Types of Culvert Flow

SPEAKER Rick Huizinga: This is Lesson 17, flow through culverts. I'm going to give you a basic introduction to flow through culverts and one of the things about this discussion is that you have to understand that a majority of the time that roadway crossings of small streams, the stream flow is conveyed by means of a culvert rather than a bridge. Culverts are much less expensive to build and much easier to build, so culverts are used predominantly for small streams. But because of their small cross-sectional area in comparison to the upstream channel and flood plain, the transition winds up becoming a case of rapidly varied flow as opposed to the gradually varied flow that we've talked about so far. And in rapidly varied flow, acceleration dominates the flow pattern rather than friction. The peak discharge can be determined from high watermarks in the headwater and tailwater areas of the culvert as we've already talked about with contracted openings. And in this lecture, I'll review the theory behind the procedures used to compute discharge through the culvert. I'll try to note some of the peculiarities of each type of indirect method and when it's appropriate for a given flow situation, and I'd like to briefly discuss the procedures behind it. But be aware that there are computer programs to assist with these computations. And if you ever need to do a culvert computation even with a computer program, it would be good to consult the USGS/TWRI that relates to this which is in Chapter 3 Book A3.

Now, what you see in front of you right now is sort of the description sketch for a culvert and I'd like to point out a few things about that. First of all, you'll notice that there are four cross-sections. There is the approach section, Section 1. There is--at Section 2 is the culvert entrance, Section 3 is the culvert exit, and Section 4 is called the tailwater area. In Section 1, you have the total depth h1 which is the depth of water plus the potential referenced from the downstream or the culvert outlet. And, of course, there is a velocity head term, alpha1 V1 squared over 2g. Then at Section 2, the depth at Section 2, it's called D sub-2, and there're is a velocity head there as well. The diameter of their pipe is shown as D sub-p, and then there is a depth at Section 3 and a depth at Section 4 as well but that depth at Section 4 is, again, referenced back to the outlet of the culvert at Section 3. There is also a z at Section 2 and that z is the difference in the culvert invert as we call that. The bottom of the culvert at Section 3 is always the point of reference of datum. And so

at the upstream end of the culvert at Section 2, the z term is the difference in elevation from downstream to upstream of the culvert.

And as you'll see, there are friction losses between Section 1 and 2, there is friction losses between Sections 2 and 3, and then there are entrance losses at Section 2 as flow enters into the culvert.

Now in culvert computations, discharge is computed by writing the energy equation between a point upstream of the culvert at Section 1 and a second point at some point either inside or downstream from the culvert. Now for a bridge in Lesson 16, we've talked about the points upstream from the bridge and at the downstream edge of the road embankment. But for a culvert, the best point for the downstream section depends entirely upon the flow conditions. And culvert computations have been broken into six types of flow conditions. For type 1 flow, critical depth occurs at the inlet and the unique thing about type 1 flow is that the culvert is on a supercritical slope or a steep slope. There are some equations that relate to this to help you determine whether or not it's type 1 flow or not and a couple of those are shown below--h sub-1 minus z over D sub-p has got to be less than 1.5 and that means that the headwater depth measured from the headwater invert, may be up to 1.5 times the culvert diameter or height. The h sub-4 over D sub-c being greater than 1 means that the tailwater dept measured from the tailwater end is less than the critical depth in the culvert. And S sub-o being greater than S sub-c means that the slope of the culvert is greater than critical or that it's a steep slope. And the downstream point in the energy equation is taken right at the culvert invert where critical depth occurs.

For type 2 flow, critical depth occurs at the outlet and this is because it's similar to type 1 except that the slope of the culvert, S sub-0, is less than critical slope which means it's a mild slope, a sub-critical slope. H sub-1 minus z over D sub-p being less than 1.5, it means again that the headwater depth measure from the headwater invert may be up to 1.5 times the culvert diameter. And h sub-4 over D sub-c being greater than 1 means that the tailwater depth is still less than critical depth in the culvert. The downstream point in a type 2 scenario is taken at the culvert outlet and you have to account for the losses in the pipe as well as upstream of the pipe.

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In type 3 culvert flow, this is when tranquil flow occurs all the way through the culvert. It's not flowing full but the tailwater depth h4 over D sub-c is greater than 1 which means the depth of flow in the pipe and downstream of the pipe is greater than the critical depth in the pipe which implies that it still has a mild slope. H sub-1 minus z over D sub-p can still be less than 1.5 as it did with type 1 and type 2, and h sub-4 over the diameter of the pipe has to be less than or equal to 1 which means the tailwater measured form the tailwater invert is less than or equal to the culvert diameter or the height. And the reason I refer to it as diameter or height is because culverts can be either circular or even oval or rectangular.

And in type 3 flow, the downstream point is taken at the culvert outlet and you have to once again consider the losses in the pipe.

Type 4 flow is a very unique case and this is the only case where the outlet is submerged. So there are no other ones--none of the other types of flow have a submerged outlet. So that is why the h sub-4 over D sub-p is greater than 1. That means the tailwater depth measured from the tailwater invert is greater than the culvert diameter or the height of the pipe, and therefore it is submerged. And therefore, h sub-1 minus z over the diameter of the pipe has to be greater than 1. That means that the headwater depth, it only has to be slightly greater than the diameter of the pipe rather than 1.5 for it to fit a type 4 scenario. The downstream point in a type 4 scenario is taken at some point just downstream of the culvert outlet. Many times in the field, it's taken at the upstream and downstream edges of the road embankment as long as you're away from the influence of the drawdown from the culvert inlet. There is no friction loss term but losses are accounted for in the denominator of the equation because there is an n term and a C term and a length term and n, of course, is the Manning's roughness and C, we will find, is a culvert coefficient that accounts for losses.

In type 5 flow, this is again another unique sort of a case. In type 5 flow, the headwater is very, very large so that h1 minus z over the D sub-p is greater than or equal to 1.5.

Of course, that means that the headwater depth is 1.5 times greater than the culvert diameter or height. And what occurs basically--this is a special case of orifice flow where the inlet acts as an orifice plate such that the orifice is small enough that you get such a contraction of flow and flow

accelerates very quickly through the pipe. H sub-4 over D sub-p again has to be less than 1 which means that the tailwater depth can be up to the culvert diameter but not greater than, and the downstream point is taken at the culvert inlet again because that's the point of contraction.

In type 6 flow, this is considered full flow with a free outfall. It's similar to type 5 except that the inlet of the pipe is more efficient which allows the pipe to flow completely full rather than being contracted down within the pipe. Headwater depth again is very large such that h1 minus z over D sub-p is greater than or equal to 1.5 and h sub-4 over D sub-p has to be less than or equal to one which means the tailwater depth again cannot be any greater than the diameter or height of the pipe. And the downstream point for the energy equation is taken at the culvert outlet and you must consider the friction losses in the pipe just you like you do with type 2. And note in this particular case that h3, the depth of the flow at the culvert outlet, is equal to the diameter of the pipe or the height of the pipe.

Now, let's talk a little bit about the inlet submersion. The six types of flow can be grouped into two different groups of three based on whether the inlet is submerged or not. In types 1 through 3, the upstream flow depth is greater than the critical flow in the culvert but that is less than the culvert diameter or D sub-1 is greater than D sub-c and D sub-c is less than the D sub-p. So if the critical depth of the culvert is greater than the culvert diameter such that D sub-c is greater than D sub-p, the culvert inlet will be submerged and it will be a type 4 through 6. Alternatively, if h sub-1 minus z over D sub-p is greater than or equal to 1.5 ignoring any of the friction losses or head losses, then the inlet will be submerged as well and it will be type 4 through 6. Now for types 1 through 3, this usually requires an iterative solution to solve for the discharge. And initially you have to assume that the velocity in the upstream reach is essentially zero such that the capital H1 term which is equal to h1, the depth at the upstream end minus z, you have to make the assumption that H1 is equal to the depth of flow at the upstream end rather and assume that the velocity head is equal to zero. And that critical depth in the culvert then is equal to two-thirds times H sub-1. You then have to determine a Q trial from which an area at the upstream end of the culvert and the velocity can be determined and then you use these parameters to compute the Q based on

the equation for the flow that it is. You then need to check your computed Q against the trial Q, adjust the parameters, and re compute it.

This is the end of this section of Lesson 17. And in the next section, we'll derive the discharge equation for the type 1 culvert flow to demonstrate the process.