PAPER 14

IMPROVING CULVERT CAPACITY THROUGH INLET MODIFICATIONS FOR SUSTAINABLE ADAPTATION TO INCREASING FLOOD RISKS

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ABSTRACT

Culverts play an important role in the stormwater drainage system and transport infrastructure of a country. They are designed to convey a specific flow capacity beneath roads, highways, or through embankments. However, culverts can become hydraulically insufficient over time due to increasing flood peaks. Flood peaks for rarer events have already increased across many parts of the world due to climate change. Additionally, continuing urbanisation increases runoff volume by expanding impermeable surfaces. Therefore, during flood events, inadequate local drainage can lead to infrastructure damage, inconvenience for road users and potential loss of life. Culverts are also often overestimated. When the river channel is wider than the culvert barrel, the momentum of water entering a square-edge culvert inlet creates a flow contraction just after the inlet, reducing discharge capacity.

Modifying the culvert inlet to provide a more gradual transition can increase capacity and negate the need to rebuild the entire inadequate culvert structure, offering a cost-effective solution with minimal traffic disruption. This study used physical modelling to evaluate inlet modifications, specifically rounded inlet edges, for circular culverts under inlet control. It was built on previous findings that wingwalls and headwalls offered limited flow improvement for circular culverts, whereas rounded or tapered inlets that guided water directly into the barrel significantly improved culvert performance. Therefore, modifications included different sizes of rounded edge inlets. A rounding radius of 0.35D was shown to improve flow by up to 44% at a headwater depth of 2D (twice the barrel height). It is envisaged that these improvements will be retrofitted to many existing culverts. Therefore, the effect of having the inlet improvement projected from the existing wall, was tested. The difference in upstream water levels was insignificant whether inlets were projected or integrated with the wall; the inlet rounding itself had a much greater impact.

A desktop case study was conducted to demonstrate how inlet improvements can be applied in practice and to assess their economic viability. The case study focused on a 600 mm diameter pipe culvert located on the R396 between Tsolo and Maclear in the Eastern Cape. The existing culvert was found to be hydraulically insufficient; however, the research shows that it can meet hydraulic requirements after retrofitting inlet modifications and significant cost savings were identified. These relatively simple inlet modifications can therefore offer a sustainable solution for adapting to increased flood risks caused by climate change and urbanisation.

INTRODUCTION

Culverts are integral to a country's stormwater drainage system and transport infrastructure (Jaeger et al. 2019). They are designed to convey a specific flow capacity beneath roads, according to Schall et al. 2012, and therefore, when roads are upgraded, existing culverts might need to be upgraded as well to comply with the new road standards Additionally, culverts can become insufficient over time due to increasing flood peaks caused by higher-intensity rainfall events and urban development (Alexander 1995, Cullis et al. 2015, McBride et al. 2022, Namanyane 2019, Wasko et al. 2021). Inadequate drainage could damage infrastructure and cause possible casualties during frequent flood events.

The flow through a hydraulically insufficient culvert could be increased by replacing the underperforming structures or adding more barrels. However, these solutions are cost intensive. A cost-effective solution might involve modifying existing culverts to increase discharge capacities (Jaeger et al. 2019). This would remove the need to overspend on conservative options such as replacements and increasing barrel structures.

A knowledge gap exists when examining rounded inlet modifications. According to Jaeger et al. 2019, a rounding of at least 15% of the culvert width offers the greatest reduction in turbulence and the greatest improvement in the discharge capacity. The study suggested that increasing the radius beyond this point is unlikely to offer any additional improvement. However, Jones et al. 2006 noted that the ideal radius of the rounding should extend to the full width of the culvert.

Another point of contention lies in the choice between implementing wall-integrated or projected inlet modifications. Jaeger et al. 2019 suggested that greater performance gains may be achieved if the inlet modifications are integrated into the headwall rather than projected into the flow path as seen in Figure 1. However, projected inlet modifications offer cost and construction advantages. Therefore, if the performance difference is marginal, projected rounded inlets may be a more practical solution compared to wall-integrated inlet edges.

Previous findings indicated that wingwalls and headwalls offered limited flow improvement for circular culverts, while rounded or tapered inlets that guide water directly into the barrel significantly improved culvert performance. Building on these findings, this study aimed to address research gaps related to circular culverts with rounded inlet edges under inlet control conditions by evaluating:

(a) Various radii of curvature for rounded edge inlets to investigate the effect of increasing the transition zone on culvert performance.
(b) The hydraulic performance between wall-integrated and projected models as depicted in Figure 1.
(c) The cost implications of retrofitting inlet modifications versus installing an additional culvert barrel in parallel, based on a case study site.

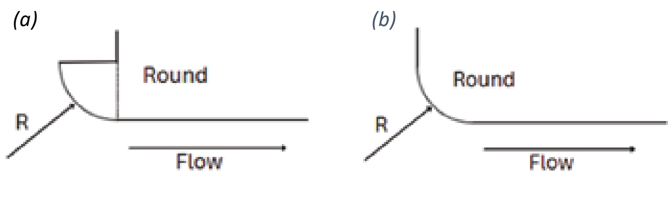

FIGURE 1: *(a) Projected model and (b) wall-integrated model*

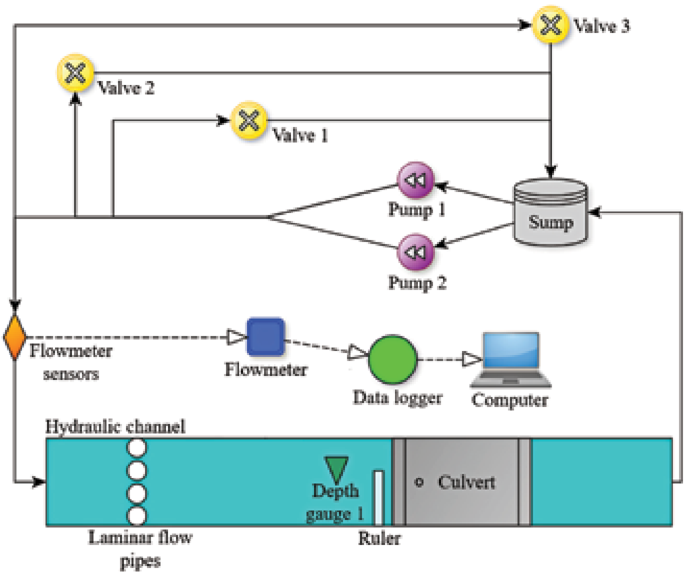

FIGURE 2: *Schematic of the experimental setup*

METHODS

Physical modelling

The experiment was conducted in a flume with a width 450mm and height of 500mm. At the upstream end, laminar flow pipes were installed to ensure uniform flow towards the culvert inlet and reduce wave action. A circular culvert model with an internal diameter (D) of 192mm, was installed downstream of the conduits. A ruler was installed just upstream of the culvert face to measure the headwater depth (H_1). A depth gauge was installed at a distance of 3D from the face of the culvert to measure flow depth. This distance was adjusted for all subsequent profiles projected from the face of the culvert. At the downstream end, a sump collected the water, which was recirculated through the system using a pump. The schematic in Figure 2 details the layout of the system.

Inlet profiles were installed and tested at the culvert entrance. Water was pumped into the flume, and flow rates were adjusted using three control valves located on the premises (Figure 2). The valves were adjusted in various

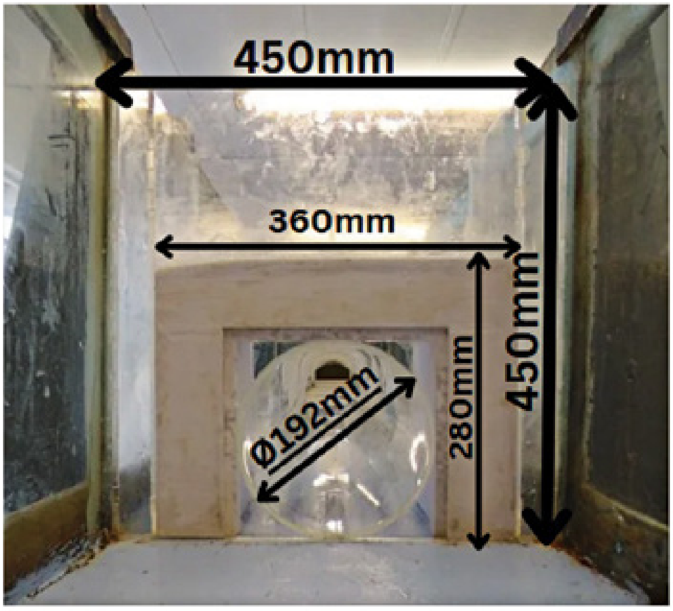

FIGURE 3: *Base model installed in the flume*

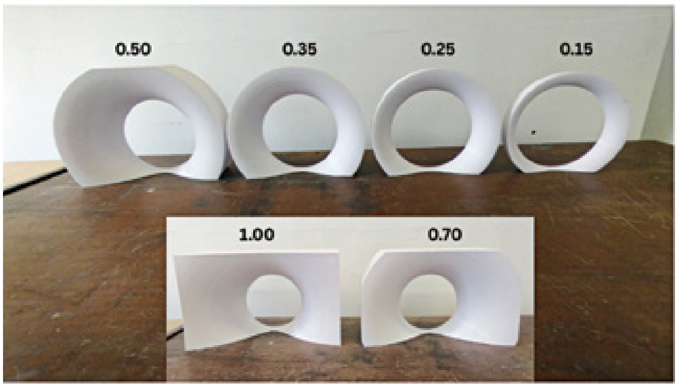

FIGURE 4: *Inlet profiles used in the physical modelling study*

sequences to achieve flow rates ranging from 4l/s to 57l/s. The flow rates were recorded utilizing an ultrasonic flow meter. Furthermore, the flow depths corresponding to each flow were measured just upstream (H_1) and at 3D upstream of the specific opening, respectively.

A set of six 3D-printed inlet models were tested against a base model to investigate the effect of increasing the transition zone for a circular culvert. The base model is a preinstalled standard circular profile (diameter: 192mm), shown in Figure 3. The 3D printed inlet models were restricted to a height of 280 mm and a width of 450mm. Each model incorporated a smooth, venturi-like shape, which is characterized by a rounding coefficient that defines the curvature. A larger coefficient results in a large, gradual curvature, whereas a smaller coefficient represents a sharper rounded inlet (adapted from Jaeger et al. 2019). This rounding coefficient is multiplied by the culvert diameter to determine the radius of curvature (R). The tested inlet curvatures included 1.0D, 0.7D, 0.5D, 0.35D, 0.25D, and 0.15D as displayed in Figure 4.

In order to examine the difference in hydraulic performance between a wall-integrated and a projected inlet, polystyrene was used as the wall material. After testing the projected inlets, polystyrene material was cut to shape and integrated around each inlet. To ensure proper integration, silicone sealant was used to bond the inlet to the polystyrene for each model. Silicone was applied with careful precision to ensure a smooth, flush bond. Both model configuration sets were tested under identical conditions to compare their hydraulic performance. Figures 5(a) and (b) display a projected model and Figure 5(c) a wall-integrated model for the 0.5D profile, which serves as an example for all the other models.

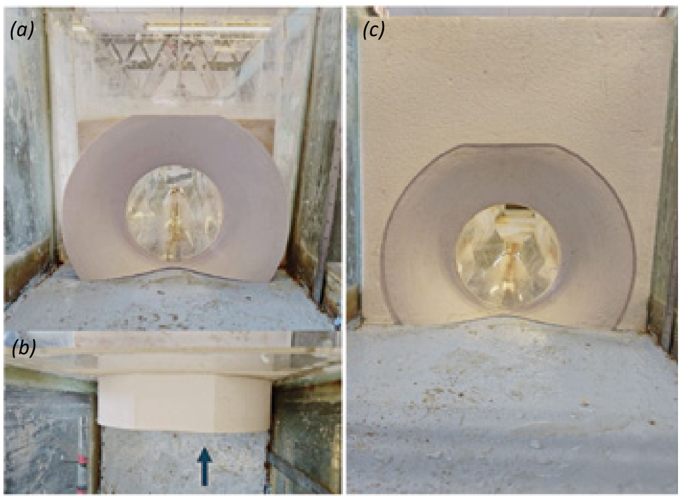

FIGURE 5: *(a) Projected inlet profile for the 0.5D model, with (b) plan view of the projected profile, (c) shows the wall-integrated 0.5D model*

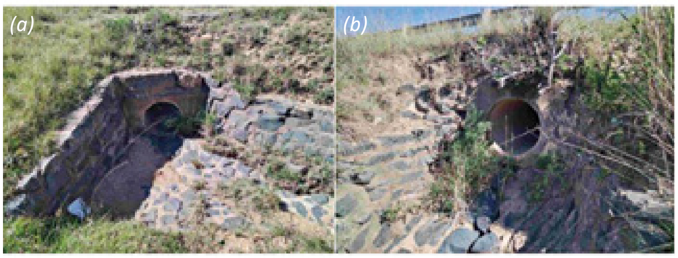

FIGURE 6: *(a) Upstream and (b) downstream conditions of the pipe culvert evaluated in the case study*

Case study: application and cost evaluation

The case study focused on a single-barrel pipe culvert located on the R396 between Tsolo and Maclear in the Eastern Cape. The culvert has a diameter of 600mm, a length of 15m and a slope of 0.0628m/m. The height from the culvert invert to the shoulder break point (SBP) is 1.11m. As seen in Figure 6, the general condition of the culvert is relatively good. There is no debris and almost no sedimentation, although some grass or weeds near the inlet may need to be cleared. Structurally, the culvert is in good condition.

The 1:10 year design flood was calculated as 0.657m^3/s, and the 1:20 year design flood as 0.820m^3/s. For culvert design, the headwater depth for the design flow rate Q_T is limited to 1.2D. For a flow rate of Q_{2T}, the maximum allowable submergence is limited to the lesser of 2D or the height from the invert to the selected backwater profile (SBP). The culvert was analysed for the given flow rates and headwater depths to determine whether it was hydraulically sufficient or not in its original state and after the application of a rounded-edge inlet.

FIGURE 7: *Water entering the base culvert model, with streamlines shown in (a) plan view and (b) elevation view; (c) shows the downstream breakaway flow*

A cost estimation analysis was also conducted to compare the cost of adding a parallel 600mm diameter pipe culvert with that of only implementing inlet modifications. This enabled an assessment of the cost benefit of inlet improvements, which eliminate the need for excavation, backfilling, and the installation of a new culvert pipe.

RESULTS AND DISCUSSION

Physical modelling results

The base model test is illustrated in Figure 7 . As the water enters the culvert, a contraction occurs (Figure 7(a)), and water dams up at the face of the culvert. A water level drop is observed at the entrance to the barrel (Figure 7(b)). This drop is attributed to the flow constriction occurring as the water moves from a wider cross-section to a narrower cross-sectional area. The contracted jet, as the flow separates from the inlet boundaries, is seen clearly on the downstream side of the culvert (Figure 7(c)). The visual results of the base model highlight the need to present a solution that reduces the effects of contraction losses at the entrance.

The results were evaluated by comparing rating curves for the base model with the wall-integrated models, and the projected model, respectively. The tests were first conducted by simply fixing the rounding to the culvert inlet to create projected inlet profiles (as shown in Figure 5(a)). The results for the different tested inlets are shown in Figure 8(a). Then, the tests were repeated with the wall built out to create a wall-integrated model (as shown in Figure 5(c)). The results for these tests are shown in Figure 8(b).

For both sets of results, the modified inlets plot to the right of the standard model. This indicates that the modified models achieve higher flow rates through the culvert at similar headwater depths, demonstrating improved hydraulic performance. The modified models have distinct trends for the flow transitions from unsubmerged to submerged conditions. Initially, all curves overlap and no major differences in flow are observed at headwater depths below 192mm (e.g. approximately at $H_1/D = 1$). This suggests that the rounded inlet edge sizes have marginal effects on culvert performance under unsubmerged flow conditions. However, as flow increases beyond this threshold, the curves begin to diverge, indicating that the effects of the rounded inlet edge size become more significant under submerged flow conditions.

While all the modified inlets enhance the culvert's performance, the 0.35D and 0.5D models demonstrate the highest efficiency. This is unexpected, as the 0.7D and 1.0D would be expected to be the top-performing inlet models (Jones et al. 2006). However, these models perform to the same standard as the 0.25D model. This indicates that a threshold is reached between the 0.35D and 0.5D models. Therefore, increasing the rounding coefficient beyond this point does not guarantee performance improvements. This suggests that an optimum point exists between 0.35D and 0.5D.

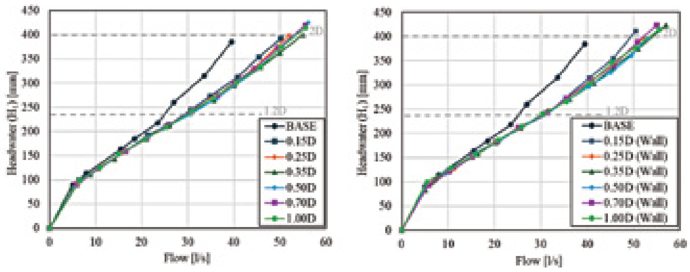

FIGURE 8: *(a) Capacity improvement with projected models of different radii; (b) capacity improvement with wall-integrated models of different radii*

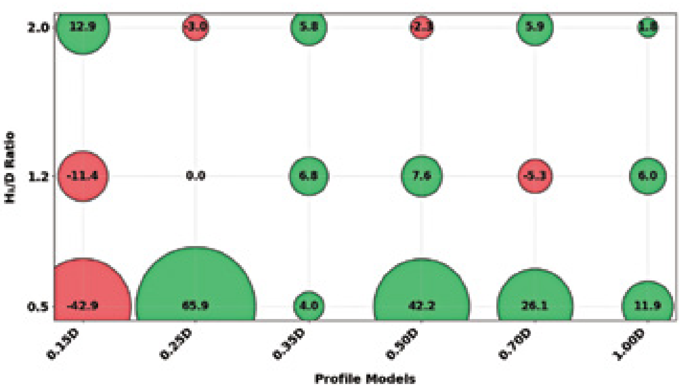

FIGURE 9: *Percentage difference for each model under different H1/D ratios (red bubbles represent better performance in the wall-integrated inlet model; green bubbles represent better performance in the projected model, with bubble size depicting the magnitude of the difference)*

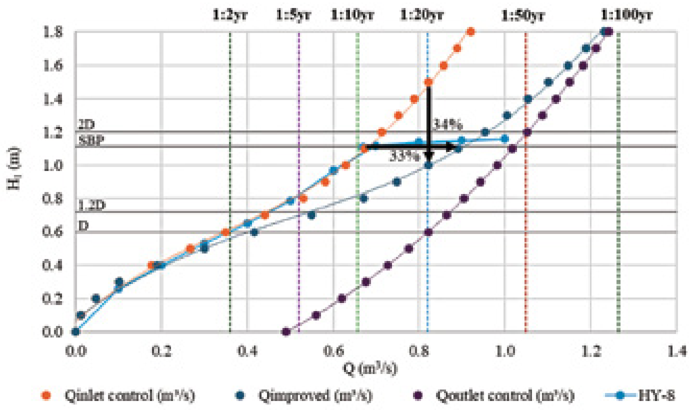

FIGURE 10: *Case study pipe culvert performance curve analysis under both inlet and outlet control as well as with a modified inlet and comparison to HY-8*

To compare the performance of wall-integrated and projected inlet models, the percentage difference in flow improvement was calculated for each condition using the following formula:

$$\textit{Percentage difference} = \frac{\textit{Projected Inlet - Wall integrated Inlet}}{\textit{Wall integrated Inlet}} \times 100$$

This percentage reflects the relative performance of the two inlet conditions at a specific H_1/D. A negative value indicates that the wall-integrated inlet model performed better than the projected model. A positive value indicates that the projected model had better performance.

Figure 9 presents these values in a bubble plot. The red bubbles represent better performance in the wall-integrated inlet model. The green bubbles represent better performance in the projected model. The size of each bubble corresponds to the magnitude of the performance difference. The inlet profiles are displayed along the horizontal axis, and the H_1/D is plotted on the vertical axis, allowing for a clear comparison of which inlet condition (wall-integrated or projected) performs better for at specific headwater depths.

Analysis of the data shows that under low headwater depths ($H_1/D = 0.5$), projected inlets generally outperform wall-integrated inlets. An exception is made for the 0.15D, where the wall-integrated condition performs better. At $H_1/D = 1.2$, the performance differences are small, within ±10%, with no consistent advantage for either inlet condition across all profiles. This suggests that either inlet condition may be acceptable at this depth.

At higher levels of submergence, the performance differences become less significant, with differences within ±6% for most profiles. As with the $H_1/D = 1.2$ condition, this indicates that either inlet condition may be acceptable under fully submerged conditions. This suggests that the inlet condition has a limited impact on flow improvement through the culvert, particularly under submerged conditions.

Since rounded-edge inlets have such a significant effect, their influence when applied in practice was evaluated.

Case study results: Application and Cost Evaluation

The 600mm diameter pipe culvert's discharge capacity was evaluated for headwater depths of 1.2D, 2D, and the height up to the SBP. The corresponding flow rates are summarised in Table 1 to determine whether the culvert is hydraulically sufficient for the design floods. The analysis indicates that the culvert is hydraulically insufficient under current conditions but becomes sufficient at headwater depths of 2D and up to the SBP once inlet improvements are applied. These headwater depths are particularly important, especially the headwater depth up to the SBP, as they define the threshold at which overtopping of the road occurs.

Figure 10 illustrates that the culvert functions under inlet control. It also presents the performance curve for the current culvert, validated against results from HY-8 software (FHWA 2016). When the same culvert is retrofitted with a projected rounded edge inlet, a noticeable flow increase is observed. For the 1:20 year flood, a 34% (500mm) reduction in headwater is observed, or alternatively, a 33% (0.221 m³/s) increase in discharge is observed at a headwater depth equal to the height from the invert to the SBP.

TABLE 1: *Case study culvert analysis for headwater depths of 1.2 D, 2 D, and the height up to the SBP*

Design flood $Q_T=Q_{10}$ (m³/s)	H_1 value	H_1 (m)	$Q_{culvert}$ (m³/s)	Sufficient (Y/N)	$Q_{improved}$ (m³/s)	Sufficient (Y/N)
0.657	1.2D	0.720	0.460	No	0.578	No
Design flood $Q_{2T}=Q_{20}$ (m³/s)	**H_1 value**	**H_1 (m)**	**$Q_{culvert}$ (m³/s)**	**Sufficient (Y/N)**	**$Q_{improved}$ (m³/s)**	**Sufficient (Y/N)**
0.820	2D	1.200	0.713	No	0.954	Yes
	Height up to SBP	1.114	0.678	No	0.900	Yes

TABLE 2: The reduction in headwater depth for each return period from Q_2 to Q_{100}

Return periods		Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	Q_{100}
1:2yr		1:5 yr	1:10 yr	1:20 yr	1:50 yr	1:100 yr	
Design flood (m³/s)		0.36	0.52	0.66	0.82	1.05	1.26
H_1 (m)	Before inlet modification	0.61	0.78	1.06	1.49	2.25	3.13
	After inlet modification	0.55	0.67	0.78	0.99	1.38	1.88
	Improvement (m)	0.06	0.11	0.28	0.50	0.87	1.25

The reduction in headwater depth for each return period from Q_2 to Q_{100} is presented in Table 2. At a return period of 1:100 years, the headwater depth upstream of the culvert is reduced by 1.25m, which lowers the water level on the road, as overtopping already occurs under those conditions. For a design flood of Q_{20}, a reduction in headwater depth of 0.5 m may be sufficient to prevent overtopping entirely.

The cost of adding an additional 600mm culvert barrel, for this specific case study, is estimated at R190 000, as shown in Table 3. This includes excavation, materials, backfilling, and labour. In comparison, the cost of retrofitting the existing culvert with an improved inlet is approximately R56 150, as shown in Table 4. This estimate accounts for the cost of moulds, concrete, reinforcement, and assumes partial demolition and reconstruction of the existing inlet structures.

When implemented, additional traffic accommodation costs must also be considered, as they are dependent on the culvert's location and surrounding road conditions. Full culvert upgrades normally occur during halfwidth road construction with closures of up to 4 km in length under normal traffic accommodation conditions. In contrast, inlet modifications are expected to require only road shoulder traffic accommodation, such as signage and delineators, allowing two-way traffic to continue with minimal disruption.

TABLE 3: Cost estimation of adding an additional 600 mm culvert barrel

ITEM No		Amount excl.VAT
1	CULVERTS	
1.1	Excavation for culvert structures	R 5 650
1.2	Backfilling	R 109 350
1.3	Concrete pipe culvert (15 m)	R 18 850
1.4	Cast in situ concrete and formwork	R 38 800
1.5	Reinforcement	R 14 600
1.6	Demolition of concrete members or elements	R 2 600
1.7	Compaction of bedding for inlets, out-lets, manholes and catchpits	R 150
TOTAL		R 190 000

TABLE 4: Cost estimation of retrofitting inlet modifications to the 600 mm culvert barrel

ITEM No		Amount excl. VAT
1	CULVERTS	
1.4	Cast in situ concrete and formwork or modified inlet moulds	R 38 800
1.5	Reinforcement	R 14 600
1.6	Demolition of concrete members or elements	R 2 600
1.7	Compaction of bedding for inlets, outlets, manholes and catchpits	R 150
TOTAL		R 56 150

Applying inlet modifications to this hydraulically insufficient culvert resulted in a cost saving of up to 70% compared to the estimated cost of rebuilding the structure to add an additional barrel.

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated different sizes of rounded edge inlets modifications for circular culverts. Previous findings have shown that rounded culvert inlets have a greater impact on the capacity of circular culverts than other retrofit improvements, such as wingwalls and headwalls. Therefore, rounded culvert improvements were further investigated to find an optimal inlet rounding curve of 35% of the culvert diameter. It was shown that projected models produce similar improvement to wall-integrated models, while requiring less material for construction and installation. In practice, inlet modifications can be applied in one of two ways: by attaching a precast concrete mould to the existing culvert inlet (i.e., projected), or by casting a new front wall with the modification integrated into the structure.

The cost analysis showed that up to 70% in cost savings could be achieved by using culvert inlet improvements instead of installing additional culvert barrels. These relatively simple inlet modifications therefore offer a sustainable solution for adapting to increased flood risks caused by climate change and urbanisation.

Further research is recommended to evaluate the performance of inlet modifications under conditions involving debris and sediment accumulation, as these reflect more realistic field scenarios and influence hydraulic efficiency. In addition, it is recommended that the practical implementation of inlet improvements in the field be assessed, with consideration given to constructability and integration with existing infrastructure. Lastly, the development of new design guidelines, or the revision of existing ones, such as SANRAL 2013, is recommended to formally incorporate inlet modifications. This should include the introduction of a flow improvement coefficient that can be used in culvert design calculations to quantify the increase in capacity.

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