

## An Excel Template for Generating Hydraulic Rating Curves for Corrugated-Metal-Pipe Culverts

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As a convenient and inexpensive method of intersecting roads and waterways, culverts occur in many shapes and sizes. Culverts range from arch-shaped concrete structures big enough to drive a truck through to circular pipes as small as six inches in diameter. Because of low cost, high endurance to the elements, and installation ease, circular-shaped corrugated-metal-pipe culverts are commonly used in Montana. The Excel template described herein will provide designers with a simple tool for developing rating curves specifically for this often-used culvert configuration. Rating curves, or graphs showing the relationship between flow rate and inlet *head*, are the basis of culvert design, but can also be used to assess the suitability of an existing culvert. Changes in upstream hydrology or downstream channel configurations may render an initially well designed culvert inadequate. Culvert failures can be the result of slow deterioration over time, or may occur under extreme flow events (Figure 1). The template documented herein should be a valuable tool in the culvert repair and replacement decision making process. The discharge relationships that have been encoded in the worksheet can be found in Bodhaine, G. L. 1967. This USGS publication was developed to provide scientists with methods to estimate flow in culverts based on inlet and outlet head. As such, the report has very detailed discharge coefficients based on physical descriptions of the culvert.



Figure 1. Culverts that failed during extreme flows.

## Flow Types

Flow profiles in culverts are difficult to calculate because the flow *control* changes as the culvert fills. There are six commonly occurring flow types, as shown in Figure 2 (Bodhaine, 1967). *Low flows* are those that do not submerge the weir inlet. At some low flows the inlet itself may act as a weir (Flow Type 1), with water passing through the *critical depth* at the inlet. In culverts that are less steep, the critical depth may be at the outlet (Flow Type 2). Or, flow in the culvert may be tranquil throughout so that the control is essentially the friction loss in the culvert barrel (Flow Type 3). *High flows* occur when the inlet is submerged. If the outlet is also submerged (Flow Type 4) then the culvert acts as a pressurized pipe. In some cases the inlet may act as an orifice (Flow Type 5). Some high flow culverts may flow as a pressurized pipe but with a free-fall at the outlet (Flow Type 6). There are two more types of flow, both having a hydraulic jump in the culvert (Chanson, 1999) but these occur infrequently enough that they are excluded here.

The flow equations in Figure 2 result from writing the *energy equation* between a control section and a location of known head (the outlet head, usually). The flow equations depend on the flow rate, the inlet and exit conditions, and the shape, slope, roughness and length of the culvert. Note that the flow equations can be solved explicitly for flow rate,  $Q$ , only if the flow is Type 4 or 5, For all other flow types the equations are implicit in  $Q$  and must be solved numerically.

TYPE	EXAMPLE	TYPE	EXAMPLE
1 CRITICAL DEPTH AT INLET $\frac{h_1 - z}{D} < 1.5$ $h_4/h_c < 1.0$ $S_0 > S_c$	$Q = CA_c \sqrt{2g(h_1 - z + a_1 \frac{V_1^2}{2g} - d_c - h_{f_{1,2}})}$	4 SUBMERGED OUTLET $\frac{h_1 - z}{D} > 1.0$ $h_4/D > 1.0$	$Q = CA_0 \sqrt{\frac{2g(h_1 - h_4)}{1 + \frac{29C^2n^2L}{R_0^{4/3}}}}$
2 CRITICAL DEPTH AT OUTLET $\frac{h_1 - z}{D} < 1.5$ $h_4/h_c < 1.0$ $S_0 < S_c$	$Q = CA_c \sqrt{2g(h_1 + a_1 \frac{V_1^2}{2g} - d_c - h_{f_{1,2,3}})}$	5 RAPID FLOW AT INLET $\frac{h_1 - z}{D} > 1.5$ $h_4/D \approx 1.0$	$Q = CA_0 \sqrt{2g(h_1 - z)}$
3 TRANQUIL FLOW THROUGHOUT $\frac{h_1 - z}{D} < 1.5$ $h_4/D \approx 1.0$ $h_4/h_c > 1.0$	$Q = CA_3 \sqrt{2g(h_1 + a_1 \frac{V_1^2}{2g} - h_3 - h_{f_{1,2,2,3}})}$	6 FULL FLOW FREE OUTFALL $\frac{h_1 - z}{D} \approx 1.5$ $h_4/D \approx 1.0$	$Q = CA_0 \sqrt{2g(h_1 - h_3 - h_{f_{1,2,3}})}$

Figure 2. Classification of flow (Bodhaine, 1967).

## Materials and Entrance Conditions

Culverts can be constructed from a variety of materials (concrete, steel, bricks...) and in a variety of shapes (circular, box, arch...). The presentation here considers only culverts made of corrugated steel (*Manning's*  $n = 0.024$ ) with circular cross sections. There are also many different entrances that can be incorporated into the variety of culvert shapes and materials. Here we will limit discussion to only the following commonly occurring entrances:

Entrance 3 - the culvert is flush with a vertical head wall or with wingwalls.

Entrance 6 - the entrance projects into the entrance channel.

Entrance 7 - the culvert is mitered flush with a sloping embankment.

Examples of entrance conditions are shown in Figure 3. The value of the *coefficient of discharge* ( $C$  in the equations of Figure 2) is a function of the type of entrance. For some flow types, the coefficient of discharge also depends on inlet head – further complicating the implicit solution of flow rate for any given inlet head. All of the appropriate tables and graphs of Bodhaine, 1967 have been encoded into automated interpolation tables in the template.



Figure 3. Entrance conditions.

## Entrance Channel

Flow types 1, 2 and 3 also depend slightly on the characteristics of the inlet channel. Flow types 4, 5, and 6 are independent of the geometry and conditions of the stream as it approaches the culvert but depend heavily on the characteristics of the culvert entrance. As such, the template requires the user to provide a simple symmetric trapezoidal description of the entrance channel. An example of a trapezoidal approximation to an irregular channel is shown in Figure 4.

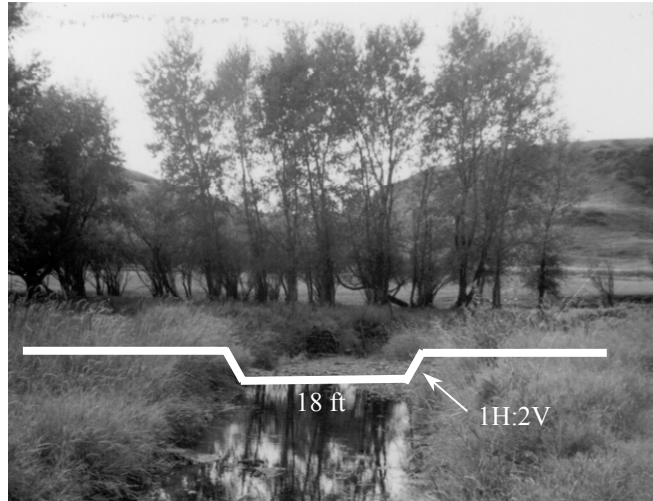


Figure 4. Trapezoidal approximation to an irregular inlet channel.

The trapezoidal approximation shown in Figure 4 would suffice for flows that are expected to remain in the channel. If extreme flows are of interest and these larger flow rates would inundate the *overbank*, the trapezoidal channel should be expanded to show the ponded conditions. An easy way to accomplish this is to keep the base width of the primary channel, but change the side slope to very gradually ascend from the main channel floor to the maximum flow depth over the overbank. Then adjust the value Manning's  $n$  to represent the dominant roughness of the overbank.

## Exit Channel

The only feature of the exit channel that influence the rating curve for a culvert is the exit head. In general, there are two cases of exit conditions. If the culvert *invert* at the outlet is sufficiently above the exit channel to prohibit exit channel backwater from interfering, enter a value of zero into the template for *tail water* depth. This insures type 2 flow for low flows and type 5 or 6 flow for high flows. If the tail water will interfere, external calculations of gradually varied flow in the exit channel will lead to the proper tail water depth.

## Limitations

This template is intended for use by persons that have some experience in open channel hydraulics and culvert design and are comfortable using Excel or a compatible spreadsheet. It is likely that there are combinations of input values that will result in errors rather than answers. Fortunately, it is also likely that these combinations do not often exist. For example, if the user enters a tail water depth that inundates the outlet of the culvert but is at an elevation lower than the *soffit* at the inlet end (a very long, very steep culvert), the program will assume Type 4 flow. In reality, this is likely Type 1 flow with a *hydraulic jump* inside the culvert, a case the template will not handle. In a few cases, red colored text will appear on the input page when unusual settings are entered. For example, if the user indicates that the tail water depth is higher than the road deck, a message occurs. Do not expect successful completion of the solution process if warning text occurs. There are also some general limitations that the user should be aware of:

- The template is written for circular-shaped corrugated-metal-pipe culverts only.
- The template is not recommended for culverts greater than 6 feet in diameter. A solution is possible for larger culverts, but these tend to flow as Type 3 over a wide range of flow rates. A more appropriate solution for large culverts can be arrived at using HEC-RAS (U.S. Army Corps of Engineers, 1998).
- The coefficients of discharge used here are for single culverts. Exercise caution if modeling multiple culverts in parallel.
- The code will not correctly deal with culverts having adverse sloped barrels.

## Input to the Template

To use the template, the user is required to enter eleven values, at most. If the default value in the template will suffice, the user need not re-enter the value. Prior to running the calculations the template must show correct values of:

- a) the culvert diameter, in feet,
- b) the culvert length, in feet
- c) the downstream slope of the culvert, in feet/feet,
- d) if the culvert projects into the entrance channel, the length of projection, in feet,
- e) the elevation of the road deck, in feet,
- f) the width of the trapezoidal entrance channel, in feet,
- g) the side slope (horizontal/vertical) of the entrance channel, in feet/feet,
- h) the value of Manning's n for the entrance channel
- i) the downstream slope of the entrance channel, in feet/feet,
- j) the tail water depth, in feet, and
- k) the entrance case, 3, 6 or 7.

Keep in mind that all depths or elevations, items e) and j) above, are measured relative to zero datum at the culvert exit invert. After the above items are satisfactory, use the mouse to left-click the "Run" button. The updates stage-discharge curve, tabulated and graphically, will soon appear on the I/O sheet.

## Interpreting Output

The output is displayed in the table and graph below the input boxes on the I/O sheet. The output is only correct, or updated, after new input if the program has been “Run” as described above. In most cases it is acceptable to interpolate between points on the graph to estimate the flow for intermediate values of inlet head. In some cases two different flow rates will be indicated for similar inlet head values. This indicates that flow may occur as two different flow types. In this case, choose the point that has the lower flow rate. Keep in mind that inlet head is measured from the zero datum at the outlet invert. So, in a sloping culvert there can be no flow until the inlet head exceeds the inlet invert elevation. Also, if the outlet is submerged, then there can be no flow until the inlet head exceeds the tail water depth at the outlet (backwards flow is not allowed).

## Glossary

The terms that are italicized throughout this report are defined, for the context of culvert design and evaluation, below.

*Coefficient of Discharge* – An empirical adjustment to the energy equation that accounts for minor energy losses at the inlet due to turbulence, eddy currents, contraction of flow lines, etc. These energy losses are a strong function of the entrance condition or geometry, a lesser function of the inlet head, and in some cases a weak function of the extent of difference between the cross sectional flow areas of the entrance channel and the inlet to the culvert.

*Control* – A phenomena in the flow path that establishes the relationship between flow rate and a measure of geometry, usually flow depth. A weir, for example, is a control structure because a weir causes water to pass through the critical depth and there is a unique relationship between flow rate and the critical depth for any flow geometry.

*Critical Depth* – The depth at which the specific energy is minimized for a given geometry and flow rate. Specific energy is the sum of the water flow depth and the velocity head.

*Energy Equation* – The relationship between the energy states at two points in a flow path. Energy is comprised of the flow depth, the channel floor and the velocity head. Energy losses are those associated with friction and minor losses due to turbulence, eddy currents, contraction of flow lines, etc. In equation form the energy equation written from a point labeled “1” to a downstream point labeled “2” occurs as:

$$y_1 + z_1 + V_1^2/2g = y_2 + z_2 + V_2^2/2g + h_m + h_l$$

where:  $y_1, y_2$  = the flow depth  $s$  at points 1 and 2, (feet)  
 $z_1, z_2$  = the elevation of the channel invert at points 1 and 2 (feet),  
 $V_1, V_2$  = the mean flow velocity at points 1 and 2 (ft/sec),  
 $g$  = the gravitational constant, 32.2 ft/sec<sup>2</sup>,  
 $h_m$  = the minor energy losses between points 1 and 2 (feet), and  
 $h_f$  = the sum of all friction losses between points 1 and 2 (feet).

**Head** – A term that implies the energy state at any cross section. In the formal definition this includes the bed elevation, the flow depth and the velocity head. In cases where the velocity is small, the velocity head is even smaller, and that term can be ignored. This relegates the “head” at a point to the value of the water surface elevation at that point as measured from a common datum.

**High Flow** – The case where the inlet end of the culvert is inundated. It turns out that the water surface at the inlet end can be a bit higher than the inlet soffit without submergence because of the contraction trajectory as flow enters the culvert. Research has used values of  $(h_1 - z)/d$  (the height of the water surface as measured from the inlet invert divided by the culvert diameter) ratios between 1.1 and 1.5 to define submergence. In the template, submergence is assumed to occur at  $(h_1 - z)/d = 1.4$ .

**Hydraulic Jump** – An abrupt transition from flow at a depth less than the critical depth to flow at a depth greater than the critical depth. Energy is exhausted in the hydraulic jump.

**Invert** - The lowest point inside the culvert.

**Low Flow** - The case where the inlet end of the culvert is not inundated (see High Flow). In the template, low flow occurs at  $(h_1 - z)/d < 1.4$ .

**Manning’s n** – A description of the roughness of the channel surface. Larger Manning’s  $n$  values indicate more resistance to flow while small values indicate a very smooth surface. The units, although rarely expressed, for Manning’s  $n$  are ft<sup>1/6</sup>. Typical values are 0.024 for corrugated metal pipe and 0.013 for smooth concrete. Complete tables of typical Manning’s  $n$  values can be found in Chow, 1958.

**Overbank** – the portion of the channel that is outside the usual flow area and usually is inundated during extreme flow events.

**Soffit** – The highest point inside the culvert.

**Tail Water** – Water in the exit channel, immediately downstream of the culvert outlet.

## Bibliography

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