https://doi.org/10.71573/yfp00c93



# Improving Hydraulic Capacity with Inlet Modifications to Box Culverts using Numerical Modelling

*Maria Dorothea Giliomee*[1,*] https://orcid.org/0009-0004-1582-6865, *Ione Loots*[1] https://orcid.org/0000-0003-0715-6852 & *Marco van Dijk*[1] https://orcid.org/0000-0002-3830-526X

[1]*University of Pretoria, Department of Civil Engineering, Pretoria, South Africa*
**Corresponding author email: u20424028@tuks.co.za*

## Abstract

Culverts can become inadequate over time due to increasing flood peaks caused by higher-intensity rainfall events and urban development. Modifying the culvert inlet to increase discharge capacity can negate the need to rebuild the entire structure. Using Cradle CFD scFLOW Hexagon software for numerical modelling, this study found that box culverts with a 15° headwall and 15° wingwall increased the flow capacity by up to 34% at a headwater depth of twice the culvert opening ($2D$). This solution provides the best balance between hydraulic performance and practical implementation. The largest improvement obtained by rounding the edges of a square box culvert is 30%. A new flow improvement coefficient, $C_{TG}$, is proposed to quantify the improvement for each type of inlet, which can be used with existing design equations to calculate the improved discharge capacity for specific inlet modifications. Implementing inlet improvements for new and existing culverts will reduce flood risks and contribute to the climate resilience of road infrastructure.

## Highlights

- Optimising culvert inlets reduces flood risks and contributes to urban climate adaptation.
- A flow improvement coefficient was derived through numerical modelling.
- Small inlet modifications prevent rebuilding an entire inadequate culvert structure.

## Introduction

Culverts are designed to convey a specific flow capacity beneath roads or through embankments (Schall *et al.*, 2012). However, increasing flood peaks can cause culverts to become insufficient (Cullis *et al.*, 2015). Flood peaks for less frequent flood events have already increased across many parts of the world due to climate change (Wasko *et al.*, 2021). Additionally, continuing urbanisation increases the volume of runoff by increasing impermeable surfaces (Schütte & Schulze, 2017). Inadequate drainage can lead to infrastructure damage, inconvenience for road users, and loss of life.

Culverts often discharge a smaller capacity than expected (Straub *et al.*, 1953). The momentum of water entering a square-edge inlet culvert creates a flow contraction, or vena contracta, just after the inlet, as seen in Figure 1 (West, 1956). At the vena contracta, the cross-sectional flow area is at a minimum, which reduces the culvert capacity (Jaeger, 2019). Modifying the culvert inlet can either increase its capacity for a specific headwater depth or pass the design discharge at a lower headwater depth.

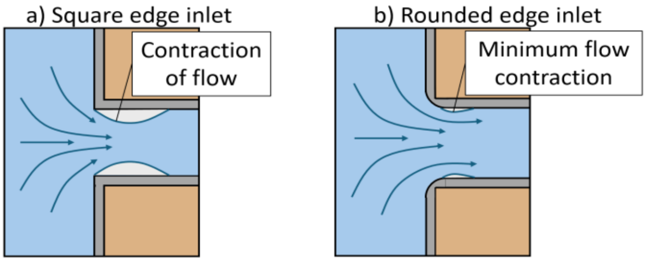


**Figure 1: Plan view of flow contraction at a square edge inlet and a rounded edge inlet, adapted from Schall et al. (2012).**

Some of the most promising inlet configurations include tapered inlets (Schall *et al.*, 2012), 15° headwalls (Ashour *et al.*, 2016), 45° wingwalls (West, 1956), and rounded inlets (at least 0.15*D* or 0.15*B*) (Jaeger, 2019). Headwalls and wingwalls are already widely used as retaining structures. Limited research has examined combinations of different wingwall and headwall angles, typically using the same angle when combined or testing wingwalls and headwalls separately. Therefore, different wingwall and headwall angles were tested and compared to rounded edge inlets. A new coefficient to quantify capacity improvements was developed to assist in designing or upgrading culverts.

# Methodology

The scFLOW software was used to evaluate different inlet configurations for square box culverts. The CFD model replicates the culvert in the hydraulic flume at the University of Pretoria, where physical studies on inlet modifications were performed. The culvert slope was 1%, which is the minimum slope to prevent silt deposition (SANRAL, 2013) and to ensure inlet control conditions since the inlet geometry has a greater influence on the flow through the barrel than under outlet control (West, 1956; Jones *et al.*, 2006). However, both flow controls benefit from optimised designs (Schall *et al.*, 2012; Jaeger, 2019). Each 3D CAD model was imported into the scFLOW Pre-Processor, where the simulation model is built, properties assigned, and boundaries applied. Figure 2a) shows the 3D CAD culvert model for the 30° wingwall and 30° headwall 200 x 200 mm box culvert, as an example. For all the models, the wingwalls extended 0.4*D* (80 mm) to the sides of the barrel, and the headwall extended 0.4*D* (80 mm) upward. This ensured that the enlarged inlet cross-sectional area remained constant. Since the experiment was symmetrical about the x-axis, the entire simulation model was split in half, as shown in Figure 2b), and a free-slip boundary condition was applied along the symmetry plane. The fluid region was defined to envelop the entire culvert. Air was the initial fluid in the domain, and water entered through the inlet at a specified constant mass flow rate. The outlet surface region had an outflow static pressure and allows both air and water to exit the domain naturally. The culvert was modelled as a rigid boundary with surface roughness, calibrated to align with the results of the physical modelling study. Other boundaries included the atmospheric interface, glass side walls and metal floor.

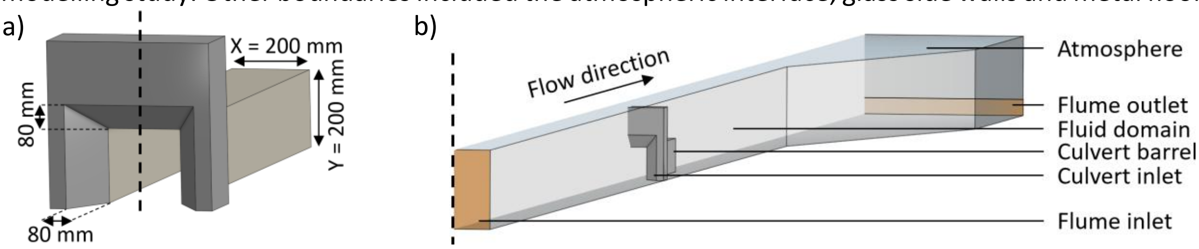


**Figure 2: a) 30° wingwall and 30° headwall box culvert model and b) the half-flume and culvert simulation setup.**

The mesh was refined until the results no longer changed noticeably, and a base size of 0.05 m was used, with local refinement to 0.025 m near the inlet, outlet, and around the culvert. A transient CFD simulation was performed to model free-surface flow, and the simulation was run with a time step of 0.01 seconds for a total of 15 000 time steps. Each model analysis began with a low flow rate, and the corresponding water depth was measured just upstream of the culvert inlet, measuring headwater $H_1$. The final $H_1$ value used for calculations was the average headwater level over the last 1 000 time steps once the water level stabilised. The flow was incrementally increased, re-analysed and the same measurement procedure followed until the headwater depth reached a maximum of 2*D*. This process was repeated for each culvert inlet model, with the average Courant number remaining close to one across all simulations. Results were visualised in the Post-Processor.

# Results and discussion

Headwater data collected during the experiments were used to generate performance curves. The standard square edge inlet performance curve for inlet control aligned with the literature, such as Austroads (2023) and Schall *et al.* (2012). It should, therefore, be possible to use the improvement coefficients developed in this study to adjust values estimated with the equations in the literature.

## Culvert inlet analysis

The type of inlet improvement had a considerable influence once the inlet was submerged ($H_1$>1*D*), as shown in Figure 3. The 5° wingwall with a 5° headwall provided the greatest flow improvement of 35% for the square box culverts, as shown in Figure 3a), followed by a 15° wingwall with a 15° headwall with a flow improvement of 34%. A decrease in wingwall and headwall angles increases flow capacity. The 5° wingwall with a 5° headwall extends 4.6*D* from the culvert barrel, making the 15° wingwall with a 15° headwall a more practical solution, extending only 1.5*D*. Figure 3b) comparing different rounded edge inlets, shows the performance of a small rounded edge inlet (0.05*D*) does not differ significantly from that of a square-edged inlet. Rounded edges of ≥0.15*D* yield similar flow improvements, confirming the findings of Jaeger (2019) for circular culverts, who suggested that increasing the radius beyond this point offers little additional improvement. The best rounded edge inlets (0.15*D*-0.45*D*), which improved flow by up to ±30%, performed similarly to a 15° wingwall with a 5° headwall.

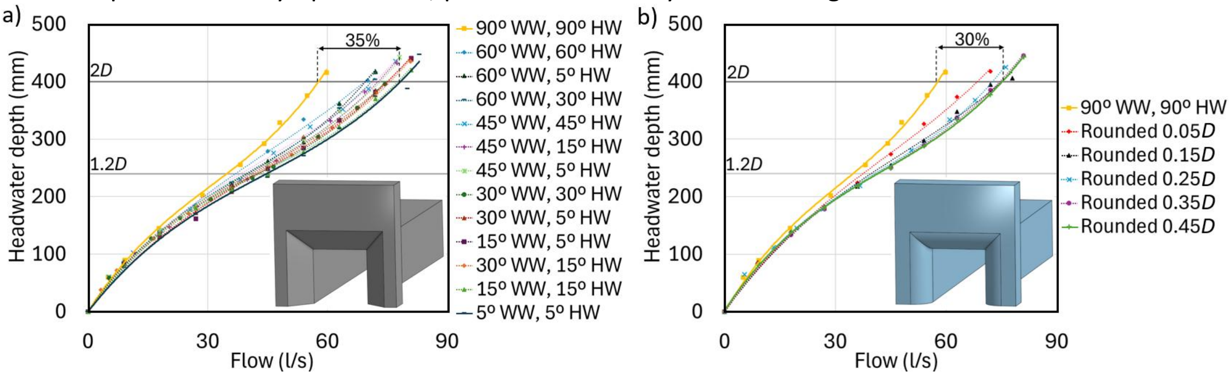


**Figure 3: Performance curves for box culverts with a) wingwalls (WW) and headwalls (HW) and b) rounded edge inlets.**

## Flow improvement coefficients

The $C_{TG}$ coefficient development is described here for the 5° wingwall and 5° headwall box culvert as a typical example. Equation 1 was used to quantify the flow improvement for each inlet.

$$Flow\ improvement\ (\%) = \frac{(Q_{Improved\ inlet} - Q_{Square\ edge\ inlet})}{Q_{Square\ edge\ inlet}} \times 100 \qquad \text{Equation 1}$$

The flow improvement was used to calculate the flow improvement coefficient, $C_{TG}$, using Equation 2.

$$C_{TG} = \frac{(Q_{Improved\ inlet} - Q_{Square\ edge\ inlet})}{Q_{Square\ edge\ inlet}} + 1 = \frac{Flow\ improvement\ (\%)}{100} + 1 \qquad \text{Equation 2}$$

The $C_{TG}$ coefficients were plotted separately for unsubmerged inlet headwater elevations, $0.5 \leq H_1/D \leq 1.2$, and submerged inlet headwater elevations, $1.2 < H_1/D \leq 2$, as seen in Figure 4a). A trendline for each section gives the $C_{TG}$ coefficient equations. Figure 4b) shows the $C_{TG}$ coefficient values for different wingwall and headwall angles at $H_1$=2*D* to visualise the best wingwalls and headwalls. Smaller wingwall and headwall angles lead to greater improvement; however, the angles should be >0°, which is the same as the 90° wingwall and headwall, standard square-edge inlet again.

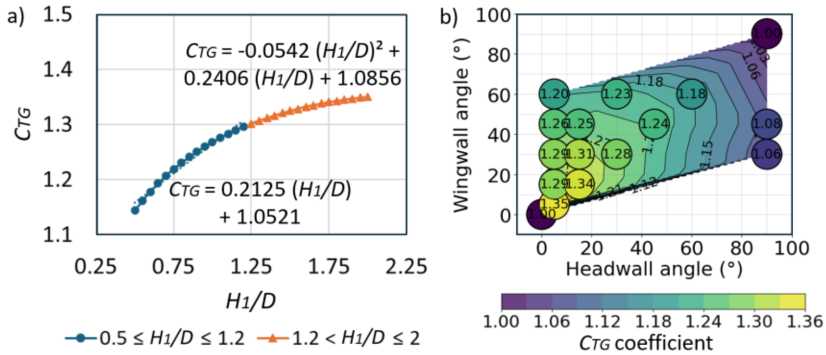


**Figure 4: a) $C_{TG}$ equations for a 5° wingwall and 5° headwall, b) $C_{TG}$ for different wingwall and headwall angles at 2*D*.**

The improved discharge for an inlet modification is calculated as shown in Equation 3. $C_{TG}$ is multiplied by the discharge calculated for a standard square edge inlet.

$$Q_{Improved} = Q_{Square\ edge\ inlet} \times C_{TG} \quad \text{Equation 3}$$

## Conclusions and future work

Stormwater systems must be assessed and upgraded as a whole. Culverts are just one component, and applying inlet modifications, particularly at road crossings in open channels where flood risk is not transferred downstream, offers a sustainable upgrade. The magnitude of improvement for the different inlets was noticeable once the inlet was submerged. This is advantageous since the culvert conveys a large volume of water during high flood events, mitigating flooding. Optimising culvert inlets can increase flow capacity by up to 34%, which can eliminate the need to rebuild an entire inadequate culvert structure. Combining different wingwall and headwall angles does not necessarily lead to greater flow improvement; instead, the smallest angles consistently provided the best performance. The 5° wingwall and 5° headwall provided the best performance but are impractical to construct due to their large size. The second-best inlet, 15° wingwall and 15° headwall, offers similar flow improvements and is more feasible given its smaller size. Both these wingwall and headwall combinations achieved greater flow improvement than the best rounded-edge inlet (0.45*D*) applied to a square box culvert. Therefore, wingwalls and headwalls may be preferable to rounded edges, as they are already commonly used and often easier to construct.

Further analysis is planned to determine the optimal balance between wingwall and headwall angles and their lengths, as this study kept the maximum wall extension to the sides and top constant. It is recommended that tests should also be conducted under outlet control conditions and at headwater levels even higher than 2*D*, to allow analysis of existing culverts with heights >2*D* between the culvert invert and road level. Culvert inlet shapes should be tested under varying conditions, including different slopes, surface roughness, embankments, misalignment, and debris or silt at the inlet.

## Acknowledgement

We thank the South African National Roads Agency SOC Limited (SANRAL) for project funding.

## References

Ashour, M. A., Aly, T. E. & Abdou, A. A. (2016) Inclined headwall is an efficient tool for maximizing the discharge efficiency through culverts. 3rd International conference (Water resources and wetlands) Tulcea, Romania.

Austroads. (2023) Guide to Road Design Part 5B: Drainage – Open Channels, Culverts and Floodway Crossings.Sydney, NSW. Austroads Ltd. AGRD05B-23.

Cullis, J., Alton, T., Arndt, C., Cartwright, A., Chang, A., Gabriel, S., Gebretsadik, Y., Hartley, F., Jager, G. d., Makrelov, K., Robertson, G., Schlosser, C. A., Strzepek, K. & Thurlow, J. (2015) An uncertainty approach to modelling climate change risk in South Africa World Institute for Development Economics Research.

Jaeger, R. (2019) *Hydraulic improvements in culverts for climate change adaptation.* Doctor of Philosophy Doctor of Philosophy, University of the Sunshine Coast.

Jones, J. S., Kerenyi, K. & Stein, S. (2006) Effects of Inlet Geometry on Hydraulic Performance of Box Culverts. Springfield, VA.

SANRAL. (2013) *The South African National Roads Agency SOC Limited Drainage Manual,* Pretoria, The South African National Roads Agency SOC Limited.

Schall, J. D., Thompson, P. L., Zerges, S. M., Kilgore, R. T. & Morris, J. L. (2012) Hydraulic Design of Highway Culverts Third Edition, Hydraulic Design Series Number 5.Colorado. FHWA-HIF-12-026. TRANSPORTATION, U. S. D. O.,

Schütte, S. & Schulze, R. E. (2017) Projected impacts of urbanisation on hydrological resource flows: A case study within the uMngeni Catchment, South Africa. *Journal of Environmental Management,* 196, 527-543. https://doi.org/10.1016/j.jenvman.2017.03.028.

Straub, L. G., Anderson, A. G. & Bowers, C. E. (1953) Importance of Inlet Design on Culvert Capacity. Minneapolis, Minnesota. University of Minnesota.

Wasko, C., Nathan, R., Stein, L. & O'Shea, D. (2021) Evidence of shorter more extreme rainfalls and increased flood variability under climate change. *Journal of Hydrology,* 603. https://doi.org/10.1016/j.jhydrol.2021.126994.

West, E. M. (1956) Hydraulic Model Studies of Culvert Operation.Lexington, Kentucky. HIGHWAYS, C. O. K. D. O.,