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IMPROVEMENTS TO THE HYDRAULIC PERFORMANCE OF CULVERTS UNDER INLET CONTROL CONDITIONS THROUGH THE OPTIMISATION OF INLET CHARACTERISTICS

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DISSERTATION SUMMARY

IMPROVEMENTS TO THE HYDRAULIC PERFORMANCE OF CULVERTS UNDER INLET CONTROL CONDITIONS THROUGH THE OPTIMISATION OF INLET CHARACTERISTICS

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Degree:	Master of Science (Applied Science) (Water Resources)

The design of culverts, a fundamental aspect of engineering hydraulics, has traditionally followed standard methodologies that may not fully consider the potential benefits of optimizing inlet characteristics, particularly under inlet control conditions. This oversight, coupled with an often overly conservative design approach, has led to the overdesign of culverts, resulting in unnecessary expenses. However, there is a renewed interest in exploring innovative design modifications to enhance culvert hydraulic performance.

The South African National Roads Agency (SANRAL) is facing challenges as it integrates provincial roads into its national network, where the existing culverts may not meet the design criteria outlined in the SANRAL Drainage Manual. Additionally, projections of climate change suggest an increase in rainfall intensity, potentially rendering original culvert capacities insufficient. While new culverts can be designed with these considerations in mind, the greater challenge lies in increasing the capacities of existing culverts without resorting to costly and inconvenient road closures for replacements or for installing additional culverts in parallel.

This research studies the enhancement of culvert hydraulic performance through novel design modifications. The study focuses on the addition of angled wingwalls and headwalls to culvert inlets, a combination that has not been extensively researched before in South Africa. Ventilation devices are also considered to introduce air into culverts.

An experimental study was undertaken, involving a model consisting of a single-barrel culvert with three headwall / wingwall combinations (90 degrees, 45 degrees, and 30 degrees), with the latter two being 3D-printed.

Results indicate that the proposed modifications significantly improve culvert hydraulic performance. Adjustments to coefficients for flow under inlet control conditions, such as increasing the Cb and Ch factors, is proposed to align with experimental data. The 45-degree and 30-degree models demonstrate flow rate improvements of 18% and 16% at $H_1/D = 1.2$, respectively, compared to the 90-degree model for specific conditions. Additionally, the inclusion of a ventilation device alters the flow from outlet control to inlet control in the experimental model under specific conditions.

The research suggests that precast headwall/wingwall elements can be easily connected to existing culverts, offering a quick, cost-effective solution that also provides added road width for pedestrian use.

Despite the structural advantages of the proposed angled headwall/wingwall element over traditional designs, the research acknowledges that cost savings might not be realized in terms of construction. However, the avoidance of road closures, excavations, culvert replacements or the installation of additional culverts in parallel and backfilling and resurfacing a road will contribute significantly to overall cost-effectiveness and cost savings.

In conclusion, this research emphasizes the feasibility and benefits of innovative design modifications for culverts to enhance hydraulic performance. The proposed solutions not only offer improved functionality but also present sustainable and cost-effective alternatives to conventional approaches, particularly in the face of infrastructure challenges and evolving environmental demands. This research contributes valuable insights to the field of hydraulic engineering, promoting adaptability and resilience in infrastructure development.

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ABSTRACT

Title:	Improvements to the hydraulic performance of culverts under inlet control conditions through the optimisation of inlet characteristics.
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This research investigates optimising inlet characteristics of culverts to improve their hydraulic performance. With the South African National Roads Agency (SANRAL) integrating provincial roads into its national network, challenges arise as existing culverts may not meet updated criteria, exacerbated by potential climate change impacts on rainfall intensity. While new culverts can account for these factors, upgrading existing ones traditionally involves road closures and replacements, prompting the exploration of in-situ improvements.

The study introduces innovative design modifications, including angled headwalls in addition to angled wingwalls, and ventilation devices, hitherto not extensively researched. Experimental simulations using a square culvert model and two angled headwall/wingwall combinations reveal performance improvements. The research emphasizes the feasibility and benefits of these modifications, presenting cost-effective alternatives to conventional culvert replacements, thereby contributing valuable insights to hydraulic engineering for resilient and adaptable infrastructure development.

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Signature of student: ______________________

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1 INTRODUCTION

1.1 BACKGROUND

Severe challenges are constraining service delivery on a provincial and local government level in South Africa. The lack of well-maintained infrastructure has a negative effect in the economies of many communities.

The results of these challenges are clearly visible in South Africa's vast network of provincial and municipal road networks, especially in the more rural areas. To counter this situation, the South African National Roads Agency (SOC) Ltd (SANRAL) is increasingly incorporating provincial roads into its national road network to meet the medium to long term developmental needs of the country.

Unfortunately, in many instances, the roads which are being incorporated were not designed to the same standards, and do not meet the current design criteria for the class of road as described in the SANRAL Drainage Manual (SANRAL, 2013).

Many culverts that form part of the existing SANRAL road network also frequently overtop during minor floods. This situation results in damage to the structure and, importantly, inconvenience and danger to road users.

In addition to this, projections show that, in South Africa, climate change may cause a tendency towards an increase in intensity of rainfall, or extreme events (Mambo *et al.* 2017). Such extreme rainfall events may, over time, cause the original design capacities of installed culverts to become insufficient.

SANRAL is therefore mandated to replace various culverts in its current and future networks. Traditionally, culvert replacements involve traffic disruptions and major capital investments. In some cases, modifying existing culverts may improve the culvert's hydraulic performance to such an extent that it meets the requirements of the class of road it serves. As costly road closures and reinstatements would no longer be required, the cost of these improvements should only be a fraction of the cost of a culvert replacement or the addition of culverts in parallel to increase capacity. In addition, modifications could be applied to culverts which frequently overtop, damaging the roadways which they serve. Improving the hydraulic performance of culverts during the design stage of various projects could also reduce project budgets during the construction phase.

However, there are currently no guidelines available to SANRAL or South African engineers to design culvert inlet modifications.

1.2 OBJECTIVES OF THE STUDY

The aim of this study is to use physical modelling to evaluate various proposed culvert inlet improvements and propose a design guide. It is envisioned that this guide could be included in the next revision of the SANRAL Drainage Manual (SANRAL, 2013) for the benefit of engineers and roads authorities in Southern Africa.

This study has the following specific objectives:

1. Comparing the results of a 90 degree culvert model to established culvert inlet control formulae;

2. To investigate the potential hydraulic improvement that can be achieved by installing angled headwall / wingwall combinations at culvert inlets over a 90 degree headwall installation;

3. To investigate whether the installation of a ventilation device has an effect on the hydraulic improvement of culverts and

4. To investigate the practical implementation of the modelled results, including the comparison of costs.

1.3 SCOPE OF THE STUDY

This study investigates culvert inlet improvements through physical modelling. Specifically, the following physical models are investigated:

1. A 90 degree headwall experimental model which is used as a control for the angled headwall / wingwall combination models. The results of this model is also be used to verify existing formulae for culvert flow under inlet control conditions.

2. Both 30 degree and 45 degree angled headwall / wingwall combination models are tested to investigate whether such an inlet improvement will lead to improved hydraulic efficiency of a culvert.

3. A ventilation device is tested to see whether it has an effect on the flow in a culvert.

The results of the physical model are analysed and the practical implementation of the results are discussed.

This study only considers inlet improvements under inlet control conditions up to $H_1 / D = 2.1$ and does not consider outlet control conditions except when considering the observations of the effect of a ventilation device. This study compares the increase in efficiency of angled headwall / wingwall inlet improvements compared to the 90 degree headwall control model only. It does not compare the increase in efficiency of an angled / headwall inlet improvement over angled wingwalls only. This comparison should be the subject of future research.

1.4 METHODOLOGY

The study was carried out by constructing an experimental culvert model in the Water Laboratory of the University of Pretoria (UP Waterlab). The model consisted of a single barrel square culvert and three headwall / wingwall (inlet) combinations (90 degree, 45 degree and 30 degree models). The 45 degree and 30 degree models were 3-D Printed due to their complex shapes.

Water was pumped through the models at various flow rates and the corresponding headwater depth recorded.

In this study, the results of the 90 degree headwall model are compared to various existing formulas for culvert flow under inlet control conditions. Additionally, these results are compared with those from the 30 degree and 45 degree experimental models in order to determine the increase on the hydraulic efficiency of these models.

The experimental model also investigates the effect of including a ventilation device, or air tube, connected in such a way to introduce air into the culvert just downstream of the inlet.

The results of this study is presented in this dissertation, and recommendations are made for the practical implementation and benefits of the proposed inlet improvements.

1.5 ORGANISATION OF THE REPORT

The report consists of the following chapters and appendices:

- Chapter 1 serves as introduction to the report.
- Chapter 2 contains a technical introduction based on a literature study. It summarises the theory around culvert hydraulics, but also emphasizes previous work done to optimise culvert performance, and contains a list of practical model studies undertaken by others.

- Chapter 3 describes the experimental setup of the model study undertaken at the Water Laboratory of the University of Pretoria (UP Waterlab), and analyses the results of the model study.
- Chapter 4 discusses the practical implementation of the modelled results, both for the design of new culverts as well as for the retrofitting of existing culverts.
- Chapter 5 contains the summary, conclusions and recommendations of the study.
- The list of references follows at the end of the report.

2 LITERATURE REVIEW

2.1 INTRODUCTION

When considering roads projects, the topography is rarely completely flat and featureless, and obstacles such as rivers or streams will be encountered at some stage or another. Many of these watercourses will only flow when it rains. Roads alignments require gentle curves, both horizontally and vertically, which frequently requires the construction of embankments. If water is allowed to collect next to these embankments, or even worse, overtop them (if the embankment was not designed to be overtopped), great damage can be caused to the roadway. This situation is also dangerous to motorists and people living downstream of the watercourse crossing.

2.2 CULVERT FORM AND FUNCTION

2.2.1 Culvert Applications

A culvert, for the purposes of this research, is a structure that allows water to flow under a road, railway tracks or any other obstruction that would inhibit such flow under gravity. In many cases, a culvert functions as a bridge-like structure designed to allow for the crossing of vehicles or pedestrians.

An obvious way to cross a watercourse is by constructing a bridge, however bridges can be very expensive and is not feasible for small watercourses, where culverts are the installed instead. Bridges generally maintain a clearance, or freeboard, between the surface of the water and the underside of the bridge, while culverts are generally designed to operate fully submerged.

When deciding between a culvert or a bridge for the crossing of a watercourse, there are various aspects to consider. In general, culverts are proposed (Schall *et al.,* 2012):

- Where bridges are not hydraulically required;
- Where debris and ice potential are tolerable;
- Where a more economical solution is required.

Conversely, bridges are generally proposed (Schall *et al.,* 2012):

- Where culverts are impractical, possibly due to topography;
- Where more economical than a culvert;

- To satisfy land-use and access requirements;
- To mitigate environmental concerns not satisfied by a culvert;
- To avoid floodway encroachments and
- To accommodate ice and large debris.

Economic considerations are of primary importance when considering the option of using either a bridge or a culvert at a stream crossing. The initial cost for a culvert is usually less than a bridge, and maintenance costs for bridges are typically more costly than for culverts (Schall *et al.,* 2012). Economics, however, is not the only consideration to keep in mind as safety and aesthetic considerations are also important.

A distinction exists between "lesser culverts" and "major culverts". Lesser culverts are culverts that are small enough to be designed by means of simplified hydraulic and hydrological analyses while more sophisticated procedures used in the hydraulic design of bridges are applicable in the design of major culverts. According to SANRAL (2013), a major culvert is a cellular structure with dimensions less than those defining a bridge, but with a clear span length (as measured horizontally at the soffit perpendicular to the faces of its supports) equal to or larger than 2.1 m, or diameter equal to or larger than 2.1 m, or a culvert with a total cross-sectional opening equal to or larger than 5 m^2. A lesser culvert, which is the focus of this research, is defined as having smaller dimensions as a major culvert (SANRAL, 2013).

In the case of lesser culverts, the optimal sizing of the culvert, operating under inlet control conditions, limits the total upstream energy (H) to 1.2 times the vertical dimension (D) (SANRAL, 2013). The objective of the sizing of a culvert in general is to convey its maximum design flood safely and sustainably, while limiting the size of the culvert to be as economical as possible.

2.2.2 Profiles and Materials

Various types of culvert cross-sections exist. The most commonly used shapes include circular, box (rectangular), elliptical, pipe-arch and arch. The shape selection is based on the cost of construction, the limitation on upstream water surface elevation, roadway embankment height and hydraulic performance (Norman *et al.*, 2001).

The selection of a culvert material may depend upon structural strength, hydraulic roughness, durability (corrosion and abrasion resistance) and constructability. The most commonly used culvert materials are concrete (both reinforced and non-reinforced), corrugated metal (aluminium or steel) and plastic (HDPE or PVC) (Schall *et al.*, 2012). Other materials may also be used. Figure 2-1 and Figure 2-2 show examples of a concrete box culvert and a corrugated metal pipe respectively. Table 2-1 below summarises types of culvert cross sections.

Table 2-1: Summary of types of culvert cross-sections

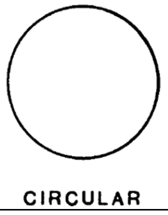
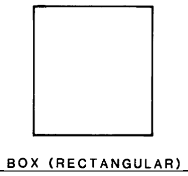
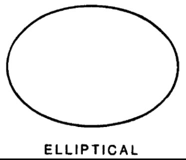
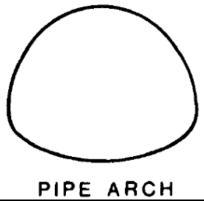
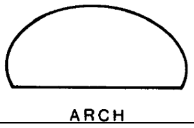
Shape	Material	Construction process	Picture
Circular	Concrete, corrugated metal, aluminium, steel, HDPE, PVC	Installation in fill as part of road construction; trenching and pipe laying; Pipe Jacking.	
Box (Rectangular)	Concrete	Installation in fill as part of road construction; Trenching and installation	
Elliptical	Corrugated metal, concrete	Installation in fill as part of road construction;	
Pipe-arch	Corrugated metal, stonemasonry, concrete	Installation in fill as part of road construction;	
Arch	Metal, Stonemasonry, Concrete	Installation in fill as part of road construction.	

Figure 2-1: Concrete box culvert (Schall *et al*., 2012)

Figure 2-2: Corrugated metal pipe culvert (Schall *et al*., 2012)

Various different culvert inlet configurations can be utilised. A summary of commonly used inlet configurations is provided in Table 2-2. Hydraulic performance, structural stability, aesthetics, erosion control and fill retention are considerations in the selection of various inlet configurations (Schall *et al.*, 2012). In South Africa, precast wingwall units are available as shown in Figure 2-3.

Table 2-2: Summary of culvert inlet configurations (Schall *et al.*, 2012)

Inlet Configuration	**Picture**
Projecting Barrel	
Cast-in-place concrete headwalls	
Precast or prefabricated end sections	
Mitered to slope	

Figure 2-3: Precast wingwall units available in South Africa (Rocla, 2020)

2.3 CULVERT HYDRAULICS

2.3.1 Inlet and Outlet Control

Culvert hydraulics are well defined by the two conditions which govern the flow through the culvert barrel. Conveniently, these two conditions are named after the position where the dominant variables which influence the head required to push the water through the culvert can be found, namely inlet and outlet control conditions.

Inlet control occurs at steep culverts and the flow in the culvert is only limited by the size, shape and configuration of the inlet. It is the sudden reduction of the cross-sectional flow area at the inlet where an open channel enters the culvert that determine the flow through the culvert, even though the actual culvert barrel could convey higher flow rates (Jaeger *et al.*, 2019). With inlet control, flow goes through critical depth near the inlet and downstream disturbances are not propagated upstream where flow is supercritical in the culvert barrel (Jones *et al.*, 2006).

Outlet control occurs for mild slope culverts where free surface flow is subcritical and for any slope where the barrel is completely submerged. In these cases, the tailwater is the control (Jones *et al.,* 2006). Under outlet control, the barrel of the culvert contributes to the head loss, and therefore calculations of outlet control incorporates parameters from inlet control as well as the length and material of the culvert and the tailwater height (Jaeger *et al.,* 2019).

It is useful to keep in mind that inlet control occurs when the flow capacity of the culvert entrance is less than the flow capacity of the culvert barrel. The culvert entrance therefore controls the headwater elevation for a given flow. Similarly, outlet control occurs when the culvert flow capacity is limited by downstream condition or by the flow capacity of the culvert barrel (Brunner *et al.,* 2018).

Inlet control occurs most often and is preferred since it yields the smallest culvert cross-section for a given upstream head and the higher flow velocities through the culvert barrel prevents the deposition of sediment inside the culvert (SANRAL, 2013).

Several different examples of inlet control are depicted in Figure 2-4.

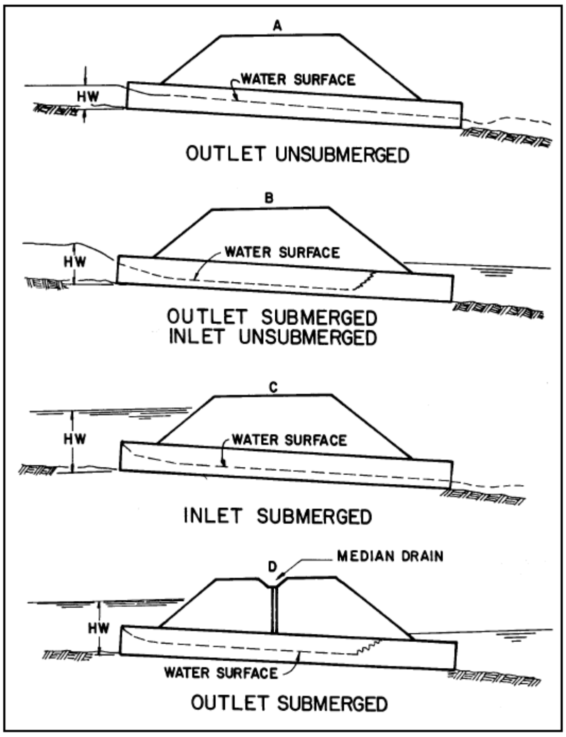


Figure 2-4: Types of inlet control (Norman *et al.,* 2001)

Sketch A in Figure 2-4 depicts a condition where neither the inlet nor the outlet end of the culvert is submerged, flow passes through critical depth just downstream of the culvert entrance with supercritical flow occurring in the barrel. In sketch B the submergence of the outlet end of the culvert does not assure outlet control, rather the submergence is caused by the hydraulic jump that forms in the barrel. Sketch C is the most typical inlet control design situation and also represents the focus of this study. Sketch D illustrates the fact that even submergence of both the inlet and the outlet ends of a culvert does not assure full flow. In this case, the median inlet provides ventilation, and if this were not the case, the flow in the culvert barrel might alternate between full flow and partly full flow.

2.3.2 Energy Equations

Bernoulli's equation states that the total energy at all points along a steady continuous streamline of an ideal incompressible fluid flow is constant, and is shown in Equation 1:

$$\boldsymbol{z + \frac{p}{\rho g} + \frac{V^2}{2g} = Constant}$$ (Equation 1)

Where:

z = Elevation (m)

p = Pressure (Pa)

V = Average velocity of the fluid at a point in the flow under consideration (m/s)

g = standard gravity (m.s^{-2})

ρ = Density of the fluid (kg/m^3)

The first term, z, is the elevation or potential energy per unit weight of fluid with respect to an arbitrary datum, called elevation or potential head. The second term, p/ρg, represents the work done in pushing a body of fluid by fluid pressure and is known as pressure energy per unit weight of fluid. The third term, $V^2/2g$, is the kinetic energy per unit weight of fluid (Featherstone, 1995).

When considering a steady flow along a streamline between two sections (say section 1 and section 2), the energy equation (Equation **1**) becomes:

$$z_1 + \frac{p_1}{\rho g} + \frac{V_1^2}{2g} = z_2 + \frac{p_2}{\rho g} + \frac{V_2^2}{2g}$$ (Equation 2)

Bernoulli's equation can be modified in the case of real incompressible fluid flow by introducing a loss term in the equation which would take into account the energy expended in overcoming the frictional resistances caused by viscous and turbulent shear stresses and other resistances due to changes of section, valves and fittings (in the case of pipe flow), etc. The turbulent losses also depend upon the roughness of the interior surface of the pipe, or culvert wall and the fluid properties of density and viscosity (Featherstone, 1995).

Therefore, for real incompressible fluid flow, the energy equation is:

$$z_1 + \frac{p_1}{\rho g} + \frac{V_1^2}{2g} = z_2 + \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + Losses$$

(Equation 3)

The general energy equation above (Equation 3) can be modified for culvert flow, as follows:

$$z_1 + y_1 + \frac{\bar{V}_1^2}{2g} = z_2 + y_2 + \frac{\bar{V}_2^2}{2g} + h_{f\,1-2} + \sum h_{l_{1-2}} \qquad \text{(Equation 4)}$$

Where:

z_1 and z_2 = upstream and downstream bed elevations (m)

y_1 and y_2 = upstream and downstream water depths (m)

$\bar{V}_1$ and $\bar{V}_2$ = upstream and downstream average velocities (m/s)

$h_{f\,1-2}$ = friction losses between cross-sections 1 and 2 (m)

$\sum h_{l_{1-2}}$ = transition losses between cross-section 1 and 2 (m)

Regardless of the flow conditions through the culvert, the energy equation (Equation 4) must be satisfied, together with the continuity equation (sum of inflows equals the sum of outflows) (SANRAL, 2013).

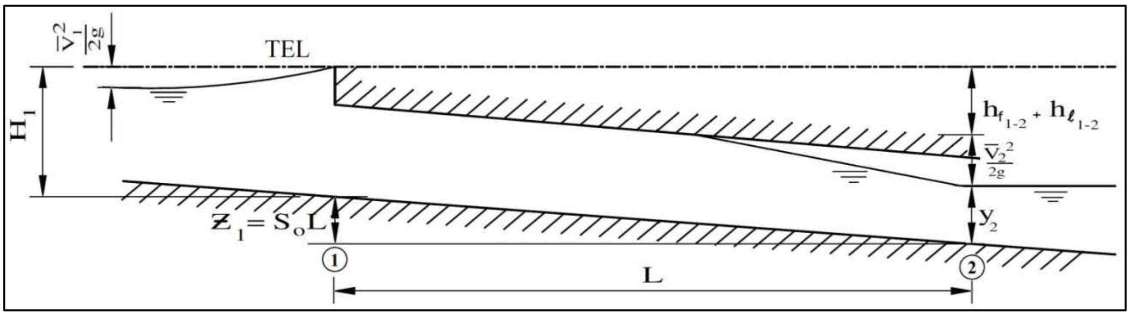


Figure 2-5: Energy components of flow through a culvert (SANRAL, 2013)

Figure 2-5 shows the energy components of flow through a culvert (SANRAL, 2013). By setting the energy reference line at the level of the downstream invert level ($z_2 = 0$), (Equation 4) can be simplified to:

$$H_1 = H_2 + h_{f\,1-2} + h_{l_{1-2}} - z_1 \qquad \text{(Equation 5)}$$

Where:

H_1 and H_2 = upstream and downstream energy levels, measured relative to the inlet invert level (m).

2.3.3 Equations for calculating the flow through culverts under inlet control

Table 2-3 summarises selected equations for calculating the flow through culverts under inlet control conditions:

Table 2-3: Equations for calculating the flow through culverts under inlet control

Reference	Type	Equation	Limitations
SANRAL, 2013	Round Culverts	$$\frac{Q}{D^2\sqrt{gD}} = 0.48\left[\frac{S_0}{0.4}\right]^{0.05}\left[\frac{H_1}{D}\right]^{1.9}$$ (Equation 6)	H$H_1/D < 0.8$
		$$\frac{Q}{D^2\sqrt{gD}} = 0.44\left[\frac{S_0}{0.4}\right]^{0.05}\left[\frac{H_1}{D}\right]^{1.5}$$ (Equation 7)	$0.8 < H_1/D < 1.2$
		$$Q = C_D A\sqrt{2g\left(H_1 - \frac{D}{2}\right)}$$ (Equation 8)	$H_1/D \geq 1.2$
	Rectangular Culverts	$$Q = \frac{2}{3}C_B B H_1\sqrt{\frac{2}{3}gH_1}$$ (Equation 9)	$H_1/D \leq 1.2$
		$$Q = C_h BD\sqrt{2g(H_1 - C_h D)}$$ (Equation 10)	$H_1/D > 1.2$
Norman et al, 2001 Schall et al., 2012	Unsubmerged Equation Form 1	$$\frac{H_1}{D} = \frac{H_c}{D} + K\left[\frac{1.811\,Q}{AD^{0.5}}\right]^M + K_s S_o$$ (Equation 11)	$\frac{Q}{AD^{0.5}} < 1.93$
	Unsubmerged Equation Form 2	$$\frac{H_1}{D} = K\left[\frac{1.811\,Q}{AD^{0.5}}\right]^M$$ (Equation 12)	$\frac{Q}{AD^{0.5}} < 1.93$
	Submerged	$$\frac{H_1}{D} = c\left[\frac{1.811\,Q}{AD^{0.5}}\right]^2 + Y + K_s S_o$$ (Equation 13)	$\frac{Q}{AD^{0.5}} > 2.21$
Marek, 2009	Fifth-degree polynomial equation	$$H_1 = [a + bF + cF^2 + dF^3 + eF^4 + fF^5]D - 0.5DS_0$$ (Equation 14) Where: $F = \frac{1.811\,Q}{BD^{\frac{3}{2}}}$ (Equation 15)	$0.5 \leq \frac{H_1}{D} \leq 3$
	Orifice Equation	$$H_1 = \left[\frac{Q}{k}\right]^2 + \frac{D}{2}$$ (Equation 16) Where: $k = \frac{0.6325Q_3}{D^{\frac{1}{2}}}$ (Equation 17)	$\frac{H_1}{D} > 3$
Charbeneau, 2005	Unsubmerged conditions	$$\frac{H_1}{D} = \frac{3}{2}\left(\frac{1}{C_e}\right)^{\frac{2}{3}}\left(\frac{Q}{BD\sqrt{gD}}\right)^{\frac{2}{3}}$$ (Equation 18)	$\frac{H_1}{D} < \frac{3}{2}C_f$
	Submerged Conditions	$$\frac{H_1}{D} = \frac{1}{2{C_g}^2}\left(\frac{Q}{BD\sqrt{gD}}\right)^2 + C_f$$ (Equation 19)	$\frac{H_1}{D} > \frac{3}{2}C_f$

Where:

H_I = Headwater depth above inlet control section invert (m)

Q = Discharge (m^3/s)

D = inside diameter (m) or height (inside) (m)

A = Full cross sectional area of culvert barrel (m^2)

S_0 = slope of culvert bed (m/m)

$C_D \approx 0.6$

B = width (inside) (m)

C_B = 1 for rounded inlets (r > 0.1B) and

C_B = 0.9 for square inlets

C_e, C_f, C_g = Representative parameter values for culvert performance

C_h = 0.8 for rounded inlets and

C_h = 0.6 for square inlets.

H_c = Specific head at critical depth (m) $(d_c = \frac{V_c^2}{2g})$

K, M, c, Y = Constants

g = standard gravity (9.81 m/s^2)

K_s=Slope correction, -0.5 (mitered inlets +0.7)

a, b, c, d, e, f = regression coefficients

F = Function of average outflow discharge routed through a culvert

It is evident from Table 2-3 that there are various equations to the designer's disposal when calculating the flow through culverts under inlet control. A comparison between these equations are shown in the performance curve in Figure 2-6. Performance curves will be explained in Chapter 2.3.4.

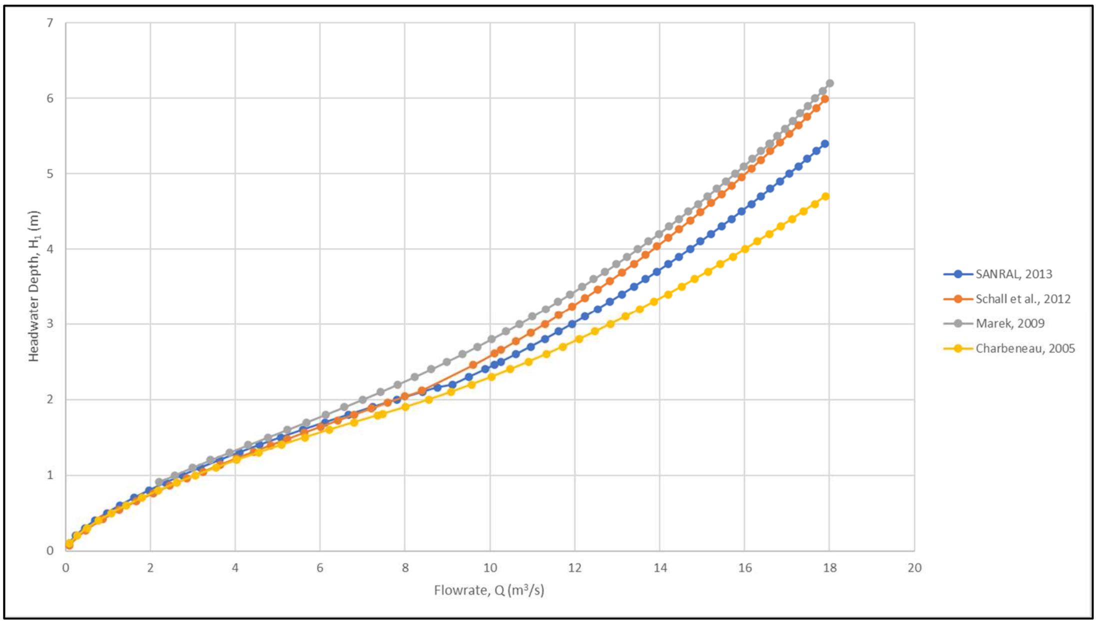


Figure 2-6: Comparison between inlet control performance curves for selected equations

Table 2-4 shows the values for the various parameters of a box culvert that were used for the comparison between performance curves in Figure 2-6:

Table 2-4: Parameters for the comparison of performance curves

Parameter	Value	Note
D	1.8 m	Assumed Height
S_0	0 m/m	Assumed no slope
B	1.8 m	Assumed width
C_b	0.9	Assumed square inlets
C_h	0.6	Assumed square inlets
M	2	Square edge in headwall
K	0.0083	Square edge in headwall
K_uS	-0.01	Square edge in headwall
a	0.144138	Box culvert with straight wingwall
b	0.461363	Box culvert with straight wingwall
c	-0.092150	Box culvert with straight wingwall
d	0.020003	Box culvert with straight wingwall
e	-0.001360	Box culvert with straight wingwall
f	0.000036	Box culvert with straight wingwall

C_e	1	Box-culvert
C_f	0.667	Box-culvert
C_g	0.667	Box-culvert
g	9.81 m/s^2	Standard gravity

The performance curves (Figure 2-6) shows that the results of the different equations tend to be very similar (for similar assumed input parameters) up to H_1/D of 0.8. From this value upwards, the formulas seem to diverge, with the Charbeneau (2005) formula calculating the lowest headwater depth for a given flowrate and the Marek (2009) (markedly at the transition zone) and Schall et al. (2012) formulae calculating the highest.

2.3.4 Performance Curves

Performance curves are plots of headwater depth versus flow rates for specific culverts. The resulting graphical depiction of culvert operation is useful in evaluating the hydraulic capacity of a culvert for various headwaters (Schall *et al*., 2012).

Both the inlet and outlet controls must be plotted on a performance curve. This is necessary because the dominant control at a given headwater is hard to predict. A control may also shift from the inlet to the outlet (or vice-versa) over a range of flow rates.

A graph which compares performance curves is shown in Figure 2-7 to graphically illustrate the results obtained for tests performed on different angles of headwall inclination. This experiment was carried out by Ashour *et al.* (2014). This graph shows that a projected headwall produced the highest headwater depth while a 15 degree headwall performed the best, with the lowest headwater depth. This suggests that a smaller angle of headwall inclination will produce the best culvert performance.

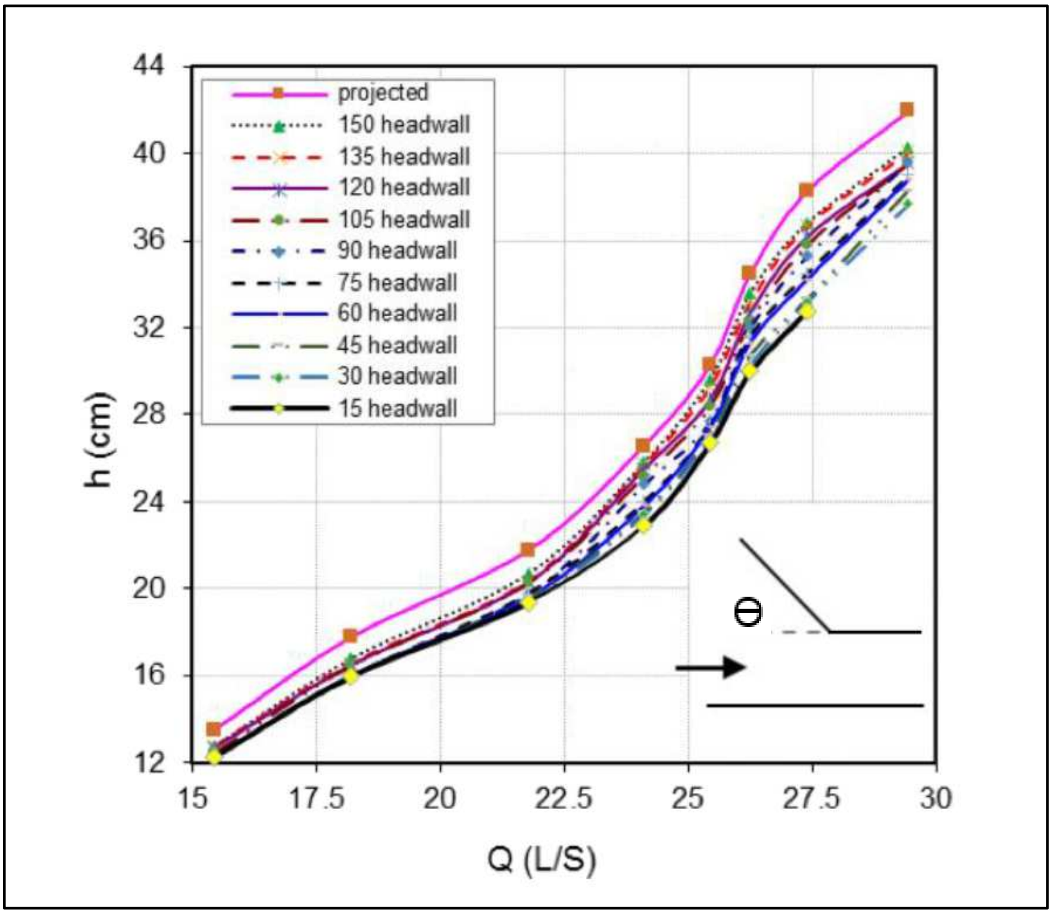


Figure 2-7: Example of a performance curve (Adapted from Ashour et al., 2014)

The component of the performance curve for unsubmerged flows are shown in Figure 2-8. The graph in Figure 2-8 (a) illustrates that a culvert initially functions as a weir for unsubmerged flows into a culvert. The component of a performance curve where flow through the culvert causes the inlet to be fully submerged on the upstream side is shown in **Error! Reference source not found.** (b).

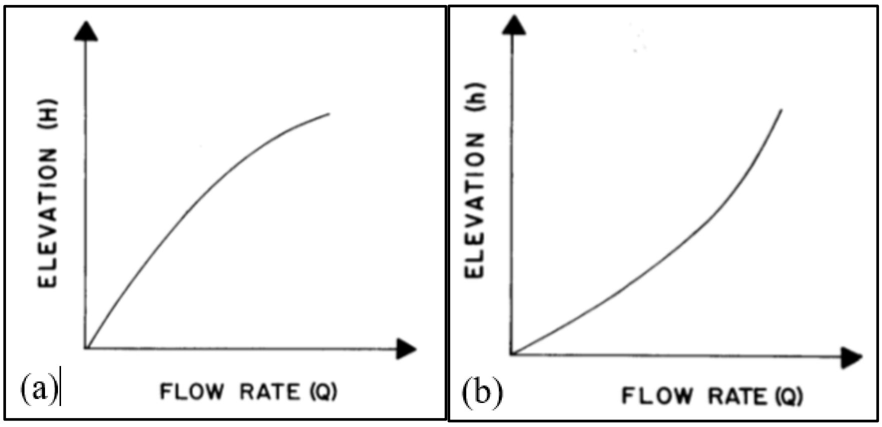


Figure 2-8: Performance curve for weir flow (Unsubmerged flow) (a) and for submerged flow (b) (Adapted from Norman et al., 2001)

Between submerged and unsubmerged flow conditions, a transition condition exists for which neither the submerged nor the unsubmerged forms of the equations provide accurate headwater predictions. Fifth-order polynomial equations were developed which predict the headwater in this uncertain region of flow, as reported by Jones *et al*. (2006).

This transition area as calculated using the fifth-order polynomial equations, as well as submerged and unsubmerged flow data is shown as an example in Figure 2-9.

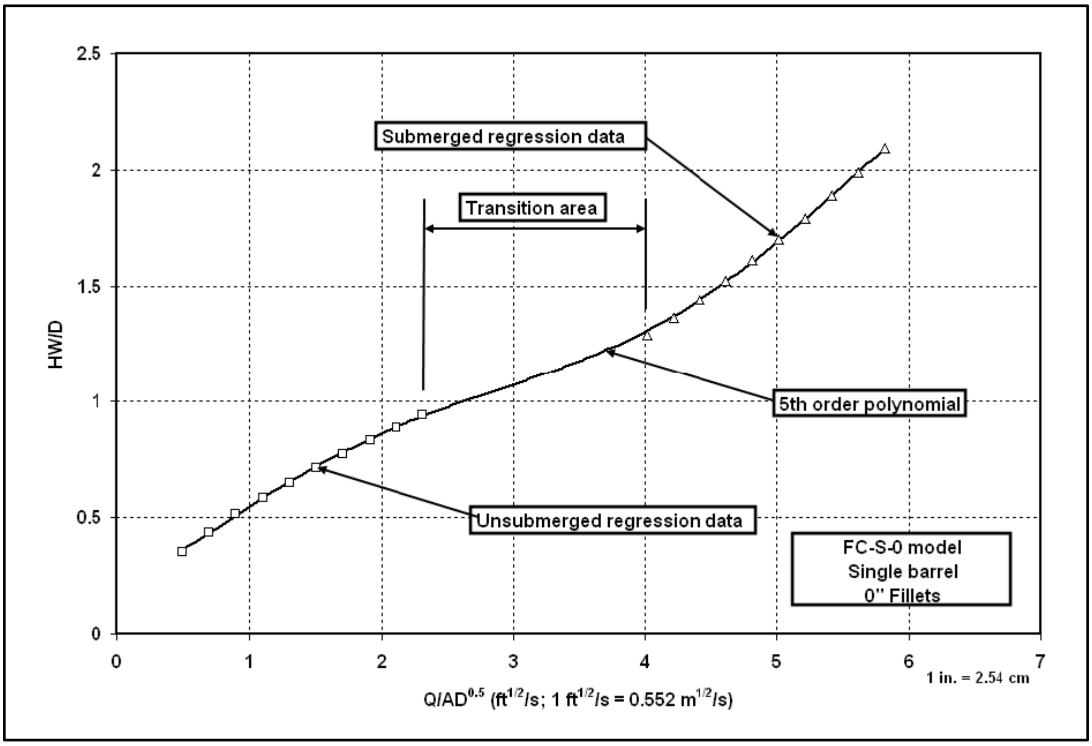


Figure 2-9: Transition Area showing unsubmerged and submerged inlet flow conditions (Jones et al., 2006)

2.4 CULVERT DESIGN

2.4.1 Simplified Design Process

A culvert's purpose is to prevent water from overtopping or collecting next to roadway embankments. The sizing of each culvert will be the result of unique physical and design parameters applicable to the culvert site, but the process to size most culverts is the same. This process is described in the SANRAL Drainage Manual (SANRAL, 2013) and can be summarised as follows:

1. Determine Q (Discharge) from hydrological calculations;
2. Determine H_{1max} (Maximum head allowable) from vertical road alignment height;

3. The design return period for different road classes is determined based on the reference 20 year recurrence interval flood (Q_{20});
4. Determine the maximum probable value of the downstream energy level (H_2) in accordance with downstream conditions;
5. The culvert can then be sized using the applicable hydraulic equations.

It should be noted that the SANRAL Drainage Manual method only gives the option to select culverts with square inlets and culverts with rounded inlets. This method therefore does not make provision for any further inlet improvements.

2.4.2 Additional Design Considerations

The hydraulic performance of a culvert is determined by its physical characteristics (number of barrels, barrel shape, barrel material and inlet configuration (Jaeger, 2019). Culverts must be designed to safely convey Q_{design}, while making sure, under all flow conditions, that the flow velocities are neither too high or too low. High flow velocities may cause downstream scouring and erosion, while low flow velocity may cause sediment build up and culvert blockage (Muste, 2009). High flow velocities, low flow depths and high outlet drops can cause problems with migration for aquatic organisms (Behlke *et al.* 1991).

The height of a culvert is constrained by site conditions. The use of multiple culverts in parallel is commonly used to convey Q_{design} while keeping the headwater at acceptable levels. To determine the hydraulic performance of multiple culverts in parallel, the capacity of one of the culverts is determined and then multiplied by the number of culverts required. Installing one of the culverts at a lower depth than the rest could assist with providing the water depth required by migrating aquatic organisms (Jaeger, 2019).

2.4.3 Hydrology and the changing climate

Much of the data and many of the variables used in the hydrological calculation methods are based on historical rainfall distribution and storm intensity data for the areas on which they are applied. The extent to which these variables may change in future as a result of climate change is the subject of intense scientific research. Recent studies have predicted, under various scenarios, decreased rainfall over various regions of Southern Africa, including the Limpopo Province of South Africa, particularly during the summer rainfall season. Significantly drier winters are also projected for the South-Western Cape. Despite predictions of general drying over most of Southern Africa, slight to moderate increases are projected over the central interior and South-Eastern parts of South Africa during spring and summer

(Mambo *et al.* 2017). Further projections show a tendency towards an increase in intensity of rainfall, or extreme events (Mambo *et al.* 2017), which is the main concern when culverts are to be designed.

2.4.4 Software Packages

Various software packages are available to assist with the design of culverts. These include, amongst others, Bentley OpenFlows CulvertMaster (Bentley, 2023)and Hydrology Studio's Culvert Studio (Hydrology Studio, 2023). Two specific software packages however, HEC-RAS (HEC-RAS, 2023) and HY-8 (HY-8, 2019), hardly need any introduction to the experienced culvert designer.

HEC-RAS (HEC-RAS, 2023) was developed by the U.S. Army Corps of Engineers Hydrologic Engineering Centre (HEC). The River Analysis System (RAS) software allows the user to perform one-dimensional steady and 1D and 2D unsteady river flow hydraulics calculations (Brunner, 2016). The software also has additional functionalities such as sediment transport and water temperature / water quality modelling. It has been the subject of various studies and has been proven to perform well in laboratory and real world applications (Brunner *et al.*, 2018 and May *et al.,* 2000).

HEC-RAS' (HEC-RAS, 2023) culvert functionality uses the US Federal Highway Administration's (FHWA) standard equations for culvert hydraulics under inlet control conditions (Equations 11, 12 and 13, see Table 2-3). For outlet control conditions, it balances the energy equation from downstream to upstream (Brunner *et al.,* 2018). Culvert calculations in HEC-RAS can be performed for nine shapes, including box (rectangular), circular, elliptical., arch, pipe arch, semi-circular, low profile arch, high profile arch and Con Span (a culvert composed of two vertical walls and an arch between them) culverts (Brunner *et al.,* 2018).

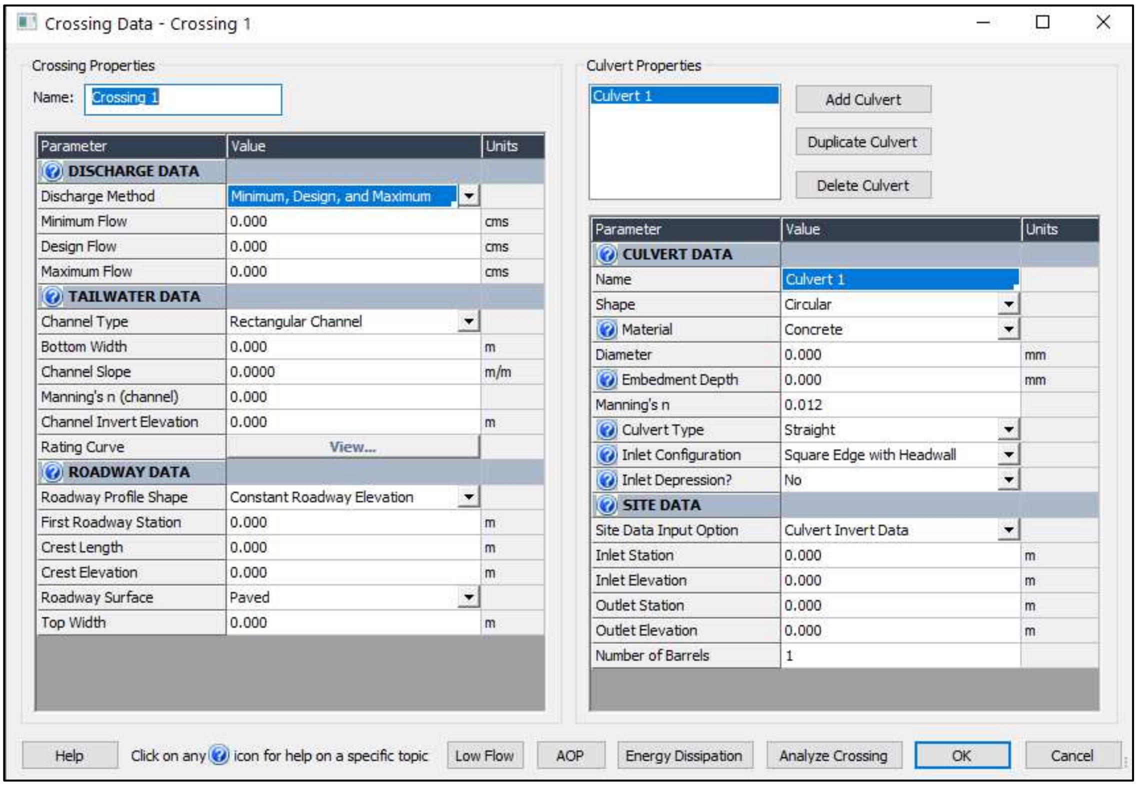
HY-8 (HY-8, 2019) was developed by the US Department of Transport, Federal Highway Administration (FHWA). Whereas HEC-RAS has the functionality to analyse culvert flow, HY-8 was developed purely for analysing culverts and performs consistently relative to standard calculations (Hotchkiss *et al.,* 2006).

HY-8 enables engineers to analyse single or multiple culverts barrels with various inlet options. Culvert shapes that can be analysed using HY-8 include circular, concrete box, elliptical., pipe arch, arch (open bottom), low-profile arch, high-profile arch, metal box, concrete open-bottom arch, and South-Dakota concrete box culvert. There is also an option to create a user defined culvert shape.

The HY-8 user also has the option to select various culvert materials, including concrete, corrugated steel, corrugated Aluminium, PVC, smooth HDPE and Corrugated PE.

HY-8 also has the functionality to analyse various types of culverts, including straight, side-tapered circular, side-tapered rectangular, slope tapered as well as single or double “broken back” culverts (culverts with multiple slopes, see Figure 2-12).

HY-8 is relatively straightforward to use. All the parameters required to simulate a culvert is defined on a single window, as shown in Figure 2-10.



Crossing Data - Crossing 1

Crossing Properties

Name: Crossing 1

Parameter	Value	Units
DISCHARGE DATA		
Discharge Method	Minimum, Design, and Maximum	
Minimum Flow	0.000	cms
Design Flow	0.000	cms
Maximum Flow	0.000	cms
TAILWATER DATA		
Channel Type	Rectangular Channel	
Bottom Width	0.000	m
Channel Slope	0.0000	m/m
Manning's n (channel)	0.000	
Channel Invert Elevation	0.000	m
Rating Curve	View...	
ROADWAY DATA		
Roadway Profile Shape	Constant Roadway Elevation	
First Roadway Station	0.000	m
Crest Length	0.000	m
Crest Elevation	0.000	m
Roadway Surface	Paved	
Top Width	0.000	m

Culvert Properties

Culvert 1

Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Concrete	
Diameter	0.000	mm
Embedment Depth	0.000	mm
Manning's n	0.012	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	m
Inlet Elevation	0.000	m
Outlet Station	0.000	m
Outlet Elevation	0.000	m
Number of Barrels	1	

Click on any icon for help on a specific topic

Figure 2-10: HY-8 Culvert / Crossing Data window

After analysing the culvert, results are given in tabular format. Rating curves, performance curves and water surface profiles can be plotted.

Kassem et al. (2006) compared data from a physical model with the headwater elevations computed by HY-8 and HEC-RAS and concluded that the comparison was satisfactory. The performance curve of this comparison is shown in Figure 2-11.

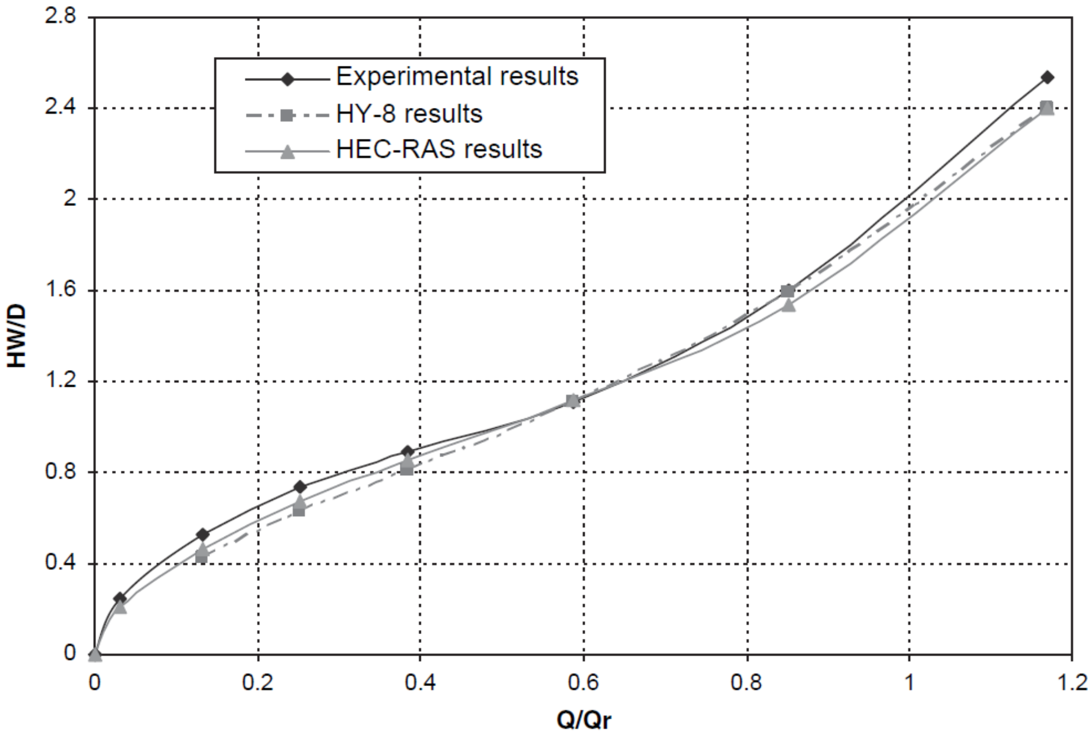


Figure 2-11: Comparison of experimental data with HY-8 and HEC-RAS results (Kassem et al. (2006))

It can be seen from Figure 2-11 that both software packages produced lower headwater depths at H_1/D values higher than 1.6 and lower than 1, compared to the experimental results.

2.4.5 Practical Considerations

Culverts may fail for a number of reasons. These include (SANRAL, 2013):

- Inadequate erosion protection and energy dissipation on the downstream side may cause scour;
- Supercritical flow approaching the culvert at an angle;
- Overtopping due to the flow in the culvert being blocked by debris;
- Scour around inlets;
- Piping between the culvert structure and the backfill and
- Culverts floating or popping up as a result of saturated fill around the culvert.

In general, the hydraulic design of culverts should minimise the disturbance to the natural equilibrium between flow and erosion processes in a watercourse. To this aim, concentrating flow should be avoided as far as possible (SANRAL, 2013).

Changing the direction of flow should be avoided if possible. Any misalignment between the culvert and the natural stream is considered bad practice, could cause sedimentation and erosion around the inlet, and reduces the capacity of the culverts (SANRAL, 2013; Jaeger, 2019). Avoiding skew inlets is especially important in multiple barrel culverts (Harrison *et al.,* 1972).

Another major cause of sedimentation is when the velocity of the flow is reduced inside the culvert, causing sediment to be deposited in the culvert, blocking the flow and blocking the passage of aquatic organisms (Jaeger, 2019). Conversely, having high flow rates through culverts can cause scouring on the outlet side (Norman *et al.,* 2001). Flow velocities through culverts should not be less than 1 m/s, and the culvert slope should not be less than 1%. Flow dissipators may have to be installed on the downstream side to ensure that the flow's erosive capacity is not significantly higher than under the original conditions (SANRAL, 2013).

If the flow upstream of the culvert is supercritical, in must be allowed to flow through the culvert virtually undisturbed to avoid considerable damming and erosion (SANRAL, 2013).

Culverts should also be placed on the lowest point of any embankment to avoid damming, which could lead to saturation of fill and foundation material (SANRAL, 2013).

It was mentioned before that the optimal sizing of the culvert, operating under inlet control conditions, limits the total upstream energy (H) to 1.2 times the vertical dimension (D). This dimension is also a good ratio to prevent siltation, inlet erosion and minimising the height of an embankment. SANRAL (2013) also states that the following minimum acceptable sizes should be considered to enable maintenance:

- For culverts up to 30 m in length:
    - 600 mm in diameter round culvert or
    - 750 mm (wide) x 450 mm (high) rectangular culvert
- For culverts longer than 30 m:
    - 900 mm in diameter round culvert or
    - 900 mm (wide) x 450 mm (high) rectangular culvert.

Debris grids can be provided if necessary, however, the flow area through the grid should be at least four times the flow area of the culvert (SANRAL, 2013).

2.4.6 Economics of culvert installations and improvements

It could happen that an existing culvert needs to be re-evaluated in terms of the flood for which it has been designed. A culvert's design flow rate could be adjusted upwards due to various factors, including changes in its catchment, the effects of climate change or due to the reclassification of the road it serves (requiring the culvert to convey floods with a higher return period).

If an existing culvert's hydraulic capacity has been calculated (by calculating the upstream energy head) and found to be insufficient for the new required design flow rate, the capacity of the culvert will have to be increased by:

- Replacing the culvert with one with a higher hydraulic capacity;
- Installing additional culverts in parallel;
- Changing the vertical alignment of the road to increase the allowable upstream energy head (H) (SANRAL, 2013 allows the level of H to be in excess of 1.2 D only under specific conditions);
- Attenuating the flood, or
- Optimising the inlet of the culvert to improve the hydraulic efficiency for culverts operating under inlet control.

These options should be carefully considered and options which are impractical, or which will not be allowed should be discarded. An economic evaluation of the remaining options should be carried out.

It has been found that improving the hydraulic efficiency of culverts by retrofitting existing culverts offers a lower cost and time efficient alternative compared to the replacement or rebuild of infrastructure (Jaeger, 2019). Additionally, it may reduce the need to close roads for major construction works, preventing additional economic costs.

2.5 PREVIOUS RESEARCH ON HYDRAULIC EFFICIENCY OPTIMISATION

To date, hydraulically optimised designs played a minor role in culvert design. There are plenty of design guidelines available to assist designers in selecting culvert sizes which will adequately convey a calculated design flood, taking into account all required parameters, but many engineers will consider the optimisation of culvert inlets risky if such optimisation could potentially reduce the size requirement of a culvert. While such a conservative approach is understandable, and even inherent in the engineering profession, there have been some research into the field of culvert inlet improvements which could enable engineers to incorporate these improvements into their designs with confidence.

Even in early research, the benefits of well-designed inlets were recognised. Straub *et al.* (1953) stated that rounded inlets have an advantage over square inlets for culverts operating under inlet control.

Ashour *et al.* (2014) found that the angle of entrance headwall inclination improves the discharge efficiency of both circular and box culverts, compared to projected culverts (similar to the one shown in Figure 2-2) of similar dimensions. The greatest improvement was found with an angle of 15° in the opposite direction of the stream. This improvement (under inlet control) was found to be 6.7% for circular culverts.

Jones *et al.* (2006) made the following findings and conclusions after experimental modelling:

- A 20.32 cm (8 inch) radius top bevel edge was the optimum shape among six shapes tested and improves culvert performance significantly. This improvement is more pronounced for multiple barrels at higher headwater depths.
- A 45° straight top bevel edge is an improvement over a square top edge with zero-degree wingwall flare edges.
- Rounded bevels for wingwall top edges had no discernible effect on culvert performance.
- The size of corner fillets, which are sometimes specified to minimise high-stress areas in the corners of rectangular culvert shapes, also had no discernible effect on the culvert performance as long as the net culvert area was used in the computation of the discharge.
- Multiple barrels had very little effect on performance curves, which gives credibility to the common practice of using single barrel design coefficients for multiple barrel culverts.
- Span to rise ratios of greater than 1:1 had very little effect on performance curves.
- Extending the inner walls onto the approach apron for multiple barrel culverts had no discernible effect on performance curves.

SANRAL (2013) states that the rounding off of inlet corners only gives a small (5% to 10%) increase in culvert capacity, however, by adapting the inlet section as shown in Figure 2-12, the capacity of long culverts with inlet control can often be increased. Harrison *et al.* (1972) states that this slope-tapered improvement's advantage is due to the additional head available at the throat section due to fall which is incorporated into the enclosed entrance section. This inlet can have over 100 percent greater capacity than a conventional culvert with square edges, depending on the height of the fall (Harrison *et al.*, 1972).

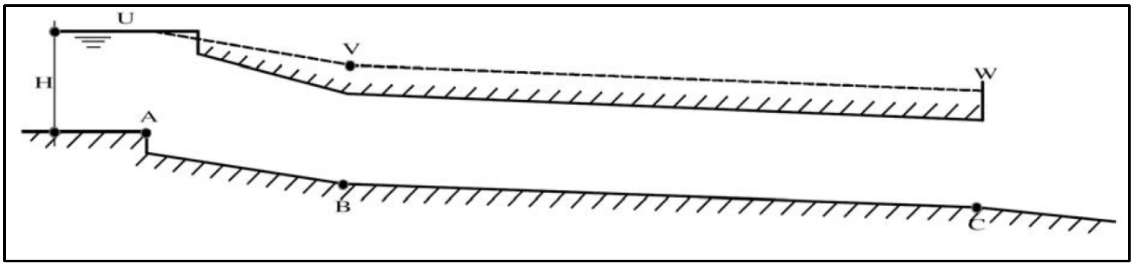


Figure 2-12: Steep culvert with dimensional and slope variations to increase the capacity (SANRAL, 2013)

Although not an inlet improvement, Dasika (1995) proposed forcing culverts to flow full by submerging the outlets of culverts to increase their capacities. The reasoning was that full flow in a culvert displaces all air within the cross-sectional area of the culvert, changing the flow to pressurized flow. Although the experiments showed that culverts operating in this way would flow more efficiently, his work was the subject of much criticism. Montes (1997) criticised this suggested approach for using two unsuitable empirical equations and suggests that it is preferable to use models that are “well grounded in rational theory”. Likewise, Jaeger (2019) found this approach to be unsuccessful and that elevating tailwater levels for discharge improvements cannot be recommended.

Jaeger (2019) also found through computational fluid dynamics modelling and an experimental flume that altering culvert inlet corners can substantially improve flow rates. He found that large, rounded inlets or 45° chamfers performed best, and that inlet angles of 30° and 60° caused greater turbulence than 45°. Specifically, he found that a rounded inlet corner with a radius of 0.15 times the culvert diameter is able to improve the flow rate up to 20% while maintaining constant headwater levels.

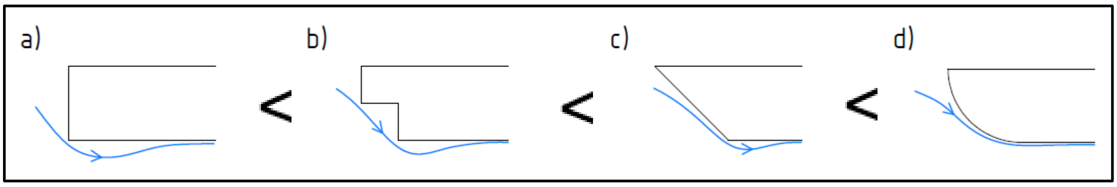


Figure 2-13: Inlet corner treatments with increasing efficiencies (adapted from Jaeger, 2019)

Figure 2-13 shows inlet corner types with increasing efficiencies: a) rectangular corner, b) socket inlet, c) straight bevel and d) round corner (Jaeger, 2019).

Kerenyi *et al.* (2005) conducted experimental model studies and found that culverts with a top bevel with a radius of 203 mm was more efficient than one with a 102 mm radius or one with a square edged bevel at the crown, which was the least efficient. The researchers also noted a significant hydraulic advantage for multiple culvert barrels over single barrels for submerged flow when modelling precast models with the optimum bevel on the top plate, especially for headwater depths of 1.5 times the culvert height.

Harrison (1972) states that bevelled edges increase culvert capacity by 5% to 20%, while side tapered inlets provide an increase in flow of 25% to 40%. He continues to state that slope-tapered inlets (similar to Figure 2-12 but with bevelled edges and side tapers) can increase the capacity of conventional culverts with square edges by over 100%.

French (1966) found that culvert performance can be increased without having to alter the culvert slope, by testing a variety of wingwall angles.

Graziano (2001) found, through model studies, that a cast-in-place, 30° flared wingwall inlet is approximately 8% more efficient than a similar model with a 0° flared inlet under unsubmerged conditions and for submerged conditions, the 30° flared wingwall resulted in a 10% lower H/D ratio than for the 0° flared inlet.

2.6 PHYSICAL MODELLING OF CULVERT SYSTEMS

2.6.1 Model Similarity

Hydraulic engineering structures can be designed using pure theory, empirical methods, semi-empirical methods (which are mathematical formulations based on theoretical concepts supported by suitable design experiments), physical models or mathematical models (Featherstone, 1995).

Dimensional analysis forms the basis for the design and operation of physical scale models which are used to predict the behaviour of their full-sized counterparts called “prototypes”. The basis of dimensional analysis is to condense the number of separate variables involved in a particular type of physical system into a smaller number of non-dimensional groups of the variables. (Featherstone, 1995). For culvert hydraulics, physical models should ensure geometric and Froude number similarity between the scale model and the prototype (Lang *et al.,* 2008).

Geometric similarity requires that all length scales are the same for the model and the prototype (length, culvert diameter, width, height etc.). This means that if the length of the culvert model is, for instance, 1/10th that of the prototype, all other dimensions should also be scaled to 1/10 (Lang *et al.,* 2008).

Froude number similarity, also known as kinematic similarity, is important for evaluating discharge and velocity. The Froude number (Fr) is defined in Equation 20:

$$Fr^2 = \frac{Q^2 B}{A^3 g} \qquad \text{(Equation 20)}$$

Where:

Q = Flow (m^3/s)

B = Width (inside) (m)

A = Area (m^2)

$g = gravitational\ acceleration\ (m/s^2)$

The Froude number is dimensionless. The velocity of discharge measured in the model and therefore be used to predict the average velocity or discharge in the prototype at the same relative depth of flow, using the Froude number (Lang *et al.,* 2008).

Dynamic similarity, or Reynolds (*Re*) number, similarity also has to be achieved for strict equivalency between model and prototype. The Reynolds number (*Re*) is defined in Equation 21:

$$Re = \frac{\rho V D_H}{\mu} \qquad \text{(Equation 21)}$$

Where:

ρ = fluid density (kg/m^3)

V = average channel velocity (m/s)

D_H = Hydraulic Diameter (m)

μ = fluid viscosity (kg/(m.s))

It is not possible, however, to achieve dynamic similarity in open channel flow models due to limitations imposed by the physical properties of the fluid (viscosity and density) (Lang *et al.,* 2008). Maintaining *Re* as high as possible in the model simulations and maintaining the same flow regime (laminar or turbulent) as in the prototype system can however minimise the error introduced by failing to maintain strict dynamic similarity.

2.6.2 Previous Physical Culvert Models in literature

Table 2-5 summarises various physical model studies carried out by researchers with regards to the optimisation of culvert performance.

Table 2-5: Previous model studies

Reference	Physical Model characteristics	Findings
Straub *et al.*, 1953	This culvert model consisted of a channel 305 mm deep, 762 mm wide and 15.24 m long in which culverts of various sizes could be installed. The upstream 3.05 m section of the channel is separated from the remainder of the channel by a bulkhead which forms the headwall of the culvert. The depth of this section was also 711 mm to permit variation in the headwater. A second bulkhead was installed at the culvert outlet. The slope of the complete unit could be varied between 0 per cent and 10 per cent. The culvert model was constructed of a 102 mm diameter pipe with an overall length of 10.67 m. The ends of the pipe were installed flush with the bulkheads. The inlet section was removable so that square and rounded inlets could be interchanged and piezometers were located at various intervals along the culvert for pressure measurements.	Rounded inlets had a head-advantage over square edged inlets for cases in which the control section was located at the inlet (inlet control).
Graziano, 2001	This model was constructed from plywood and the entire model was 11 m in length in total. A weir and a floating plywood wave suppressor was installed in the headbox to ensure a uniform flow in the headbox towards the culvert inlet. Downstream of the culvert barrel, the tailbox was equipped with an adjustable tailgate in order to create downstream control conditions. Water depths at various points in the culvert system were measured with a pressure transducer. The various inlets to be tested were constructed of acrylic. The aim of the model was to investigate the effect on culvert performance of wingwall flare, constant bevel height, wingwall mitre slope, parapets and the culvert barrel slope.	• A cast-in-place, 30^o flared wingwall inlet is approximately 8% more efficient than a similar model with a 0^o flared inlet under unsubmerged conditions. • For submerged conditions, the 30^o flared wingwall resulted in a 10% lower HW/D ratio than for the 0^o flared inlet.
Jones *et al.*, 2006	This physical culvert model consisted of a headbox of 2.44 m long by 2.44 m wide by 1.22 m high and a tailbox of 2.44 m long by 1.83 m wide by 0.92 m high. The headbox and tailbox were connected by the culvert barrel. Five electronic pressure sensors were built into the floor of the headbox and tailbox. An additional 40 pressure sensors were used to measure the hydraulic grade line inside the culvert model barrels. A two-dimensional robot was used to measure the velocity distribution in the tailbox and an automated tailgate at the downstream end of teh tailbox allowed for the adjustment of the tailwater depth. The model was fully automated (pump / flowmeter and tailgate / pressure sensor control logic) and was network controlled. Culvert barrels were constructed out of Plexiglas and the inlets designed of modular parts which could easily be changed for various configurations.	• A 20.32 cm (8 inch) radius top bevel edge was the optimum shape among six shapes tested. This improvement is more pronounced for multiple barrels at higher headwater depths. • A 45^O straight top bevel edge is an improvement over a square top edge with zero-degree wingwall flare edges. • Rounded bevels for wingwall top edges had no discernible effect on culvert performance. • The size of corner fillets, had no discernible effect on the culvert performance. • Multiple barrels had very little effect on performance curves.

Reference	Physical Model characteristics	Findings
		• Span to rise ratios of greater than 1:1 had very little effect on performance curves. • Extending the inner walls onto the approach apron for multiple barrel culverts had no discernible effect on performance curves.
Ashour *et al.*, 2014	This experimental setup consisted of a very large masonry model (25 m in length with a trapezoidal channel profile of 0.84 m bottom width, 0.55 m in height and side slopes of 1:1). The culvert barrel was 1.5 m in length. Both circular and box culvert models were tested under both inlet and outlet control conditions for flows between 15 and 40 l/s. The aim of the model was to test the impact of various headwall inclination angles on culvert efficiency.	• The angle of entrance headwall inclination improves the discharge efficiency of both circular and box culverts. • The greatest improvement was found with an angle of 15^{O} in the opposite direction of the stream. This improvement (under inlet control) was found to be 6.7% for circular culverts.
Jaeger, R. 2019	To test Dasika's conclusions (Dasika, 1995) a test flume was used with a width of 0.6 m and a total length of 5 m, with the culvert model inlet installed after 2.5 m. The maximum headwater height in the channel was 0.5 m and the tailwater could be raised up to 250 mm. The flow rate in the channel was controlled by a variable speed drive pump. Flows were measured using a magnetic flow meter. The water entered the channel through an overflow construction to reduce turbulence in the headwater. Rectangular and round culvert shapes were tested. Both shapes were tested for different lengths (0.4 m, 0.7 m and 1 m). Tests were carried out at flow rates up to 15 l/s and slopes up to 2.5 degrees. Culvert inlets had straight headwalls and sharp, rectangular inlet corners. To model improvements in discharge rates, a Perspex culvert model was placed in the centre of the 5 m x 0.6 m channel with the opening 20 mm above the ground level. A circular culvert model (length 100 mm and inner diameter 105 mm) was integrated into a sheet of Perspex to give a flush, rectangular inlet corner. A square edge with a headwall and a rounded inlet setup was tested. The experimental setup allowed for headwater heights of up to 0.6 m. A submerged overflow inlet was provided to reduce turbulence. Headwater depth measurements were taken with a ruler. A variable speed pump and magnetic flow meter completed the model.	• Elevating tailwater levels for discharge improvements cannot be recommended. • Altering culvert inlet corners can substantially improve flow rates. • Large, rounded inlets, or 45^{o} chamfers performed best, and inlet angles of 30^{o} and 60^{o} caused greater turbulence than 45^{o}. • Rounded inlet corners with a radius of 0.15 times the culvert diameter is able to improve the flow rate up to 20% while maintaining constant headwater levels.

2.7 SUMMARY OF LITERATURE STUDY

It is evident that the hydraulics of culvert design is well understood and successfully applied all over the world. The optimisation or improvement of the hydraulic performance of culverts have, unfortunately, not been a priority for many decades, with some renewed interest only observed recently. The research has shown that the hydraulic performance of culverts can be increased significantly by applying various improvements to the inlets of culvert which operate under inlet control conditions.

Another concern is that the capacities of installed culverts sometimes become insufficient due to factors such as climate change, changes in the culvert catchment area or changes in the classification of the road which the culvert serves. Research into the improvement of inlet characteristics of existing culverts by means of retrofitting is limited, even though it has been found that improving the hydraulic efficiency of culverts by retrofitting existing culverts offers a lower cost and time efficient alternative compared to the replacement or rebuild of infrastructure (Jaeger, 2019).

3 MODEL STUDY

This chapter describes the physical model which was constructed to test the hydraulic performance of culverts under inlet control conditions through the optimisation of selected inlet characteristics. The results of the experiments which were carried out is discussed and compared to selected established culvert equations.

The aim of the physical model was to test the following:

- The effect on hydraulic performance achieved by angled wingwalls and headwalls, and the optimum angle to achieve the best performance.
- The effect of including a ventilation device on the hydraulic performance of a culvert.

An experimental culvert model was constructed in the Water Laboratory of the University of Pretoria (UP Waterlab). The model consisted of a single barrel square culvert and three headwall / wingwall (inlet) combinations. The model channel and culvert barrel were constructed out of clear Plexiglass with a thickness of 10 mm. Two of the three culvert inlets were 3-D Printed. The model frame was hinged on one side and had two hydraulic jacks on the other side in order to be able to adjust the culvert slope. The model was supplied with two BADU Porpoise 22 1.1 kW pumps, installed in parallel. A mechanical flowmeter was supplied on the upstream side of the model. PVC conduits were cut into 200 mm lengths and pasted together and installed on the upstream side of the model channel in order to ensure uniform flow towards the culvert inlet and reduce wave action. Additionally, in order to reduce turbulence at the culvert inlet, water entered the model in a sump upstream of the PVC conduits. Figure 3-1 shows a drawing of the culvert model and Figure 3-2 shows a schematic flow diagram. In Figure 3-1 ISO denotes an isolation valve and WM denotes a water meter.

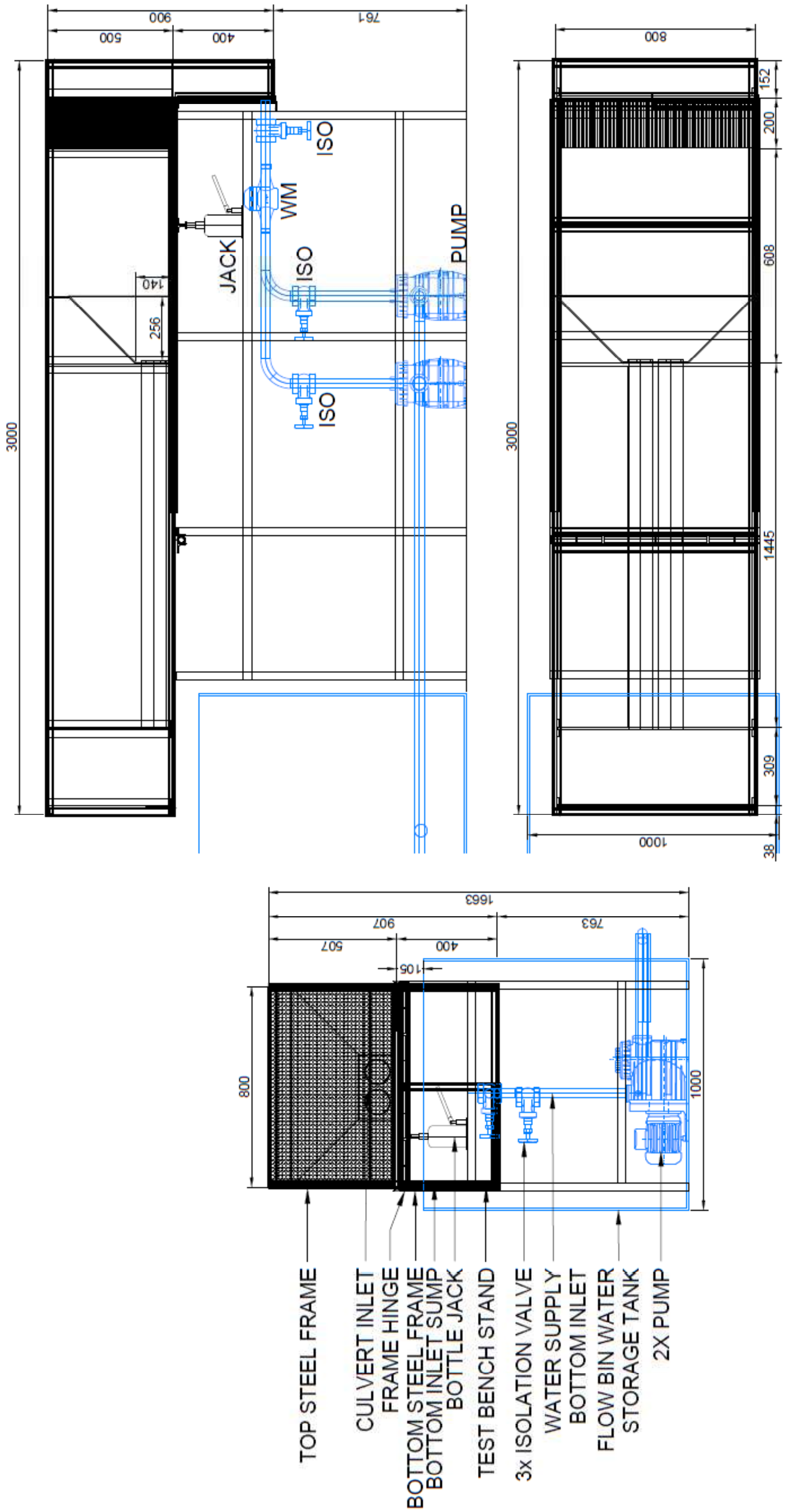


Figure 3-1: Drawing of experimental model

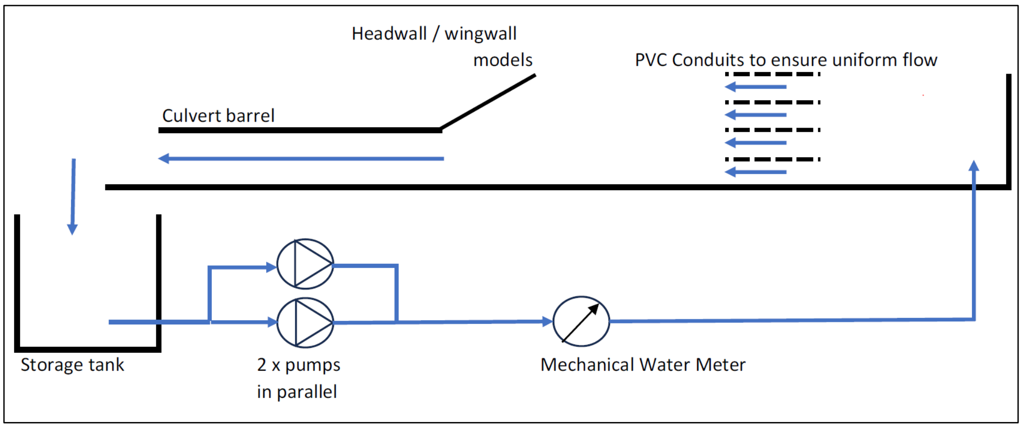


Figure 3-2: Schematic flow diagram of model

Three angles for the headwall and wingwalls were selected, namely 90 degrees, 45 degrees and 30 degrees. Both the wingwalls and headwalls were positioned at these angles, measured parallel with the inside of the culvert walls, opposite to the direction of flow. Since these configurations for the 45 degree and 30 degree models created complex shapes, these models were 3D printed as mentioned previously. The three headwall / wingwall models were printed so that their inlets could fit inside of a collar which was provided on the plexiglass culvert section. Figure 3-3 and Figure 3-4 show drawings of the 45 degree and 30 degree models respectively.

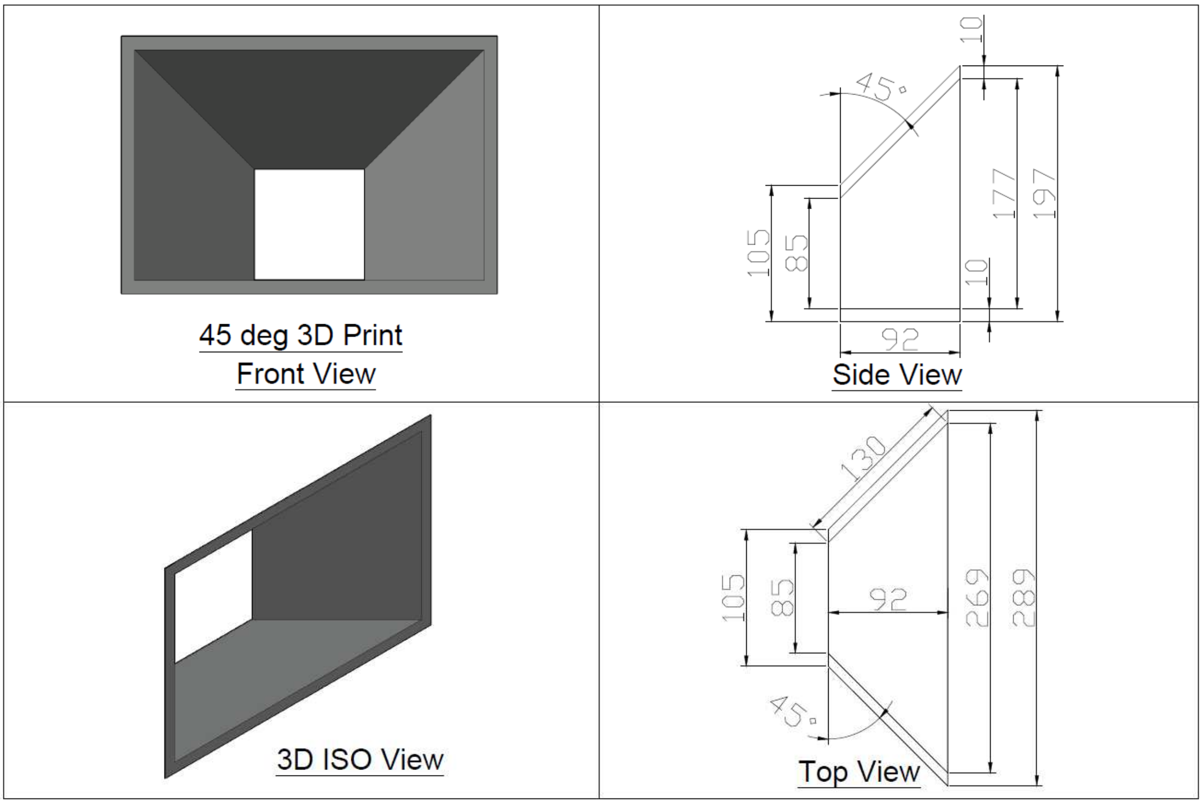


Figure 3-3: Drawing of the 45 degree model headwall / wingwall model

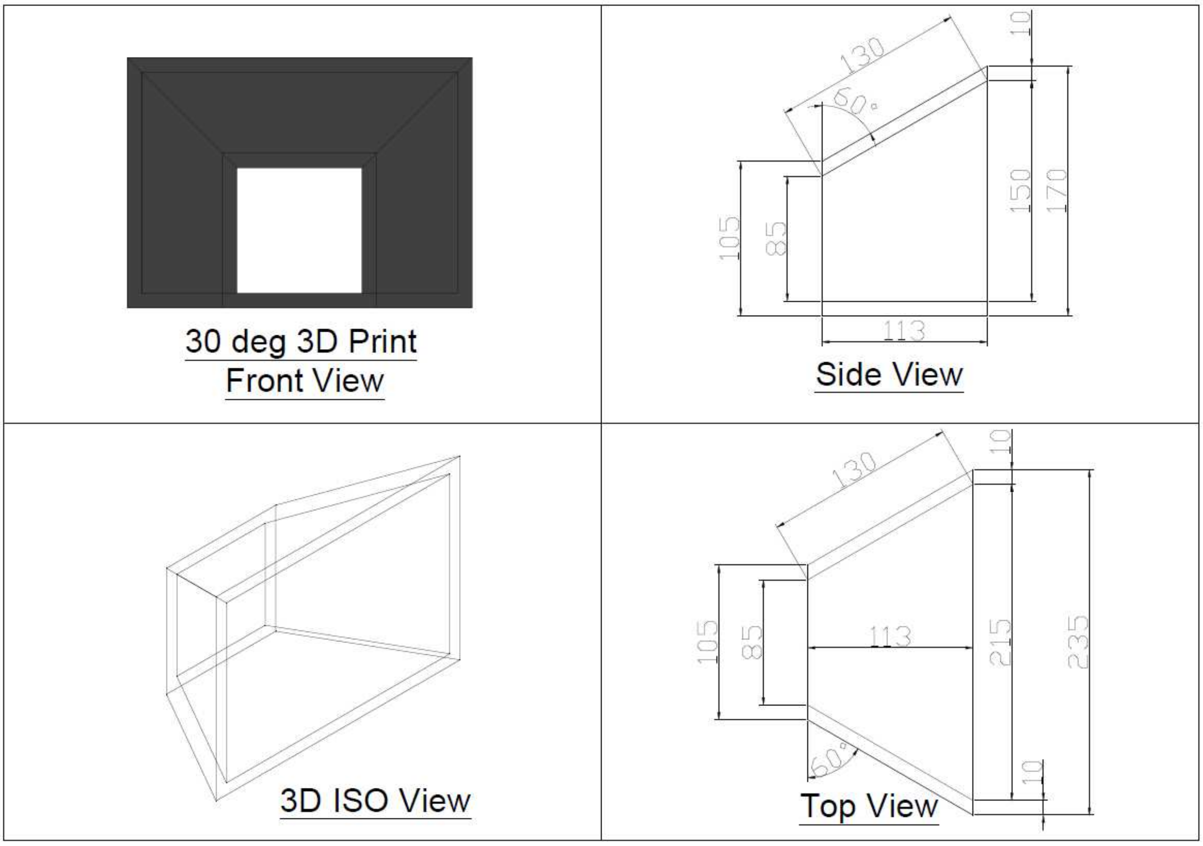


Figure 3-4: Drawing of the 30 degree headwall / wingwall model

A plastic tube was attached through the bottom of the culvert channel just upstream of the headwall. The purpose of this tube was to be able to take water level measurements without any wave interference. Additionally, a small plexiglass tube was attached through the collar on the culvert section in order to test the effect of introducing air into the culvert section downstream of the culvert inlet (refer to Figure 3-9).

Figure 3-5 shows the culvert from the downstream side. Note the PVC Conduits upstream of the 3D printed culvert inlet. Figure 3-6 shows the culvert from the upstream side. The PVC Conduits were stuck together in two parts to provide for flexibility in the setup of the model.

Figure 3-7 shows the culvert model with the 45 degree 3D printed inlet installed. Note the collar on the clear culvert section where the inlet is installed and the clear ventilation tube. Figure 3-8 shows the same 3D printed inlet from another angle. Note the attached plastic tube through the bottom of the model channel and the mechanical flowmeter. Figure 3-9 shows a close-up view of the 3D printed culvert inlet with the ventilation tube clearly visible.

Figure 3-5: Culvert model from downstream side

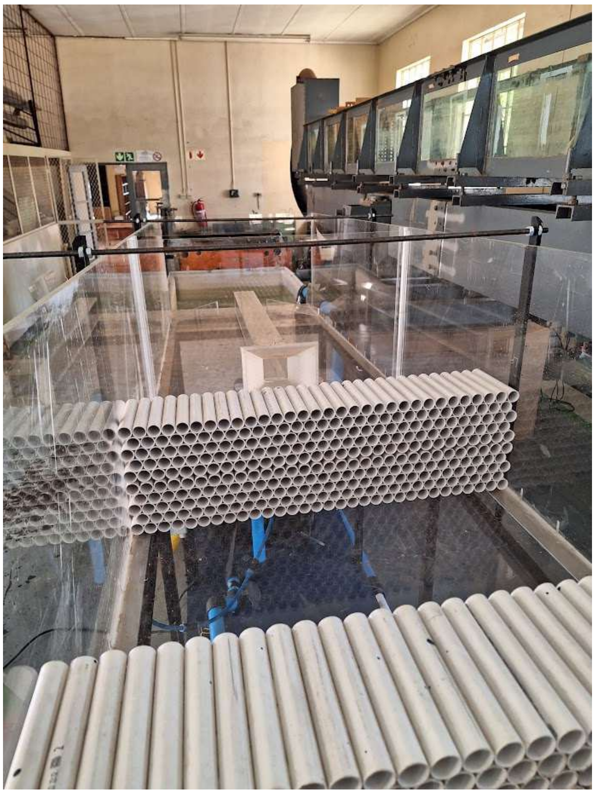


Figure 3-6: Culvert model from upstream side

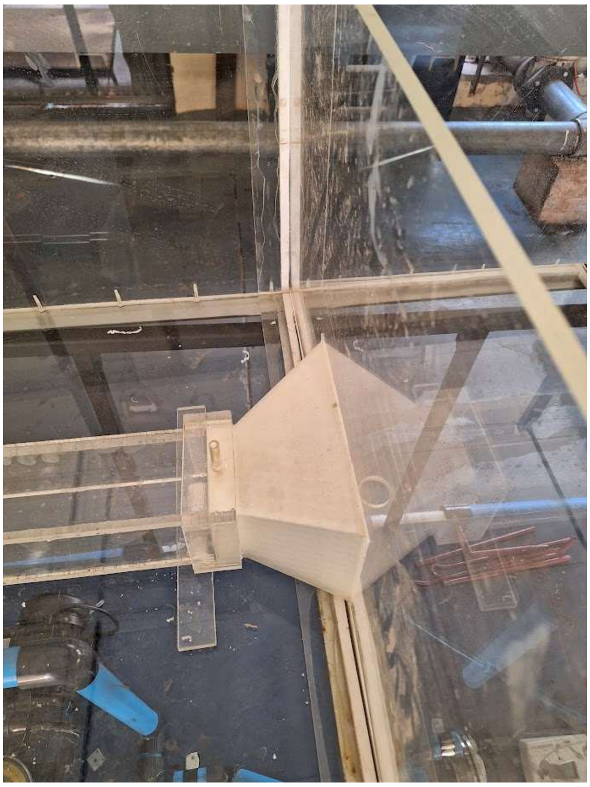


Figure 3-7: Culvert model showing 3D printed inlet

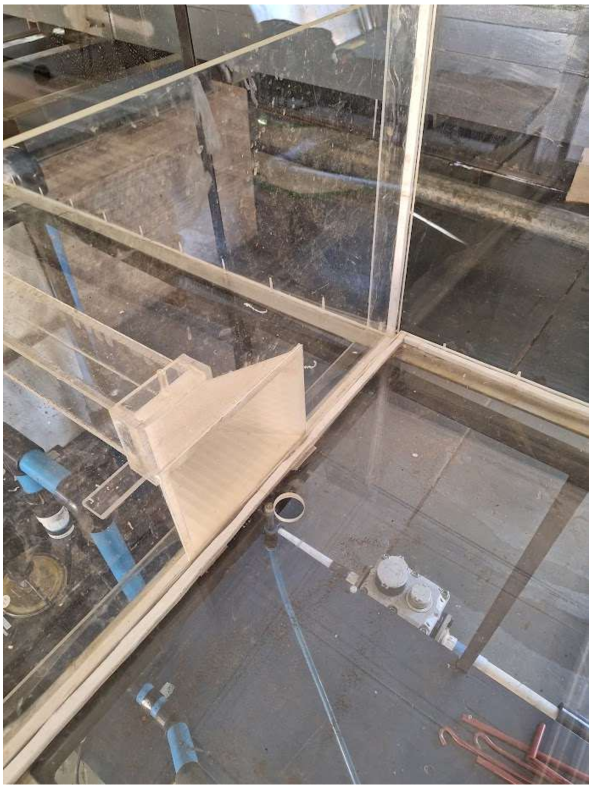


Figure 3-8: Culvert model with 3D printed inlet

Figure 3-9: Close up view of the 3D printed culvert inlet

To carry out the experiments, a headwall model was selected and fixed in place in the channel using Silicone sealant to ensure water tightness. The sealant was allowed to dry for 24 hours before water was pumped through the model. Before the experiments were started, the culvert channel was levelled using a spirit level. The pumps were started and switched off again after a short while. The water in the channel was allowed to flow out and settle at the lower edge of the inlet model. This water level was then marked on the measurement tube as the lowest level from which all measurements were taken. The ventilation tube was blocked while inlet conditions were being tested.

The isolation valve downstream of the water meter was used to throttle the flow from the pumps, starting with a very small flow rate. The flow rate was measured by taking measurements from the mechanical flow meter using a stopwatch. At least seven measurements were taken in this way and an average flow rate was determined. A specific flow rate was allowed to flow through the model for at least two minutes before the water depth was measured. This was done to allow the water depth in the model to stabilise. The water depth was measured on the measurement tube. This process was repeated while progressively allowing more water through the isolation valve until the valve was completely open. The same process was then followed while closing the isolation valve progressively.

Figure 3-10: 90 degree headwall model with water flowing

Figure 3-11: 30 degree model with water flowing

Figure 3-10 and Figure 3-11 show the water flowing through the 90 degree headwall and the 30 degree headwall respectively.

4 RESULTS OF MODEL STUDY

The results for each headwall / wingwall model experiment are discussed in this Chapter.

4.1 ANALYSIS OF EXPERIMENTAL DATA

Figure 4-1 shows a flow diagram of analyses that were undertaken with the experimental data.

4.2 The adequacy and appropriateness of fifth degree polynomial trendlines fitted to the experimental data

The measured headwater depths for each of the three experimental models were plotted against the average flow rates as measured and described in Chapter **Error! Reference source not found.**. Based on recommendations in the literature (Marek, 2009), a fifth degree polynomial trendline was fitted to each plot. The graphs with the experimental data and for the 90 degree-, 45 degree- and 30 degree headwall / wingwall models are presented in Figure 4-2; Figure 4-5 and Figure 4-8 respectively.

The coefficient of determination (R^2) was calculated for each model. Table 4-1 shows the fifth degree polynomial equation and R^2 value for each model.

Table 4-1: 5th degree polynomial equations and R^2 values

Model	Equation	R^2
90 degree	$y = -0.0145x^5 + 0.3017x^4 - 1.7882x^3 + 2.3747x^2 + 26.083x + 8.7124$ (Equation 22)	0.9948
45 degree	$y = 0.0088x^5 - 0.2511x^4 + 2.8054x^3 - 14x^2 + 47.338x - 3.8691$ (Equation 23)	0.9993
30 degree	$y = -0.0044x^5 + 0.0837x^4 - 0.3313x^3 - 1.2071x^2 + 26.244x + 7.0525$ (Equation 24)	0.9987

The R^2 value for each of the models indicates that the fifth degree polynomial trendline fits the experimental data very well, with an error of less than 1%. A residual analysis for each model performed and plotted as shown in Figure 4-3; Figure 4-6 and Figure 4-9 for the 90 degree-; the 45 degree- and the 30 degree headwall / wingwall models respectively. The plots show no pattern (the data are randomly dispersed) and therefore it is concluded that a fifth-order polynomial model is appropriate for the experimental data for all three models. Additionally, 95% confidence intervals were calculated for each model and is shown in Figure 4-4, Figure 4-7 and Figure 4-10.

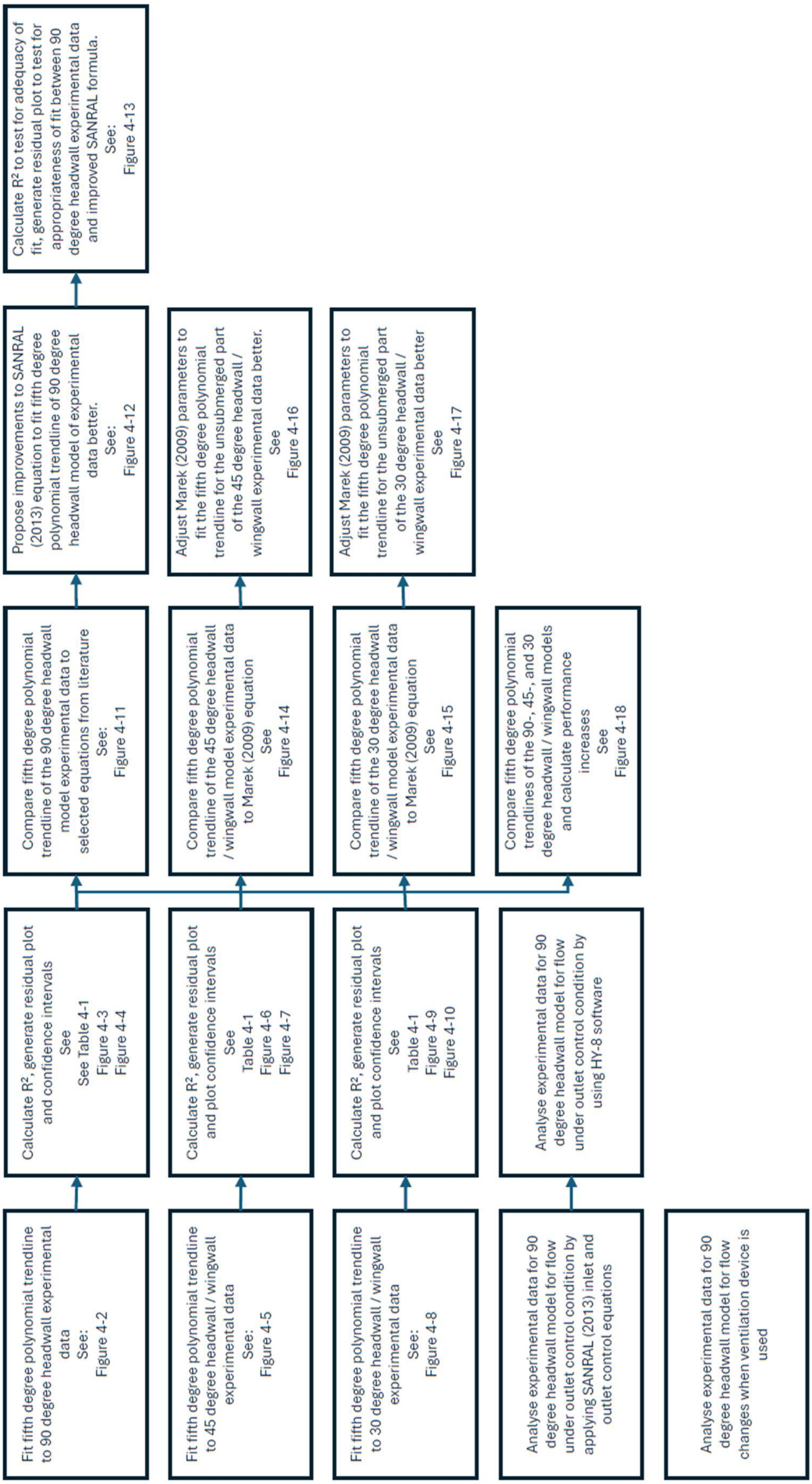


Figure 4-1: Flow diagram of analyses undertaken

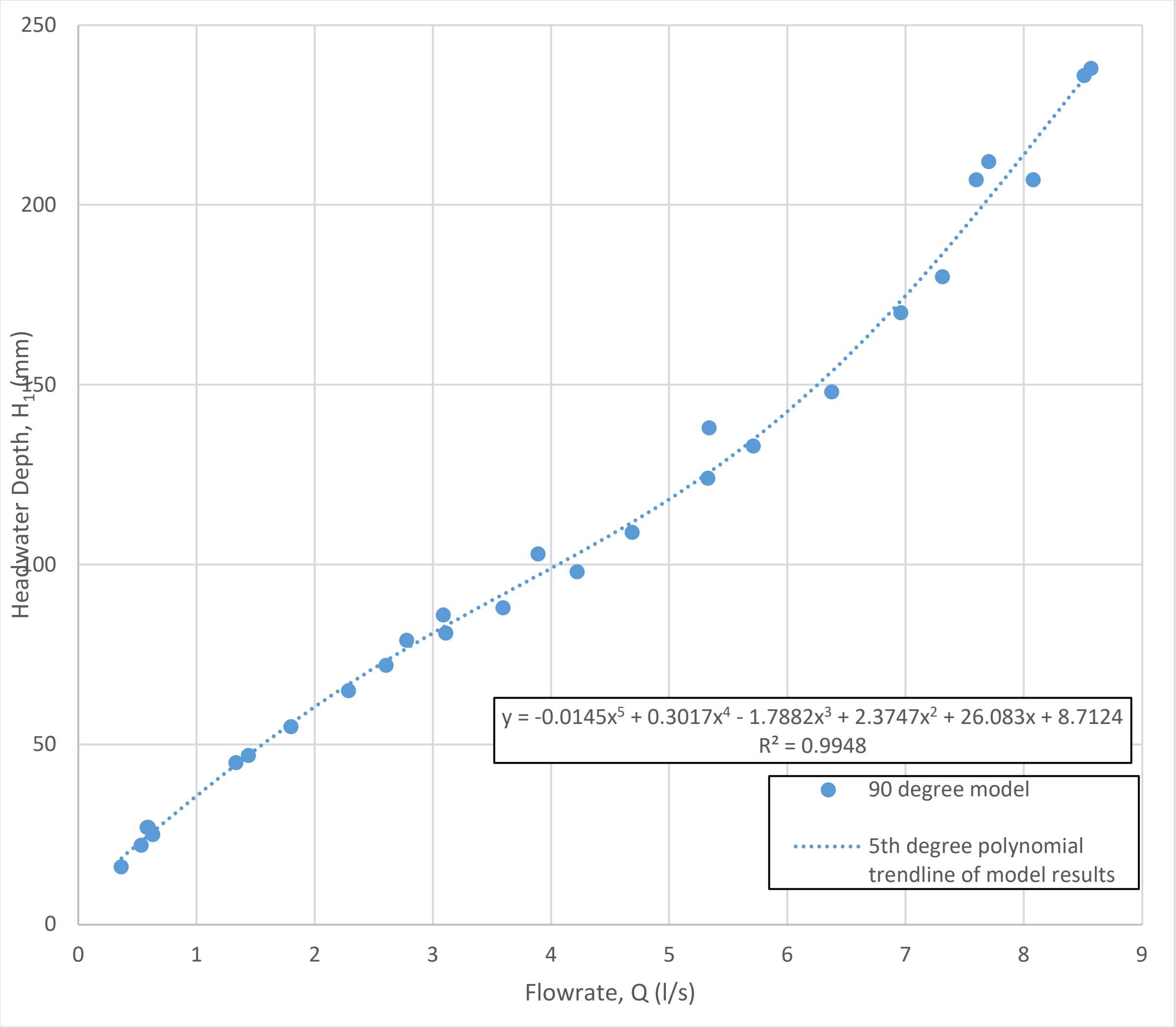


Figure 4-2: 90 degree Experimental results fitted to a 5th degree polynomial trendline

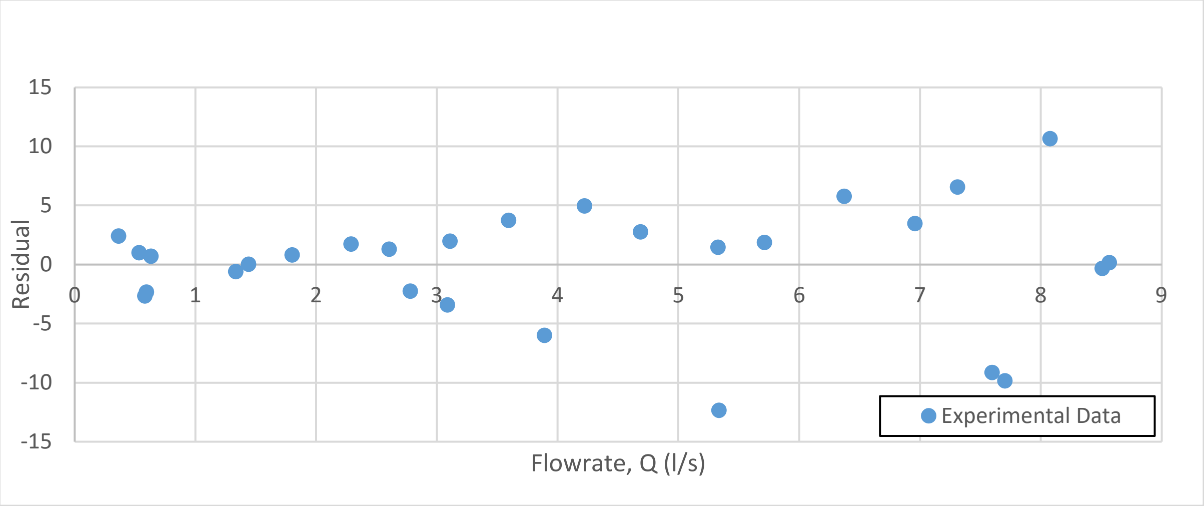


Figure 4-3: Residual analysis plot of the 90 degree model

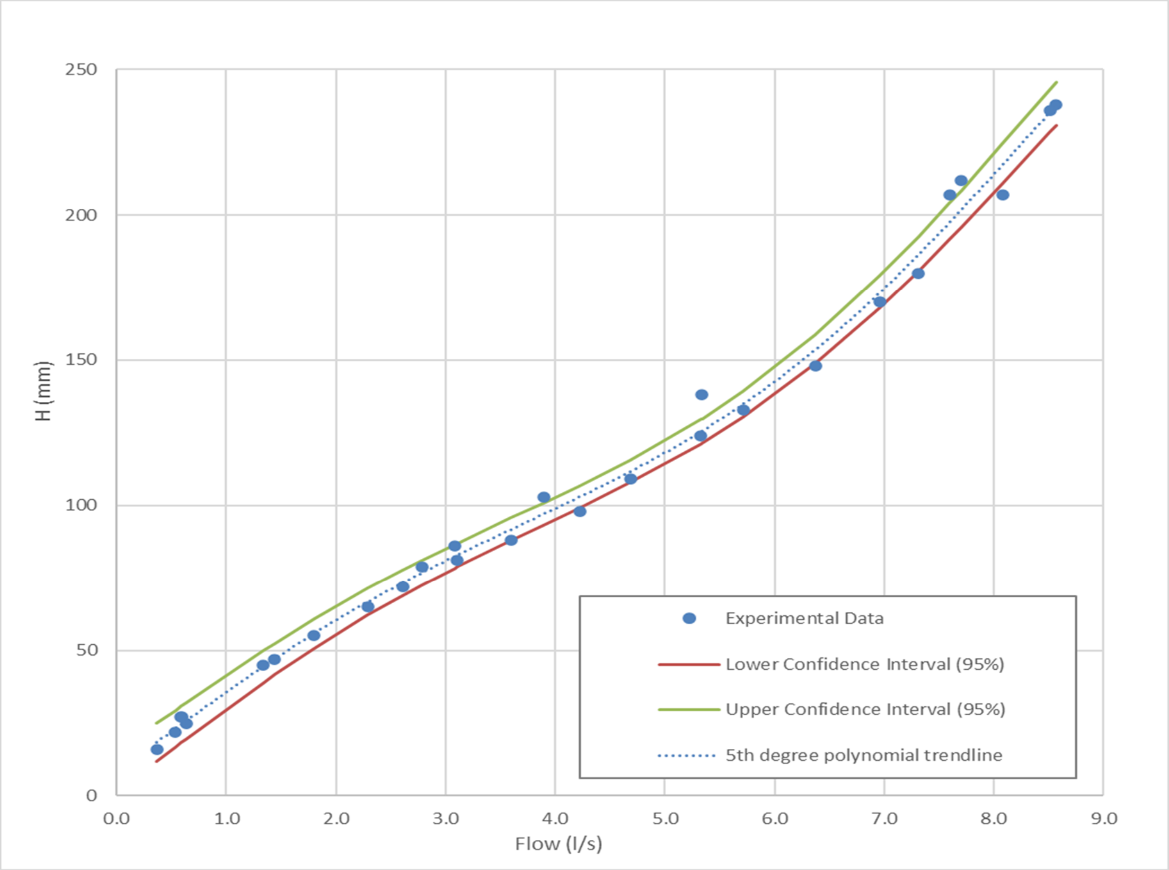


Figure 4-4: Confidence intervals (95%) for the 90 degree model

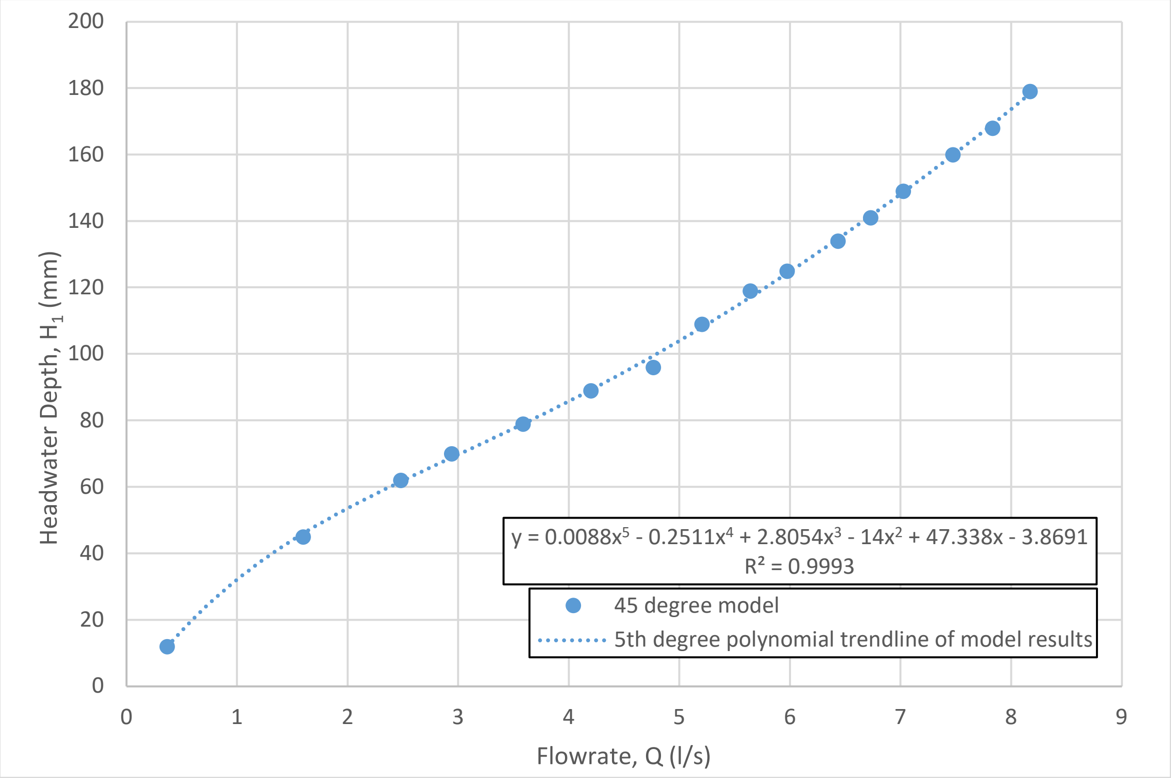


Figure 4-5: 45 degree Experimental results fitted to a 5th degree polynomial trendline

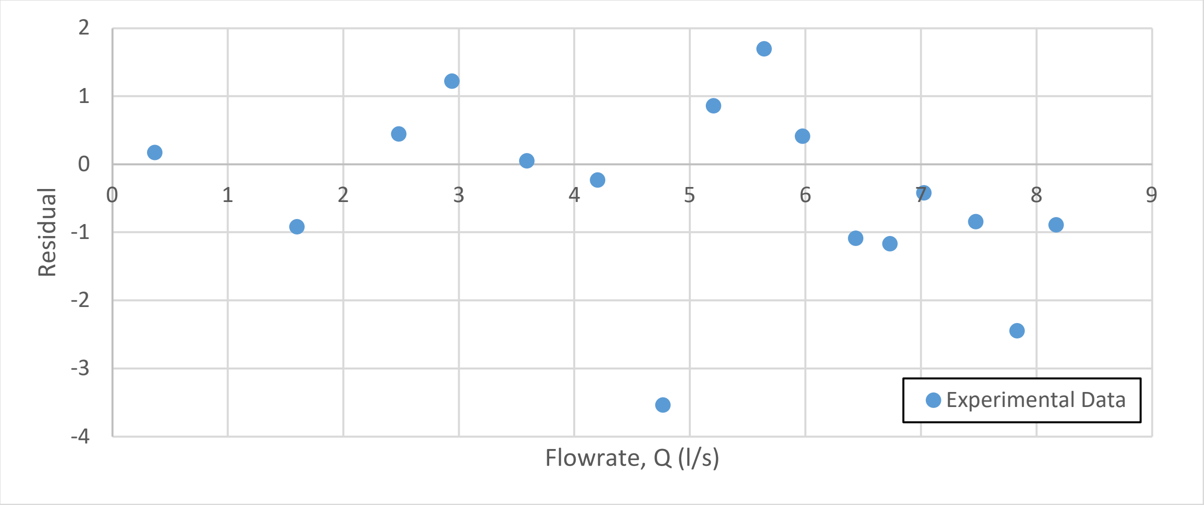


Figure 4-6: Residual analysis plot of the 45 degree model

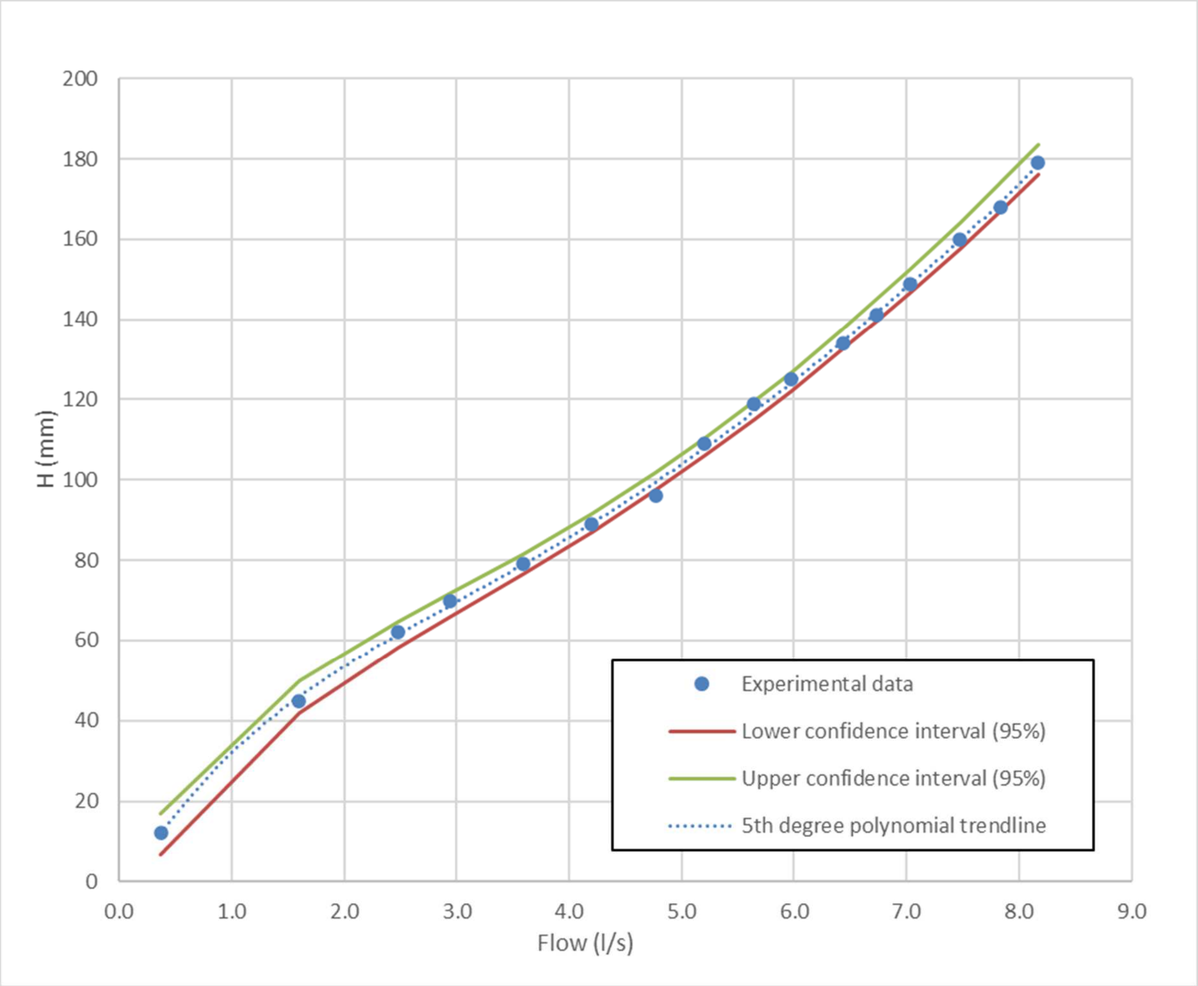


Figure 4-7: Confidence intervals (95%) for the 45 degree model

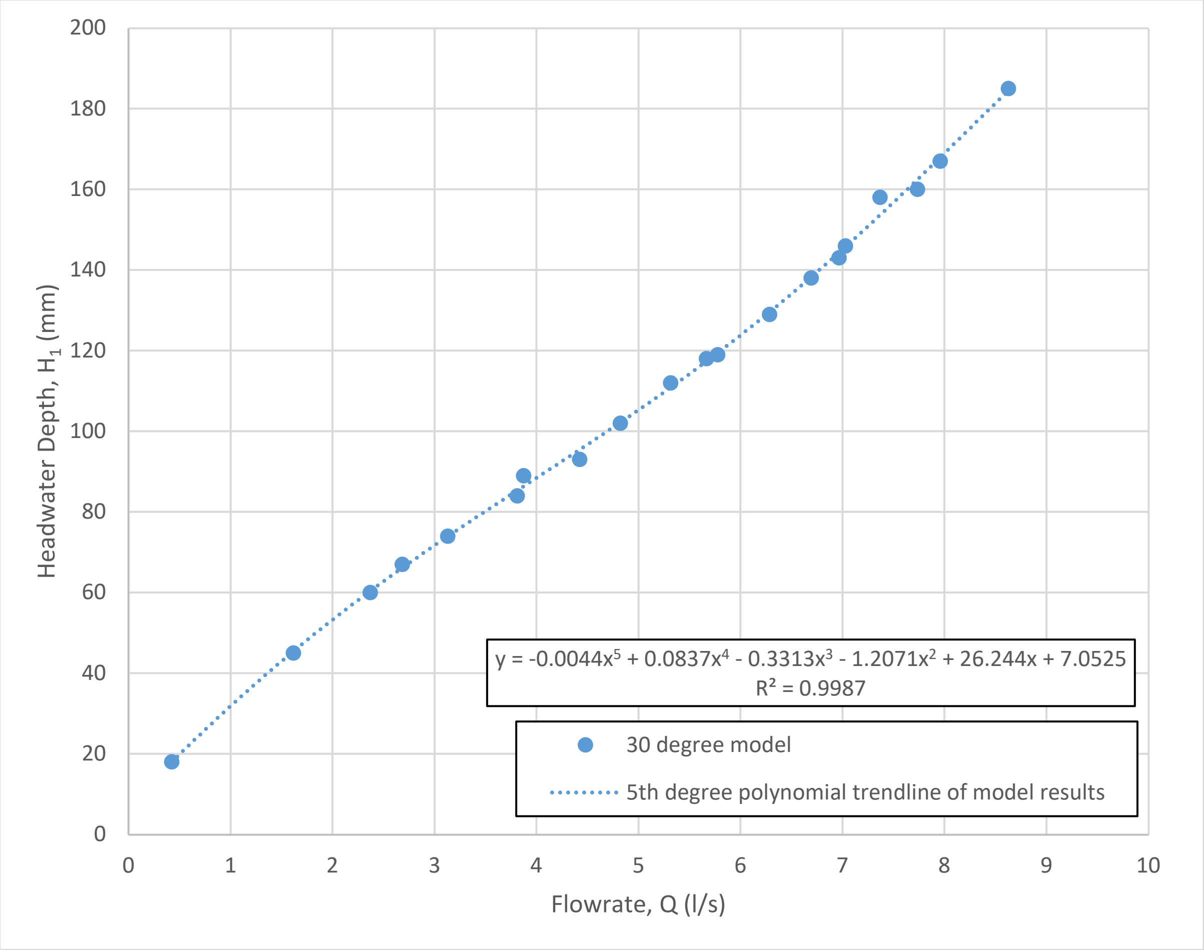


Figure 4-8: 30 degree Experimental results fitted to a 5th degree polynomial trendline

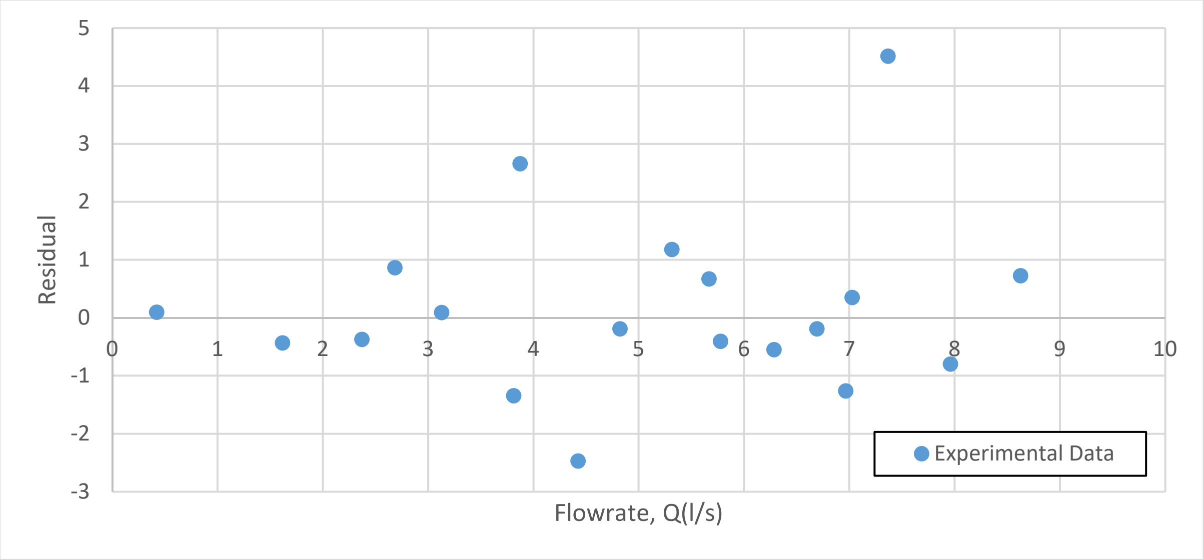


Figure 4-9: Residual analysis plot of the 30 degree model

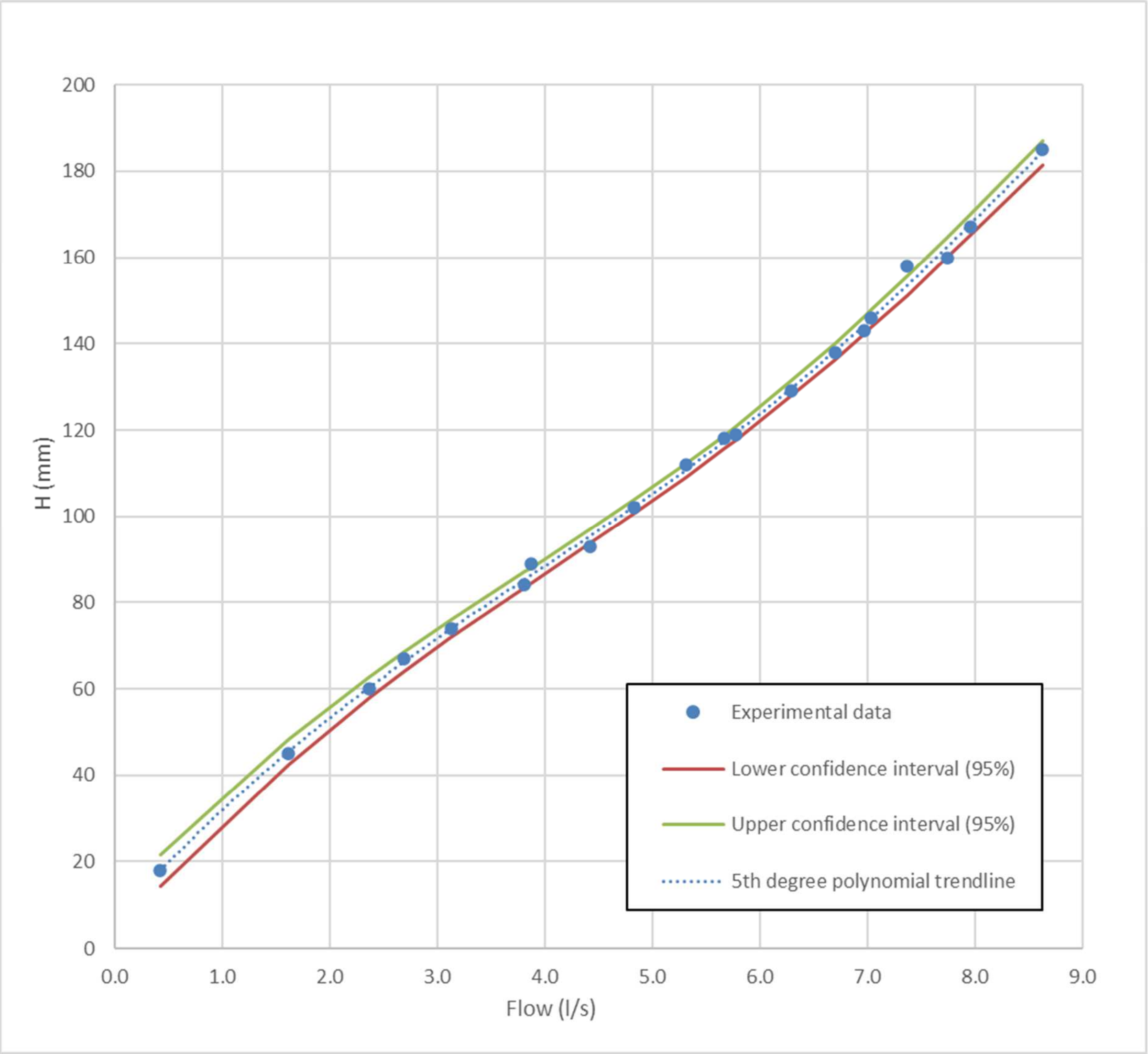


Figure 4-10: Confidence intervals (95%) for the 30 degree model

4.3 90 degree headwall / wingwall model

The measured data and the trendline for the 90 degree headwall / wingwall model are again presented in Figure 4-11. Also presented on this figure, for comparison, are inlet control performance curves for selected equations, calculated using the dimensions of the 90 degree model (see also Figure 2-6). Figure 4-11 shows that the measured data tracks the performance curves for selected equations well and is therefore considered credible. For unsubmerged flow, the results fit the performance curve for Shall et al. (2012) the best. For submerged flow (from about $H_1/D > 1.2$) the trendline tracks between SANRAL, 2013 and Charbeneau, 2005.

The fifth-degree polynomial trendline based on the measured data was specifically compared to the SANRAL (2013) equation and performance curve. It was found that increasing the Cb factor from 0.9 to 0.91 for square inlets, and increasing the Ch factor from 0.6 to 0.625 for square inlets and applying Equation 9 for H_1/D values equal and smaller than 1.235, and applying Equation 10 for values above 1.235 yields a performance curve that approximates the fifth-degree polynomial trendline based on the measured experimental data. This improvement is shown in Figure 4-12. The coefficient of determination (R^2) value between the improved performance curve and the experimental data was calculated to be 0.99548, indicating a very good fit. A residual analysis was carried out and is shown in Figure 4-13. The plot shows no pattern (the data are randomly dispersed) and therefore it is concluded that the improved SANRAL formula is appropriate for the experimental data.

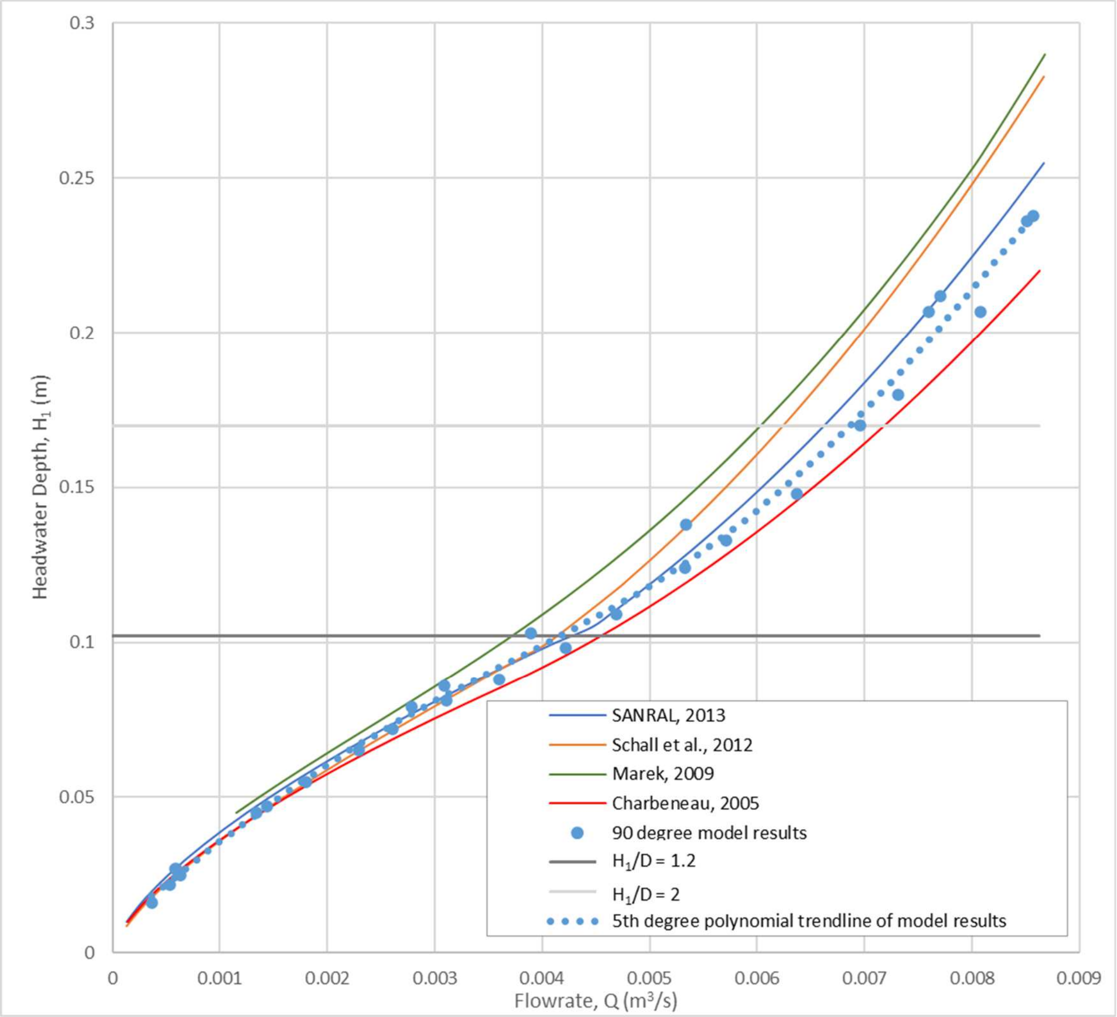


Figure 4-11: 90 degree model results

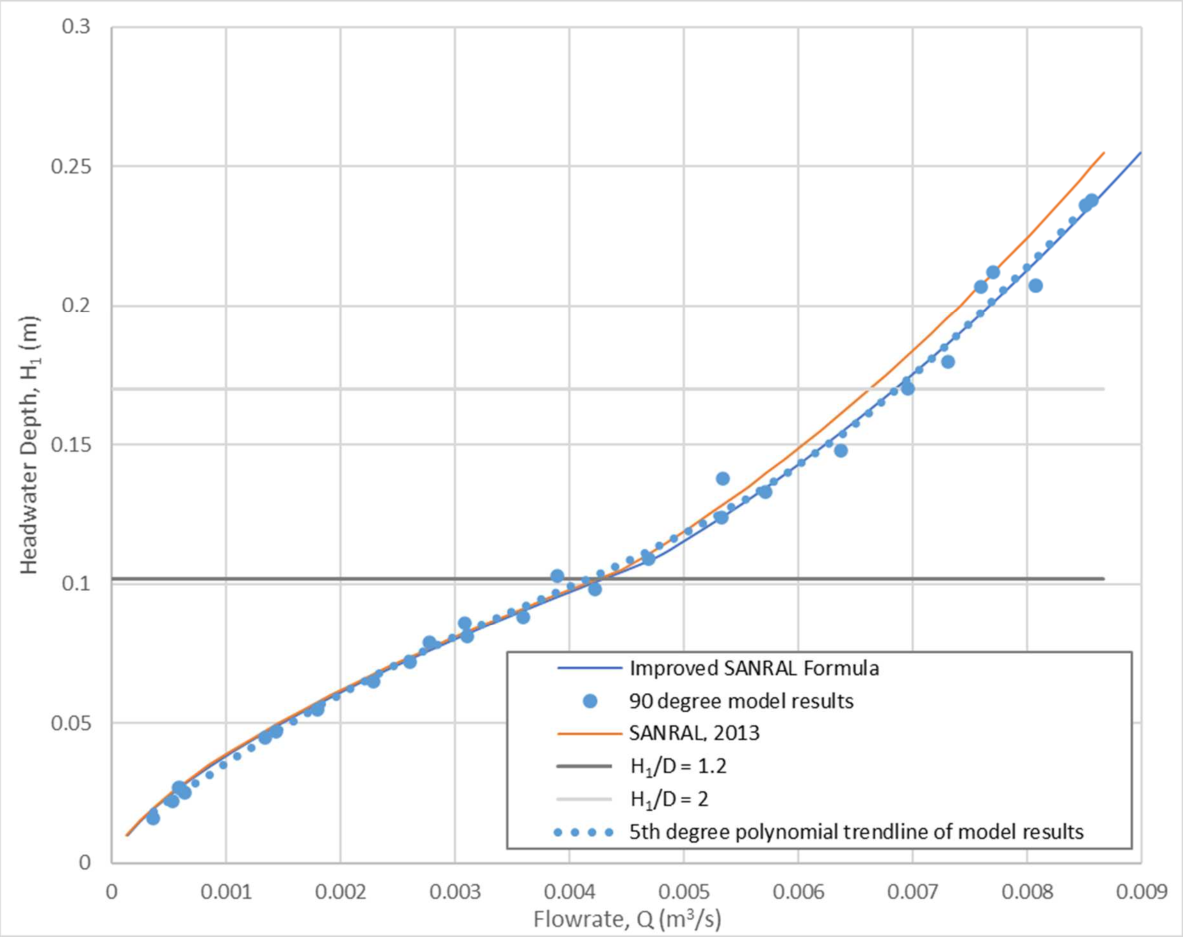


Figure 4-12: SANRAL improved formula compared to SANRAL (2013) and experimental data.

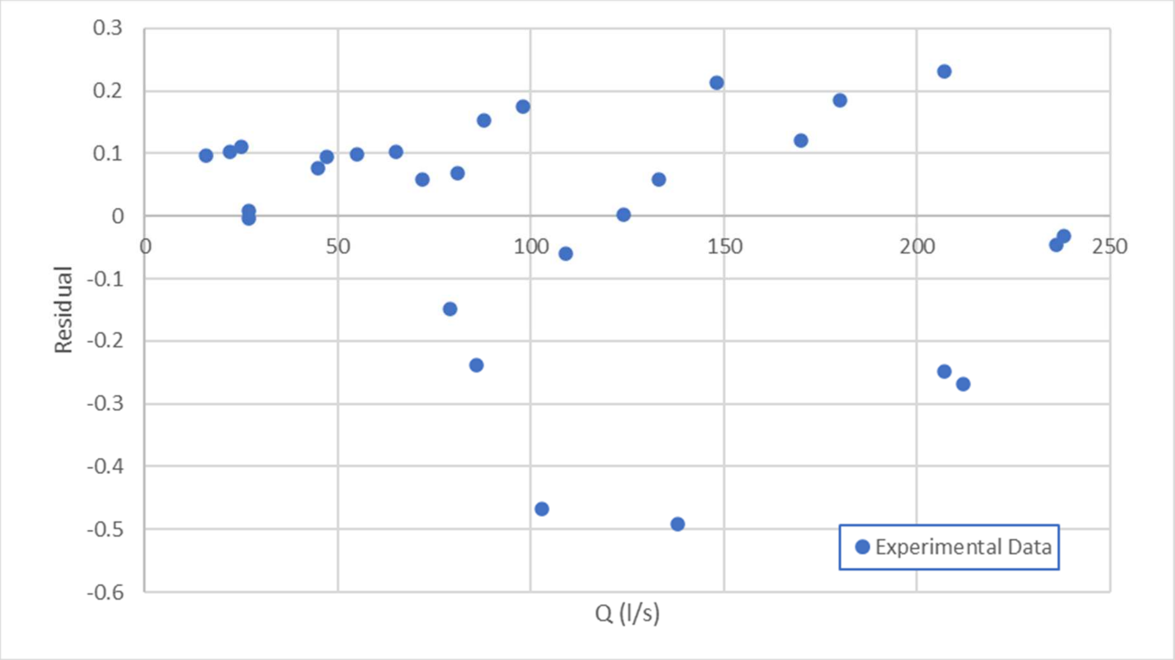


Figure 4-13: SANRAL improved formula Residual Analysis plot.

4.3.1 45 degree headwall / wingwall and 30 degree headwall / wingwall models

The 30 degree and 45 degree models incorporated an angled headwall, in addition to angled wingwalls. It seems that this additional improvement has not been studied in detail before. To determine the impact of the angled headwall, it was decided to compare the results to the 5th order polynomial formula proposed by Marek (2009) (see equations 14 to 17) calculated for similar dimensions as the experimental model, but using parameters for angled, or flared wingwalls as shown in Table 4-2:

Table 4-2: Parameters for 30 degree to 70 degree flared wingwalls (Marek, 2009)

Parameter	Value
a	0.072493
b	0.507087
c	-0.11747
d	0.02217
e	-0.00149
f	0.000038

The comparison between the calculated performance curves using Marek (2009) and the experimental data for the 45 degree and the 30 degree headwall / wingwall models are presented in Figure 4-14 and Figure 4-15 respectively.

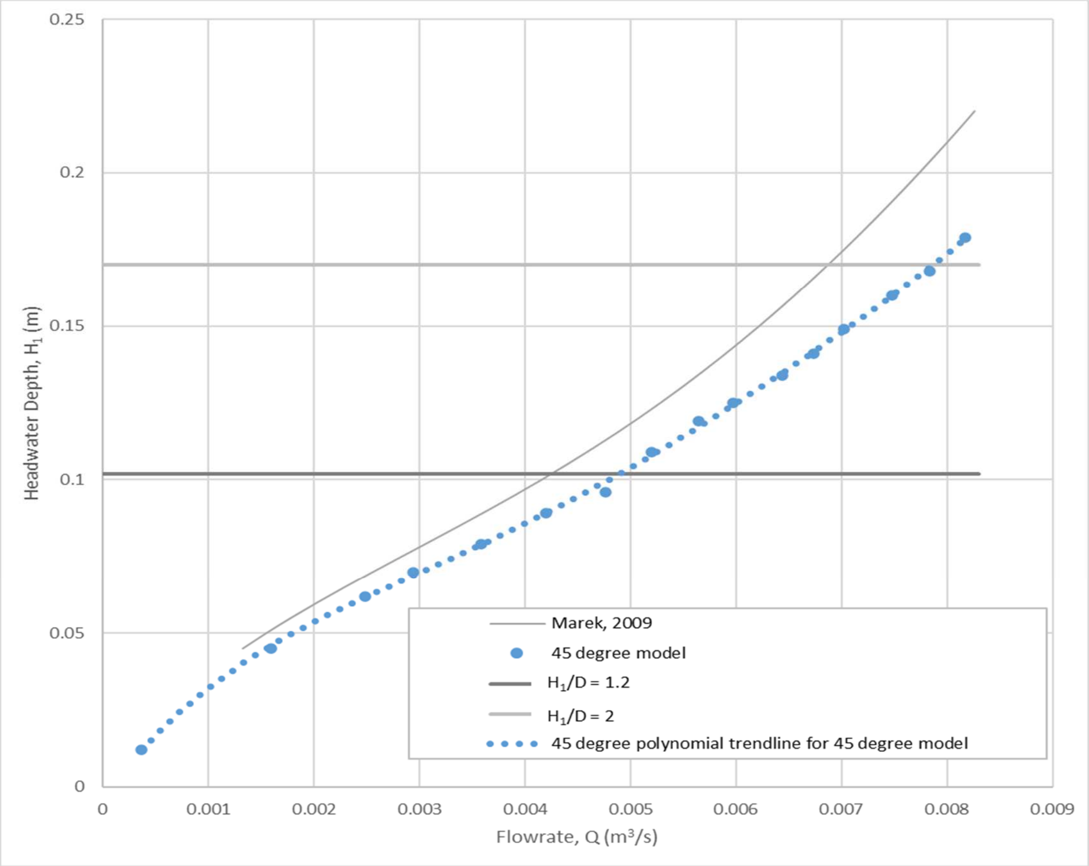


Figure 4-14: Comparison between Marek, 2009 and the 45 degree headwall / wingwall modelled results

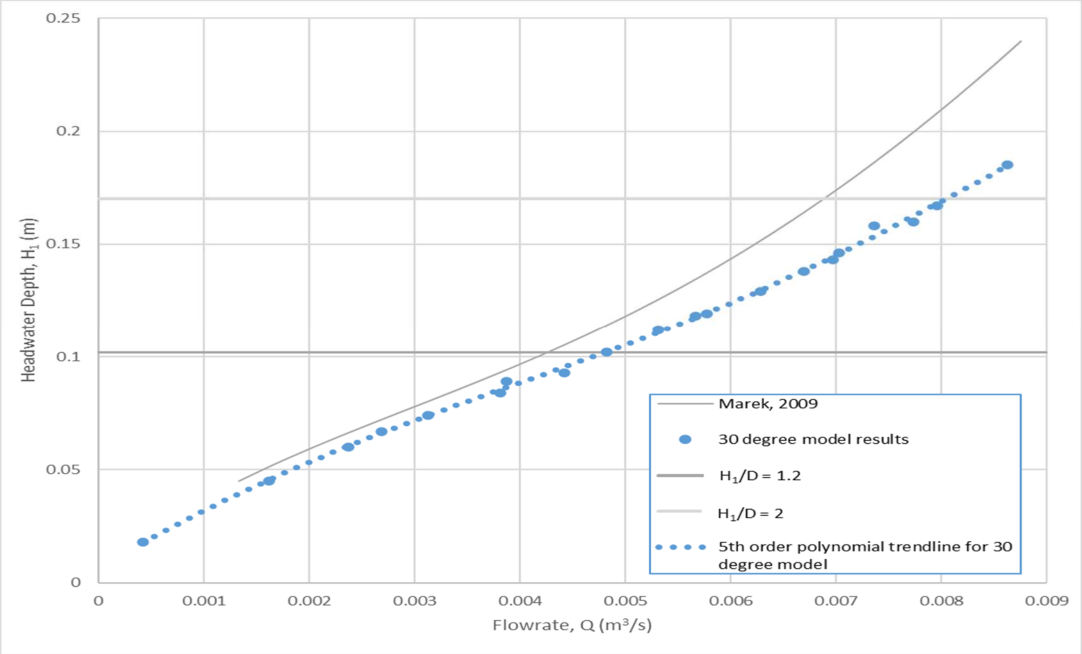


Figure 4-15: Comparison between Marek, 2009 and the 30 degree headwall / wingwall modelled results

For comparison, it was decided to adjust the parameters for the equation proposed by Marek (2009) to fit the modelled results better. In both cases, setting the parameter a = 0, yielded a graph that fit the modelled results better for flows where $H_1 < 0.085$ m (or $H_1/D < 1$), where the angled headwall improvement cannot influence the flow of the water through the culvert. For flows where $H_1 > 0.085$ m (or $H_1/D > 1$), a divergence between the Marek (2009) equations and the modelled results can clearly be seen, with the angled headwall improvement clearly resulting in a reduction in headwater depth for similar flows. These results, for the 45 degree and 30 degree headwall / wingwall models, are presented in Figure 4-16 and Figure 4-17 respectively.

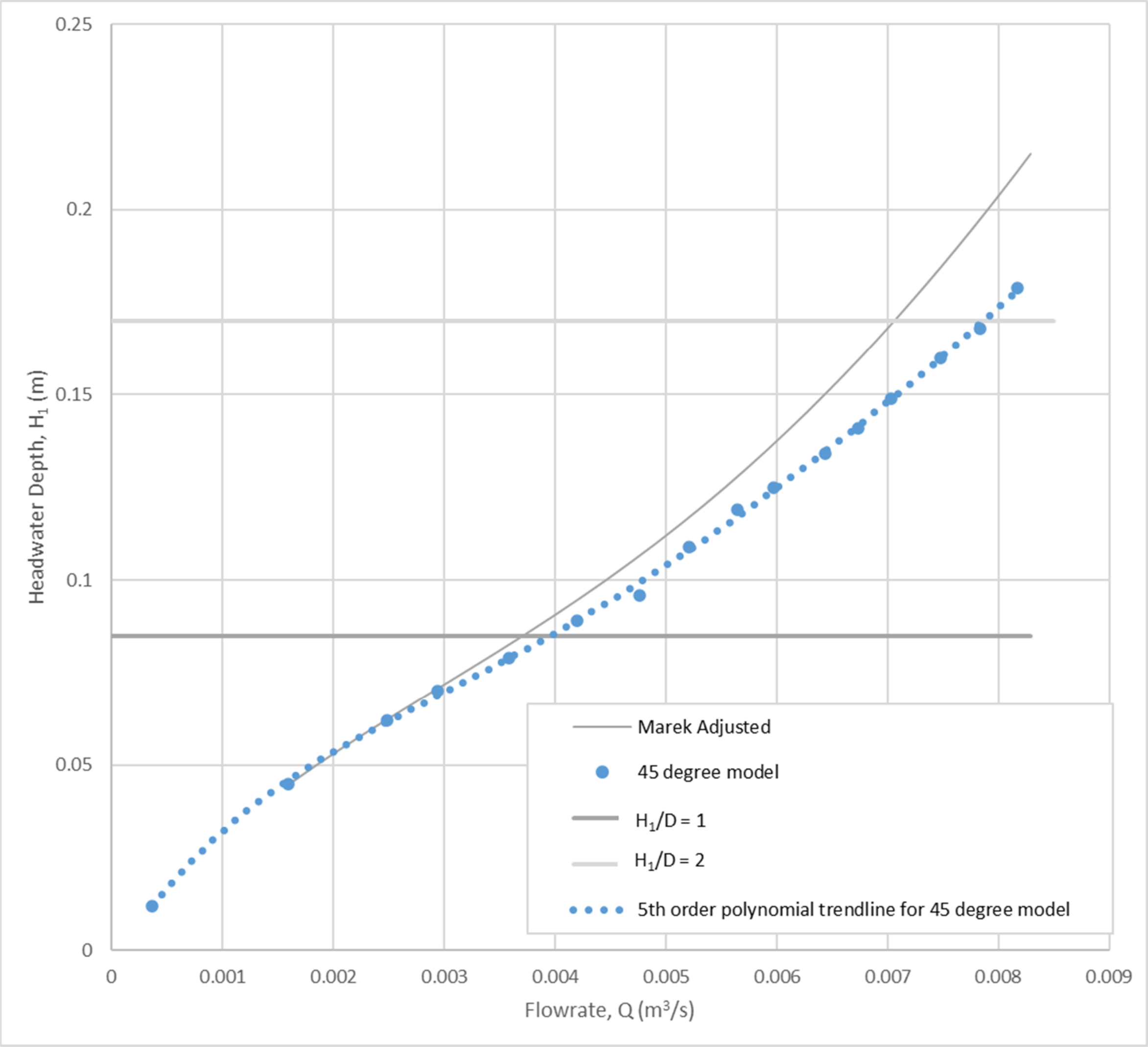


Figure 4-16: Comparison of Marek, 2009 with a = 0 and modelled results for the 45 degree headwall / wingwall model

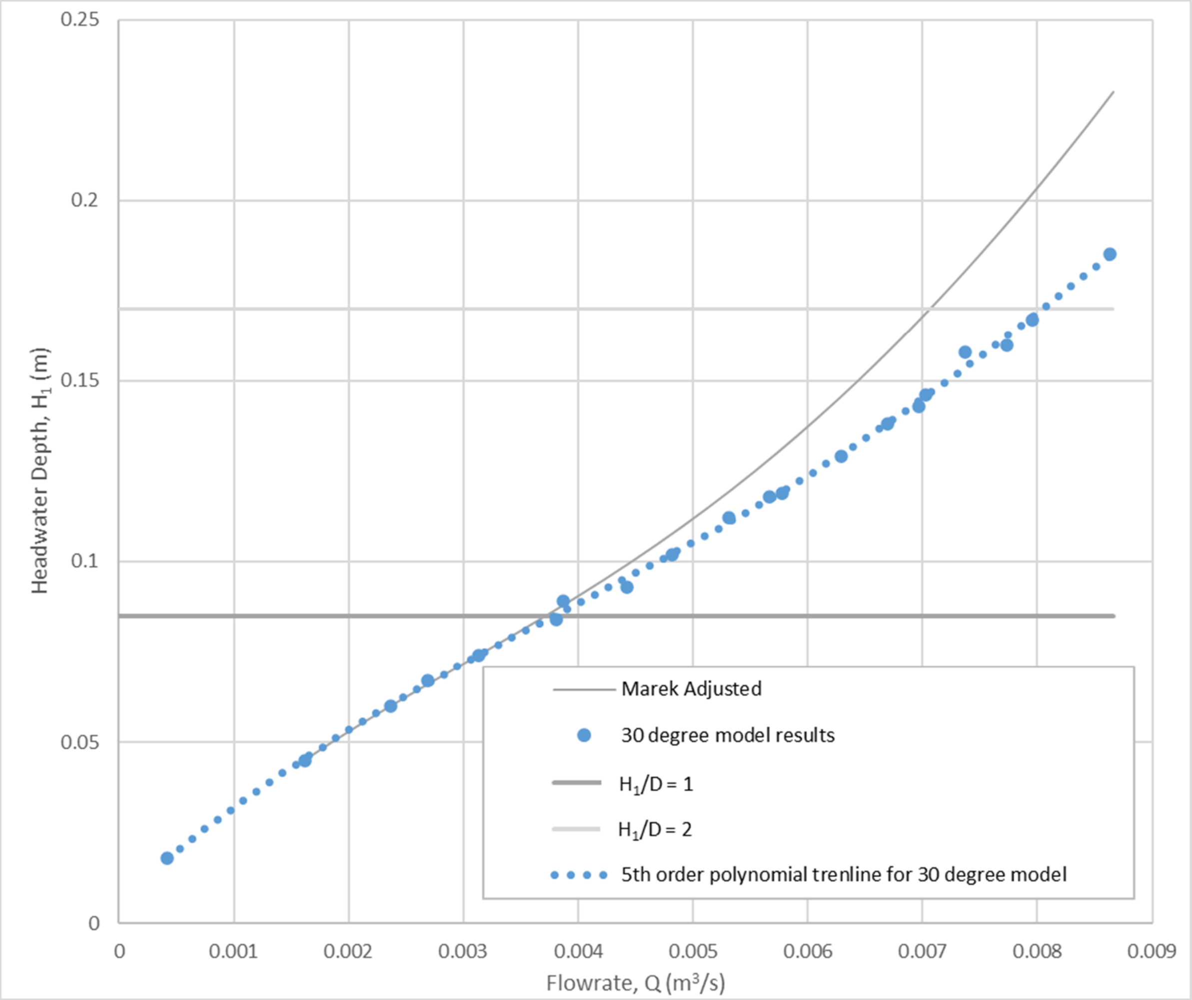


Figure 4-17: Comparison of Marek, 2009 with a = 0 and modelled results for the 30 degree headwall / wingwall model

4.3.2 Comparison between 90 degree-; 45 degree- and 30 degree headwall / wingwall models

The measured data and the trendlines were plotted and compared to the 90 degree model data (see**Error! Reference source not found.**) and is presented Figure 4-18**Error! Reference source not found.**. The reduction in headwater depth for the 30 degree and the 40 degree models, compared to the 90 degree model can clearly be seen.

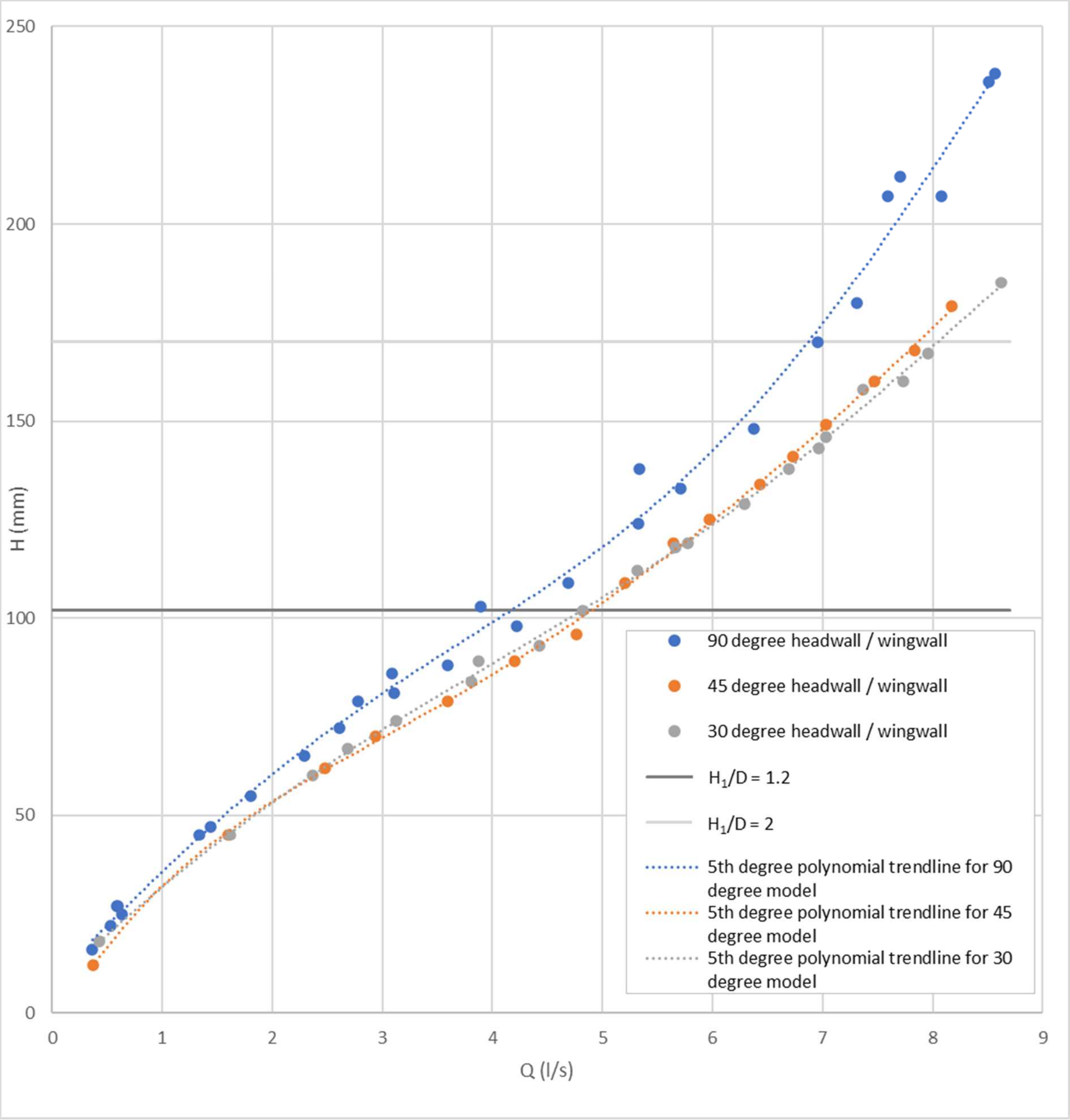


Figure 4-18: Comparison of 90 degree-; 45 degree- and 30 degree headwall / wingwall model experimental data

Table 4-3 presents the expected flowrates (as calculated using the fifth degree polynomial trendlines), as well as the 95% lower and upper confidence intervals as presented in Figure 4-4 for the 90 degree headwall / wingwall model.

Table 4-3: Calculated flowrates for the 90 degree headwall / wingwall model

H_1/D	Lower confidence interval (95%) flowrate (l/s)	Expected flowrate (l/s)	Upper confidence interval (95%) flowrate (l/s)
0.8	2.138	2.360	2.790
1	3.003	3.233	3.661
1.2	3.953	4.153	4.580
1.5	5.233	5.407	5.749
2	6.802	6.916	7.111

Table 4-4 presents the expected flowrates (as calculated using the fifth degree polynomial trendlines), as well as the 95% lower and upper confidence intervals as presented in Figure 4-7 for the 45 degree headwall / wingwall model.

Table 4-4: Calculated flowrates for the 45 degree headwall / wingwall model

H_1/D	Lower confidence interval (95%) flowrate (l/s)	Expected flowrate (l/s)	Upper confidence interval (95%) flowrate (l/s)
0.8	2.693	2.891	3.288
1	3.810	3.955	4.237
1.2	4.782	4.895	5.114
1.5	5.997	6.105	6.318
2	7.685	7.817	8.074

Table 4-5 presents the expected flowrates (as calculated using the fifth degree polynomial trendlines), as well as the 95% lower and upper confidence intervals as presented in Figure 4-10 for the 30 degree headwall / wingwall model.

Table 4-5: Calculated flowrates for the 30 degree headwall / wingwall model

H_1/D	Lower confidence interval (95%) flowrate (l/s)	Expected flowrate (l/s)	Upper confidence interval (95%) flowrate (l/s)
0.8	2.668	2.789	3.039
1	3.684	3.792	4.007
1.2	4.732	4.812	4.913

H_1/D	Lower confidence interval (95%) flowrate (l/s)	Expected flowrate (l/s)	Upper confidence interval (95%) flowrate (l/s)
1.5	6.104	6.187	6.349
2	7.941	8.049	8.266

Table 4-6 summarises the expected increase in flow for the 45 degree- and 30 degree headwall / wingwall models, compared to the 90 degree headwall / wingwall model using the calculated flowrates presented in Table 4-3; Table 4-4 and Table 4-5.

Table 4-6: Flowrate increase for the 45 degree- and 30 degree headwall / wingwall models compared to the 90 degree headwall / wingwall model

H_1/D	45 degree headwall / wingwall model flowrate increase compared to results from the 90 degree headwall / wingwall model			30 degree headwall / wingwall model flowrate increase compared to results from the 90 degree headwall / wingwall model		
	Lower confidence interval (95%)	Expected increase	Upper confidence interval (95%)	Lower confidence interval (95%)	Expected increase	Upper confidence interval (95%)
0.8	25.9%	22.5%	17.9%	24.8%	18.2%	8.9%
1	26.9%	22.3%	15.7%	22.7%	17.3%	9.5%
1.2	21.0%	17.9%	11.7%	19.7%	15.9%	7.3%
1.5	14.6%	12.9%	9.9%	16.7%	14.4%	10.4%
2	13.0%	13.0%	13.6%	16.7%	16.4%	16.2%

4.4 INCLUSION OF A VENTILATION DEVICE

A ventilation tube was installed in the culvert barrel, just downstream of the culvert inlets (see Figure 3-9). While the experiments were being carried out, as described in Chapter **Error! Reference source not found.**, the ventilation pipe was blocked so that no air could move freely between the atmosphere and the inside of the culvert barrel via the ventilation tube.

During experiments where the flow rate was great enough to cause the culvert to be submerged sufficiently, and after the relevant readings were taken, the culvert was forced to operate under outlet control conditions by blocking the outlet of the culvert manually and allowing the culvert to fill up and flow full. The downstream blockage was removed, and if the culvert continued to flow full, the blockage in the ventilation pipe was removed after the flow was allowed to stabilise. When this was done, air would enter the culvert barrel, which would then stop flowing full. The flow regime would therefore return to inlet control conditions within a couple of seconds. It was found that an aeration device (a long PVC tube) which was manually inserted through the inlet into the barrel of the culvert, had the same effect. Unfortunately, due to the limitations of the pumps installed in the model, this effect could only be tested at the maximum flow rate of 8.51 l/s on the 90 degree model.

The inclusion of a ventilation device therefore could, under some circumstances, enable culverts flowing under outlet control conditions to return to flow under inlet control conditions, as the entered air reduced the friction the flow experienced at the top of the culvert. Since the effect of a ventilation device happens downstream of the inlet of a culvert, it does not technically fall within the scope of this research dissertation but could be the subject of future research.

4.5 90 DEGREE MODEL UNDER OUTLET CONTROL CONDITIONS

The purpose of this research is to optimise the hydraulic performance of culverts under inlet control conditions, however, an interesting outlet control result presented itself during the experimental tests which warrants further analyses and discussion here.

During the experimental tests it was decided to block the outlet of the culvert manually until the entire culvert barrel was flowing full (see chapter 4.4). The blockage was then removed, and, in the case of the maximum pump rate on the 90 degree model, the culvert continued to flow full under outlet control conditions. However, the level at H_1 dropped significantly while the culvert was flowing under outlet control conditions (H_1 = 181 mm) as opposed to inlet control conditions (H_1 = 236 mm).

These results were thus further tested in various ways. Firstly, the inlet control formula (Equation 10, for $H_1 / D > 1.2$) (SANRAL, 2013) was used to calculate H_1, using $C_h = 0.625$. This formula yielded an H_1 = 0.234 m (the H_1 measured was 0.236 m). Using a C_h = 0.6 yielded H_1 = 0.248.

Thereafter, the measured results during outlet control were checked using the outlet control formula (SANRAL, 2013):

$$H_1 - H_2 = \frac{K_{in}\bar{v}_1^2}{2g} + \frac{K_{out}\bar{v}_2^2}{2g} + \frac{\bar{v}^2 n^2 L}{R^{\frac{4}{3}}} \qquad \text{(Equation 25)}$$

Where:

$K_{in} = 0.5$

$K_{out} = 1$

$n = 0.009\ s / m^{1/3}$

$L = 1.445$ m

$D = 0.085$ m (culvert depth)

$B = 0.085$ m (culvert width)

$B_1 = 0.8$ m (upstream canal)

$B_2 = 0.8$ m (downstream canal)

$Q = 0.00851\ m^3/s$

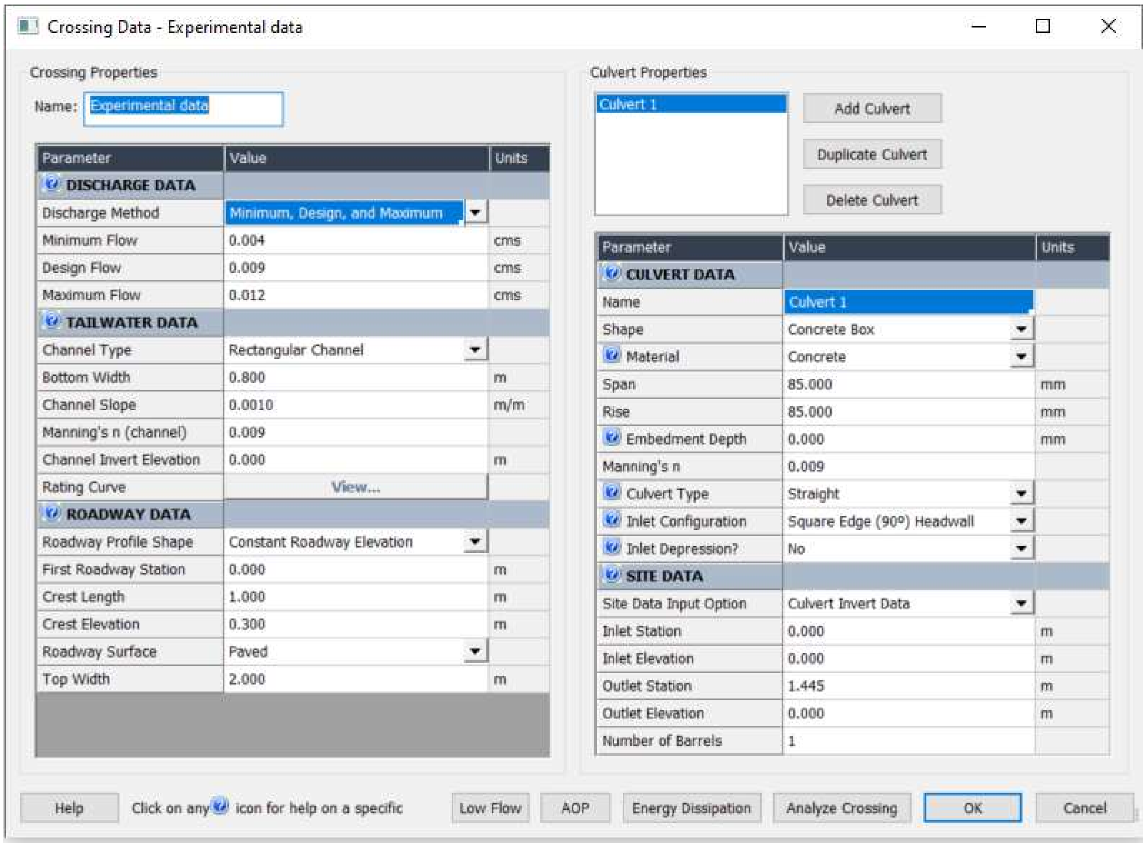
$g = 9.81\ m/s^2$

Equation 22 calculated $H_1 = 0.220$ m which is lower than the inlet control equation result, proving that outlet control can be more efficient than inlet control for the selected n, K_{in} and K_{out} values and other conditions present during the testing of this model.

The calculated H_1 value of 0.220 is significantly higher than the measured result of $H_1 = 0.181$ m. If K_{in} is reduced to 0.1 and n is assumed to be 0.0085 s / $m^{1/3}$ a H_1 value of 0.085 m is calculated. This could mean that the culvert barrel is smoother than assumed but also that the inlet losses are much less than assumed.

Kassem et al. (2006) compared data from a physical model with the headwater elevations computed by HY-8 and HEC-RAS and concluded that the comparison was satisfactory. It was therefore decided to use the HY-8 (HY-8, 2019) software package to simulate the results of the calculations.

Figure 4-19 shows the input data for this simulation in HY-8.



Crossing Data - Experimental data

Crossing Properties

Name: Experimental data

Parameter	Value	Units
DISCHARGE DATA		
Discharge Method	Minimum, Design, and Maximum	
Minimum Flow	0.004	cms
Design Flow	0.009	cms
Maximum Flow	0.012	cms
TAILWATER DATA		
Channel Type	Rectangular Channel	
Bottom Width	0.800	m
Channel Slope	0.0010	m/m
Manning's n (channel)	0.009	
Channel Invert Elevation	0.000	m
Rating Curve	View...	
ROADWAY DATA		
Roadway Profile Shape	Constant Roadway Elevation	
First Roadway Station	0.000	m
Crest Length	1.000	m
Crest Elevation	0.300	m
Roadway Surface	Paved	
Top Width	2.000	m

Culvert Properties

Culvert 1

Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Concrete Box	
Material	Concrete	
Span	85.000	mm
Rise	85.000	mm
Embedment Depth	0.000	mm
Manning's n	0.009	
Culvert Type	Straight	
Inlet Configuration	Square Edge (90º) Headwall	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	m
Inlet Elevation	0.000	m
Outlet Station	1.445	m
Outlet Elevation	0.000	m
Number of Barrels	1	

Click on any icon for help on a specific

Figure 4-19: HY-8 input data for experimental observations

The culvert crossing was analysed. Figure 4-20 shows the performance curve for the analysis.

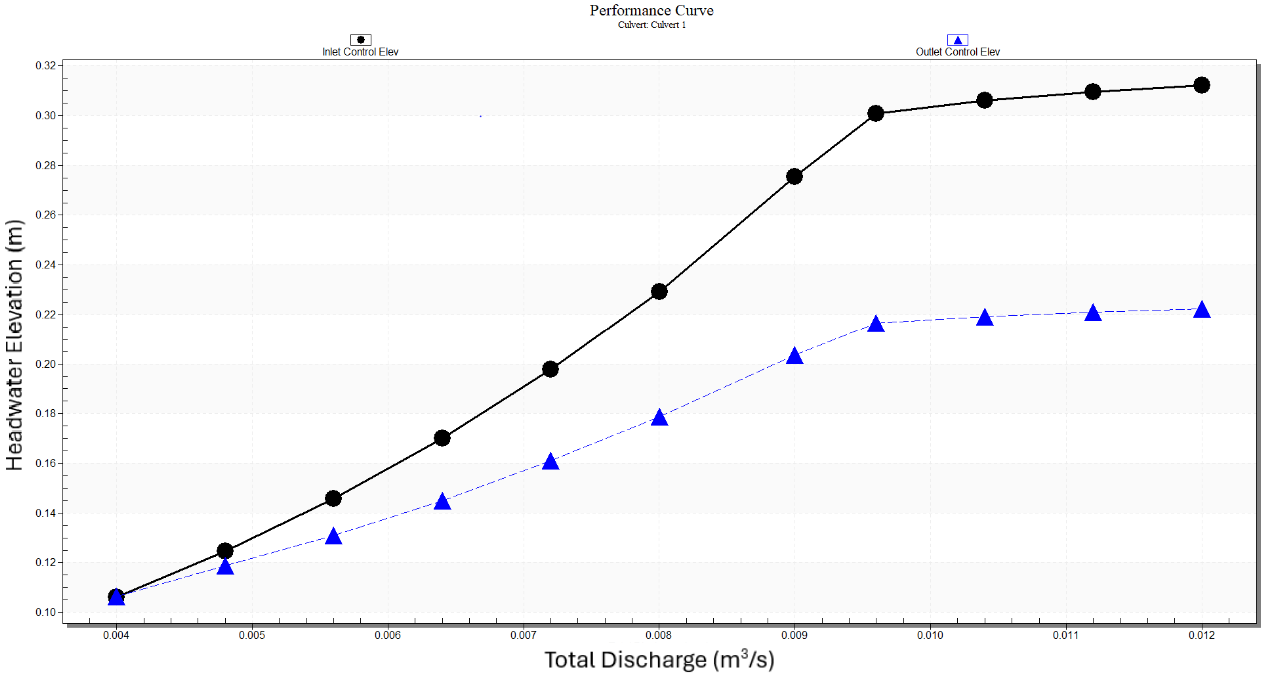


Figure 4-20: HY-8 performance curve results for experimental observations

For the flow of 8.51 l/s, the HY-8 simulation calculated a headwater depth of 0.192 m for outlet control and 0.250 m for inlet control. At these flow conditions, HY-8 calculated the flow type for outlet control to be 7-H2c, which means the following:

- Outlet Control
- Culvert flows partly full
- Submerged inlet
- Horizontal culvert
- Critical outlet depth

Jaeger *et al.* (2019) found that some culvert configurations perform better under outlet control than under inlet control at higher flow rates, and when headwater levels are above 1.5 times the culvert height, outlet control can be more efficient than inlet control in culverts with high inlet losses and very low pipe losses. This is the case in the 90 degree model of this study where the culvert frictional losses are very low.

4.6 DISCUSSION

It was found that fitting fifth degree polynomial trendlines to the experimental data was appropriate for all three models, and adequate trendlines (with an error of less than 1%) were fitted in each case.

It was shown that existing culvert flow formulae and graphs compare well with the results of the model study. It was found that the SANRAL, 2013 formula can be improved to fit the experimental data for the 90 degree headwall / wingwall model as follows:

- Increasing Cb from 0.9 to 0.91 for square inlets;
- Increasing Ch from 0.6 to 0.625 and
- Applying Equation 9 for H_1/D values equal and smaller than 1.235 and
- Applying Equation 10 for H_1/D values above values of 1.235.

It was found that 30 degree and 45 degree angled wingwalls together with similarly angled headwall improves the performance of a culvert when compared to square headwalls and wingwalls. This performance increase is summarised in Table 4-6. The following increases in flowrates were observed (at a 95% confidence interval), when compared to the 90 degree headwall / wingwall model:

- 45 degree headwall / wingwall model:
    - At H_1/D of 1.2, an increase of between 11.7% and 21%

  - At H_1/D of 1.5, an increase of between 9.9% and 14.6%
  - At H_1/D of 2, an increase of between 13% and 13.6%
- 30 degree headwall / wingwall model:
  - At H_1/D of 1.2, an increase of between 7.3% and 19.7%
  - At H_1/D of 1.5, an increase of between 10.4% and 16.7%
  - At H_1/D of 2, an increase of between 16.2% and 16.7%

A significant increase in performance between the 30 degree and 45 degree models was not observed. This correlates to the work done by Marek (2009) where the same parameters were given for the 5th order polynomial equations for flared wingwalls between 30 degrees and 70 degrees (see Table 4-2).

It was also found that the angled headwall improves the performance of the culverts more than just the improvement that can be expected with angled wingwalls only (see Figure 4-16 and Figure 4-17). Of course, this improvement is only realised at flow depths of more than $H_1/D = 1$. Unfortunately, due to the limitations of the models tested, it is not possible to calculate the percentage increase in efficiency that the angled headwall is responsible for, compared to angled wingwalls only. This is partly due to the fact that the modelled results for the 90 degree headwall cannot directly be compared to the 90 degree results calculated by Marek (2009). This increase in efficiency should be the subject for future research. It is recommended that the results of this research be used to develop a CFD (Computational Fluid Dynamics) model which can also be used to calculate this increase in efficiency.

Furthermore, it was found that the inclusion of a ventilation device could, under some circumstances, force culverts flowing under outlet control conditions to flow under inlet control conditions, should it be preferred. The mechanism, quantum and conditions under which these improvements could be realised should be the subject of future research.

5 PRACTICAL IMPLEMENTATION OF MODELLED RESULTS

This chapter discusses the practical implementation of the modelled results.

Increasing the hydraulic performance of culverts can be beneficial during the design of new culverts and also when there is a need to retrofit an existing culvert. Each of these use-cases will be discussed below.

5.1 DESIGN OF NEW CULVERTS

When designing a new, unimproved culvert using standard design methodologies, a designer may find that the design flow rate may be equal or slightly less than the calculated hydraulic capacity of a selected precast box culvert with standard dimensions. Under these circumstances, the designer will often choose a conservative approach by selecting a standard precast box culvert with larger dimensions, or, if this is not possible, by specifying that a second box culvert be installed to operate in parallel to the first one. Both of these approaches will result in an over-designed culvert system with significant additional cost to the project. The results from the experimental models undertaken as part of this research should give designers comfort that, with some improvements to a culvert's inlet characteristics such as the inclusion of angled headwall and wingwalls, a conservative approach is still possible without resulting in an over-designed culvert.

This research has shown that designing a culvert with a 30 or 45 degree angled wingwalls and headwall can provide additional hydraulic capacity of between 16% and 18% respectively for $H_1/D = 1.2$. These improvements can therefore also result in a culvert being specified, even if the design flow rate is 16% - 18% more than the calculated hydraulic capacity of such a culvert when designed using standard design methodologies.

5.2 RETROFITTING EXISTING CULVERTS

The South African National Roads Agency (SOC) Ltd (SANRAL) is increasingly incorporating provincial roads into its national road network to meet the medium to long term developmental needs of South Africa. In many instances, the roads being incorporated do not meet the design criteria for the class of road as described in the SANRAL Drainage Manual (SANRAL, 2013) as the roads were not necessarily built to the same criteria. Of particular concern is that a road's classification (after incorporation) may require its drainage culverts to convey a design flood with a higher return period than the one it was originally designed and constructed for.

In addition to this, projections show that, in South Africa, climate change may cause a tendency towards an increase in intensity of rainfall, or extreme events (Mambo *et al.* 2017). Such extreme rainfall events may, over time, cause the original design capacities of installed culverts to become insufficient. If improvements can be made to existing culverts in situ to increase their capacities, it may negate the need for expensive culvert replacements or for additional culverts to be installed in parallel. In the case of existing culverts, the cost and inconvenience of closing a road in order to upgrade the capacity of a culvert also needs to be taken into account.

If it is determined that an existing culvert's capacity could be increased sufficiently by retrofitting it with the proposed angled headwall / wingwall improvement, a precast element can easily be prepared and connected to the existing culvert with MBT (Mechanically bolted) couplers.

MBT couplers are suitable where it is not convenient to have the bar ends prepared for parallel thread or tapered thread couplers. The bars are supported within the coupler on two serrated saddles. Bars are locked in place by a series of special lockshear bolts, the heads of which shear off when the predetermined tightening torque is reached, providing a visual check of correct installation.

To connect the precast angled headwall / wingwall unit to the existing culvert, the horizontal rebar from the existing culvert should be carefully exposed and equipped with the MBT couplers. The precast unit's horizontal rebar can then be fixed to the opposite end of the couplers. The interface joint can then be sealed.

The angled headwall / wingwall elements will widen the culvert crossing. This additional space on one side of the culvert can be used to accommodate walkways for pedestrian traffic, as an added benefit.

Manufacturers of precast culverts should be encouraged to also manufacture precast 30 degree and 45 degree headwall / wingwall elements.

5.3 VENTILATION DEVICE DISCUSSION

It was found that a ventilation device could cause the flow through some culverts to flow under inlet control conditions where it would otherwise have flowed under outlet control conditions. This could be a benefit that a designer may wish to utilise.

A ventilation device could be constructed into a new culvert when it is built by connecting the culvert, just downstream of the inlet, to the roadway above it with a pipe. A PVC pipe with a diameter of 160 mm (nominal diameter) or smaller could be installed through a hole in the top of the culvert. The pipe can be grouted into the hole in the culvert. The inlet of the ventilation device on the roadway should be equipped with a grid cover to prevent debris from getting stuck in it. Alternatively, a flexible hose could be attached to the culvert with brackets, from the inside of the culvert, just downstream of the inlet, through the inlet and up the headwall. Such a retrofit, although easy to install, may impede the flow through the culvert to some degree and needs careful consideration.

The installation of a ventilation device has shown an effect in this experimental model, but the extent of the effect and the conditions under which a benefit may be realised should be the subject of future research. A ventilation device can be installed relatively easily and cheaply in new culvert installations without any known disadvantage. A ventilation device could even be incorporated into the road drainage system.

5.4 COST COMPARISON

At the time of this research, SANRAL is upgrading the national route R63 near Komga in the Eastern Cape of South Africa. The scope of work included the following:

- Upgrade of 1.75 km of community access roads;
- Construction of 3.6 km of walkways;
- New public transport facility in Komga;
- Road works, structures and ancillary works on the R63 between km 21.70 and km 43.64;
- Project scope on the R63:
  - Widening of the existing road prism and layer works to accommodate 13.4 m cross section;
  - Localised horizontal realignment to obtain minimum design sight distance;
  - Construction of 6.9 km of new passing lanes;
  - Rehabilitation of existing pavement layers and
  - Lengthening of river bridge, rail underpass bridge and major culverts.

Contractors have been appointed for these works and the Bills of Quantities was used to obtain up-to-date costs for culvert installation elements.

From the Scope of Work of this project, four culvert lengthening projects were identified which comprised of single barrel box culverts which had to be lengthened in order to fit the new width of the roads. These culvert lengthening projects comprised additional lengths of concrete culverts with the construction new wingwalls and apron slabs on at least one side.

The four culvert lengthening projects comprised of the following culvert sizes:

- 3 m x 3 m;
- 4 m x 3.8 m;
- 3.4 m x 3.65 m and
- 2.95 x 2.35 m.

The drawings and priced bills of quantities for the scope of works were used to isolate the following elements related to the culvert lengthening projects:

- Concrete rates and volumes
- Rebar rates and weights and
- Shuttering rates and costs.

For each of the culvert sizes, a proposed angled headwall / wingwall inlet was designed to replace the wingwall and apron slabs in the drawings as designed.

Structurally, the proposed angled headwall / wingwall element has a distinct advantage over a traditional wingwall and apron slab combination as the concrete and rebar can be rationally designed and specified, unlike in heavy cantilever wingwalls.

Table 5-1 summarises the differences in quantities between the original wingwall and apron slab design and the new angled headwall / wingwall inlet design (all other components of the projects were assumed to be the same):

Table 5-1: Comparison between original design (wingwalls and apron) and new design (angled headwall and wingwalls)

ID	W x H (m)	Barrel cross sectional area (m^2)	Wingwall and apron design	Angled headwall / wingwall design
1	3 x 3	9	Shuttering = 97 m^2	Shuttering = 120 m^2
			Rebar = 3.439 tons	Rebar = 2.7 tons
			Concrete = 35.5 m^3	Concrete = 17.2 m^3
2	4 x 3.8	15.2	Shuttering = 63.9 m^2	Shuttering = 140 m^2
			Rebar = 4.5 tons	Rebar = 3.5 tons
			Concrete = 28.5 m^3	Concrete = 22.4 m^3
3	3.4 x 3.65	12.41	Shuttering = 94.8 m^2	Shuttering = 134 m^2
			Rebar = 5.7 tons	Rebar = 3.3 tons

ID	W x H (m)	Barrel cross sectional area (m^2)	Wingwall and apron design	Angled headwall / wingwall design
			Concrete = 36.5 m^3	Concrete = 21 m^3
4	2.95 x 2.35	6.93	Shuttering = 39.5 m^2	Shuttering = 107 m^2
			Rebar = 3.0 tons	Rebar = 2.8 tons
			Concrete = 19.2 m^3	Concrete = 17.9 m^3

The costs of the new angled headwall / wingwall inlets were calculated using the same rates in the corresponding bills of quantities for the original designs. Table 5-2 summarises the calculated cost savings between the traditional wingwall and apron design cost and the proposed angled headwall / wingwall design.

Table 5-2: Cost Comparison between original design (wingwalls and apron) and new design (angled headwall and wingwalls)

ID	W x H (m)	Barrel cross sectional area (m^2)	Wingwall and apron design cost	Angled headwall / wingwall cost	Cost saving
1	3 x 3	9	R212,755.00	R202,580.00	R10,175.00
2	4 x 3.8	15.2	R186,700.50	R207,996.00	-R21,295.50
3	3.4 x 3.65	12.41	R327,453.00	R293,550.00	R33,903.00
4	2.95 x 2.35	6.93	R174,100.50	R163,266.00	R10,834.50

As can be seen from Table 5-2, there is no direct trend when comparing barrel size to cost savings between traditional wingwall and apron design culvert inlets and the proposed angled headwall / wingwall design when considering the SANRAL projects as discussed. This is due to the individual site conditions having played a role in the design of the culverts. What is clear though, is that there may be no real cost saving when considering the two different culvert inlet types. More data on existing projects may reveal a clearer trend in this regard.

The real cost saving which could be expected when installing an angled headwall / wingwall combination is that the proven increase in flow through the culvert may now allow for the effective drainage of a design flood with a larger return period (for example from a 1:10 to a 1:20 year flood), negating the need to install a larger culvert, or additional culverts in parallel, with activities associated with such a project, including:

- Excavations costs

- New culvert costs
- Layer works and resurfacing costs and
- Costs and disruption associated with re-directing traffic during the construction activities.

These costs will differ between different projects, taking into account the sizes of culvert barrels, local site conditions, the length of the culvert, etc. However, none of these significant costs will apply if a headwall / wingwall inlet is installed should the additional flow negate the need to increase the size of the culvert barrel or install additional culverts in parallel.

6 CONCLUSIONS AND RECOMMENDATIONS

The design of culverts is a staple of engineering hydraulics courses all over the world, yet the standard methodologies which are used to design them does not always take into account the benefits that could be achieved by optimising inlet characteristics for culverts flowing under inlet control conditions. This fact, together with an overly conservative approach by some designers, have caused many culverts to be overdesigned and more expensive than what they need to be. Recently, however, it seems that there have been renewed interest in this field which is encouraging.

The South African National Roads Agency (SOC) Ltd (SANRAL) is incorporating many provincial roads into its national road network. These roads were not necessarily constructed to meet the design criteria for the class of road as described in the SANRAL Drainage Manual (SANRAL, 2013). In some cases, a road's classification (after incorporation) may require its drainage culverts to convey a design flood with a higher return period than the one it was originally designed and constructed for.

An added concern is that, according to projections, climate change may cause a tendency towards an increase in intensity of rainfall, or extreme events (Mambo *et al.* 2017) in South Africa which may cause the original design capacities of the installed culverts to become insufficient.

These factors can, of course, be taken into account when a new culvert is being planned and culverts can in such a case be designed to safely convey the required design flow. A bigger challenge, however, is with increasing the capacities of existing culverts. Traditionally, this would require that a road be closed, and either the existing culvert be removed and replaced either with a new culvert of larger dimensions, or additional culverts be installed in parallel. Many times, the cost and inconvenience of closing or redirecting a road in order to upgrade the capacity of a culvert is prohibitive. If improvements can be made to existing culverts in situ to increase their capacities, it may negate the need for expensive culvert replacements projects.

This research looked at the benefit of adding not only angled wingwalls, but also an angled headwall to the inlets of culverts to increase their hydraulic performance, a combination which has not yet been the subject of much research. The installation of a ventilation devices was also considered to introduce air into a culvert which may be flowing under outlet control conditions. The research was carried out by simulating flows through a culvert using an experimental model which was constructed in the University of Pretoria Water Laboratory.

The model consisted of a single barrel square culvert and three headwall / wingwall (inlet) combinations (90 degrees, 45 degrees and 30 degrees). The 45 degree and 30 degree headwall / wingwall models were 3-D Printed.

The results of the experimental model for the 90 degree model compared favourably with previous research and established formulas. For a square headwall, various improvements are proposed for the SANRAL, 2013 coefficients for flow under inlet control conditions. It was found that increasing the Cb factor from 0.9 to 0.91 for square inlets and increasing the Ch factor from 0.6 to 0.625 for square inlets and applying Equation 9 for H_1/D values equal and smaller than 1.235, and applying Equation 10 for values above 1.235 yields a performance curve that approximates the fifth-degree polynomial trendline based on the measured experimental data.

The 45 degree and 30 degree models compared favourably with established 5th order polynomial equations and coefficients up to H_1/D of = 1, and showed an improvement in flow rates for the same headwater above this point. It was found that the 45 degree and 30 degree models showed an increase in performance when compared to the results of the 90 degree model, as follows:

- 45 degree headwall / wingwall model:
    - At H_1/D of 1.2, an increase of between 11.7% and 21%
    - At H_1/D of 1.5, an increase of between 9.9% and 14.6%
    - At H_1/D of 2, an increase of between 13% and 13.6%
- 30 degree headwall / wingwall model:
    - At H_1/D of 1.2, an increase of between 7.3% and 19.7%
    - At H_1/D of 1.5, an increase of between 10.4% and 16.7%
    - At H_1/D of 2, an increase of between 16.2% and 16.7%

It was also found that a ventilation device caused the flow to change from outlet control to inlet control in the experimental model.

This research found that precast headwall / wingwall elements can easily be connected to existing culverts if an increase in hydraulic performance is required. Not only is this a quick and relatively cost effective solution, but the added road width can be used for pedestrian traffic.

For new and existing culverts, adding a ventilation device to the culvert may be a cost effective method of ensuring that the culvert flows under inlet control conditions in certain cases. A ventilation device can also be incorporated into the road's drainage system.

Structurally, the proposed angled headwall / wingwall element has a distinct advantage over a traditional wingwall and apron slab combination as the concrete and rebar can be rationally designed and specified, unlike in heavy cantilever wingwalls. It was found, however, that this benefit may not necessarily translate into a cost saving. Real cost savings can however be achieved when negating the need to close or divert a road, excavating and removing the existing culvert and replacing it with a culvert of a larger capacity, or installing additional culverts in parallel, and then reinstating the road with the relevant layer works and surface.

This study has identified the need for further research to be carried out as follows:

- A detailed study into the potential benefits of installing a ventilation device in culverts;
- The increase in efficiency of an angled / headwall inlet improvement over angled wingwalls only.
- A Computational Fluid Dynamics model should be developed, incorporating this study, to aid in future culvert flow calculations.

In conclusion, this research underscores the feasibility and benefits of enhancing culvert hydraulic performance through innovative design modifications. The proposed solutions offer not only improved functionality but also sustainable and cost-effective alternatives to the conventional approach of closing roads for extensive culvert replacements. As infrastructure challenges persist, these findings contribute valuable insights to the evolving field of hydraulic engineering, promoting resilience and adaptability in the face of changing environmental and infrastructural demands.

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