Debris Retention Upstream of Culverts: Pier Structure Optimization Through Physical Modelling

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ABSTRACT

Debris accumulation at culvert inlets during flash floods can cause severe hydraulic blockage and overtopping. This study investigated non-mechanised debris piers as a cost-effective alternative for South African stormwater management infrastructure. Froude-scaled physical modelling in a hydraulic flume was used to assess the effects of pier layout angle (30º, 60º, 90º), pier shape (circular, square, downward teardrop and upward teardrop) and V-apex orientation on debris retention, backwater rise, and hydraulic blockage. Debris retention and backwater significantly decreased as pier angle widened. Pier shape had an overall weak influence and was not found to significantly affect the pier performance. The upstream-facing V-apex resulted in lower backwater accumulation by diverting debris toward the sides of the channel, rather than retaining it in the center. Hydraulic blockage was lowest at 90° due to improved debris alignment allowing for more debris to cleanly pass through the culvert. Higher pier-side retention did not correspond to lower culvert blockage. Trade-off and sensitivity analyses identified 90° upward teardrop piers with an upstream-facing V-apex as optimal and robust. This preliminary debris testing provides a foundation for future debris pier testing with the aim of developing technical design guidelines for debris piers in South Africa and similar developing countries, where the use of mechanised structures is not practical.

KEYWORDS: Debris, culvert, blockage, hydraulic model, debris retention, backwater

1 INTRODUCTION AND BACKGROUND

Urban flooding is exacerbated by debris accumulation at culvert inlets, which reduces hydraulic capacity and increases the likelihood of upstream inundation, erosion, and structural failure (Diehl and Bryan 1993; Bradley et al. 2005; Balkham et al. 2010; Schmocker and Hager 2013; Blanc et al. 2014; Panici and De Almeida 2018; Miranzadeh et al., 2023). Flow through these culverts partially blocked by debris is governed by the culvert geometry, channel flow characteristics, and debris properties (Miranzadeh et al., 2023). Debris characteristics vary with catchment conditions (Diehl and Bryan 1993), and blockage formation depends on debris orientation relative to flow and pier structures (De Cicco et al., 2020).

A range of debris retention structures is used internationally with mixed success (Blanc et al., 2014). Mechanised debris control structures have shown to be highly effective, however, developing countries like South Africa face poor infrastructure management through lack of planning, limited funding, corruption and vandalism or theft (Mazele and Amoah, 2022). Therefore, non-mechanised debris control structures present an ideal solution for mitigating culvert blockage in South Africa and other developing countries. Piers placed upstream of culverts can retain debris effectively while reducing inlet maintenance compared to deflectors or racks (Wallerstein et al., 1997). The efficiency of such systems depends on providing adequate retention volume (Blanc et al., 2014), with pier spacing small enough to trap debris, yet wide enough to maintain flow and allow machinery access (Wallerstein et al., 1997; Schmocker and Hager, 2013; Lange and Bezzola, 2006). Spacing becomes less important once initial accumulation occurs (Lange and Bezzola, 2006). Debris volume and Froude number strongly influence backwater rise, whereas pier diameter has limited effect. Pier shape controls water surface profiles and blockage probability, with flat shapes most prone to blockage and ogival shapes least (Schmocker and Hager, 2013; Panici and De Almeida, 2020). Wallerstein et al. (1997) found a V-shaped configuration with the apex pointing downstream provided optimal retention with minimal backwater rise, although only circular piers at a 60° orientation were assessed.

The present study therefore investigates the pier shape and orientation with a V-shaped configuration that maximizes debris retention at the piers while minimizing backwater and culvert hydraulic blockage. It further examines whether orienting the V apex upstream could redirect debris toward channel margins, reducing trapping between piers. Identifying the most effective pier arrangement can significantly reduce culvert blockage, thereby mitigating flood risk and infrastructure damage.

2 METHODOLOGY

The study modified the V-shaped pier retention structure, identified as the most effective debris-retention system in previous research, and tested scaled physical models of a culvert–pier system in a hydraulic channel. A constant, subcritical flow of 12.8 l/s (Fr = 0.45) was used for the model to ensure deep flow, minimize meniscus effects, and maximize blockage probability under uncongested conditions (De Cicco et al., 2020). Flow was measured using an ultrasonic flow meter. Froude similarity (Fr_{model} = $Fr_{prototype}$ = 0.45) governed scaling, with model dimensions based on standard portal culverts (Web-1) and pier configurations from Lange and Bezzola (2006). A scale ratio of n = 12.5 was applied, based on the restricted flume width of 450 mm and a 1500 x 1500 mm rectangular portal culvert with three barrels as the prototype. Figure 1 shows the dimensions (mm) of the model culvert used in the experiments.

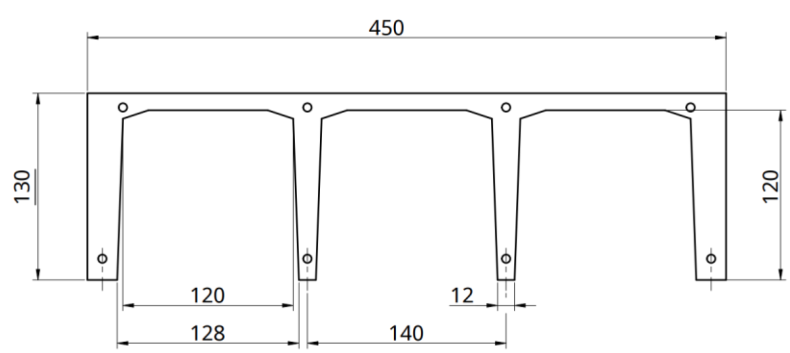


Figure 1 : Dimensions of the model culvert

Piers of circular, square and teardrop shapes were constructed from dowels and medium density fiberboard each with a constant 32 mm cross-section. Pier diameters were chosen to be consistent with an existing structure at Faerie Glen Nature Reserve, South Africa, since pier diameter has minimal influence on debris accumulation or backwater rise (Schmocker & Hager, 2013; Panici & De Almeida, 2020). The pier rig was positioned 1.2 m upstream of the culvert in the model, maintaining proportional field spacing to that of the Faerie Glen Nature Reserve debris pier system. Clear pier spacing *s* was set at 100 mm, satisfying L ≥ 1.5s (Lange and Bezzola, 2006), where L is the minimum length of debris that will initially get caught. This ensures debris ≥ 150 mm would be retained at the piers rather than at the culvert ($L_{culvert}$ ≥ 192 mm; Web-1). The pier rig dimensions (mm) for the model are shown in the side and front-view schematic in Figure 2.

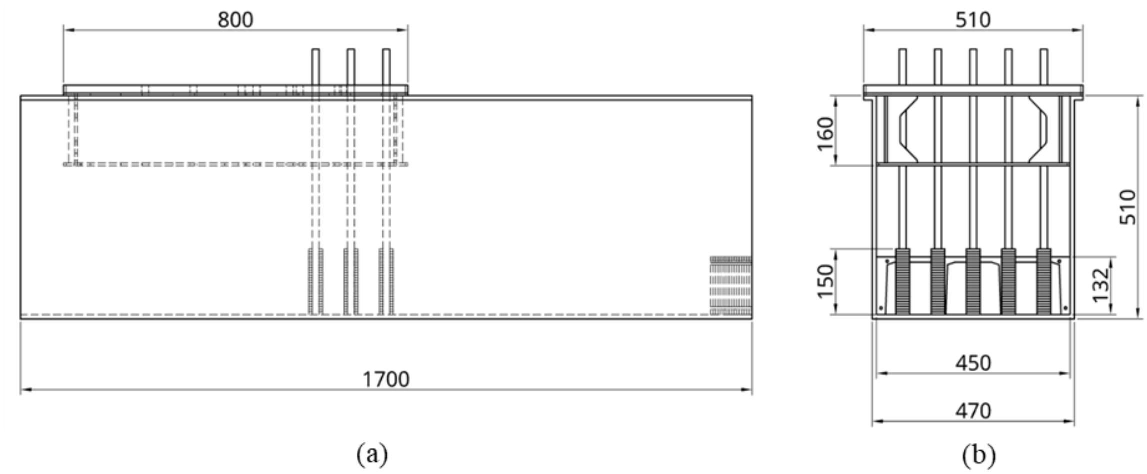


Figure 2: Dimensions of the (a) side view and (b) front view of the model pier rig

To avoid overestimating accumulation associated with using uniform debris material in testing (Panici and De Almeida, 2018), a non-uniform debris mixture of various shapes and lengths, including plastic bags to reflect debris common in developing regions, was used in line with Lyn et al. (2003). A total of 200 pieces of mixed debris was used in the experiments. Water levels were recorded at four locations before and after debris release. A baseline test without piers established culvert behaviour under uncontrolled accumulation. For all other tests, debris was released over two minutes from 4.15 m upstream of the culvert and the water level was measured at specified locations upstream of the culvert. Figure 3 shows the positioning of the four water level measuring points used in the tests, with the pier rig being placed 1.2 m upstream of the culvert. After each run, debris retained at the piers, retained at the culvert, and passing downstream were counted.

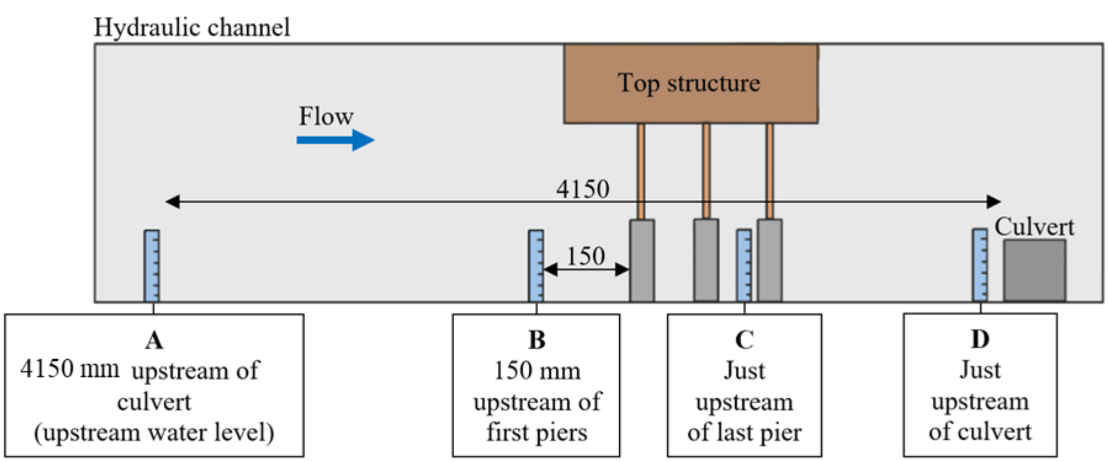


Figure 3: Position of water-level measuring points in the model

Three V-shape angles (30°, 60°, 90°) were tested with apex directions both upstream and downstream, across four pier shapes: circular, square, upward (apex facing upstream) teardrop, and downward (apex facing downstream) teardrop. Each configuration was tested in triplicate. The most effective configuration was defined as retaining the most debris at the piers, for the lowest backwater accumulation with minimal culvert blockage. The debris retention was calculated as a percentage of the total amount of debris fed during a single test that was caught at the piers. The backwater rise was measured as the change in backwater height after debris is added into the flume. Hydraulic blockage was calculated as a percentage using Eq. (1):

$$Hydraulic\ blockage\ (\%) = \frac{H_{blocked} - H_{unblocked}}{H_{blocked}}\ x\ 100 \tag{1}$$

The debris retention, backwater accumulation and hydraulic blockage result data were plotted and visually analyzed to determine trends in the data. Multiple linear regression (MLR) analyses were then conducted in RStudio, to determine the significance of the influence of the predictors (pier angle, pier shape, V-apex direction) on the responses (debris retention, backwater rise, hydraulic blockage). All predictors were considered to be categorical, and a 95 % confidence interval was used in the MLR, therefore any predictor with a p-value ≤ 0.05 was deemed as significant. Lastly, a multi-objective trade-off analysis was also done in RStudio to determine the optimal pier structure based on the main objectives of minimizing hydraulic blockage and reducing backwater rise, with the secondary objective of maximizing debris retention at the piers. The data for each objective was normalized (since the units of each objective were not the same) according to Eq. (2). A weighted sum approach was then used to calculate a trade-off score for the tests done (see Eq. (3)), and the configurations with the highest trade-off score were chosen to have optimal performance. H_{norm}, B_{norm} and D_{norm} represent the normalized hydraulic blockage (%), backwater rise (mm) and debris retention (%) respectively. A sensitivity analysis was done on weightings w_1, w_2 and w_3 using 500 iterations with randomly generated weightings in RStudio, to ensure that the chosen optimal configuration performed consistently well.

$$Data_{norm} = \frac{Data - Data_{min}}{Data_{max} - Data_{min}} \tag{2}$$

$$Trade - off\ Score = w_1(1 - H_{norm}) + w_2(1 - B_{norm}) + w_3(D_{norm}) \tag{3}$$

3 RESULTS AND DISCUSSION

3.1 Debris retention

The average results of the percentage of debris retained at the piers for each layout angle and pier shape are shown in the bar charts of Figure 4. The bar charts generally exhibit a slight decrease in the debris retention at the piers as the pier layout angle becomes wider. The MLR showed that debris retention decreased slightly (but not significantly) from 30º to 60° ($p = 0.20 > 0.05$) and decreased significantly at 90° ($p = 0.00045$). The pier shape demonstrated a very slight decrease in the debris retention as the shaped changed from circular and square to teardrop shaped for the V-apex facing downstream. The pier shape did not exhibit consistent trends in the debris retention at the piers for the V-apex facing upstream, however the circular pier shape resulted in the least debris retention at the piers compared to the other shapes. From the MLR, square piers significantly increased debris retention ($p = 0.015$), however the upward ($p = 0.12$) and downward teardrop ($p = 0.062$) showed weak, non-significant increases in the debris retention, compared to the circular piers. There was also no distinct trend observed in debris retention when changing the V-apex from upstream to downstream-facing. The MLR showed that changing the V-apex direction had no significant effect ($p = 0.46$).

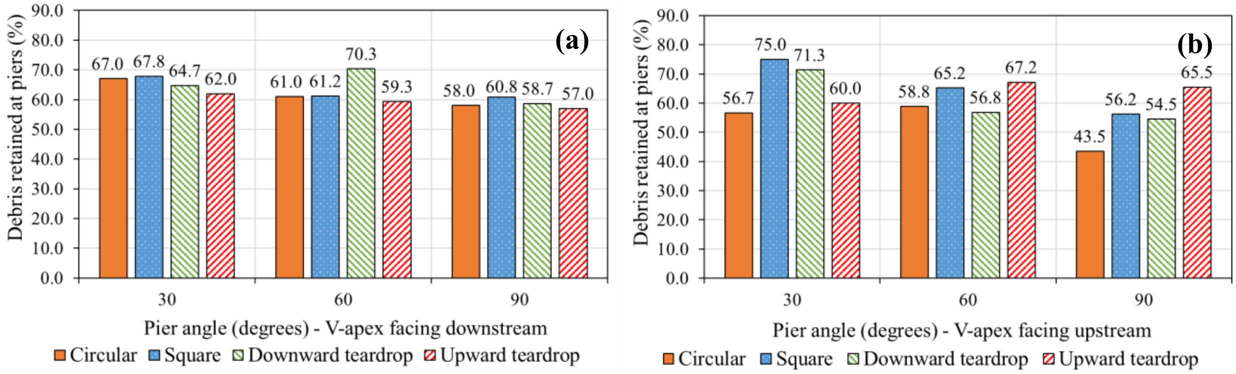


Figure 4: Bar charts of average debris retention for V-apex (a) downstream and (b) downstream

3.2 Backwater accumulation

The average results of the backwater rise at the piers for each layout angle and pier shape are shown in the bar charts of Figure 5. From the charts, there is a distinct decrease in the backwater rise across all pier shapes as the pier layout angle becomes wider. Therefore, the narrower the pier angle layout, the higher the backwater accumulation at the piers. This is directly related to the debris accumulation at the piers, as it was determined previously that the narrow pier angles allow for greater debris accumulation at the piers, therefore resulting is more blockage at the piers and higher backwater. The MLR showed that the backwater accumulation decreased significantly with increasing pier angle, with both 60° and 90° having $p < 0.001$, and 90° producing the largest decrease. Pier shape did not seem to consistently influence the backwater rise, seen by the fluctuating trends in the backwater rise between the pier shapes.

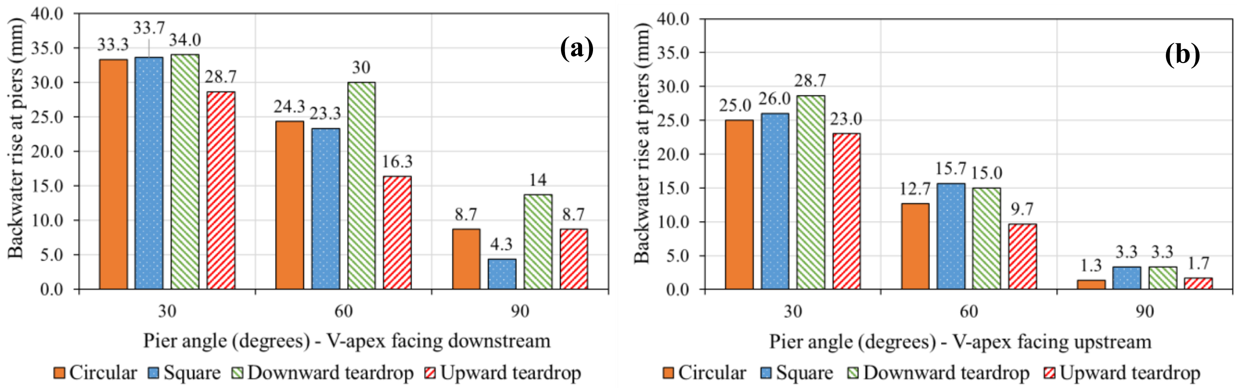
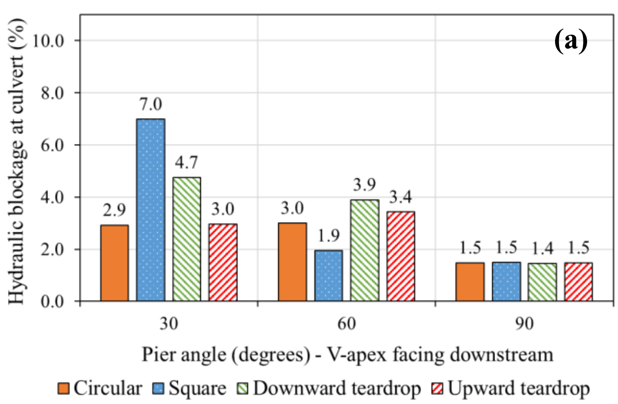


Figure 5: Bar charts of average backwater for V-apex (a) downstream and (b) downstream

The upward teardrop pier shape was generally seen to have the lowest backwater accumulation, and the downward teardrop the highest backwater accumulation. From the MLR, square piers showed no significant effect ($p = 0.92$), while the upward teardrop ($p = 0.088$) and downward teardrop ($p = 0.058$) showed weak, non-significant decrease and increase to the backwater accumulation respectively, compared to the circular piers. The backwater accumulations for the pier configurations with the V-apex facing downstream were higher than those with the V-apex facing upstream. From the MLR, the V-apex facing downstream significantly increases backwater accumulation ($p < 0.001$) compared to the V-apex facing upstream. Although changing the V-apex direction had no significant effect on the amount of debris accumulated at the piers, the placement of where the debris was caught in-channel influenced the backwater accumulation. When the apex faced downstream, it allowed the debris to get caught in the middle of the channel between the arms of the V, causing significantly more backwater rise opposed to when the apex faced downstream and more debris tended to be retained on the sides of the channel.

3.3 Hydraulic Blockage

The averaged results of the percentage hydraulic blockage at the culvert for each layout angle and pier shape are shown in the bar charts of Figure 6. Baseline tests resulted in an average of 18.4% hydraulic blockage at the culvert. Compared to the baseline, the average hydraulic blockage with the inclusion of pier structures ranged from 0% - 10.3% across all tests done. This demonstrates that even the worst performing pier configuration (upward teardrop, 30º pier angle with V-apex facing upstream) allowed for a 44% decrease in the hydraulic blockage, showing the effectiveness of these pier structures placed upstream of culvert. Across the pier angle, it can be seen that the hydraulic blockage decreases as the angle becomes wider. The MLR showed a slight (non-significant) decrease in hydraulic blockage from 30º to 60° ($p = 0.20$) and a significant decrease at 90° ($p = 0.0082$). Wallerstein et al. (1997) based the optimal pier structure on its ability to retain the most debris for minimal backwater. Therefore, it was intuitively assumed better debris retention at the piers results in less culvert blockage. In this case, although more debris was retained at the piers for narrower pier layout angles, the wider angles resulted in better orientation of debris to pass through the culvert openings and flow further downstream, therefore resulting in lower hydraulic blockage at the culvert.



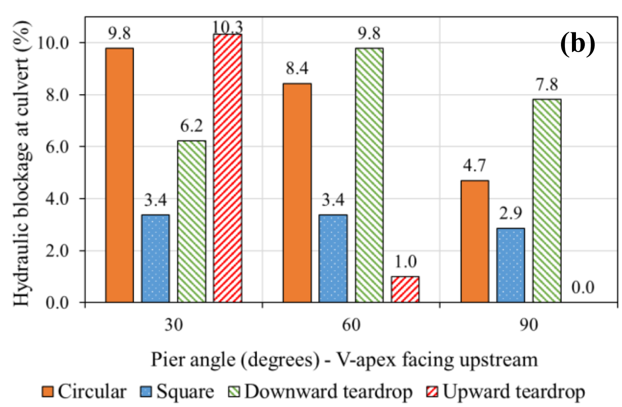


Figure 6: Bar charts of average hydraulic blockage for V-apex (a) downstream and (b) downstream

The circular and downward teardrop piers had greater hydraulic blockage compared to the square piers, however the pier shape generally did not exhibit any distinct trends in the hydraulic blockage. The MLR confirmed that all pier shapes showed small, non-significant reductions in blockage ($p > 0.1$). The configurations with the V-apex facing downstream tended to have smaller hydraulic blockages at the culvert compared to the upstream-facing V-apex, confirmed by the MLR which showed the V-apex facing downstream to significantly reduce hydraulic blockage ($p = 0.0083$), compared to the upstream V-apex.

3.4 Multi-Objective trade-off analysis

Although optimal pier structures were recommended based on their ability to retain the most debris for minimal backwater (Wallerstein et al., 1997), it has been shown in this study that increasing the debris retention at the piers does not necessarily decrease the debris accumulations at the culvert. Therefore, a three-way trade-off between the hydraulic blockage, backwater rise, and debris retention at the piers was done instead to determine the optimal pier configuration. Hydraulic blockage was prioritized and given a weighting $w_1 = 0.5$, while backwater rise had $w_2 = 0.3$ and debris retention a weighting of $w_3 = 0.2$.

Table 1 gives the results of the trade-off score and weighting sensitivity analysis done in RStudio. Based on the chosen weightings, the upward teardrop pier shape with the V-apex facing upstream for 90° and 60° pier angles performed the best, with trade-off scores of 0.937 and 0.826 respectively. Additionally, 90° angles with the V-apex facing downstream also performed well, demonstrating that the 90° angle offers the best trade-off between hydraulic blockage, backwater rise and debris retention. The sensitivity analysis revealed that the top three performing pier configurations for the chosen weighting remain in the top 5 for nearly 100 % of the 500 iterations run with varying weightings. Therefore, 90° and 60° pier angles with upward teardrop pier shapes and the V-apex facing upward are recommended as the optimal pier structures, due to their superior trade-off performance, as well as their stability across weighting scenarios. Additionally, since the change in pier shape showed weak influence on the pier performance, a general pier angle recommendation of 90° pier angles, with any pier shape, and the V-apex facing upstream or downstream is considered optimal.

Table 1: Results of trade-off analysis and sensitivity analysis of the top 5 pier configurations

Pier angle (°)	Pier shape	V-apex	Trade-off score	Top 5 frequency (%)
90	Upward teardrop	Upstream	0.937	100
60	Upward teardrop	Upstream	0.826	99.8
90	Square	Downstream	0.810	97.2
90	Circle	Downstream	0.753	80.0
90	Upward teardrop	Downstream	0.747	25.2

4 CONCLUSIONS

This study investigated how pier angle, shape, and V-apex orientation influenced the debris retention at piers, backwater accumulation at piers, and culvert hydraulic blockage at culverts. Visual data analyses and multiple linear regression were used to determine the type of influence and significance level.

Debris retention decreased as pier angle became wider, with 90° pier angle showing a significant reduction in debris retention. Square piers increased the debris retention, however other shapes showed generally weak effects, and the V-apex orientation showed no significant influence on retention. Backwater rise also decreased with wider pier angles, with 60° and 90° producing significant reductions compared to 30°. The V-apex facing upstream demonstrated significantly lowered backwater accumulations by diverting debris toward the sides of the channel rather than trapping it in the center. This provides cause for the expansion of the use of debris piers not just for in-channel retention, but potentially diversion of the debris to the sides of the channel and onto sloped channel banks, which would majorly benefit the reduction of backwater accumulation in-channel. Hydraulic blockage at the culvert was substantially reduced by widening the pier angle, with 90° providing the lowest blockage due to improved debris alignment, allowing for clear passage through the culvert. Pier shape had a weak influence on hydraulic blockage, and the downstream-facing V-apex reduced blockage significantly. Notably, higher debris retention at piers did not guarantee lower hydraulic blockage at the culvert, with wider angles (particularly 90°) resulting in lower culvert hydraulic blockage, even while exhibiting lower debris retention at the piers. Further testing with angles wider than 90° is recommended to determine whether favorable debris alignment continues toward 180°.

A multi-objective trade-off analysis minimizing hydraulic blockage and backwater and maximizing debris retention found that 90° and 60° pier angles with upward teardrop piers and the apex facing upstream were optimal, with 90° pier angles consistently offering the best combined performance. Sensitivity analyses confirmed these configurations were robust across variations in the weightings used. Overall, 90° pier angles with either V-apex orientation are recommended as the optimal pier arrangement, since pier shape generally had non-significant effects.

The results of this study provide a starting point for formalized debris pier testing in South Africa and similarly developing countries. Like all debris testing, there is an inherent degree of randomness associated in its hydraulic behaviour. However, further experimental testing by expanding the range of currently tested variables, considering other influencing factors (such as flow rate, channel dimensions, culvert dimensions, debris transport mechanism, sediment etc.,) and increasing the scale of the model will allow for the development of technical design guidelines for the implementation of debris piers upstream of culverts in developing countries and other parts of the world where non-mechanised solutions are the most practical.

5 ACKNOWLEDGEMENTS

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