b. At the inlet end
    c. Both a and b.
    d. Neither a nor b.

24. The pipe life for corrugated steel pipe is a function of which of the following?
    a. Pipe thickness
    b. Pipe coatings
    c. Soil and water resistivity
    d. All of the above

25. Based on the Caltrans multiplier for pipe thickness, how much longer will 12 gage steel pipe last compared to 16 gage steel pipe?
    a. 1.3 times
    b. 1.8 times
    c. 2.3 times
    d. 2.8 times