Final Report on the

DETERMINATION OF ENTRANCE LOSS COEFFICIENTS FOR PRE-CAST REINFORCED CONCRETE BOX CULVERTS

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The overall conclusion of the study is that by and large the current Iowa DOT design specifications for CIP culverts can be used for multi-barrel PC culvert design. For unsubmerged flow conditions the difference in the hydraulic performance curves and headloss coefficients for PC and CIP culverts are within the experimental uncertainty. Larger differences (specified by the study) are found for submerged conditions when the flow is increasingly constricted at the entrance in the culvert. The observed differentiation is less important for multi-barrel culverts as the influence of the wingwalls decreases with the increase of the number of barrels.

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1) Culvert 2) Concrete Box Culverts 3) Cast-in-Place Culverts (CIP)

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Determination of Entrance Loss Coefficients for Pre-Cast Reinforced Concrete Box Culverts

December 27, 2012

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1. Introduction

1.1 Background

Culverts are common hydraulic structures that pass streams under roadways in a variety of flow conditions without producing considerable scour that threatens the stability of the structure or sedimentation in the vicinity of the culvert. Culverts are ubiquitous for secondary roads crossing small streams in the state of Iowa as well as in many rural U.S. Midwestern areas. Currently the Iowa DOT uses Cast-in-Place (CIP) and Pre-cast (PC) reinforced concrete boxes (RCBs) fit with wingwalls at the entrance and exit sections of the culvert barrels to transition the streams under the roadway systems. The CIP culvert design guidelines are based on research conducted 30 years ago and are limited to single box culverts. The Iowa standard design manual typically recommends 30-degree flared wingwalls for CIP boxes and straight wingwalls for the PC boxes. For the latter a 4-in bevel on the inside edges of the wingwalls and top slab is recommended.

There is an increased interest to construct Pre-Cast (PC) Twin and Triple RCB's in Iowa due to the efficiency associated with their production in controlled environment and decrease of the construction time at the culvert site. The design of the PC culvert is, however, based on guidelines for single barrel box culverts constructed with CIP approaches. The most of widely recognized manual on culvert hydraulics is the FHWA Hydraulic design Series No. 5 (HD-5) (FHWA, 1985) and based on research conducted in the 1960s and 1970s (FHWA, 2006). Less information is available from studies conducted on multiple barrel box culverts and even fewer on RCBs with straight wingwalls (e.g., FHWA, 2006). The transition from CIP to PC boxes requires additional information for substantiating the design specifications currently used.

1.2 Problem statement

Currently, the sizing of multi-barrel box culverts is based on the performance curves of single boxes multiplied by the number of barrels to attain an appropriate conveyance for the extreme flows. Wingwalls attached to single-barrel boxes are typically attached at the entrance and exit of the culverts to conduct the flow directly into the barrel reducing accordingly the contraction losses. Multiple barrel culverts share a single set of wingwalls hence the interior barrels produce lower hydraulic losses, Cast-in-place (CIP) culverts are typically provided with flared wingwalls set at various degrees with respect to the culvert axis. Construction considerations favor PC culverts with straight wingwalls. The change in orientation for the PC culverts from the typical oblique to straight wingwalls produces change of inlet geometry with further implications in the flow transport capacity. Finally, additional gains in the flow capacity can be obtained by "streamlining" the culvert top edges at the inlet. Estimating the entrance losses taking into account all the above factors is critical for providing appropriate design, especially for the newly built PC culverts. Similar studies with the one presented here are the FHWA(2004) and FHWA (2006). They investigated in partnership with the South Dakota DOT rectangular shaped culverts with a number of inlet geometry conditions representing inlets that are currently available for highway culverts in that state.

Our study focuses on single and multi-barrel PC and CIP culverts in various conditions and configurations using Iowa specific design specifications. The following culvert designs were provided by IDOT for the present study:

- Cast-In-Place (CIP): RCB-GI-87, TWRCB-GI-87, and TRRCB-GI-01 (http://www.iowadot.gov/bridge/v8eculstd.htm)
- Pre-Cast (PC): 1080 (http://www.iowadot.gov/bridge/v8preculstd.htm)

In order to fill the gaps in the information for supporting the current design guidelines, our study set the following objectives:

- Determine the effect of inlet geometry on flow capacity for single and multi-barrel CIP and PC culverts
- Determine the effect to span-to-rise ratio, wingwall-flare angle, and slope on flow capacity for various culvert geometry
- Determine the effect of culvert top edge treatment for the inlet geometry for optimizing the design of both types of box culverts

The study analyzed the above objectives for both unsubmerged and submerged conditions corresponding to inlet and outlet control, respectively. Given that the available guidelines and experimental studies of the entrance losses for culverts are limited to single barrel culverts, we conduct a series of physical modeling experiments to determine the entrance losses for PC Twin and Triple RCB's designs. In addition to determining the inlet losses, we compare the velocities and shear stresses associated with a straight vs. flared wing wall for a range of flow conditions. This could determine if a certain configuration provides better dissipation of the energy to mitigate potential erosion/scour at the inlet or outlet of a box culvert.

2. Theoretical background and literature review

The chapter reviews the fundamental theoretical consideration for the analysis of data obtained through this study and the related information available in the literature for setting a basis for the study. Given that the theoretical background is quite well established and extensively treated in references, only salient features will be reproduced herein.

Culvert design fundamentally involves the optimal selection of the barrel cross-section that passes the design discharge, and material that depends on the structural strength, hydraulic roughness, durability, and corrosion/abrasion resistance. The hydrology and hydraulic analyses are both required for a design. The hydrologic analysis of the culvert is needed to estimate the design discharge; on the other hand, the hydraulic analysis is required for the optimal design in conveying the design discahrge. A complete theoretical analysis of the hydraulics of a particular culvert is arduous, because of the fact that the flow regime varies from culvert to culvert and even varies over time for a given culvert.

Bodhaine (1982) classified culvert flow into six types during the peak flow, illustrated in the Figure 2-4, on the basis of the location of the control section and the relative height of the headwater and tailwater elevations. Three of these flow types (1, 2, and 3) are for low-head flow when the ratio of headwater depth and the opening of culvert is less than 1.5. Two are for high-head flow (5, and 6) when the ratio is larger than or equal to 1.5. The last one is for submerged flow condition.

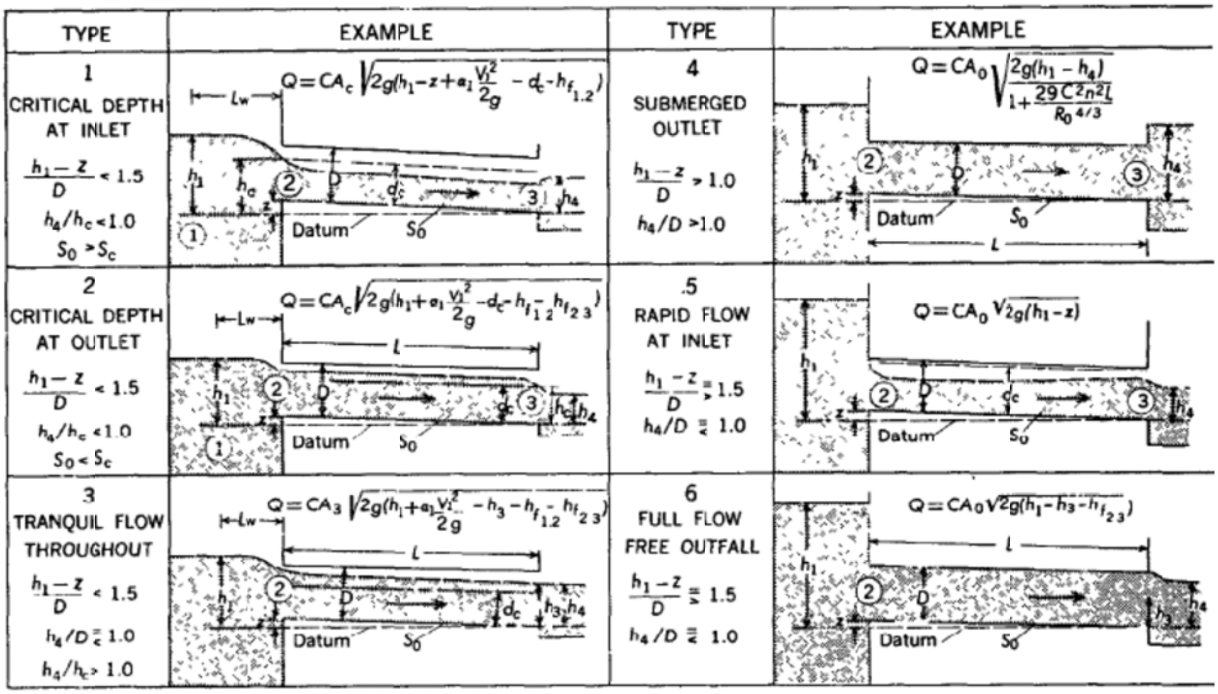


Fig 2-1 Classification of culvert flow

National Bureau Standards (NBS) complete a series of research, sponsored by Federal Highway Administration (FHWA), in early 1950's. These reports provided a comprehensive analysis of culvert hydraulics under various flow conditions. These results were used to develop culvert design graphs, called nomographs. It is to analyze a culvert for various types of flow control and then design for the control which produces the minimum performance. In their research, the flow conditions include the cross-section of a culvert flowing fully and partly. The former is pressure flow and the other is free surface flow. Normann (1985) classified two basic types of flow control from the preceding result of NBS and FHWA: inlet and outlet control. The concept to classify is the location of the control section. It is presented in Hydraulic Design of Highway Culverts (Norman, 1985) and is widely used in the culvert design. Culverts with inlet control have supercritical flow in barrels and the control section is near inlet. Culverts with outlet control have subcritical flow in barrels and the control section is at the downstream of culverts.

Culverts, with inlet and outlet submerged conditions, perform as a conduit. However, the hydrodynamic of culvert is regarded as open channel if culverts have either inlet or outlet unsubmerged condition. Culvert may operate under either inlet or outlet control with a given flow rate, so the potential operating condition is not easily determined. Instead, the concept of the culvert minimum performance is used to design a culvert under the peak discharge.

Figure 2-2 illustrates four different examples of inlet control that depends upon the submergence of inlet and outlet ends of the culvert. In Figure 2-2a, neither the inlet nor the outlet of the culvert is submerged. The control section just downstream of the entrance and the flow in the barrel is supercritical. Partly full flow occurs through the barrel, and approaches normal depth at the outlet. Figure 2-2b shows that the outlet is submerged and inlet is unsubmerged. In this case, the flow just downstream of the inlet is supercritical and a hydraulic jump occurs in the barrel. Figure 2-2c is a typical design situation. The inlet is submerged and the outlet flows freely. The flow in the barrel is supercritical and partly full over its length. Critical depth is located just downstream of the culvert entrance, and the flow is approaching normal depth at the downstream end. Figure 2-2d shows an unusual condition illustrating the fact that even submergence of both the inlet and the outlet ends of the culvert does not have full flow through the barrel. In this case, a hydraulic jump may form in the barrel; the median inlet provides ventilation of the culvert barrel.

A culvert under inlet control performs as weir when the inlet is unsubmerged, and as orifice when it is submerged. If the entrance is unsubmerged, the inlet control section is near the entrance of the culvert. Application of the energy equation neglecting head loss at control section of Figure 2-3 shows:

$$y_c + \frac{V_c^2}{2g} = E_c = HW \qquad (1)$$

where y_c is critical depth near the entrance of culvert, V_c is critical velocity, E_c is critical specific energy, and HW is headwater.

For critical flow in the rectangular box culvert $y_c = 2/3E_c$, Charbeneau (2006) derived from equation (1) and assumed $V_c = Q/(C_b B y_c)$, where Q= barrel discharge, C_b = coefficient expressing effective width contraction associated with the culvert entrance edge conditions, and B = width (span) of culvert. Therefore, equation (1) can be written as:

$$\frac{HW}{D} = \frac{3}{2}\left(\frac{1}{C_b}\right)^{2/3}\left(\frac{Q}{A\sqrt{gD}}\right)^{2/3} \qquad (2)$$

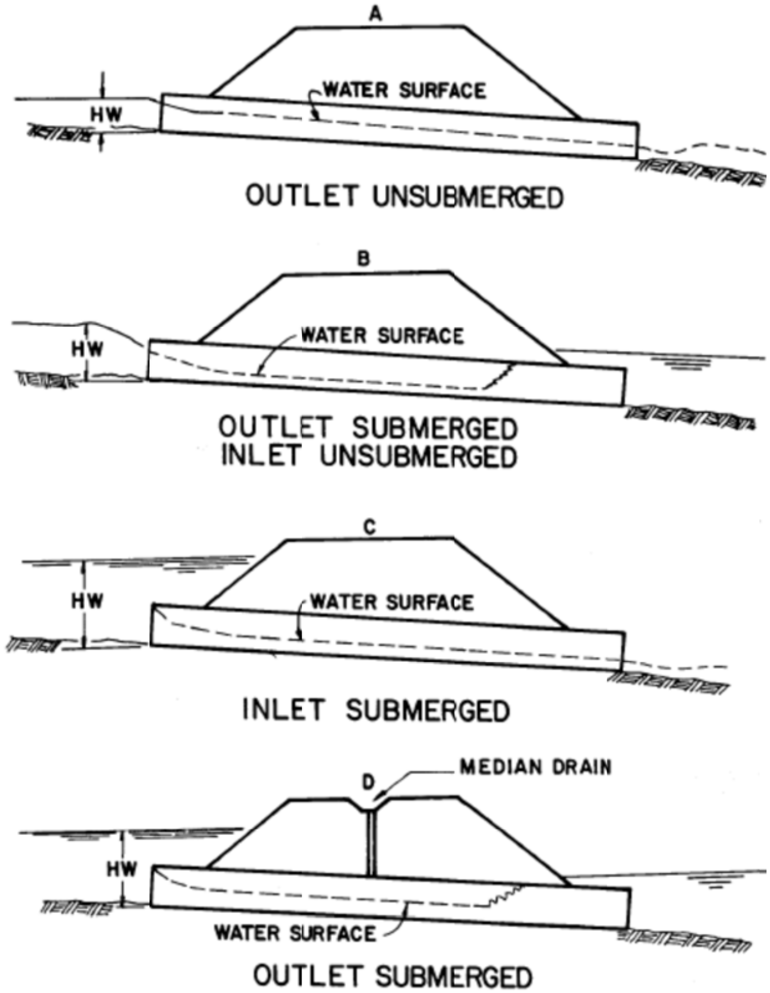


Fig 2-2 Types of inlet control, (Normann et al. 1985)

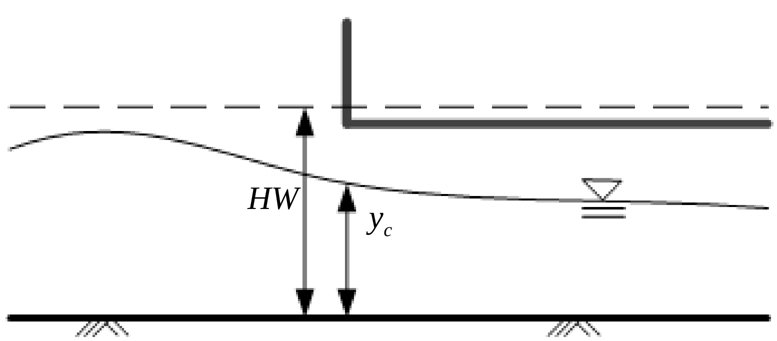


Fig 2-3 Culvert entrance acts like weir

In equation (2), D=culvert rise (height); and A=full culvert cross section area (A=BD for a box culvert).

If head loss is considered and the distance between entrance and control section is substantial, energy equation at control section shows:

$$HW = E_c + h_L - L^{'}S \tag{3}$$

In equation (3), h_L is head loss, $L^{'}$ is distance between entrance and control section, and S is channel slope. For rectangular box culvert, the above equation could be written as:

$$\frac{HW}{D} = \frac{3}{2}\left(\frac{1}{C_b}\right)^{2/3}\left(\frac{Q}{A\sqrt{gD}}\right)^{2/3} + \frac{h_L}{D} - \frac{L^{'}}{D}S \tag{4}$$

Based on studies of NBS, FHWA developed two equations for unsubmerged inlet control performance which have the similar form of equation (2):

$$\frac{HW}{D} = \frac{E_c}{D} + Kg^{M/2}\left[\frac{Q}{A\sqrt{gD}}\right]^{M} - 0.5S \tag{5}$$

$$\frac{HW}{D} = Kg^{M/2}\left[\frac{Q}{A\sqrt{gD}}\right]^{M} \tag{6}$$

In equation (3) and (4), S is slope of the culvert, K and M are the coefficients based on the culvert configuration. Equation (3) could be modified for rectangular box culvert (Charbeneau, 2002):

$$\frac{HW}{D} = \frac{3}{2}\left[\frac{Q}{A\sqrt{gD}}\right]^{2/3} + Kg^{M/2}\left[\frac{Q}{A\sqrt{gD}}\right]^{M} - 0.5S \qquad (7)$$

According to the report of Normann (1985), the constant M is 0.667 of equation (4) for rectangular culvert box:

$$\frac{HW}{D} = Kg^{1/3}\left[\frac{Q}{A\sqrt{gD}}\right]^{2/3} \qquad (8)$$

When culvert inlet is submerged, the culvert performs as either an orifice or as a sluice gate. The culvert performance acts like orifice (Norman, 1985) could be presented by:

$$Q = C_d A\sqrt{2gh} = C_d BD\sqrt{2g(HW - 1/2\, D)} \qquad (9)$$

In equation (9), Cd is a discharge coefficient that must be evaluated for differentinlet conditions, A is the culvert inlet full area, h is the head on the culvert centroid, and His the upstream headwater. The discharge coefficient is approximately equal to Cd = 0.6 forsquare-edge entrance conditions. The equation resulting when the culvert acts as a sluicegate is similar. For a sluice gate the performance equation is (Henderson, 1966):

$$Q = C_c BD\sqrt{2g(HW - C_c D)} \qquad (10)$$

In equation (10), Cc is a contraction coefficient. The above equations can be expressed as the performance equation. Charbeneau (2006) applied energy equation with HW representing the headwater specific energy shown in Figure 2-7:

$$HW = \frac{v_{en}^2}{2g} + C_c D \tag{11}$$

In equation (11), v_{en} =velocity within the culvert entrance; and C_c =contraction coefficient associated with flow passing the culvert entrance. Energy losses can be neglected and be included within coefficients. With the equation (11), the discharge is calculated from:

$$Q = (C_b B)(C_c D)v_{en} = C_b C_c A\sqrt{2g(HW - C_c D)} \tag{12}$$

Equation (12) could be written as a performance equation:

$$\frac{HW}{D} = \frac{1}{2(C_b C_c)^2}\left(\frac{Q}{A\sqrt{gD}}\right)^2 + C_c \tag{13}$$

For submerged inlet conditions, Norman (1985) have been fit the data from experiments performed by National Bureau of Standards an equation:

$$\frac{HW}{D} = Y + cg\left[\frac{Q}{A\sqrt{gD}}\right]^2 - 0.5S \tag{14}$$

In equation (14),Y, c are the constants based on the culvert configuration.

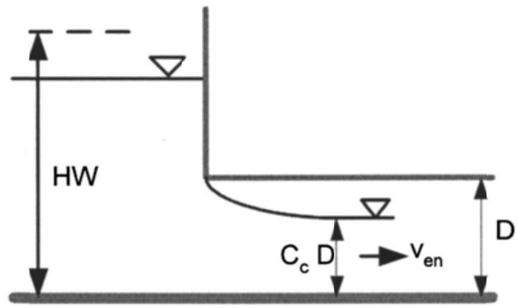


Fig 2-4 Culvert entrance acting as a submerged sluice gate, Charbeneau (2006)

When culvert flows with outlet control, critical depth do notoccur near the entrance and the flow condition in the culvert barrel is subcritical. Figure 2-5 illustrates five examples of outlet control in which all cases have the control section at the outlet end or further downstream. Outlet control occurs when the barrel is incapable of conveying as much flow as the inlet opening. Figure 2-5a represents the classic full flow condition, with both inlet and outlet submerged. The barrel is in pressure flow throughout its length. This condition is often assumed in calculations, but seldom actually exists. Figure 2-5b depicts the outlet submerged with the inlet unsubmerged. For this case, the headwater is shallow enough so that the inlet crown is exposed as the flow contracts into the culvert. Figure 2-5c shows the entrance submerged to such a degree that the culvert flows full throughout its entire length while the exit is unsubmerged. This is a rare condition. It requires an extremely high headwater to maintain full barrel flow with no tailwater. The outlet velocities are usually high under this condition. Figure 2-5d is the typical condition. The culvert entrance is submerged by the headwater and the outlet end flows freely with a low tailwater. For this condition, the barrel flows partly full over at least part of its length (subcritical flow) and the flow passes through critical depth just upstream of the outlet. Figure 2-8e is another typical condition, with neither the inlet nor the outlet end of the culvert submerged. The barrel flows partly full over its entire length leading to a subcritical flow profile in the barrel.

Outlet flow condition can be described by the energy equation. Full flow, as depicted in Figure 2-6, is a typical type of outlet control culverts. The culvert flow full can be computed between section 1 and 4. Neglecting the velocity head in section 1, and friction loss between 1 and 2, and between 3 and 4, the energy equation shows:

$$H + S_0 L = TW + \frac{V_4^2}{2g} + h_L + h_{2-3} + h_{ex} \tag{15}$$

In equation 15, H is water depth at section 1 that can be replaced as HW, TW is water depth at section 4, h_L is loss due to entrance contraction, h_{2-3} is friction loss between 2 and 3, and h_{ex} is loss due to sudden expansion between 3 and 4. According to Jain (2000), $h_L = \left[\left(1/C_d^2\right)-1\right]\left(V_3^2/2g\right)$ and $h_{ex} = \left[\left(V_3^2/2g\right)-\left(V_4^2/2g\right)\right]$, where Cd is discharge coefficient. Based on Manning discharge formula, h_{2-3} could be written into $n^2 L V_3^2 \big/ R_0^{4/3}$. An expression of equation 15 can be modified as a performance equation:

$$\frac{HW}{D} = \frac{TW}{D} + \frac{n^2 Lg}{R_0^{4/3}}\left(\frac{Q}{A\sqrt{gD}}\right)^2 + \frac{1}{2C_d^2}\left(\frac{Q}{A\sqrt{gD}}\right)^2 - \frac{L}{D}S_0 \tag{16}$$

In equation 16, R_0 is hydraulic radius in the barrel, and n is Manning coefficient.

Comparing to inlet control equations, the HW and discharge relationship under outlet control would be affected not only entrance geometry of the culvert, but also TW and roughness in the barrel. Normann (1985) considered the full flow culvert and calculated the outlet control flow condition with energy equation.

$$HW + \frac{V_1^2}{2g} = TW + \frac{V_4^2}{2g} + H_{loss} \quad (17)$$

neglected the approaching velocity and exit velocity, and obtained:

$$HW = TW + H_{loss} \quad (18)$$

Where H_{loss} is total loss and represented as:

$$H_{loss} = \left(1 + K_e + \frac{2gn^2L}{R_0^{4/3}}\right)\frac{V^2}{2g} \quad (19)$$

In equation 18, K_e is a coefficient varying with inlet configuration, and V is velocity in the barrel.

If upstream and downstream are both unsubmerged, the flow with mild channel slope can have free-surface flow in the culvert (Figure 2-7). The control section would occur at the outlet end or further downstream. The flow is partly full in the culvert and can be described by the energy equation between section 1 and 3 if control section is at section 3 in the Figure 2-7.

$$H + \frac{V_1^2}{2g} + S_0L = y_3 + \frac{V_3^2}{2g} + h_L + h_{1-2} + h_{2-3} \quad (20)$$

If the control section is at the further downstream, the energy equation should apply between section 1 and 4:

$$H + \frac{V_1^2}{2g} + S_0L = y_4 + \frac{V_4^2}{2g} + h_L + h_{1-2} + h_{2-3} \quad (21)$$

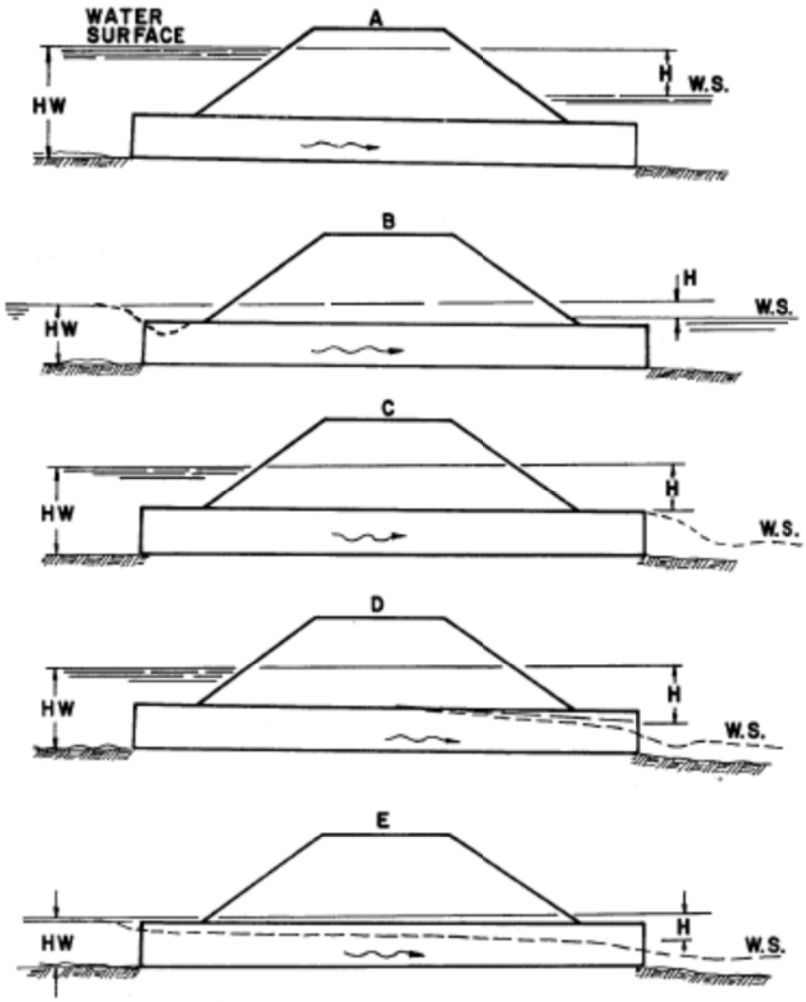


Fig 2-5 Types of outlet control, Normann (1985)

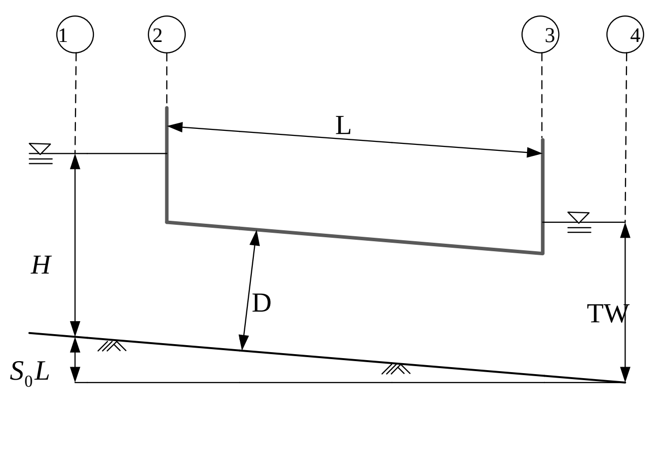


Fig 2-6 Culvert with submerged upstream and downstream

However, for the inlet to remain unsubmerged, the depth in section 3 is equal to that in section 4. Therefore, the above two equations can be similarly analyzed. In equation 17, the water depth at section 3 can be replaced as TW (Jain, 2000), head loss $h_L = \left(1/C^2 - 1\right)V_3^2/2g$ due to entrance, h_{2-3} could be written into $L\left(Q^2/K_2K_3\right)$, and h_{1-2} can be neglected.

$$HW = TW - \frac{V_1^2}{2g} + \frac{1}{C_d^2}\frac{V_3^2}{2g} + \frac{LQ^2}{K_2K_3} \tag{22}$$

From the studies of NBS and FHWA, the outlet control flow conditions wereonly analyzed for full barrel flow. If free-surface flow is occurring as Figure 2-10, the factors along the culvert all influence the performance of the culvert. Equation 18 cannot easily be written into a performance equation. It is necessary to calculate the backwater profile based on the tailwater depth.

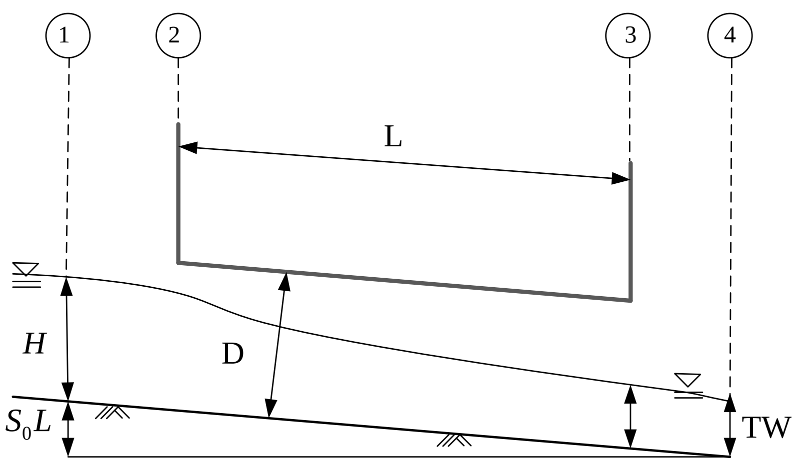


Fig 2-7 Culvert with unsubmerged upstream and downstream

3. Experimental Procedures and setup

3.1 Specifications on measurements and culvert model coding

The parameters used to build the performance curve equations in unsubmerged and submerged in this study are based on HDS-5 (Normann 1985):

- Unsubmerged condition: $$\frac{HW}{D} = Kg^{M/2}\left[\frac{Q}{A\sqrt{gD}}\right]^{M} \quad (6)$$
- Submerged condition: $$\frac{HW}{D} = Y + cg\left[\frac{Q}{A\sqrt{gD}}\right]^{2} - 0.5S \quad (14)$$

In the above equations, HW (measured in the model with pressure sensors) is defined as the headwater depth above inlet-control section invert. D is interior height of the culvert barrel. Q measured with calibrated orifice is discharge through the culvert barrel. A is the full cross sectional area of culvert barrel. S is the barrel slope (0.005 and 0.02 for this study). K, M, c, and Y are regression constants calculated from the measure data. Performance curves shown in this study are also assembled using regression curves applied to the experimental data.

The research team in close collaboration with the Technical Advisory Committee for the project established the test matrix that included 9 geometric configurations and 2 slopes tested in un-submerged and submerged conditions. The optimization study was tested on single, twin, triple, PC culverts with consideration of the following changes to the inlet geometry: top edge with 4” bevel and top edge with 8” radius. A total of approximately 50, tests were conducted in the test facility built for the study (see Section 3.2). The culvert models investigated in the study were labeled using the following specifications:

- culvert type: PC or CIP for pre-cast and cast-in-place, respectively
- number of barrels, i.e., 1, 2 or 3
- span size of barrel, i.e. S12
- rise size of the barrel, i.e., R12 or R6

In accordance with the labeling above, a pre-cast three box culvert with 12-ft span and 12-ft rise should be labeled as PC3-S12-R12. The flume slope is indicated by an additional label. For instance, the above model installed into the mild slope will be labeled as PC3-S12-R12-M. A total of 12 configurations for two slopes were sequentially tested to obtain their performance curves. The culvert model configuration and specifications studied here are summarized in Tables 3-1 and 3-2. The outcomes of the present study are performance curves and entrance loss coefficients for one, two, and three-box culverts of various configurations.

Table 3-1 PC culvert models

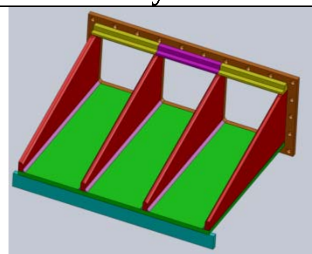
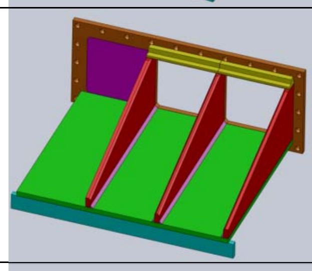
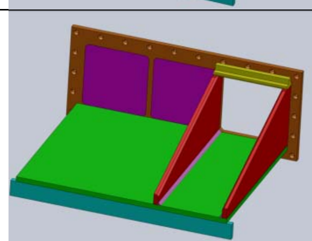
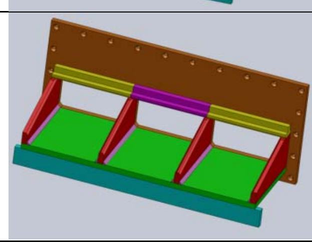
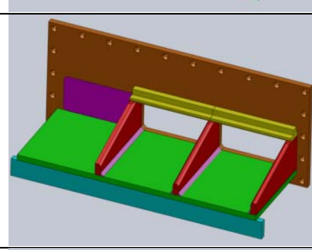
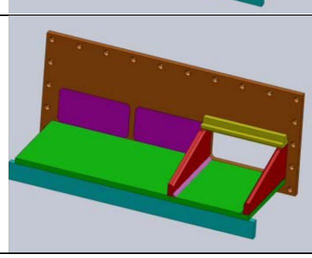
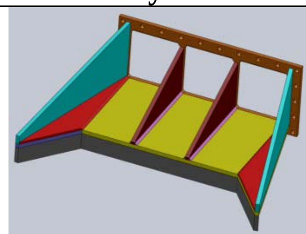
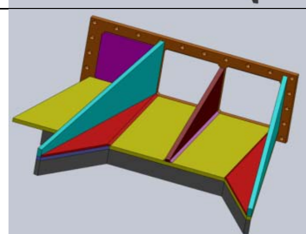
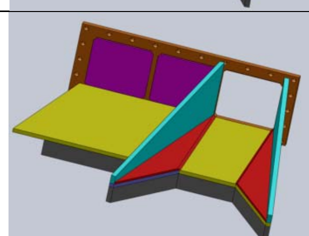
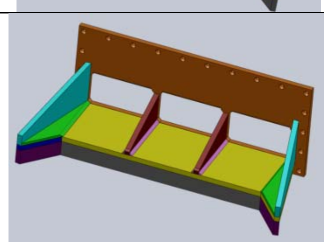
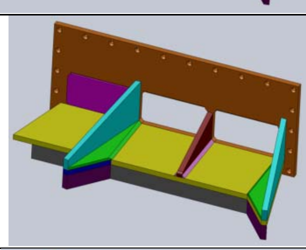
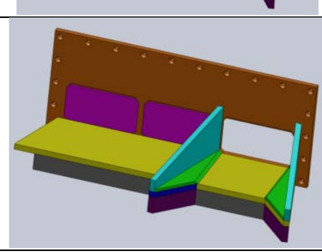
Model	Layout	Box type	Edge Condition
PC3-S12-R12		3×12’×12’	4” bevel at the top of lintel
PC2-S12-R12		2×12’×12’	4” bevel at the top of lintel
PC1-S12-R12		12’×12’	4” bevel at the top of lintel
PC3-S12-R6		3×12’×6’	4” bevel at the top of lintel
PC2-S12-R6		2×12’×6’	4” bevel at the top of lintel
PC1-S12-R6		12’×6’	4” bevel at the top of lintel

Table 3-2 CIP culvert models

Model	Layout	Box type	Edge Condition
CIP3-S12-R12		3×12’×12’	4” bevel at the top of lintel
CIP2-S12-R12		2×12’×12’	4” bevel at the top of lintel
CIP1-S12-R12		12’×12’	4” bevel at the top of lintel
CIP3-S12-R6		3×12’×6’	4” bevel at the top of lintel
CIP2-S12-R6		2×12’×6’	4” bevel at the top of lintel
CIP1-S12-R6		12’×6’	4” bevel at the top of lintel

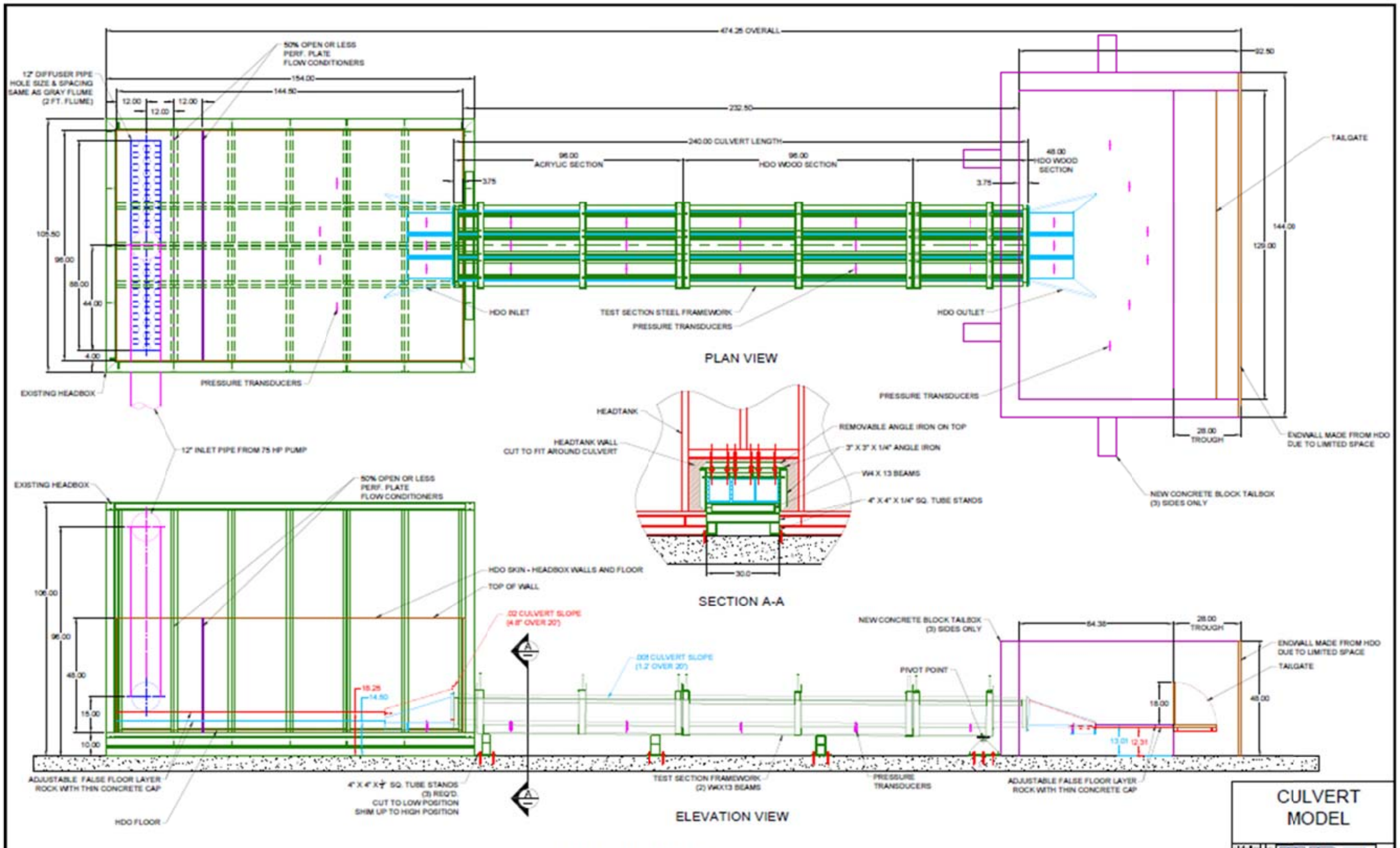
3.2 Experimental Facility

The laboratory studies were conducted in a model built at IIHR – Hydroscience & Engineering, The University of Iowa. The model included headbox, tailbox, and tunnel barrels (the actual body of the culvert). The culvert barrel was built using a modular concept that enabled the change from a configuration to another with minimum changes. The culvert structure entailed a basic fixed frame for the culvert barrel spanning the width of 3 culvert widths. The barrel consisted of a metallic frame walled with plexiglass sheets. The dividing walls between barrels and the ceiling were designed to allow for changing the height of the culvert and the thickness of the wall in order to accommodate the two constructive approaches: CIP and PC.

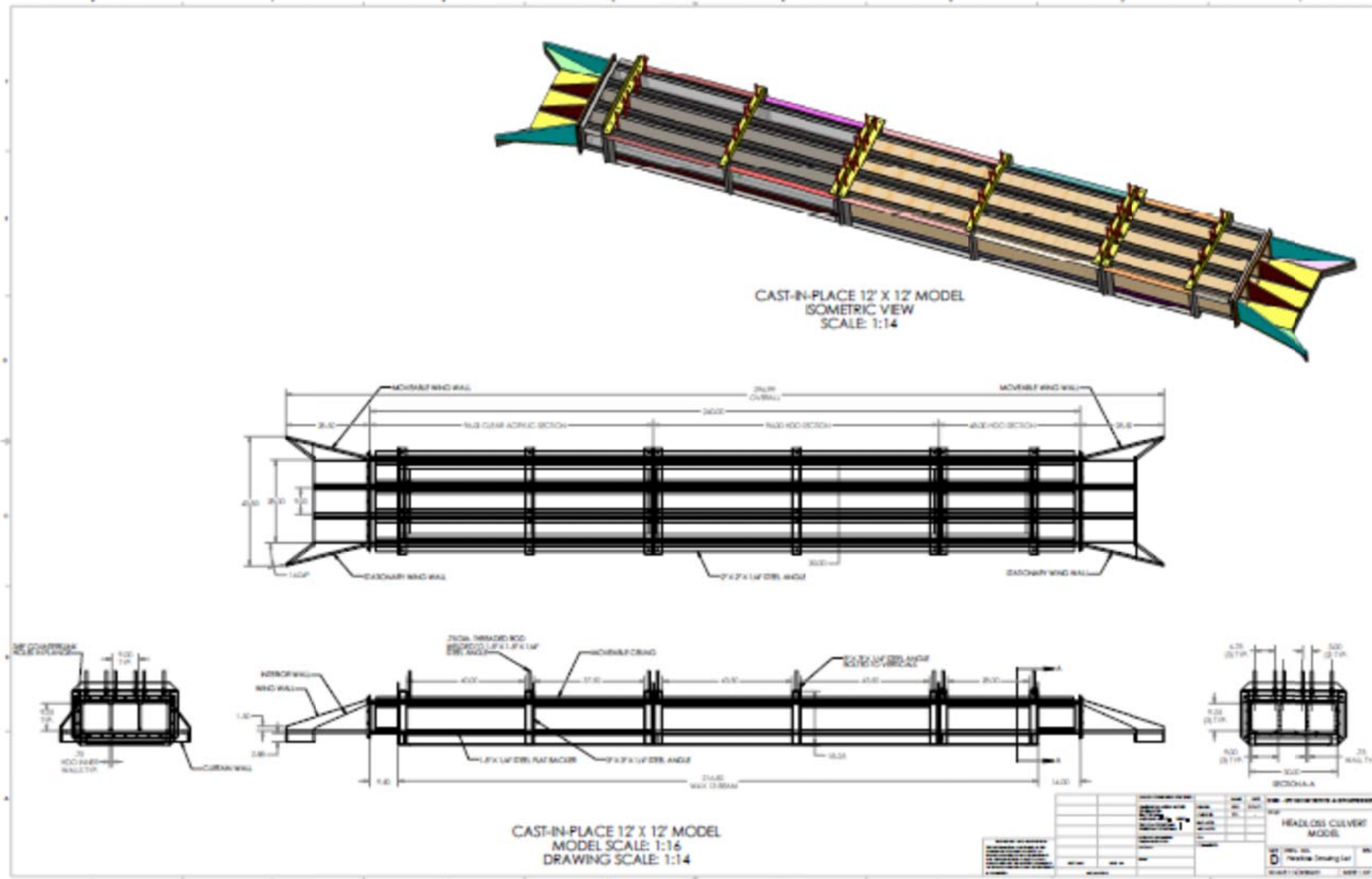
The culvert ends were separately constructed and attached sequentially to the culvert barrel (see Fig 3-2c and Section 3.1). Different culvert geometries were sequentially placed at the two ends of the culvert barrel in the headbox and tailbox. The slope of the culvert barrel was adjusted by rotating the entire culvert body around a joint at the downstream end of the model at the junction with the tailbox. The headbox is 13-ft long, 8.75-ft wide, and 8.75-ft deep (see Fig 3-2a). The tailbox consisted of a 7.7-ft long, 12-ft wide, and 4-ft deep basin located at the end of the culvert barrel. The tailbox was fit with an adjustable tailgate for water depth control. Fig 3-2b illustrates the model in the present configuration.

The flow rate in the facility was controlled by butterfly valves in the supply lines and variable frequency drive (VFD) controllers on the pumps. All culvert model ends (inlet and outlet) used for the tests were made of machine-milled plywood covered by water-resistant paint (see Fig 3-2). As can be noted from Tables 3-1 and 3-2, the 1, 2 and 3 box-culverts were set in the same constructive mounting. In order to provide equivalent approaching flow conditions for all tests, for each culvert type the walls of the headbox were adjusted to center the flow in the axis of the culvert model, irrespective of the number of barrels in the model. The inserts used to center the flow on the culvert were handled with a small crane set on the structure of the headbox.

The flow distribution in the headbox is a critical parameter for ensuring that the modeling results are accurate. A non-uniform approaching flow will affect the hydraulic losses at the culvert entrance with adverse consequences on the obtained results. The flow entering the tailbox from a perforated distribution pipe was further conditioned by several flow controllers set in the headbox next to the diffuser to uniformly distribute the flow approaching the culvert inlet. In order to check the quality of the flow, several pressure taps were set on the bottom of the headbox, culvert barrel, and in the tail box. They read the water level measurement at each location by connecting the pressure taps to a manometer panel. The flow pattern at the entrance of the culvert model was verified by acquiring velocity profiles in dense verticals distributed across the headbox width.



CULVERT MODEL
1:16 SCALE


CAST-IN-PLACE 12' X 12' MODEL
ISOMETRIC VIEW
SCALE: 1:14
CAST-IN-PLACE 12' X 12' MODEL
MODEL SCALE: 1:16
DRAWING SCALE: 1:14
HEADLOSS CULVERT MODEL

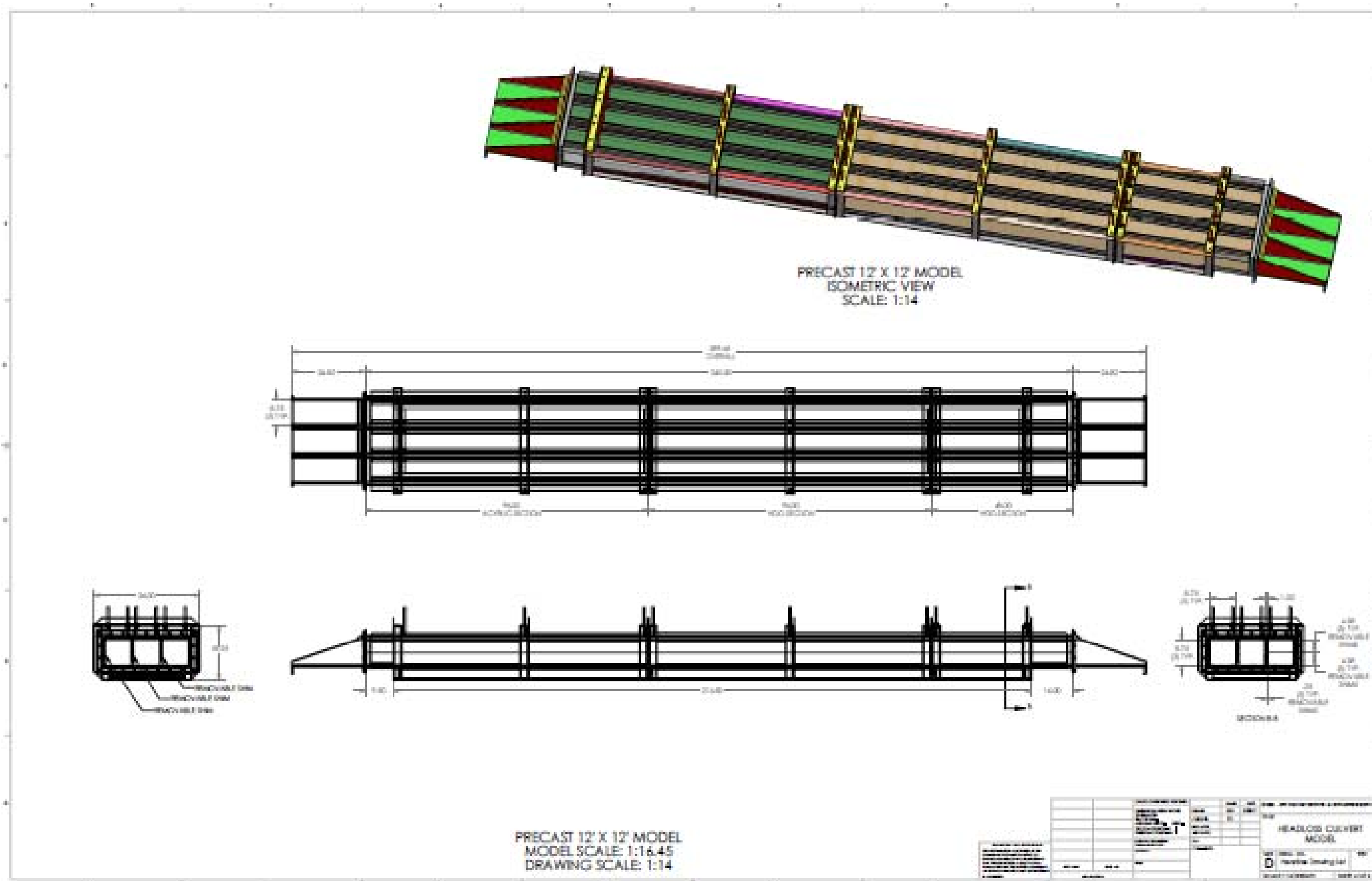


Fig 3-1. Model layout; a) general view; b) cast inplace culvert model; c) the pre-cast culvert model
(each of these drawings should be placed in landscape mode on a separate page)

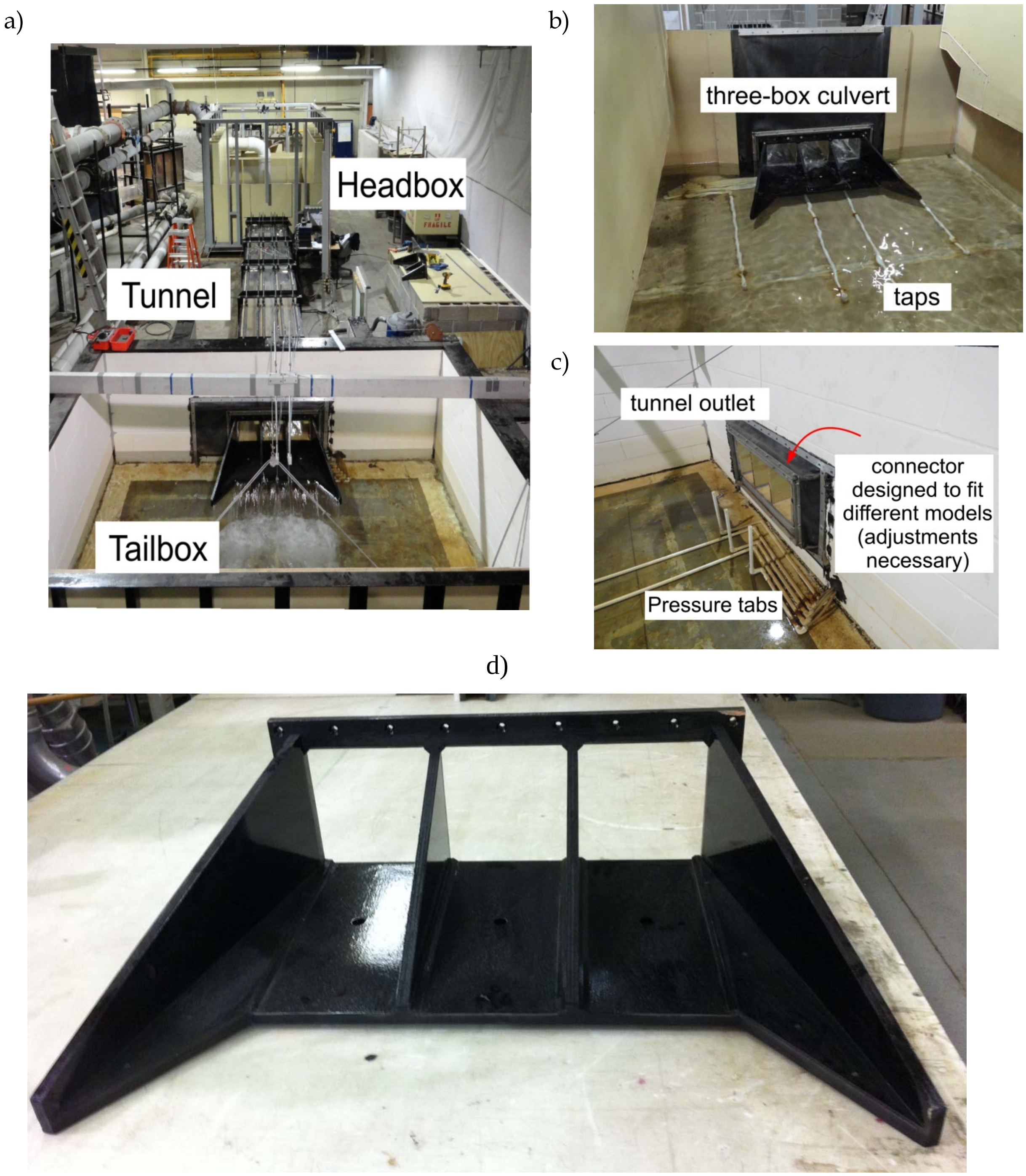


Fig 3-2. The pre-cast culvert model: a) culvert entrance; b) culvert outlet; and c) culvert barrel; d) close view of a detachable culvert inlet

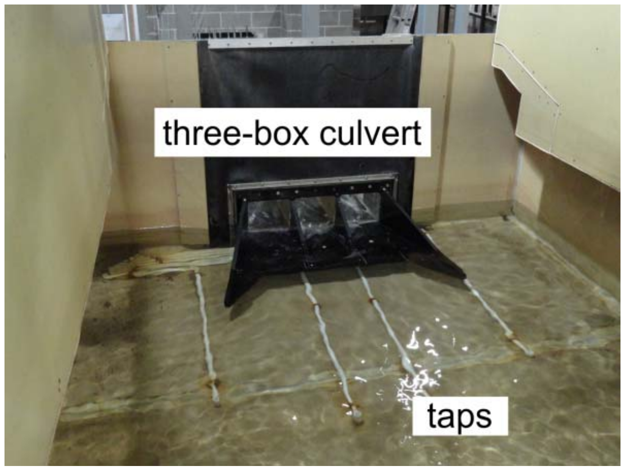
3.3 Scaling considerations and model validation

The scale of the culvert models were based on a Froude number similarity. The corresponding geometrical scales are 1:16.45 for PC and 1:16 for CIP. The slight difference, non-essential for the results of the study, was generated from constructive considerations. More specifically, a common base was used for both types of culverts in the model as explained in the previous section. The layout of the PC and CIP culvert models fitted in the above flume are illustrated in Figure 3-2b. Froude scaling relationships were applied to calculate expressions relating model and prototype values. These expressions are summarized in Table 3-3.

Table 3-3 Model similitude criteria for PC and CIP culvert models

Variable	**Relationship**	**PC models**	**CIP models**
Length	L_r	0.0608	0.0625
Slope	$S_r = L_r/L_r$	1.0000	1.0000
Velocity	$V_r = L_r^{1/2}$	0.2466	0.2500
Time	$T_r = L_r^{1/2}$	0.2466	0.2500
Acceleration	$A_r = V_r/T_r$	1.0000	1.0000
Discharge	$Q_r = V_r*A_r = L_r^{5/2}$	0.0009	0.0010
Force	$F = L_r^3$	0.0002	0.0002
Pressure	$P_r = L_r$	0.0608	0.0625
Reynolds number	$R_{er} = L_r^{3/2}$	0.0150	0.0156

The roadway embankment protection is a common for the culvert structure. Tests were conducted to compare the difference between the culvert model with and without embankment protection (Figure 3-3). The performance curves in Figure 3-4 show that embankment protection does not have essential (systematic) effect on the performance curves. When flow condition was unsubmerged the embankment slight enhanced the culvert capacity. For submerge condition the embankment barely affected the culvert. Given the lack of significant influence on the obtained results, the experiments in this study are conducted without embankment installed in models.



The culvert model with embankment protection

The culvert model without embankment protection

Fig 3-3 The culvert model with and without embankment protection

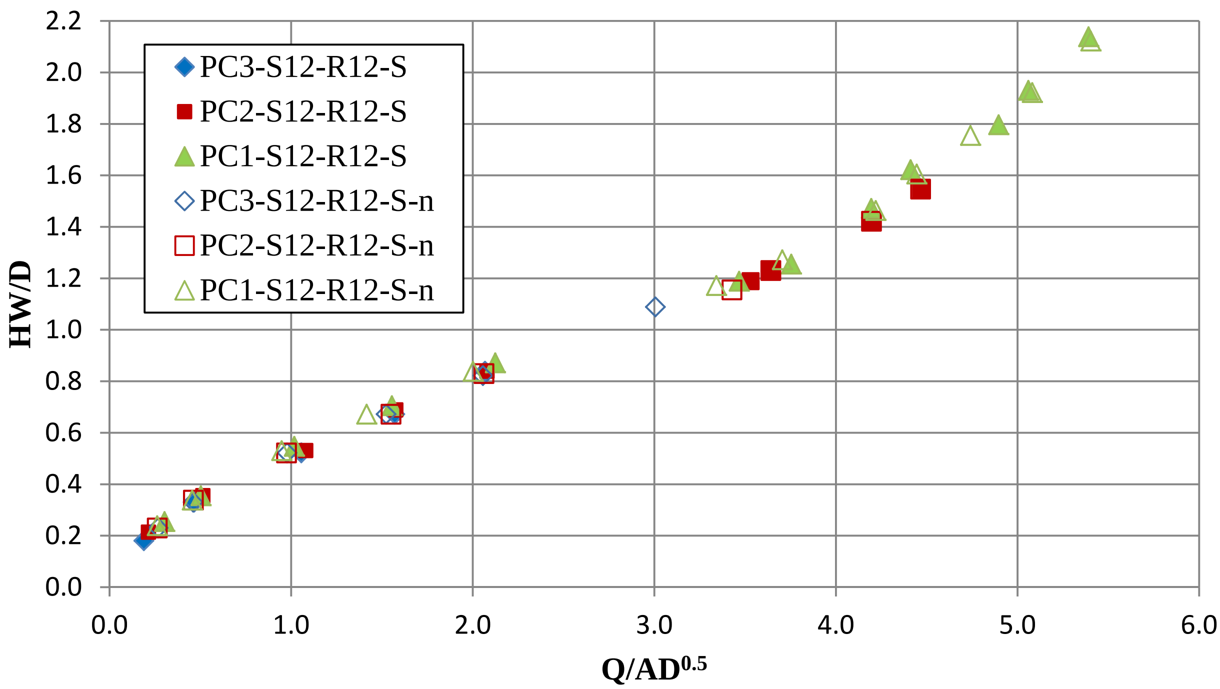


Fig 3-4 Inlet-control performance curves of PC-S12-R12 w and w/o embankments

The velocity profiles were measured with Pitot tubes placed in the culvert model headbox and tailbox as well as along the tunnel. Figure 3-5 shows the velocity distributions on the side barrels were symmetry for the submerged flow condition. The symmetry of the velocity distribution in the side barrels demonstrates that the conditioning of the flow in the headbox was good leading to a uniform and symmetric flow in the culvert model.

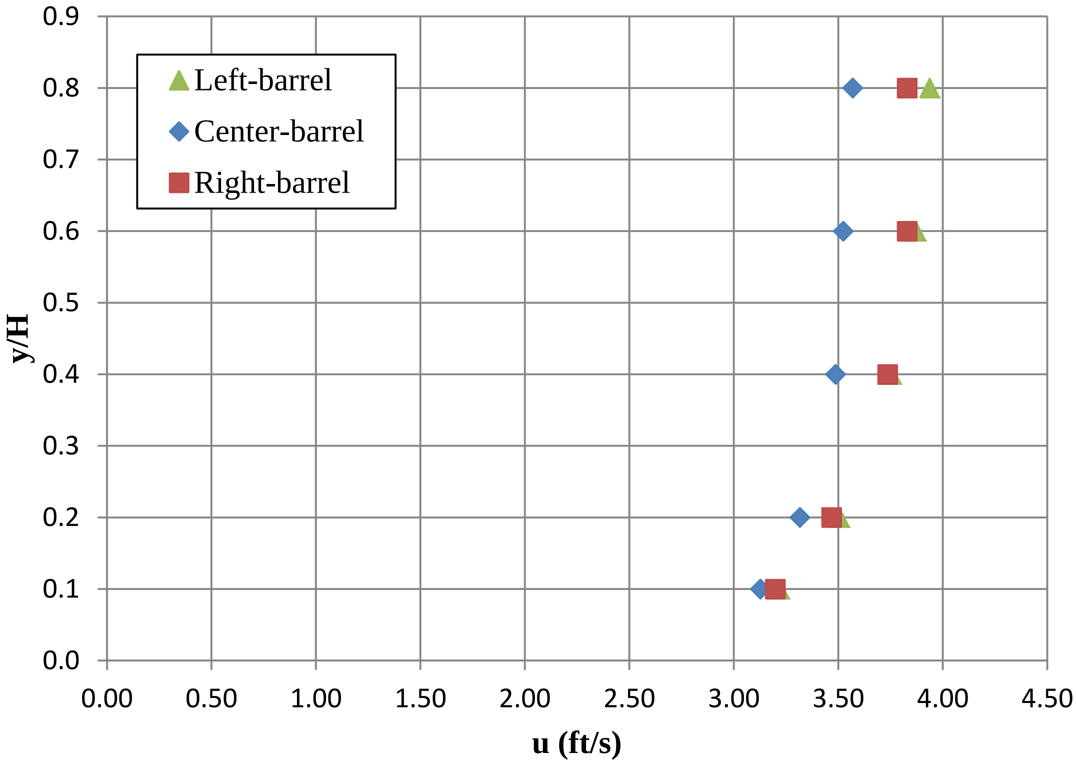


Fig 3-5 Velocity profiles in three barrel with the discharge = 2.447 ft^3/s

To validate the performance of our designed culvert models, three CIP models were selected and compared to FHWA inlet control equation (Equation 6 and 14). Figure 3-6 shows that the performance curves measured from IIHR models were close to the calculated curve. The small differences in the performance curves are associated with experimental uncertainty. The results obtained through these preliminary tests lead to the conclusion that the flume and ancillary instrumentation provide good quality performance curves for the culverts under analysis. Once the flume was validated with FHWA equation, the culvert models based on the Iowa manual were developed with the aforementioned scale ratios (see also Tables 3-1 and 3-2).

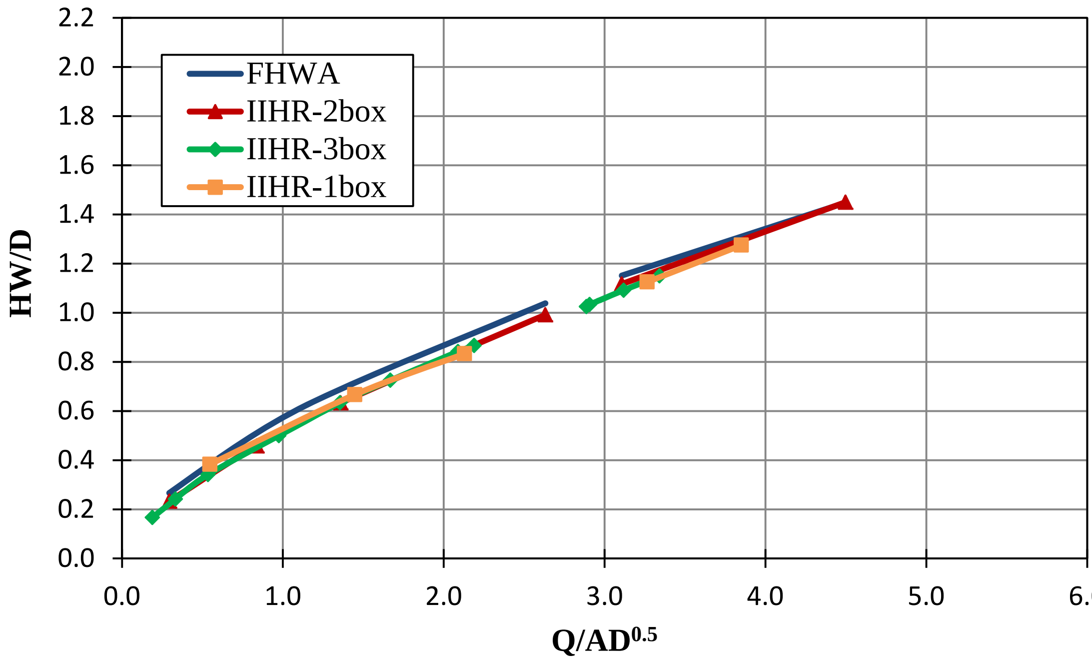


Fig 3-6 Performance curves of three different culverts compared to FHWA formula

3.4 Instrumentation

In order to construct the hydraulic performance curves the individual variables involved in Equations (6) and (14) need to be measured in the model to be jointly used with the information on culvert geometry. Specifically, that data acquisition focused on measurements for water depth, discharge, and velocity. The techniques for measuring these variables are described next.

3.4.1 Water Flow Rate

The water flow in the system was supplied by two pumps connected to a 125,000 gallon underground reservoir. The model can be separately or jointly connected to a 70 HP pump and a 60 HP pump for the necessary designed flow rates. Precise flow rate control is provided by butterfly valves in the supply lines and variable frequency drive (VFD) controllers on the pumps. Flows were measured with weigh-tank calibrated orifice and elbow style flow meters accurate to +/-2% of the total flow.

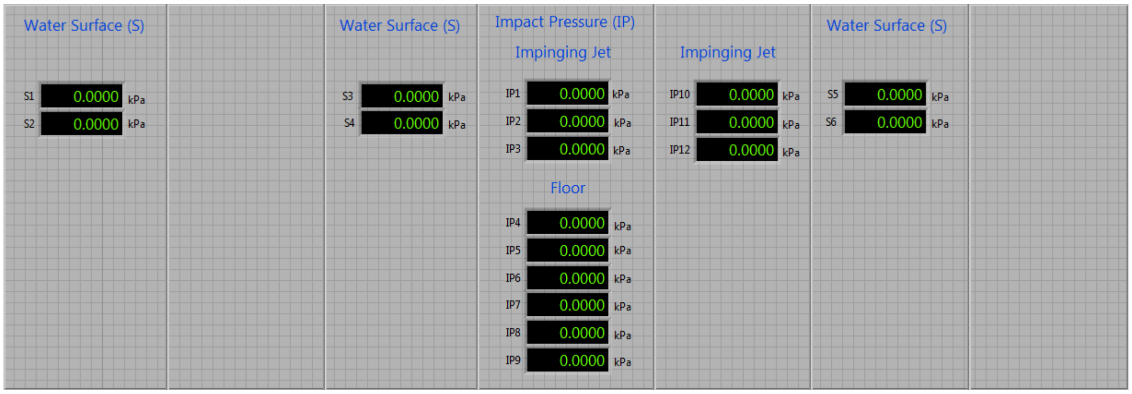
3.4.2 Manometers and Pressure Sensors

Water surface levels in the vicinity of the culvert model and hydraulic grade line (HGL) along culvert channel were measured directly either with manometer or with pressure sensor (see Figure 3-7). The manometer equipped with a vernier scale accurate to +/- 0.0005 ft. Water pressure, if needed, was measured with Measurement Specialties LM Series 0-1 psi pressure sensors. The manufacturer specifies accuracies of +/- 7% of full scale output. The sensors feature 1/2-inch NPT male fittings for simplified installation in the bottom of the inlet and tunnel. An image of the pressure sensor is shown in Figure 3-8.

The calibration of the Measurement Specialties LM Series 0-1 psi pressure sensors deployed in the vicinity of culvert model was done by our research team. Figure 3-9 illustrates the calibration plot for the sensors which converts voltage into pressure (inches of water column) from our recent research project. The initial calibration was repeatedly checked during the tests for shifting and zeroing biases.

a)

b)



c)

Fig 3-7 Intruments for water surface measurement: a) pressure sensor system, b) in-house developed Labview-based software, and c) manometer

Fig 3-8 Measurement Specialties LM Series 0-1 psi pressure sensor

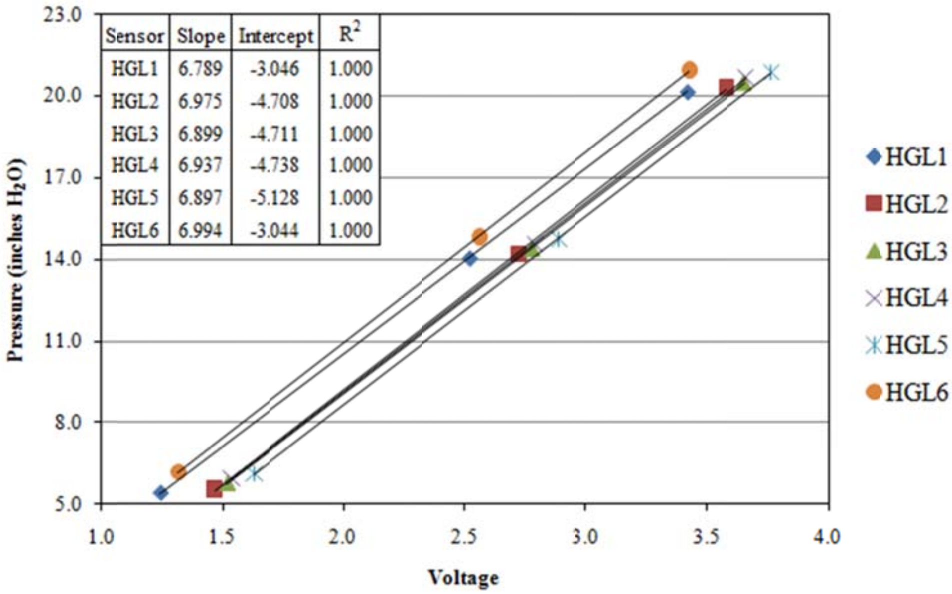


Fig 3-9 Typical sensor calibration curves

3.4.3 Velocities

The Pitot tubes placed at the culvert models and tunnel were applied to measure the velocity profiles. The velocity was calculated by measuring the pressure difference of the manometer:

$$v = \sqrt{2gh} \tag{15}$$

where v is velocity, g is gravity, and h is the difference in manometer.

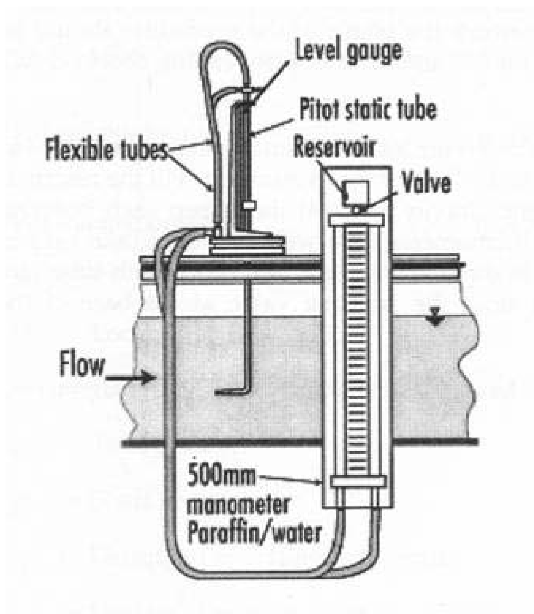


Fig 3-10 The Pitot tube and manometer used for measuring velocity in the flume (photography downloaded from: http://www.jfccivilengineer.com)

4. Experimental results

The series of experiments were conducted to substantiate the pertinent information a form suitable for supporting the culvert design specifications that account for the effect of multiple barrels, span-to-rise ratio, channel slope on the performance curve, as well as for detecting the optimum geometry for the inlet. The latter results were obtained from tests that isolated the effects of the change of the wingwall edge geometry.

4.1 Effect of number of barrels

Single box culverts are the common means of roadway crossings for smaller streams. While this culvert design provides an economical solution to the crossing, the adverse effects of conveying the stream through a single opening can ultimately be very costly due to scouring of the bed in the vicinity of the structure. Consequently, the multiple boxes culverts are recommended for conveying larger discharge. The available culvert design manuals for multiple culverts are not adequately addressing the following issues:

a) the impact of applying the single barrel coefficient for multiple culverts,
b) the quantitative specification of the hydraulic coefficients associated with the flow conveyance equations for PC multi-barrel culverts for various geometry and settings and over a range of flow conditions. Note that PC culverts are geometrically different than the CIP culverts.

4.1.1 PC culverts

For PC culvert model tests, the results show that there is almost no difference in the performance of multiple barrels and single barrel culverts for unsubmerged flow conditions (Figure 4-1 to 4-4). For the submerged flow conditions, Figures 4-3 and 4-4 show the presence of a considerable difference for multiple barrel culverts when compared to the single barrel model especially for high flows with steep barrel slopes (i.e., 0.02). The difference is not substantial for the same configuration culverts set on mild slopes (0.005). These results support the practice of using the single barrel coefficients for multiple barrel design in unsubmerged conditions and use of differentiated coefficients when operated in submerged conditions.

The flow conveyance coefficients derived from the experimental tests plotted in Figures 4-1 to 4-4 are summarized in table 4-1. For inlet control equation when flow is under unsubmerged condition the coefficients (K, M) are similar for single and multiple barrel culverts. The coefficients (c, Y) for submerged flow conditions show that twin and triple barrels are different compared to single barrel. There is no essential difference between twin and triple barrel culverts. The obtained results are in good agreement with the laboratory results reported in FHWA (2006) for mild slopes. The differentiation is more pronounced for culvert barrels set at steeper slopes as the dynamic head is commensurately increased for higher slopes.

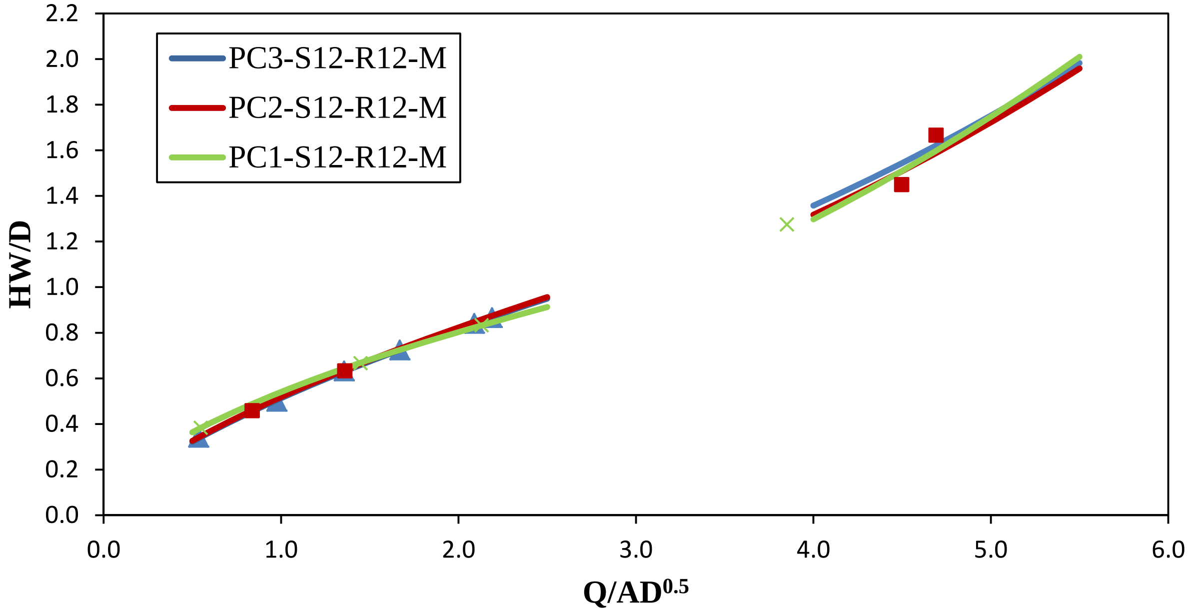


Fig 4-1 Inlet-control performance curves of PC-R12-S12 with barrel slope =0.005

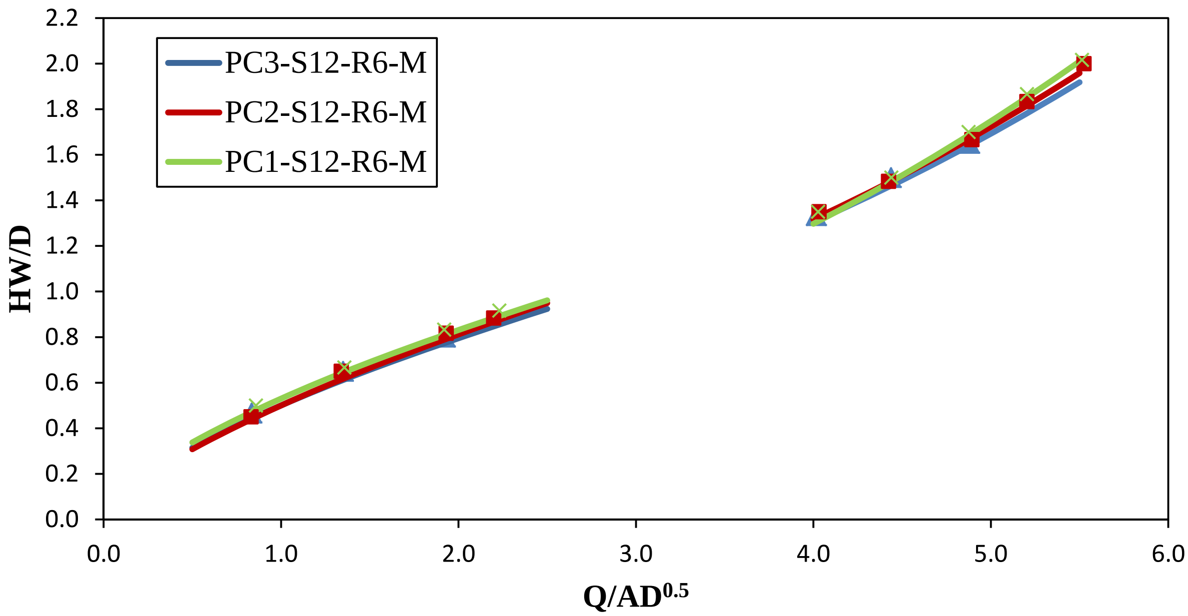


Fig 4-2 Inlet-control performance curves of PC-S12-R6 with barrel slope =0.005

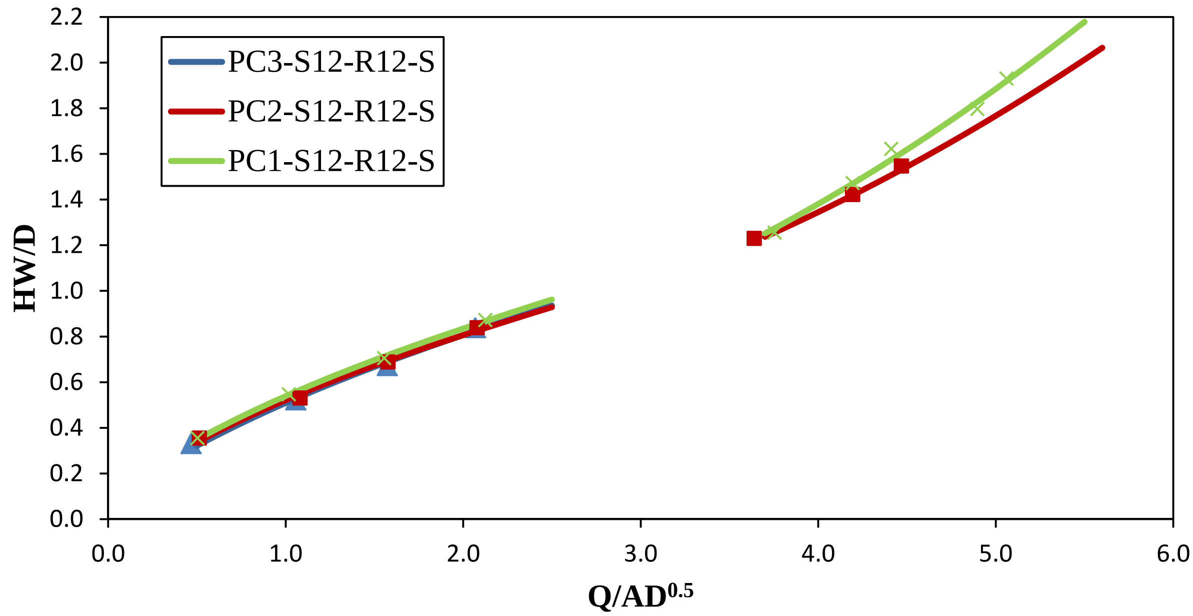


Fig 4-3 Inlet-control performance curves of PC-S12-R12 with barrel slope =0.02

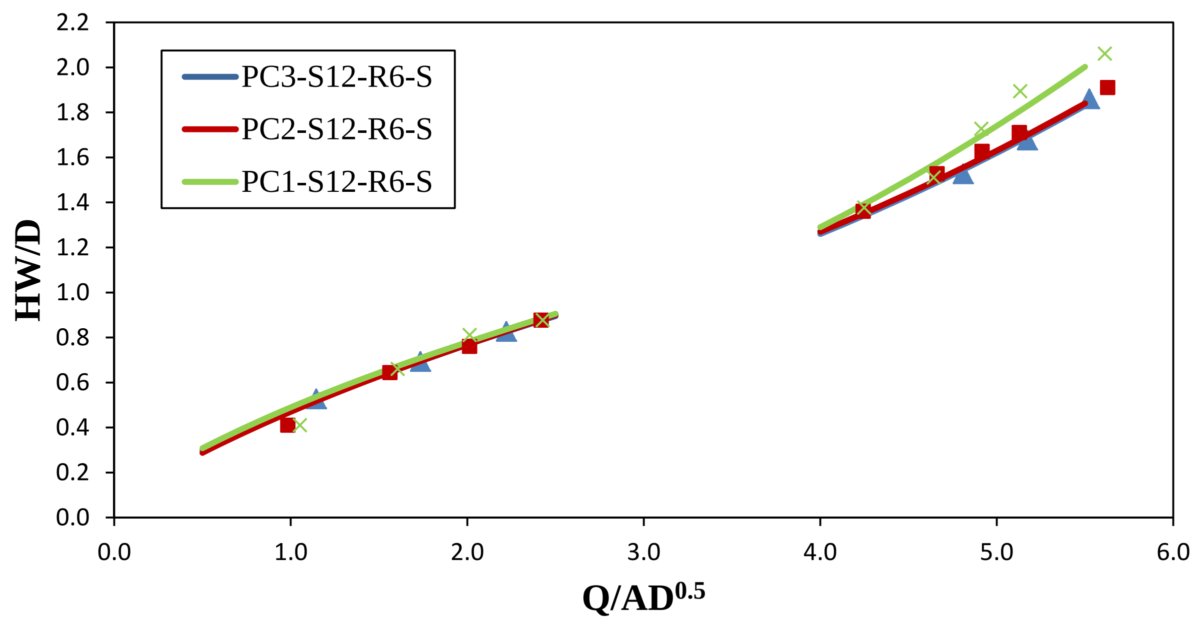


Fig 4-4 Inlet-control performance curves of PC-S12-R6 with barrel slope =0.02

Table 4-1 Regression coefficients for PC culverts

Model	Slope	K	M	c	Y
PC1-S12-R6	0.005	0.53	0.65	0.050	0.50
	0.02	0.49	0.67	0.050	0.50
PC2-S12-R6	0.005	0.50	0.70	0.045	0.60
	0.02	0.47	0.71	0.040	0.64
PC3-S12-R6	0.005	0.50	0.67	0.043	0.62
	0.02	0.48	0.68	0.040	0.63
PC1-S12-R12	0.005	0.54	0.57	0.044	0.66
	0.02	0.54	0.63	0.056	0.51
PC2-S12-R12	0.005	0.52	0.67	0.044	0.66
	0.02	0.52	0.63	0.047	0.62
PC3-S12-R12	0.005	0.51	0.67	0.044	0.66
	0.02	0.51	0.65		

4.1.2 CIP culverts

The experiments for CIP culvert models were conducted to provide a reference for the comparison of the performance curves and flow conveyance coefficients for PC culverts. It is expected that the CIP culverts with the 30-degree flared wingwall are less conducive to differentiation between single and multiple culverts as the flow at the entrance is better conditioned by the transition created by the wingwalls. The experimental results confirmed these expectations showing a better grouping (closer agreement) between single and multiple barrel CIP culvert models for both unsubmerged and submerged flow conditions for both the mild and steep slopes (Figure 4-5 to 4-8). The coefficients derived from the tests are summarized in table 4-2. Although there are slight differences between the single barrel and multiple barrel hydraulic performance, it is reasonable to estimate the performance curves of multiple barrel culverts with the coefficients derived from the single barrel culvert.

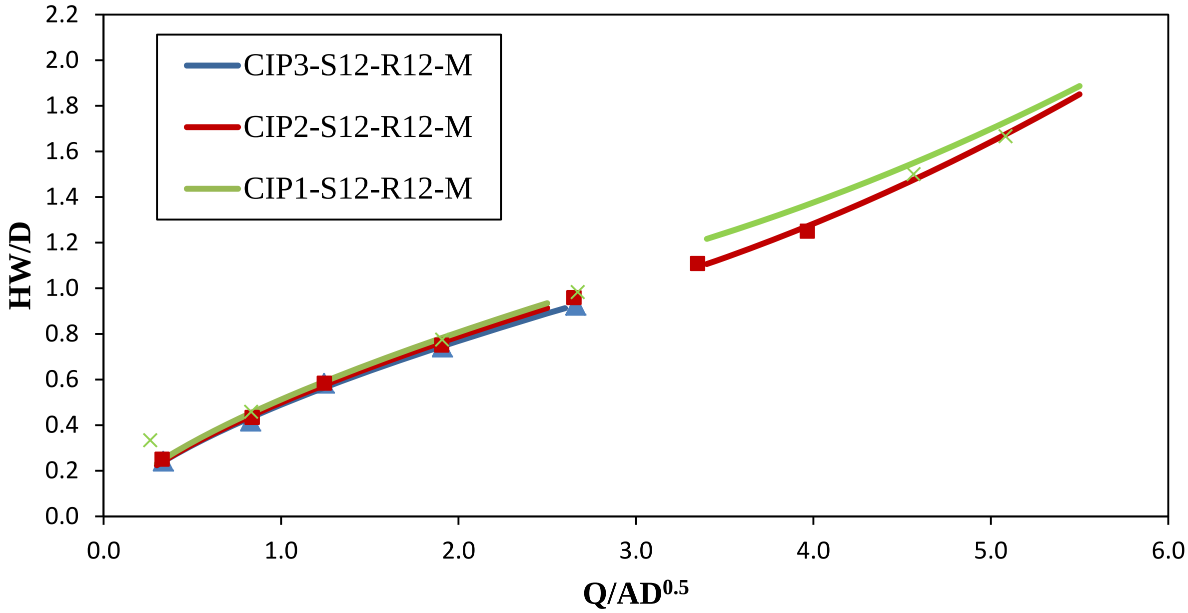


Fig 4-5 Inlet-control performance curves of CIP-S12-R12 with barrel slope =0.005

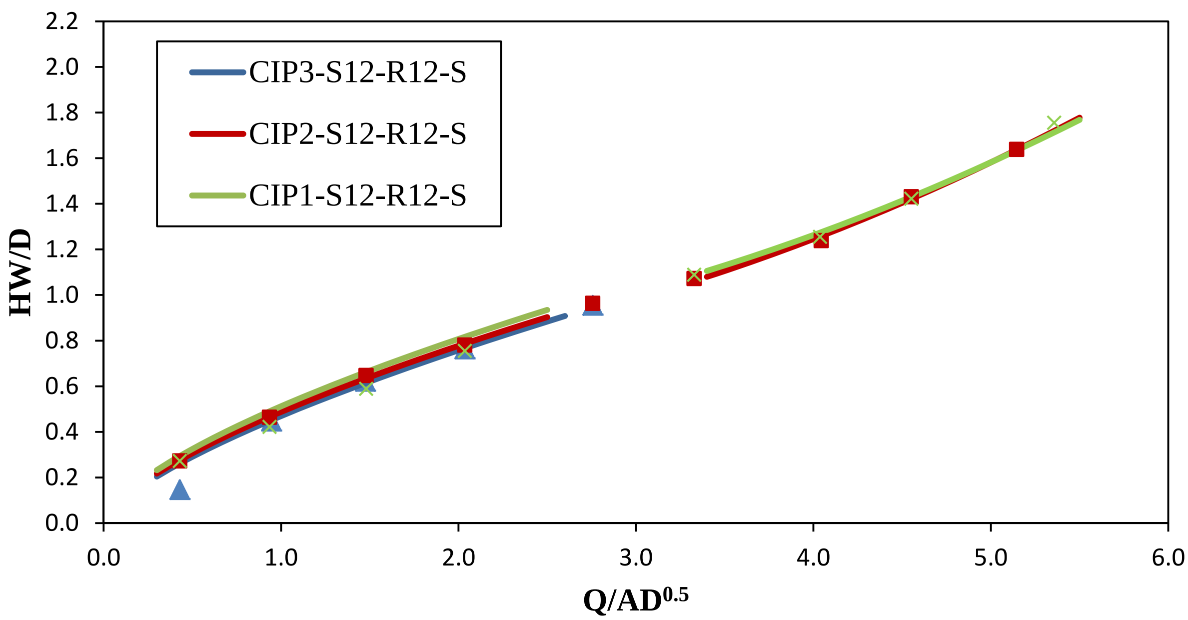


Fig 4-6 Inlet-control performance curves of CIP-S12-R12 with barrel slope =0.02

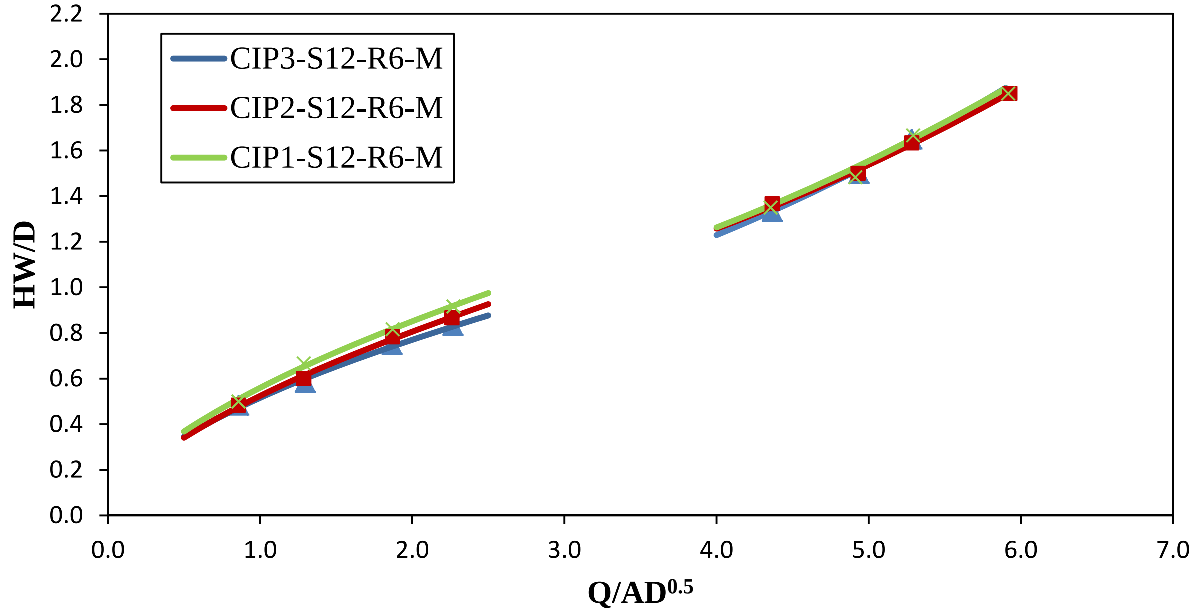


Fig 4-7 Inlet-control performance curves of CIP-S12-R6 with barrel slope =0.005

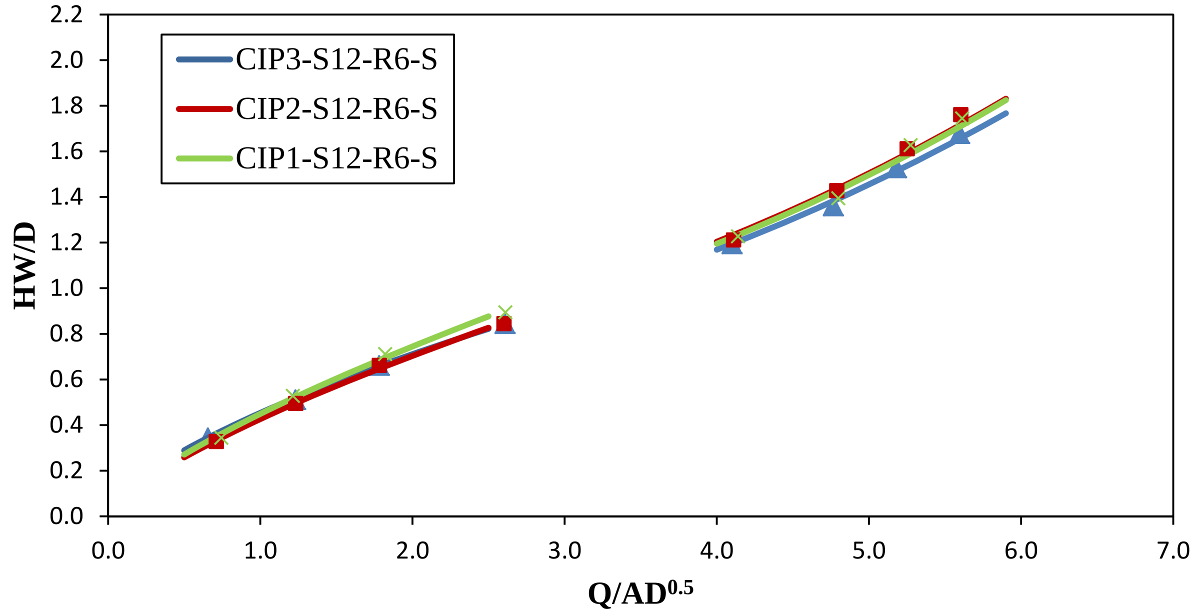


Fig 4-8 Inlet-control performance curves of CIP-S12-R6 with barrel slope =0.02

Table 4-2 Regression coefficients for CIP culverts

Model	Slope	K	M	c	Y
CIP1-S12-R6	0.005	0.56	0.61	0.032	0.75
	0.02	0.45	0.73	0.033	0.67
CIP2-S12-R6	0.005	0.53	0.62	0.031	0.75
	0.02	0.43	0.72	0.033	0.68
CIP3-S12-R6	0.005	0.52	0.58	0.034	0.68
	0.02	0.45	0.69	0.032	0.67
CIP1-S12-R12	0.005	0.51	0.65	0.033	0.81
	0.02	0.47	0.66	0.035	0.71
CIP2-S12-R12	0.005	0.50	0.66	0.037	0.65
	0.02	0.48	0.67	0.037	0.66
CIP3-S12-R12	0.005	0.50	0.65		
	0.02	0.47	0.69		

While not investigated in our study, a topic worth to be mentioned within the study context is the effect of extending the center walls for multiple barrel culverts. Experimental studies (such as FHWA, 2006) show that the extension of the walls between the central barrels does not affect the entrance coefficients or the performance of the culverts irrespective of the flow condition (submerged, unsubmerged) or wingwall geometry (flared or straight).

4.2. The effect of wingwall flare angle

The role of the wingwalls is to guide the approaching channel flow entering the culvert barrel. For CIP culverts the wingwalls are usually flared. Angles of 15, 30, and 45 degrees are the most common angles. For PC culvert the wingwalls are straight and practically of the same size as those used for CIP culverts. The experimental data collected through this study enable to compare the effect of the wingwall flare angle on PC and CIP operations. In general the use of flared wingwalls is more beneficial as their layout produce a better streamlining of the flow at the culvert entrance hence reducing the entrance hydraulic losses.

The hydraulic advantage of the flared wingwall over the straight ones can be observed in Figure 4-9 and 4-10, where the CIP culvert fit with flared wingwalls performed better than the PC culvert models, especially at high discharges. The findings are consistent with those in the FHWA (2006) study for South Dakota DOT culvert geometries. Furthermore the FHWA study found slight changes in the culvert performance irrespective of their type with the increase in span-to-rise ratio as the cross sections for these cases are not so much affected by the contraction of the flow upstream the culvert. The hydraulic advantage of the flared wingwall is materialized through lower headlosses at the culvert as can be observed in table 4-2.

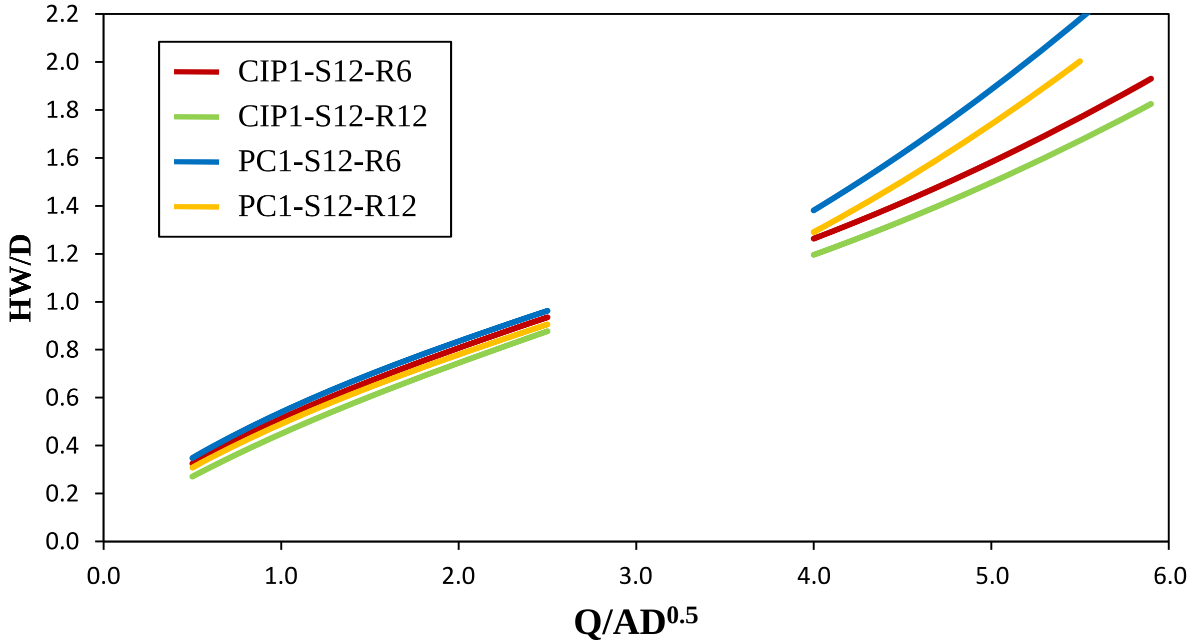


Fig 4-9 Inlet-control performance curves of all one-box models with slope =0.02 (experimental points were removed to better substantiate the differences between curves)

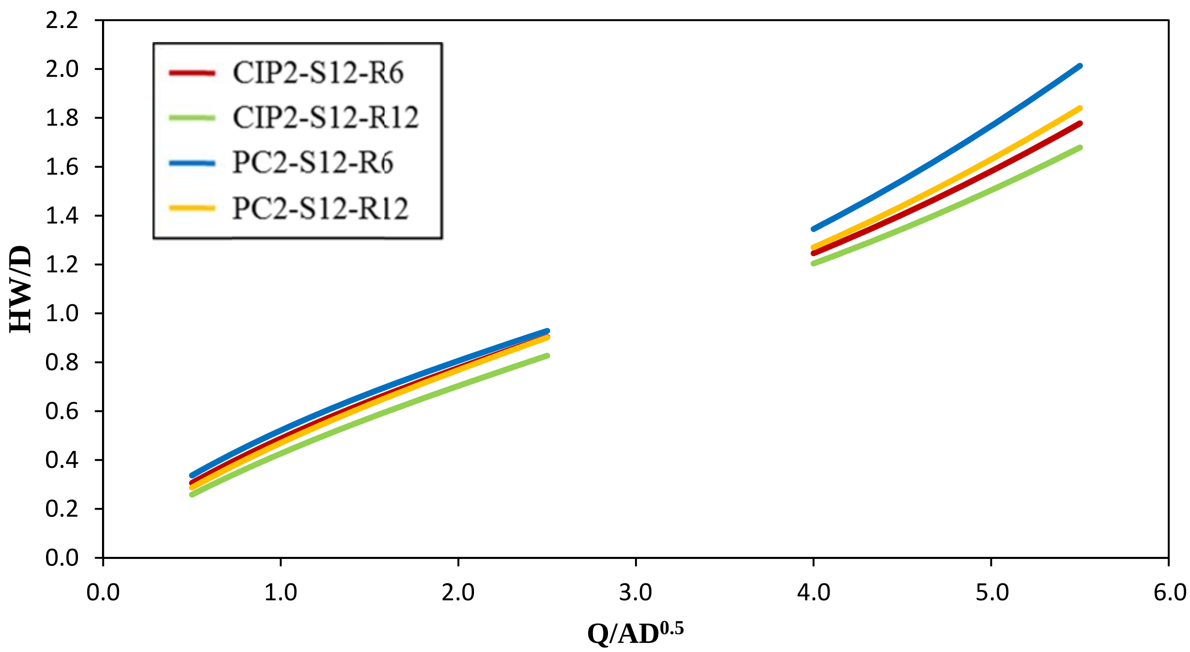


Fig 4-10 Inlet-control performance curves of all twin-box models with slope =0.02 (experimental points were removed to better substantiate the differences between curves)

Overall, it can be stated that the flared wingwalls induce less losses of the flow energy at the culvert entrance. This observation is more pertinent to single barrel culverts, as in the case of multi-barrel culverts a smaller percentage of the flow is influenced by the presence of the wingwalls. The observation is confirmed by the performance curve plots whereby it can be observed that the curves for both submerged and unsubmerged regimes become closer as the number of barrel increases. Recent studies (Ho, 2010) show that fitting the culvert with flared wingwalls requires an increase of the cross section of the stream in the immediate vicinity of the culvert. This expansion immediately upstream the culvert creates an area prone to sedimentation with negative impacts on the culvert operation. Specifically, the sediment deposits stabilized by the growth of vegetation lead in time to considerable obstruction of the flow and associated increase of energy losses.

4.3 Effect of culvert barrel slope

The effect of the culvert barrel slope is shown in Figure 4-11 for PC single barrel culvert model. The differentiation is not very pronounced for unsubmerged flow conditions. The differentiation is more substantial for high flows as the dynamic head is commensurately increased due to the increased grade line of the bed. In design, distinction should be made for flow conveyance coefficients only when the culverts operate in submerged flow conditions.

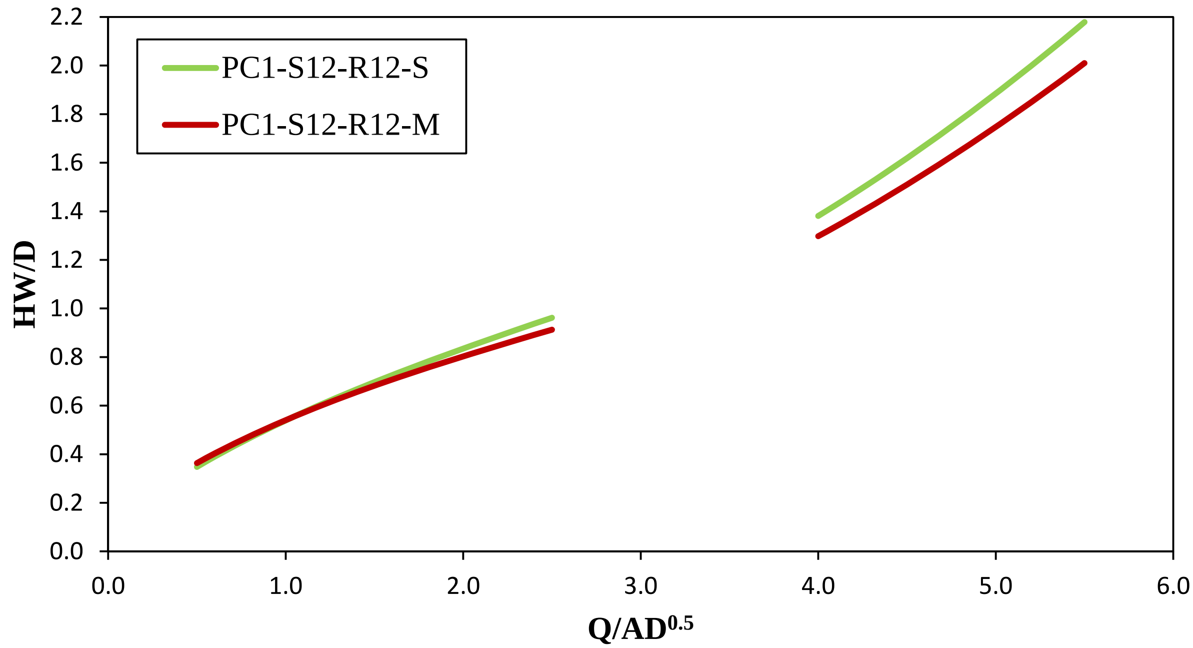


Fig 4-11 Inlet-control performance curves of PC1-S12-R12 with two barrel slopes (experimental points were removed to better substantiate the differences between curves)

4.4 Effect of span-to-rise ratio

For unsubmerged flow situations it is not expected that the flow conveyance is significantly affected by the span-to-rise ration up to the point of full-section flow (submerged condition). This expectation holds for both PC and CIP single and multi-barrel culverts. The expectation is confirmed by the experimental results shown in Figure 4-12 for the single PC culvert model operated under inlet control. A slight loss in performance might occur as the span-to-rise ratio increases for submerged flow. Figure 4-13 shows similar results for CIP culvert models. Taking into account the experimental scatter, one may conclude that there is no difference between the performances of the culverts for unsubmerged flow conditions. The performance slightly decrease when span-to-rise ratio increases for both types of culvert models.

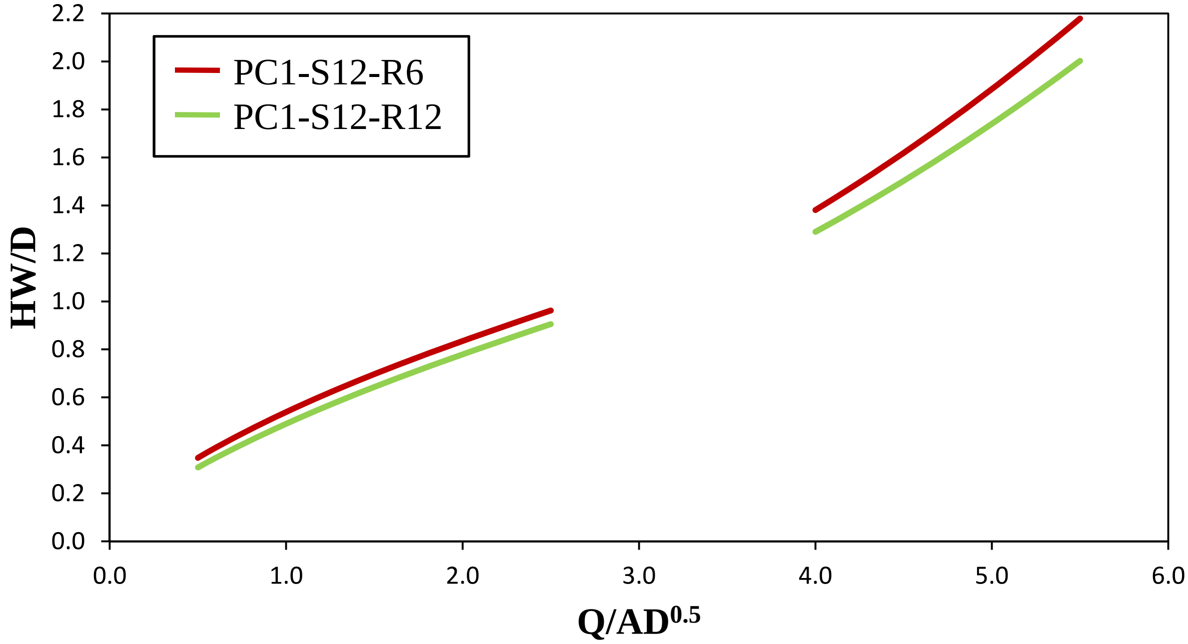


Fig 4-12 Inlet-control performance curves of PC1-S12-R12, PC1-S12-R6 with slope =0.02 (experimental points were removed to better substantiate the differences between curves)

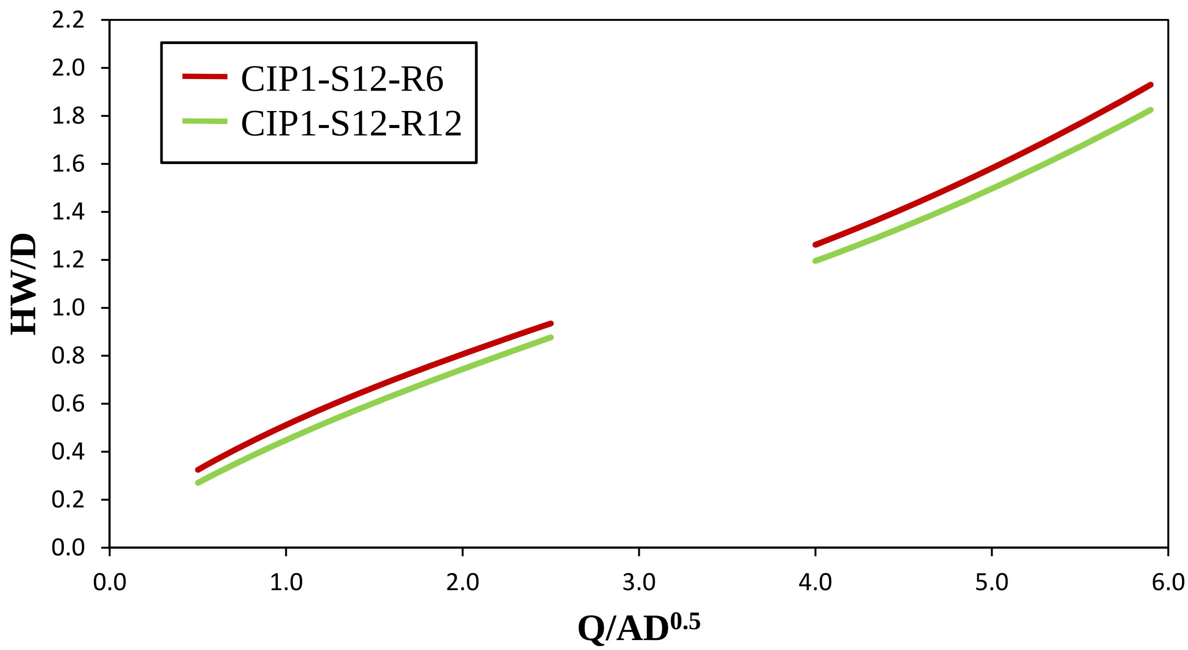


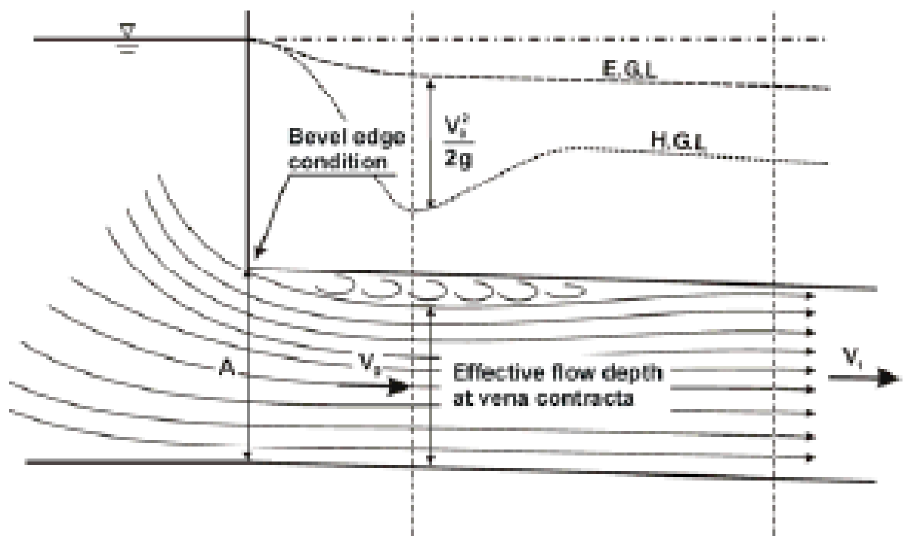
Fig 4-13 Inlet-control performance curves of CIP1-S12-R12, CIP1-S12-R6 with slope =0.02 (experimental points were removed to better substantiate the differences between curves)

4.5 Effect of the top edge geometry

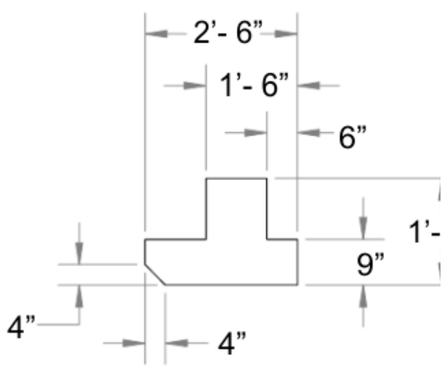
While the geometry of the edges of the entrance cross section is fixed for bottom and the side walls, the top edge can be further conditioned to diminish the losses associated with the flow conveyance. Consequently, an additional set of tests focused on quantitatively characterize the effect of the top edge from several alternate shapes that were suggested. This effect is only relevant for the submerged flow situations when the flow is in contact with the culvert ceiling. For flow levels higher than the culvert ceiling a contraction develops at the culvert entrance that further increases the total head losses, as indicated in Figure 4-14a (FHWA, 2006). Tests were conducted with 8-in radius top edge (labeled with the suffix "–op" in the plots) and 4-in bevel top edge (reference condition) as illustrated in Figures 4-14b and c. The effect of the edge shape was tested on PC culvert models. FHWA (2004) investigated the effect of the wingwall top edge for submerged flow conditions. The results indicate that the performance curves were practically unchanged indicating that the shape of the wingwall top edge investigated in their study is not affecting the operation or the hydraulic losses of the culverts. The same conclusion was drawn by the FHWA (2004) study about the effect of the corner fillets set along the corners of the rectangular culvert cross section.

The optimal top bevel conducted in this test is 8-in radius top edge. The PC culvert models with the optimal bevel were labeled as PC-S12-R12-op and PC-S12-R6-op. Figures 4-15 and 4-16 show the performance curves for each PC culvert model with optimal top bevel. One of the results displayed by the plots show that the multiple barrel culverts perform hydraulically better than the single-barrel ones. Compared to CIP culvert model, the PC culvert model with the optimum curved top bevel showed closer agreement with the CIP culvert model at headwater to culvert depth ratios greater than 1.4. It is reasonable to expect that the optimum top bevel will have a more pronounced effect on performance at the high headwater depths as the number of barrels and total span increase. The mixed PC and CIP results plotted in Figure 4-17 show that the bevel optimization does not make the PC culvert as efficient as the CIP homologous culvert.

a)



b)



c)

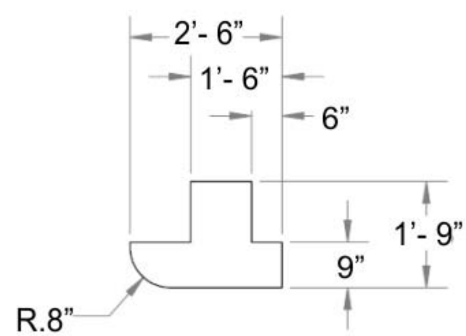


Fig 4-14 a) Top edge condition (FHWA 2006), b) tested 4-in bevel top edge, and c) tested 8-in radius top edge

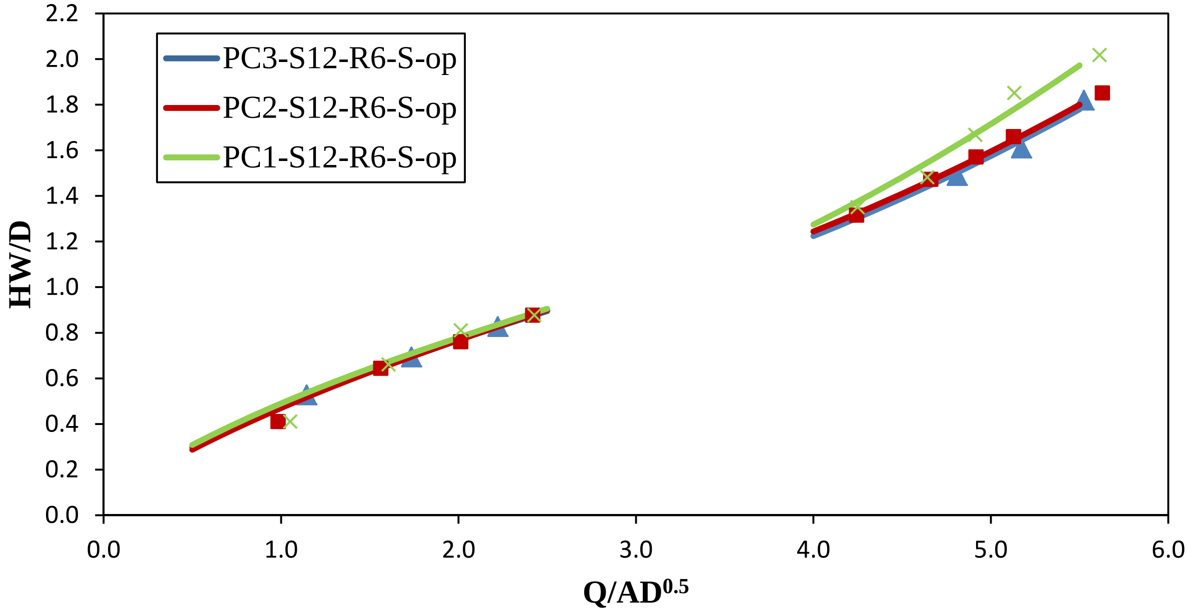


Fig 4-15 Inlet-control performance curves of PC-S12-R6-op with barrel slope =0.02

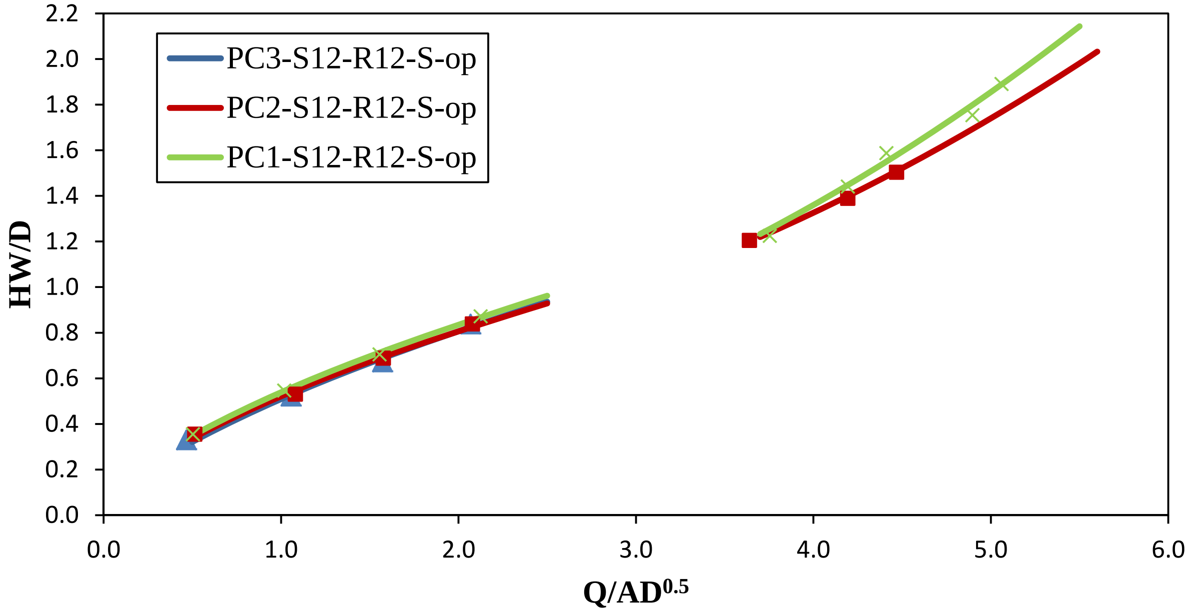


Fig 4-16 Inlet-control performance curves of PC-S12-R12-op with barrel slope =0.02

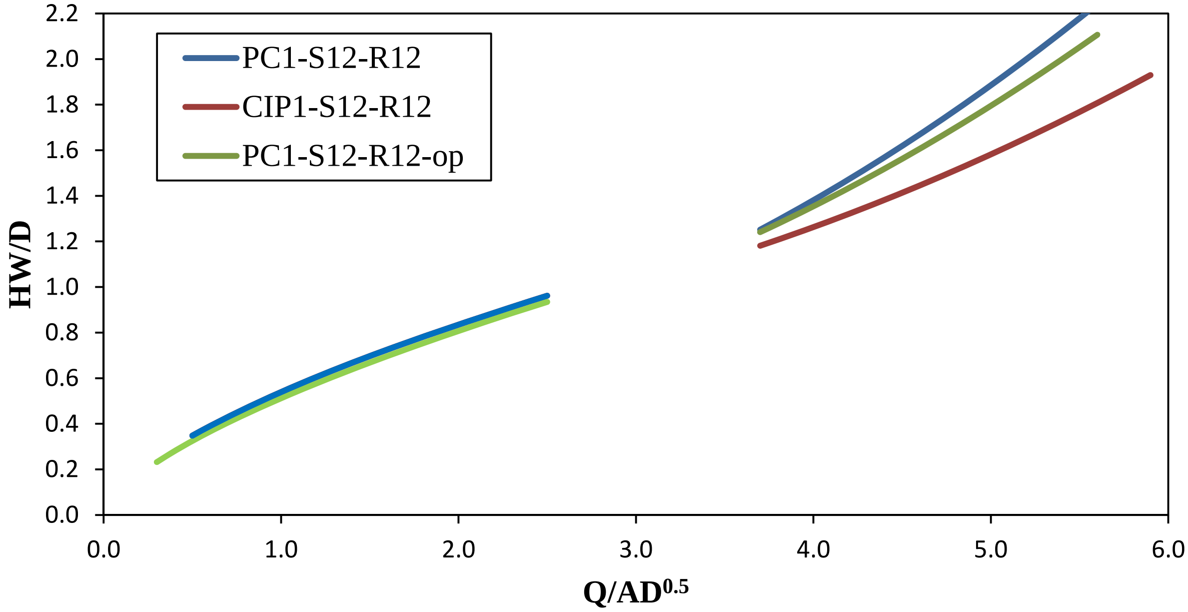


Fig 4-17 Performance curves of PC-S12-R12-op compared to PC-S12-R12 and CIP-S12-R12 (experimental points were removed to better substantiate the differences between curves)

4.6 Shear stress at culvert outlet

The presence of local scour at structure outlet is a common occurrence for single and multiple culverts. During the storm events the channel flow experiences a contraction at the entrance and an expansion at the outlet as it passes through the culvert. The velocity is increased throughout the culvert length and potentially results in local scour at the culvert inlet and outlet. The critical section indicated by IDOT personnel is the culvert outlet. The factors that affect the local scour at the outlet are not only dependent to the flow characteristics. Soil type, duration of the flow, characteristics of the channel and bank, channel slope, culvert shape, and velocity at the outlet are all contributing factors to the local scour. In this section we only evaluate the effect of channel slope and culvert shape on the local shear stress ad one of the contributing factor of local scour at the outlet.

For this purpose, velocity profiles were measured with the Pitot tubes in side barrels of triple culverts where the velocity is larger than in the central barrel. The tests were conducted for three culvert models: PC3-S12-R12-M, PC3-S12-R12-S and CIP3-S12-R12-M. The evaluated shear stress and its variation with channel slope and culvert shape effects are shown in Figures 4-18 to 4-20). The shear stress as the indicator of the scour at the outlet was estimated from the measured velocity profiles in conjunction with regression lines constrained to the law of the wall method. We assumed that the velocity profile in the lower portion of an open channel flow has a logarithmic structure, hence the law of the wall can be applied for this region:

$$u = \frac{u'}{\kappa}\ln\left(\frac{y}{y_0}\right) = m\ln y + b \qquad (23)$$

where u = mean velocity, u' = shear velocity, κ = von Karman's constant, y = distance above bed, and m is slope of the regression line = u'/κ .

After the slope of the regression line was calculated, the shear stress was estimated based on:

$$\tau = \rho u'^2 \qquad (24)$$

The results of the shear stress at the outlet of each culvert model are presented in Table 4-3. It can be noticed that the shear stress increases with the channel slope. The plots also suggest that the CIP culvert model displays less shear stress at the outlet compared to the PC culvert model which is also expected by the spread of the flow facilitated by the oblique wingwalls. Although the prediction of scour hole at outlet is difficult, the present results indicate that more protection against scour is needed for PC culvert outlets in comparison with CIP culverts.

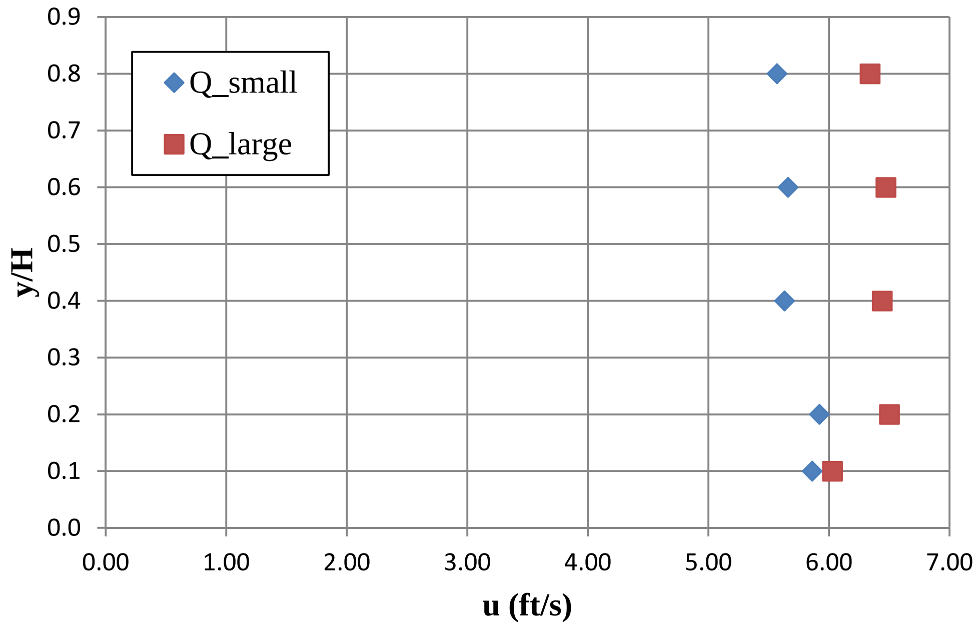


Fig 4-18 Vertical velocity profiles at the left barrel outlet for PC3-S12-R12-M for stream discharges of 3.14 and 4.51 ft^3/s

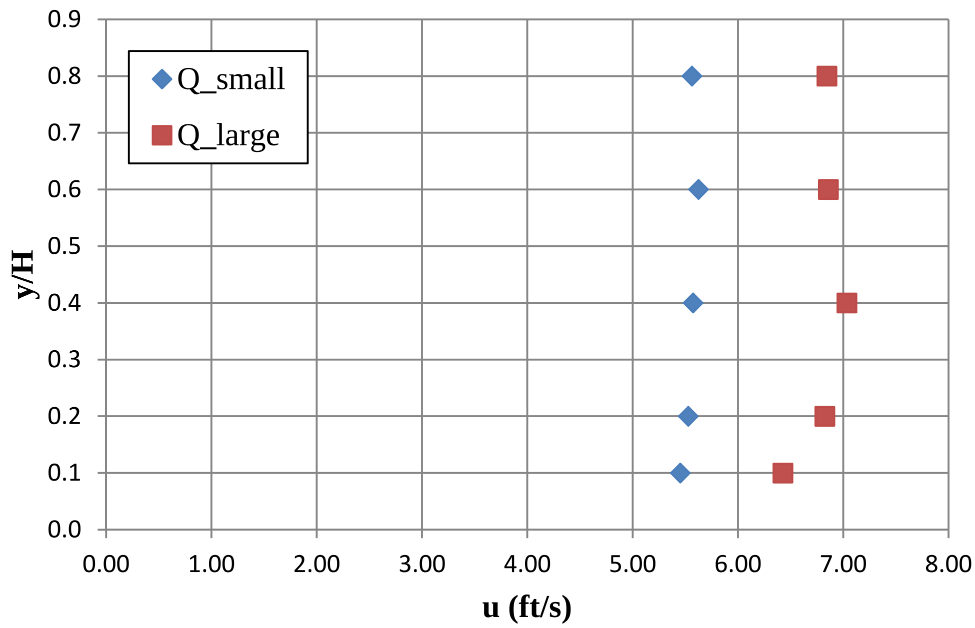


Fig 4-19 Vertical velocity profiles at the left barrel outlet for PC3-S12-R12-S for stream discharges of 2.16 and 4.45 ft^3/s

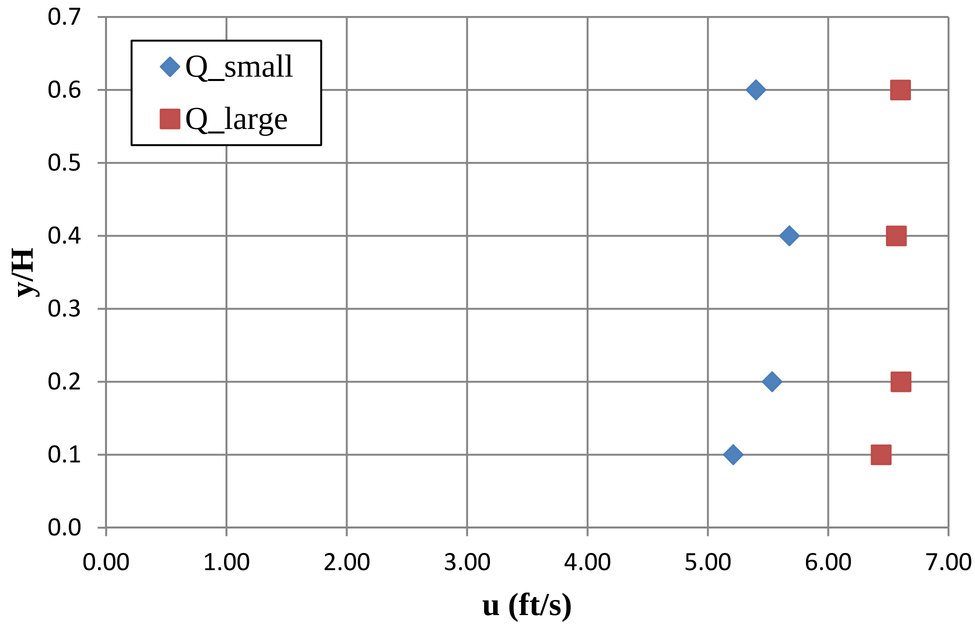


Fig 4-20 Vertical velocity profiles at the left barrel outlet for CIP3-S12-R12-M for stream discharges of 2.24 and 4.55 ft^3/s

Table 4-3 Estimation of shear stress for various culvert models

Model	m	κ	u'	ρ	τ
PC3-S12-R12-M	0.1366	0.41	0.05601	1.936	0.00607
PC3-S12-R12-S	0.1931	0.41	0.07917	1.936	0.01213
CIP-S12-R12-M	0.0746	0.41	0.03059	1.936	0.00181

5. Conclusion and Recommendations

The increased number of single and multi-barrel PC culverts constructed by Iowa DOT rather than the conventional CIP culverts emphasizes the need to conduct additional research for documenting specifications on the hydraulic aspects of the PC culvert operations. Of special interest for this purpose are the evaluation of the entrance loss coefficients and the construction of the hydraulic performance curves for culverts of various configurations operating in a variety of flow conditions and topographic settings. These hydraulic specifications are further used in conjunction with software programs used to design culverts. The results of the study are expressed in non-dimensional form such as they are unit-system independent and can be readily used in specialized culvert design software.

Following the experimental study, there are a set of conclusions that are emerging from the analyses of the results:

- Multiple barrel CIP culverts have little effect on the performance curves for single CIP culverts when operating in unsubmerged and submerged conditions (see Figures 4-5 to 4-8). The single-, twin-, and triple-barrel culverts can reasonably be combined as a single performance curve without much loss in accuracy for any type of CIP culvert. This conclusion stands for mild and steep slopes. This conclusion endorses the current practice of using single-barrel design coefficients for multi-barrel culverts.

- The presence of multiple barrels has a more pronounced effect on the performance curves for PC culverts (see Figures 4-3 and 4-4). For mild slopes the differences are not essentials for both unsubmerged and submerged flow conditions (see Figures 4-1 and 4-2). For steeper slopes the difference in the performance curves for single-, double-, and triple-barrel culverts is noticeable, especially for the unsubmerged flow condition. As a consequence, distinct coefficients for entrance losses and performance curves need to be used for high flows that fill in the cross section when the culvert is set on steep slopes.

- The presence of flared wingwalls (such as those associated with CIP culverts) better “streamline” the flow at the culvert entrance making the culvert more advantageous from the hydraulic performance perspective in comparison with the straight wingwall culverts (such as those associated with the PC culverts), as illustrated in Figures 4-9 and 4-10. A direct consequence of this finding is that the CIP culverts are more efficient hydraulically then the PC ones. The differentiation between the culvert performances is more substantial for culverts operating with inlet control at high discharges. These observations are more evident for single barrel culverts, as for multiple barrels a smaller percentage of the flow is influenced by the wingwalls. It should mentioned at this point that the decision to choose a CIP or PC culvert design does is not only driven by the hydraulic performance of the culverts but also by the other considerations such as construction price and associated operational problems such as sedimentation. An on-going study conducted by the authors (Ho, 2010) showed that the presence of flared wingwalls create additional problems in operation due to the sedimentation that is easily developed in the expansion area at the entrance of the culverts.
- The effect of the culvert barrel slope (shown in Figure 4-11) is not of considerable importance for unsubmerged flow conditions (low discharges). The differentiation is more substantial for high flows where both the performance curves and the flow conveyance coefficients need to be chosen commensurate with the magnitude of the slope.

- The change in span-to-rise ratio was found to not affect the hydraulic performance of the culvert in the unsubmerged conditions. Slight decrease in performance is noted with the span-to-rise ration increases for submerged flow conditions. PC culverts are most sensitive to this parameter then the CIP culverts. The trends mentioned above are less important as the number of barrels increases.
- The top edge shape of the culverts impact the flow conveyance efficiency only when the culverts operate in high flows that fill the culvert cross section leading to a pipe flow situation. The two geometries for the top edge investigated in the study show little difference with the change in edge shape. However, as expected from theoretical considerations and proven with detailed experiments by FHWA (2006), the 8-in radius top edge suggested by IDOT should have a more positive impact on the head losses than our result indicate, hence it is recommended for implementation.

Overall it can be concluded that the study on the hydraulic performance of the CIP and PC culverts suggests that the implementation of the Iowa DOT design for PC culverts is feasible for implementation for most of the cases investigated. For unsubmerged flow conditions the difference in the performance curves and headloss coefficients are minor, practically within the uncertainty of the experimental data. Differentiations as noted above are more substantial for high flows when the flow is increasingly constricted at the entrance in the culvert. The differentiation due to various factors is less important for multi-barrel culverts as the influence of the wingwalls decreases with the increase of the number of barrels. Accounting for their reduced cost, efficiency in construction, and (potentially) the better performance with respect to the conveyance of sediment, the transition from CIP to PC culverts seems to be in general headed in the right direction. Corrections to the performance curves and entrance loss coefficients should be applied for high flows creating submerged conditions and certainly for single-barrel culverts. The regression curves produced for the performance curves accounting for various changes investigated in the present study (i.e., culvert geometry, culvert slope, span-to-rise ratio, number of barrels, wingwall flare angle, and top edge geometry) can be conveniently used for designing various culvert configurations, settings, and flows.

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