Integrated Urban Drainage Modelling Guide

Appendix F

Modelling Culvert Inlets

CIWEM Chartered Institute of Water and Environmental Management

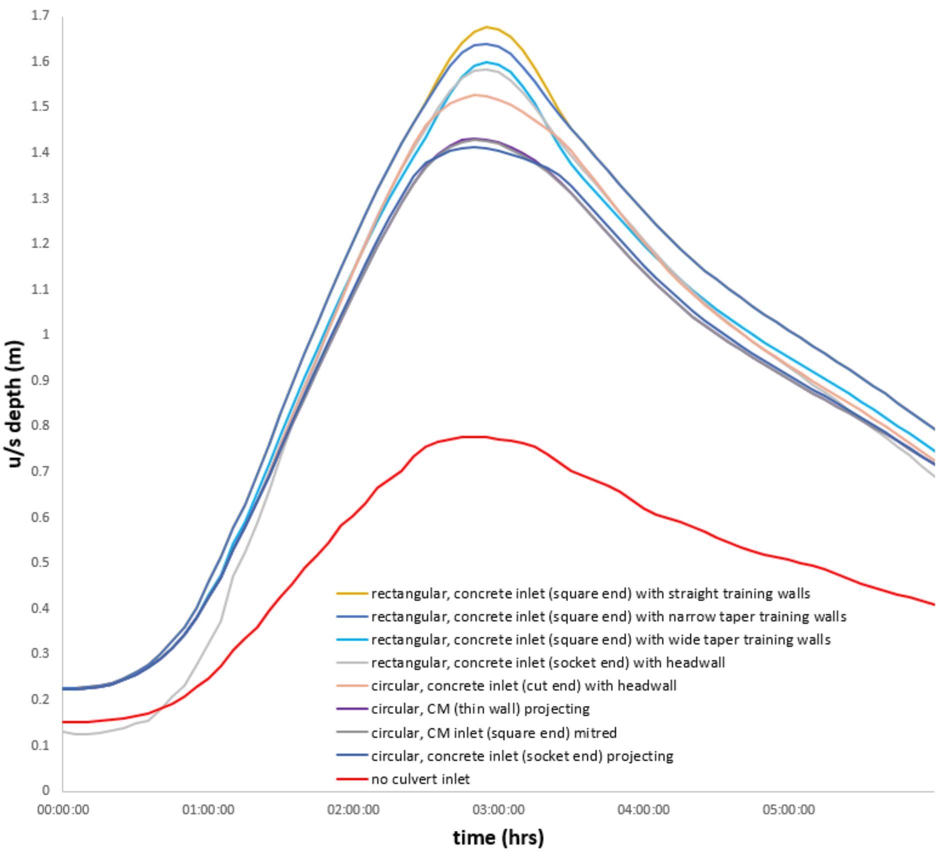
F1. Introduction

This appendix should be read in conjunction with the CIRIA "Culvert, Screen and Outfall Manual" (2019) which provides complimentary information on the design and operation of culverts, screens and outfall.

This appendix has been based on the paper presented at the CIWEM UDG 2019 Spring Conference by Gary Buck from Richard Allitt Associates Ltd. The contents of the paper was to fill the gap in information specific to the UK for the modelling of culvert inlet types commonly found in the UK. This includes types which are not covered by the CIRIA guide.

For integrated urban drainage models which includes sections of culverted watercourse it is important that the inlet arrangements are correctly modelled. Most sewers are barrel controlled, but the flow through most watercourse culverts is inlet controlled and in many instances the culverts do not run full bore or surcharged because of the limitations of the inlet; this makes satisfactory modelling of the inlet particularly important in respect of flood risk assessments.

Figure 1 – Depths at upstream end of a nominal culvert in ICM using a range of inlets



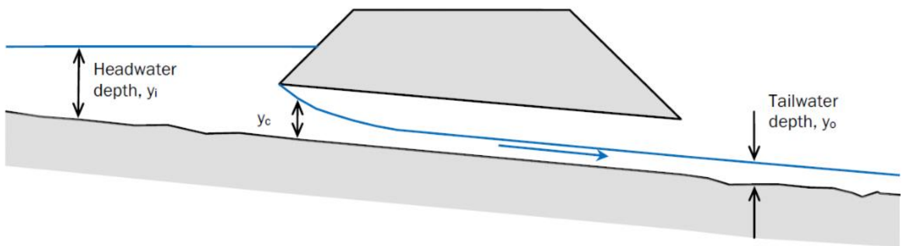
The representation of culvert inlets in all modelling programs is critical in determining how headwater depths vary over a range of operating conditions. Figure 1 shows the upstream depths using a hypothetical range of inlets for a relatively short section of 1200mm diameter culvert (including the case with no culvert inlet). For this nominal case there is a greater than 20% difference in the range of depths depending on the selected culvert inlet, and the consequences of not using a culvert inlet are apparent. In this example the difference in headwater level is as much as one metre which in terms of flood risk would be significant.

Most modelling programs base the representation of culvert inlets on physical modelling studies which were undertaken in the USA in the 1950's for commonly used culvert shapes and inlets found in the USA. The parameters used in most modelling programs are identical and accordingly the parameters set out in this appendix apply to most modelling programs. The range of culvert shapes and inlet arrangements frequently found in the UK is far wider and accordingly there is little or no information in most modelling program documentation for commonly found culvert shapes. This appendix consolidates the available information relating to culvert inlets, focussing on the parameters that need to be specified within the software and helps to fill in the gaps for the missing culvert shapes and inlet arrangements.

F2. Culvert Flow Control

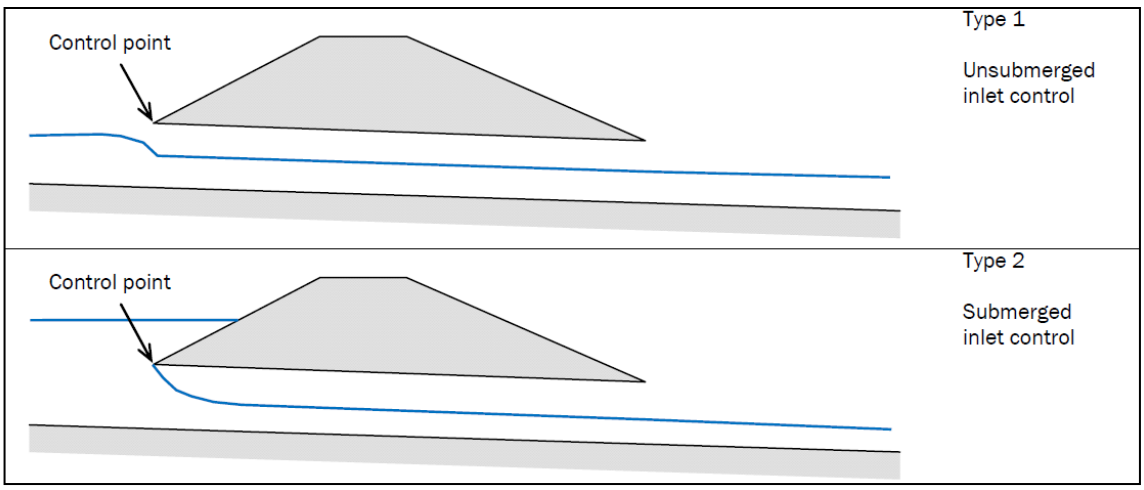
A typical culvert consists of an inlet, a barrel and an outlet, as shown in Figure 2. The flow conditions, and control location, for any given culvert vary over time. Culverts can flow full or part full (free surface) depending on the inlet geometry, the characteristics of the barrel, and the conditions upstream and downstream of the culvert. Full flow in a culvert barrel is very rare, generally at least some of the barrel flows part full.

Figure 2 – Typical culvert section



The flow control in a culvert is defined as either inlet or outlet control, depending on the location of the controlling section. Inlet control occurs when the barrel capacity is greater than the flows that the inlet can accept. The control section in this case is located just inside the culvert entrance. Critical depth occurs in this region, and supercritical flow is established immediately downstream. For inlet control, hydraulic characteristics downstream of the control section generally do not affect the capacity of the culvert.

Figure 3 – Flow types for a culvert under inlet control

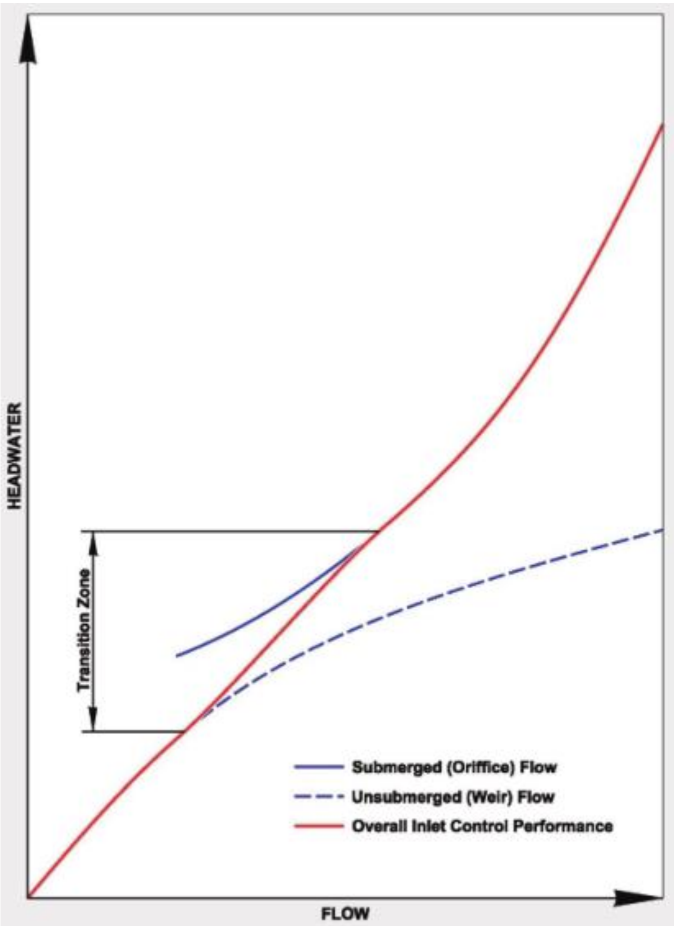


The CIRIA 'Culvert, Screen and Outfall Manual' (2019) is the primary source of information in the UK regarding culvert hydraulics, and many of the modelling program helpfiles refer to the relevant equations and tables associated with culvert inlets in the guide. The guide presents information that is based on research conducted in the US by the National Bureau of Standards (NBS) under the sponsorship of the Bureau of Public Roads (now the Federal Highways Administration, FHWA), dating back to 1955.

The principal types of flow control are listed in the guide and Types 1 and 2 are shown in Figure 3, which indicate inlet control in free flow and submerged conditions (other types are possible). For free flow inlet control the inlet operates as a weir, causing a large energy loss and drop in water level, with an increase in velocity as the flow contracts into the culvert. For submerged inlet control the inlet operates as an orifice, and the flow separates from the soffit at the inlet. A hydraulic jump may occur downstream depending on the tailwater depth.

For a given culvert under inlet control, the headwater depth can be plotted against the discharge for both the free flow and submerged conditions, with the curves resembling those for a corresponding weir or orifice respectively. The transition between free and submerged conditions can be approximated with a line between these curves, as illustrated in Figure 4.

Figure 4 – Inlet control curves



Source: (Hydraulic Design of Highway Culverts, Third Edition, 2012)

Equations describing the relationship between the flow and headwater depth have been developed for the free flow and submerged cases (Hydraulic Design of Highway Culverts, Third Edition, 2012).

The condition of free flow is not simply when the water level is below the culvert soffit level, but is defined as the case when the discharge intensity is less than 3.5 (discharge intensities greater than 4 indicate submerged flow conditions): where q_i is the discharge intensity, Q is the discharge (m^3/s) and A_b is the cross-sectional area of the culvert barrel (m^2).

$$q_i = \frac{1.811Q}{A_b D^{0.5}} \qquad (1)$$

For free flow inlet control, one of equations (2) or (3) are applied. The first of these is based on the specific head at critical depth, adjusted with two correction factors (Equation A):

$$\frac{HW_i}{D} = \frac{H_c}{D} + k\left[\frac{1.811Q}{A_b D^{0.5}}\right]^M - 0.5S_0 \qquad (2)$$

where HW_i is the headwater depth above the inlet control section invert (m), D is the culvert height (m), S_0 is the slope, and H_c is the specific head at critical depth (m).

The simplified version is an exponential equation similar to a weir equation (Equation B):

$$\frac{HW_i}{D} = k\left[\frac{1.811Q}{A_b D^{0.5}}\right]^M \qquad (3)$$

Equation (2) is more favourable theoretically, however the simplified equation (3) is the only form for which there is available data for some inlet arrangements.

For submerged inlet control, the following applies:

$$\frac{HW_i}{D} = c\left[\frac{1.811Q}{A_b D^{0.5}}\right]^2 + Y - 0.5S_0 \qquad (4)$$

For sub-critical flow in the channel, the relevant equation above can be replaced by the following if it provides a higher water level in the channel immediately upstream of the culvert inlet:

$$h_i = k_i \frac{v_b^2}{2g} \qquad (5)$$

where h_i is the headloss across the inlet (m), k_i is the inlet headloss coefficient, and v_b is the velocity at the culvert inlet (m/s).

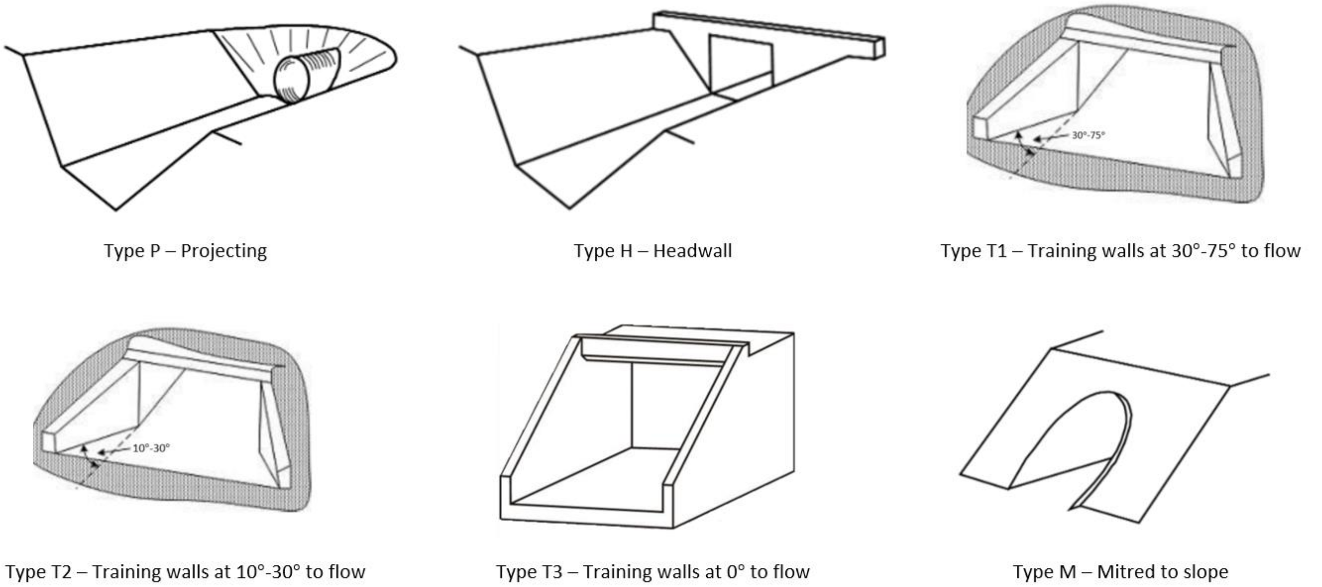
The type of flow is identified during simulations within most modelling programs. The parameters:-

- k *(unsubmerged inlet control loss coefficient)*,
- M *(exponent of flow intensity for inlet control)*,
- c *(submerged inlet control loss coefficient)*,
- Y *(submerged inlet control adjustment factor)* and
- K_i *(inlet headloss coefficient)*

in equations (2, 3, 4 & 5) need to be specified for culvert inlets in the modelling program. These parameters are dependent on the type of inlet arrangement. Guidance on the range of values to use for these parameters is given in the modelling program helpfiles, and further enhanced in the next section of this appendix.

F3. Parameter Values

The culvert inlet parameter values are dependent on the inlet arrangement (i.e. the combination of the inlet type, edge type, culvert material and culvert shape), and the available values are based on research undertaken in the US. Unfortunately, many of these arrangements are not commonly used in the UK



Sources: (Culvert Design and Operation Guide, 2010), (HY-8 User Manual v7.5, 2016), (A Better Design for Box Culverts?, 2005)

Figure 5 – Typical culvert inlet types found in the UK

and there are also many in use in the UK for which no information is available. Consequently there is currently a shortfall in the parameters frequently required. In order to fill some of the gaps, a list of the typical inlet types found in the UK has been developed. These are shown in Figure 5 (using a simplified terminology for the types). These fall into 4 main categories (Projecting, Headwall, headwall with Training walls, and Mitred), however the flare of the training walls (wide taper, narrow taper or straight) also has an impact on the inlet hydraulics. There are a limited number of conduit and edge types (square edge, pipe socket end or chamfered, bevelled edge, thin wall, etc.) commonly associated with these inlet types.

Table 1 through to 6 list the inlet arrangements identified as being typically encountered in the UK, and the associated culvert inlet parameter values are presented. The unshaded values are extracted directly from modelling program helpfiles, and the shaded values have been taken from other sources where available, or by using best judgement. It is important to note that coefficients for rectangular shapes should not be used for nonrectangular (circular, arch, pipe-arch, etc.) shapes and vice-versa.

Table 1 shows the parameter values associated with projecting type (Type P) culvert inlets. No parameter values are available in modelling program documentation for circular concrete pipes with the cut end projecting, or for circular plastic pipes (thin edge) projecting. For plastic pipes, the same parameter values as for thin edge corrugated metal have been used.

Table 1 – Type P (Projecting) parameter values

Material	Culvert Shape	Edge Type	Inlet loss	Free flow			Submerged inlet	
			k_i	equation	k	M	c	Y
Concrete	Circular	Socket end	0.3	full (2)	0.0045	2.0	0.0317	0.69
Concrete	Circular	Cut end (sq)	0.5	full (2)	0.0098	2.0	0.0398	0.67
Plastic	Circular	Thin wall	0.9	full (2)	0.0018	2.5	0.0243	0.83
Corrugated Metal	Circular	Thin wall	0.9	full (2)	0.0018	2.5	0.0243	0.83

There are approximately 100 combinations of inlet arrangements with parameters listed in the 'Hydraulic Design of Highway Culverts' (2012), and of these there are only a small number of combinations where the culvert material is the only variable. In these cases, there is some variation in the parameter values, however the culvert material appears to have much less significance than the inlet type or edge type for a given conduit shape. Figure 6 shows the quasi-dimensionless head-discharge curves applied in the FHWA culvert hydraulics analysis software HY-8 (2016) for circular pipes of varying inlet configuration. The only two instances listing materials (which differ) are relatively closely matched. The closest match for square end projecting in these plots is square edge with headwall, so these values have been used in Table 1 for this case.

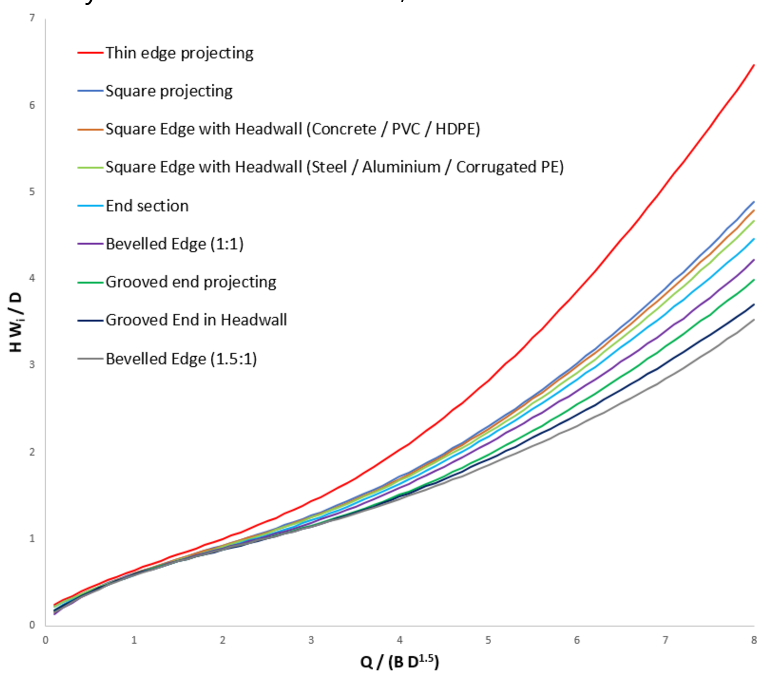


Figure 6 – Quasi-dimensionless head-discharge curves for circular pipes in HY-8

Table 2 shows the parameter values associated with headwall (Type H) culvert inlets with headwalls (no training walls). Typical modelling program helpfiles include the standard concrete and corrugated metal varieties. The parameter values for circular concrete pipes have been applied for the plastic pipes. No parameter values are available for the brick and stone arch culverts. The only arch culverts with available data are of corrugated metal, however the edge type for this material differs from the brick and stone culverts and typical US arch culverts are a lot flatter than those is the UK which are more likely to be 'sprung arches'. For arch culverts we have applied the values for rectangular culverts with 90° headwall and 45° bevels for the free flow case (i.e. the lower part of the arch). Figure 6 appears to indicate that the edge type has a greater effect on the headloss at the inlet than the inlet type. We have therefore used the values for circular culverts with 45° bevels for the submerged case (i.e. the top part of the arch), since there is no data available for this culvert arrangement with a headwall. This data has also been used for the brick and stone circular culverts for both the submerged and free flow cases.

Table 2 – Type H (Headwall) parameter values

Material	Culvert Shape	Edge Type	Inlet loss	Free flow			Submerged inlet	
			k_i	equation	k	M	c	Y
Concrete	Circular	Socket end	0.3	full (2)	0.0078	2.0	0.0292	0.74
Concrete	Circular	Cut end (sq)	0.5	full (2)	0.0098	2.0	0.0398	0.67
Concrete	Rectangular	Socket end	0.5	simple (3)	0.5150	0.667	0.0375	0.79
Concrete	Rectangular	Plain end (sq)	0.5	full (2)	0.0610	0.75	0.0400	0.80
Brick	Circular	Bevelled[1]	0.2	full (2)	0.0018	2.5	0.0300	0.74
Brick	Arch	Bevelled	0.2	simple (3)	0.495	0.667	0.0300	0.74
Stone	Circular	Bevelled	0.2	full (2)	0.0018	2.5	0.0300	0.74
Stone	Arch	Bevelled	0.2	simple (3)	0.495	0.667	0.0300	0.74
Plastic	Circular	Plain end (sq)	0.5	full (2)	0.0098	2.0	0.0398	0.67
Corrugated Metal	Circular	Plain end (sq)	0.5	full (2)	0.0340	1.5	0.0553	0.54

[1] It is assumed that all brick and stone culverts will (because of their age) have a slightly rounded edge which is best assumed as equivalent to a bevelled edge.

Table 3 shows the parameter values associated with culvert inlets with headwalls and training walls (Type T1) at 30°-75° to the flow. The only parameter values available in most modelling programs for this type of inlet are for concrete rectangular (box) culverts with square edges. The South Dakota concrete box data (2006) has been used for box culverts with the socket end as the edge.

Most of the research with training walls has been undertaking using box culverts, however a limited number of studies used concrete open-bottom arch culverts (1999). This data could be used for the brick and stone arch culverts found in the UK, however these differ as they are sprung arches with vertical walls in the bottom part.

Figure 7 shows the quasi-dimensionless head-discharge curves applied in HY-8 (2016) for rectangular box culverts of varying inlet configuration. Figure 6 and Figure 7 both appear to indicate that the edge type has a greater effect on the headloss at the inlet than the inlet type. For a 1:1 bevelled edge, there is little difference in the curves for box culverts with or without a 45° training wall. This has been assumed to also be the case for metal, brick and stone culverts, and the concrete pipe with the socket end at the inlet.

No data is available for circular conduits with a square end; however, the concrete open-bottom arch data could be used (with caution) as the best alternative.

Table 3 – Type T1 (Training walls at 30º to 75º to flow) parameter values

Material	**Culvert Shape**	**Edge Type**	**Inlet loss**	**Free flow**			**Submerged inlet**	
			k_i	**equation**	k	M	c	Y
Concrete	Circular	Socket end	0.2	full (2)	0.0078	2.0	0.0292	0.74
Concrete	Circular	Cut end (sq)	0.5	simple (3)	0.470	0.68	0.040	0.62
Concrete	Rectangular	Socket end	0.2	simple (3)	0.440	0.74	0.040	0.48
Concrete	Rectangular	Plain end (sq)	0.3	full (2)	0.0260	1.0	0.0385	0.81
Brick	Circular	Bevelled	0.2	full (2)	0.0018	2.5	0.0300	0.74
Brick	Arch	Bevelled	0.2	simple (3)	0.495	0.667	0.0300	0.74
Stone	Circular	Bevelled	0.2	full (2)	0.0018	2.5	0.0300	0.74
Stone	Arch	Bevelled	0.2	simple (3)	0.495	0.667	0.0300	0.74
Plastic	Circular	Plain end (sq)	0.5	simple (3)	0.470	0.68	0.040	0.62
Corrugated Metal	Circular	Plain end (sq)	0.5	full (2)	0.0340	1.5	0.0553	0.54

Figure 7 – Quasi-dimensionless head-discharge curves for rectangular box culverts in HY-8

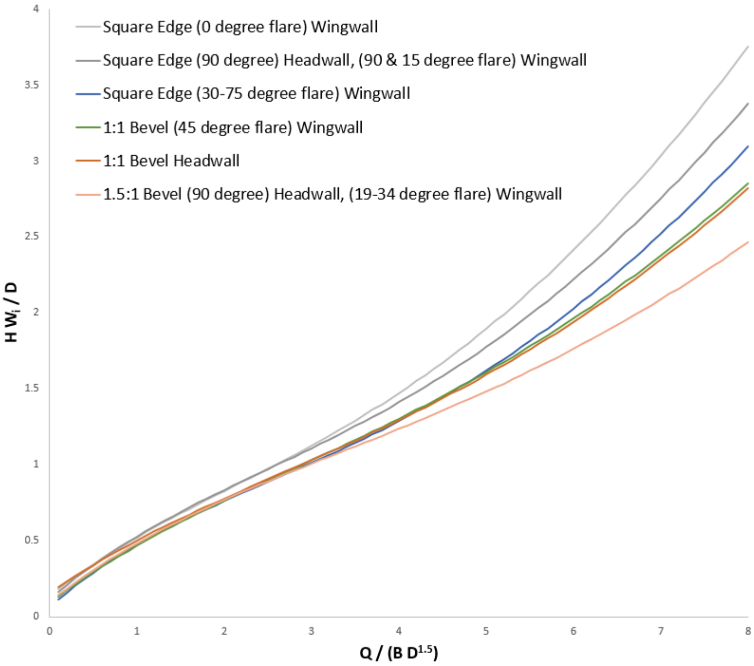


Table 4 shows the parameter values associated with culvert inlets with headwalls and training walls at 10°-30° to the flow (Type T2). The only parameter values available in most modelling program documentation for this type of inlet are for concrete rectangular (box) culverts with square edges, and unfortunately there are no other combinations available in the previous studies.

The parameter values for box culverts with square edges and headwalls with training walls at 10°-30° to the flow are very similar to those for box culverts with square edges and headwalls with training walls at 0° to the flow. This has been assumed to also be the case for box culverts with the socket end, and the corresponding values available from previous studies have been applied in Table 4. The parameter values for all the circular and arch culverts for Type T2 have been assumed to be the same as for Type T1.

Table 4 – Type T2 (Training walls at 10° to 30° to flow) parameter values

Material	**Culvert Shape**	**Edge Type**	**Inlet loss**	**Free flow**			**Submerged inlet**	
			k_i	**equation**	k	M	c	Y
Concrete	Circular	Socket end	0.2	full (2)	0.0078	2.0	0.0292	0.74
Concrete	Circular	Cut end (sq)	0.5	simple (3)	0.470	0.68	0.040	0.62
Concrete	Rectangular	Socket end	0.2	simple (3)	0.560	0.62	0.045	0.55
Concrete	Rectangular	Plain end (sq)	0.5	full (2)	0.0610	0.75	0.0400	0.80
Brick	Circular	Bevelled	0.2	full (2)	0.0018	2.5	0.0300	0.74
Brick	Arch	Bevelled	0.2	simple (3)	0.495	0.667	0.0300	0.74
Stone	Circular	Bevelled	0.2	full (2)	0.0018	2.5	0.0300	0.74
Stone	Arch	Bevelled	0.2	simple (3)	0.495	0.667	0.0300	0.74
Plastic	Circular	Plain end (sq)	0.5	simple (3)	0.470	0.68	0.040	0.62
Corrugated Metal	Circular	Plain end (sq)	0.5	full (2)	0.0340	1.5	0.0553	0.54

Table 5 shows the parameter values associated with culvert inlets with headwalls and training walls at 0° to the flow (Type T3). The only parameter values available in most modelling program documentation for this type of inlet are for concrete rectangular (box) culverts with square edges. The South Dakota concrete box data (2006) has been used for the rectangular conduits with the socket end as the edge. Unfortunately, there are no other combinations available in the previous studies. For the missing values, the same values as for Type T2 have been applied.

Table 5 – Type T3 (Training walls at 0º to flow) parameter values

Material	**Culvert Shape**	**Edge Type**	**Inlet loss**	**Free flow**			**Submerged inlet**	
			k_i	**equation**	k	M	c	Y
Concrete	Circular	Socket end	0.2	full (2)	0.0078	2.0	0.0292	0.74
Concrete	Circular	Cut end (sq)	0.5	simple (3)	0.470	0.68	0.040	0.62
Concrete	Rectangular	Socket end	0.2	simple (3)	0.560	0.62	0.045	0.55
Concrete	Rectangular	Plain end (sq)	0.7	full (2)	0.0610	0.75	0.0423	0.82
Brick	Circular	Bevelled	0.2	full (2)	0.0018	2.5	0.0300	0.74
Brick	Arch	Bevelled	0.2	simple (3)	0.495	0.667	0.0300	0.74
Stone	Circular	Bevelled	0.2	full (2)	0.0018	2.5	0.0300	0.74
Stone	Arch	Bevelled	0.2	simple (3)	0.495	0.667	0.0300	0.74
Plastic	Circular	Plain end (sq)	0.5	simple (3)	0.470	0.68	0.040	0.62
Corrugated Metal	Circular	Plain end (sq)	0.5	full (2)	0.0340	1.5	0.0553	0.54

Table 6 shows the parameter values associated with culvert inlets mitred to the slope (Type M) of the embankment. Corrugated metal is the only commonly used material that is cut to the slope in this way, and the parameter values are available in the documentation for most modelling programs for this type of inlet. The parameter values listed for ARMCO pipe arch culverts are for 450mm diameter corner radius's.

Table 6 – Type M (Mitred to slope) parameter values

Material	**Culvert Shape**	**Edge Type**	**Inlet loss**	**Free flow**			**Submerged inlet**	
			k_i	**equation**	k	M	c	Y
Corrugated Metal	Circular	Plain end (sq)	0.7	full (2)	0.0018	2.5	0.0300	0.74
Corrugated Metal	Pipe arch	Plain end (sq)	0.7	full (2)	0.0300	1.0	0.0463	0.75
Corrugated Metal	Full arch	Plain end (sq)	0.7	full (2)	0.0300	2.0	0.0463	0.75

All of the parameter values in the above tables that are included in the documentation for most modelling program helpfiles were determined empirically from physical modelling. A best endeavours approach (stopping short of CFD modelling) has been used to identify appropriate values to use where values are missing for typical UK configurations.

If more accurate values are required the best approach is likely to be using Computational Fluid Dynamics (CFD) modelling coupled with a comparison to previous physical modelling results to give a more comprehensive set of parameters.

The inlet loss value, k_i, has been taken either from the values quoted in previous studies, or the recommendations within the 'Hydraulic Design of Highway Culverts' (2012).

F4. Screens

Another common feature at culvert inlets is the inclusion of trash screens, which also impact the hydraulics at the inlet. The 'Culvert, Screen and Outfall Manual' (2019) is useful in that it highlights the headlosses associated with screens and the associated degree of blinding or blockage. The approach to identify the geometrical properties of the screen, and the appropriate method of deriving the headlosses (calculating afflux for weir control, calculating headlosses due to expansion and contraction around the bars for culvert inlet control, or calculating afflux for orifice control through the screen), are detailed. The EA 'Blockage Management Guide' (2019) also provides useful information.

In some of the available hydraulic modelling software packages screens (and their associated parameters) are included within the culvert inlet control. In other programs screens are represented independently of the culvert inlet and should be modelled as physically arranged. However, culvert inlets in many programs (where they are modelled separately) use the properties of the inlet channel within the calculations, and therefore if a screen is located upstream of the culvert inlet then a short section of open channel will be required between the trash screen and the culvert inlet. This short length of channel should match the shape, etc., of the channel upstream of the trash screen. Care needs to be taken when modelling trash screens with differing degrees of blockage to avoid the flows backed up upstream of the screen finding a way around the screen by overland flow into the short length of open channel between the screen and the culvert inlet.

F5. Other Considerations

Further considerations regarding more complicated culvert arrangements include the use of multiple barrels, side and slope tapered inlets, and skewed channel approaches or barrels. Research into these has also been conducted and is summarised in the 'Hydraulic Design of Highway Culverts' (2012). Parameter values are listed for use within the same equations herein, however it is recommended that the user familiarises themselves with the limitations for each individual case.

For multiple barrels, the 'Culvert, Screen and Outfall Manual' (2019) mentions that identical barrels in parallel may be modelled. The multiple barrel functionality in some modelling programs is an improvement in that it allows the user to model multiple conduits without having to include multiple culvert inlets (which may otherwise cause an over-estimation in the headlosses). Culverts of different shapes and sizes can be modelled, but this may require a simplification by the user.

Tapered and/or stepped or depressed inlets have several possible control sections and the parameters are dependent on which section is controlling (for circular and rectangular culverts, different parameter values are listed for throat controlling and face controlling). Similarly, parameter values are available for some combinations of skewed headwalls or barrels (single or multiple), however the range is rather limited (all using concrete box culverts).

The FHWA culvert hydraulics analysis software HY-8 (2016) takes a different approach to many modelling programs when selecting the culvert inlet. HY-8 prompts the user to select the culvert shape, material and inlet configuration, without needing to supply any inlet parameter values. As the user selects the culvert shape (e.g. circular), the list of materials reduces to those with available parameters. Likewise, selection of the material (e.g. concrete) reduces the list of types accordingly. Selection of the inlet configuration (e.g. square edge with headwall) completes the process.

F6. Conclusions and Recommendations

It is important to include culvert inlets where culverted watercourses exist within our integrated urban drainage network models. The appropriate arrangement for each culvert inlet should be represented in the model by applying suitable parameter values to reflect the inlet type, edge type, material and barrel shape. The consequences of applying inappropriate values, or not including the culvert inlet at all, could lead to incorrect levels being predicted in the upstream watercourse.

Empirical parameter values are available for a variety of inlet arrangements (as listed in the helpfiles for many modelling programs), however the range currently presented in previous studies is more relevant to the types of culverts found in the US. The types of culvert inlets more typically found in the UK have been listed and recommended parameter values for these arrangements have been provided. Some of these values have been either interpreted from the available sources or arrived at using best judgement. If more accurate values are required, it is suggested that CFD modelling is undertaken to give a more comprehensive set of parameters.

F7. References

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