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Analysis of the performance of debris screens at culverts

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Construction of a culvert will impact ambient hydraulic characteristics such that upstream flow depths may increase due to any constriction at the inlet. Exacerbating this, flow can be further restricted within a culvert due to internal blockage by debris. Screens to prevent debris entering a culvert may also cause blockages, thus heightening the flood risk. In response to this problem, the research reported in this paper made use of a Froude-scaled physical model to investigate how screen blockage by debris is influenced by the geometry and positioning of a screen. Analysis based on 105 000 debris passes is used to show that, as expected, the potential for screen blockage by debris increases as the ratio of debris length to bar spacing increases. Furthermore, screen angle and position is shown to have a significant influence on blockage potential. This research involved the development of a methodology that can be used to assess the efficiency of different trash screen configurations. To build upon the analysis from this initial research and continue working towards the development of a predictive model that can aid future screen design, the research needs to be extended to look at the process of cumulative debris build up on screens.

Notation

A	screen angle
D	percentage of debris pieces blocked
L	debris length
P	ratio of flow velocity at the point of screen intersection with the water surface to a base upstream flow velocity measured at a distance equal to three channel widths upstream of the culvert inlet
Q	discharge
S	bar spacing

1. Introduction

Flood risk in urban areas has often been managed through the construction of culverts. They can, however, complicate river maintenance and reduce the ability of channels to convey flows associated with intense storms. Many of these installations were originally designed to accommodate major flooding (often a 1 in 30 year event), but these volumes may no longer be adequate owing to the predicted impacts of climate change, land use changes and policy developments.

Alteration to a river channel by the construction of a culvert can change the characteristics of the upstream flow, often increasing backwater elevation as a result of the volume of water being constricted as it enters the culvert. This effect can be exacerbated by the presence of debris if it becomes trapped within the culvert or at its inlet (Balkham *et al.*, 2010). As a consequence, culverts – especially those that are prone to becoming blocked – may significantly increase the potential for out-of-bank flows and therefore the risk of serious flooding. Although such problems are often minor, more extreme events can result in significant socio-economic implications and may even put lives at risk, either directly through the flood waters or as a result of structural damage to buildings and infrastructure (FFAG, 2011; Pitt, 2008; RSSB, 2004).

Since the mid-1990s, the potential for increased flooding caused by culverts has been recognised and both the Environment Agency and the Scottish Environmental Protection Agency now discourage culverting (CIWEM, 2010). The Scottish Executive, in advice to local authorities on planning and flooding, notes that culverts are a frequent cause of local flooding, particularly if their design or maintenance is inadequate (Scottish Executive, 2004).

Trash screens (sometimes referred to as debris screens or grilles) are often installed at the upstream end of culverts to prevent the entry of debris. Unless these are well designed and maintained they may be a hazard in themselves and can actually increase the potential for flooding if they result in a build up of debris that would have passed directly through the culvert. In response to this, UK guidelines for screen design focus mainly on ensuring that sufficient screen area is provided to handle the expected debris load, while recommendations for individual screen elements (e.g. bar spacing) are generally based on anecdotal evidence and site-specific environmental or safety concerns (Environment Agency, 2009). However, as many different trash screen configurations can influence blockage potential, a better understanding of the influence of individual screen elements is required to ensure that the flood risk associated with the blockage of culvert trash screens is minimised. For example, while meeting any design limits required to address safety concerns in terms of preventing unauthorised access, there is a need to determine the minimum bar spacing necessary to exclude material that could potentially block or damage the culvert without trapping material that would otherwise pass harmlessly downstream.

This paper presents the results of laboratory-based research undertaken to increase understanding of debris screen performance. In particular, the research focuses on how blockage at screens is influenced by both the geometry and positioning of the screen, and the prevailing hydraulic conditions.

2. Experimental facilities

2.1 Physical model

A flume facility located within the School of the Built Environment at Heriot-Watt University was used to build a Froude-scaled physical model to undertake experimental tests. The flume was 22 m long, 0·75 m wide and 0·5 m deep, with a variable bed slope. The initial flume slope was set at 0·006 m/m. The flume walls were constructed from glass and the raised floor of the flume from marine plywood to allow the culvert invert to be set flush with the channel bed. A circular culvert was built 8·25 m downstream of the flume inlet to allow flow conditions to stabilise before reaching the culvert. The culvert was made from a section of plastic pipe 0·3 m in diameter and 2 m long. The culvert inlet had a headwall made from a sheet of 10 mm thick smooth plastic, which was vertical and set flush with the inlet orifice. Wingwall structures were not included. This structure was scaled to represent a prototype circular culvert situated in a straight watercourse with consistent roughness and a flow approach in line with the inlet. A trash screen that could be placed at various angles over the culvert inlet was constructed from rectangular cross-section steel bars. Each individual bar was moveable so that a variety of bar spacings could be achieved at each screen angle. The screen could be placed at various positions upstream of the culvert inlet. A schematic illustration of the flume design is shown in Figure 1, and Table 1 details the geometric dimensions of the model and prototype.

Water supply to the flume was provided via a gravity-fed pipe from a constant head tank and passed into the flume through a stilling tank. The flow rate entering the flume was controlled via a discharge valve. On exiting the flume, the flow passed into a

	Model: m	Prototype: m
Channel width	0·75	2·50
Upstream reach	8·25	27·50
Downstream reach	15·50	51·67
Culvert length	2·00	6·67
Culvert diameter	0·30	1·00
Bar cross-section	0·003 × 0·012	0·01 × 0·04
Bar spacing	0·03	0·10
Bar spacing	0·04	0·13
Bar spacing	0·05	0·18
Bar spacing	0·06	0·20
Bar spacing	0·08	0·27
Bar spacing	0·10	0·33
Bar spacing	0·15	0·50

Table 1. Froude-scaled dimensions for model and prototype

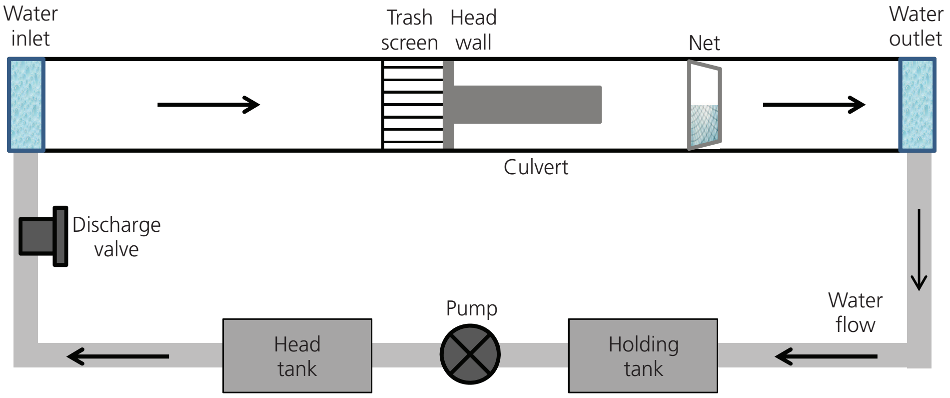

Figure 1. Physical model setup

holding tank sufficiently far downstream to ensure there was no relevant backwater effect and was then pumped to the constant head tank and re-circulated. The culvert operated under inlet control for the entire set of experiments.

A prototype minimum bar spacing of 100 mm was used: this is just below the recommended maximum bar spacing for culvert access security screens (120 mm) (Environment Agency, 2009) and the maximum selected such that the screen would comprise a minimum of at least one bar across the culvert orifice.

The current recommendation for screen angles in the UK is between 45° and 60° to allow for maintenance and effective trash removal (Environment Agency, 2009). In the model, three angles were tested: 45° and 60° to replicate the extremes adopted for most prototypical screens in the UK, and a lower angle of 30° to determine the impact of a screen angle outside the recommended range, which had the potential to provide an increased screen area. All screen angles were measured relative to the channel bed.

A Froude similarity approach was adopted as this was considered the most appropriate method for ensuring similitude between the model and a generic prototype (Novak *et al.*, 2010; Wallerstein *et al.*, 2001). This gave greater flexibility in the model environment by allowing a relaxation in Reynolds number. However, viscous forces can be influential in scale models so, to minimise potential errors resulting from these effects, the flume slope and discharges were selected such that turbulent sub-critical flow was maintained upstream of the culvert inlet. Elastic effects are very small in water and so no consideration was given to scaling Mach number. In contrast to most prototypical conditions, steady flow conditions were adopted to constrain the potential complexity of the model and help isolate the impact of the controlling parameters under investigation. Table 2 summarises the flow conditions used during the testing and corresponding prototype values. Once the required discharge was established, the flow was allowed to stabilise before any testing was undertaken.

2.2 Testing methodology

Natural flood management (NFM) is now being promoted as a cost-effective catchment-scale approach to managing flood risk. One NFM strategy is to slow the passage of water through the use of riverbank planting or floodplain woodland (Nisbet and Thomas, 2008). In addition, overland flow paths may be reduced through the use of grass or tree buffer strips. Although both these strategies may have a positive effect on peak flood rates, they may also contribute to heavy debris load in the watercourse, particularly during storm events. Given the increased potential for blockage at culverts from these measures, the focus of this investigation was on the blockage potential of woody debris. The use of natural twigs has been used in some physical modelling studies (e.g. Lyn *et al.*, 2003) and can offer a more realistic representation of debris. However, natural twigs were considered inappropriate in this case as, although the use of complex geometries inherent in natural debris was felt to be a useful tool, particularly in qualitative studies, it presented a number of difficulties in clearly defining dimensions. To minimise potential scaling issues with complex geometries, dowel was used to represent woody debris. The use of dowels to represent woody debris has previously been considered a suitable approach for a number of other key studies into debris transport in rivers. This is because length, diameter and buoyant depth are considered the main characteristics influencing debris transport, while accumulation with shape, texture and roughness are secondary factors (e.g. Bocchiola *et al.*, 2006a, 2006b; Braudrick and Grant, 2000, 2001; Cherry and Beschta, 1989; Van Sickle and Gregory, 1990; Wallerstein *et al.*, 2001). Although cylindrical dowel is not representative of more complex woody debris geometry, it does offer a reasonable representation of non-rooted, defoliated, cylindrical logs that may often occur in rivers as a result of wood harvesting and maintenance or as a result of forest fires (Rosso *et al.*, 2007; Rulli *et al.*, 2006). In addition, woody debris from coniferous sources typically has a cylindrical, non-branching geometry.

Ten different debris lengths (Table 3) were used to assess blockage. The use of these lengths was justified by general field observations that suggest channels with naturally eroding banks tend to be able to actively transport buoyant debris that is not greater than half the channel width (Braudrick *et al.*, 1997); this

Model		Prototype	
Depth: m	Discharge: m^3/s	Depth: m	Discharge: m^3/s
0·070	0·005	0·233	0·104
0·143	0·021	0·476	0·428
0·180	0·035	0·600	0·706

Table 2. Froude-scaled flow conditions for model and prototype

Debris length: m	
Model	Prototype
0·025	0·083
0·050	0·167
0·075	0·250
0·100	0·333
0·150	0·500
0·200	0·667
0·275	0·917
0·300	1·000
0·325	1·083
0·350	1·167

Table 3. Froude-scaled debris length for model and prototype

condition was replicated in the flume by selecting a maximum debris length of 0·35 m.

Each length of debris was tested 100 times to minimise the potential for sampling error, resulting in 1000 debris passes for each test case (100 repetitions of 10 lengths). One hundred and five test cases were assessed during the testing and therefore the results generated were based on 105 000 debris passes.

Individual pieces of dowel were introduced into the flow 5 m upstream of the point of intersection of the screen and the water surface. With the aim of having the dowels oriented randomly in the flow, they were dropped vertically from a height of 0·25 m into the mid-channel; this method was identified during initial testing as producing the required random entry orientation.

Once introduced to the flow, each piece of debris was allowed to travel downstream independently. When a piece became blocked by the trash screen it was removed before the next piece arrived. A net placed across the flume downstream of the culvert outlet was used to retrieve debris pieces that passed through the screen. A piece of debris was considered to have been blocked by the screen if it

- bridged across two or more bars
- was balanced across a single bar
- was wedged between two bars or between the bars and either the sidewalls or headwall (see Figure 2).

3. Influence of bar spacing, screen angle and discharge

3.1 Bar spacing

In the plots shown in Figure 3, the percentage debris blocked is shown as a contoured surface with bar spacing S on the x-axis

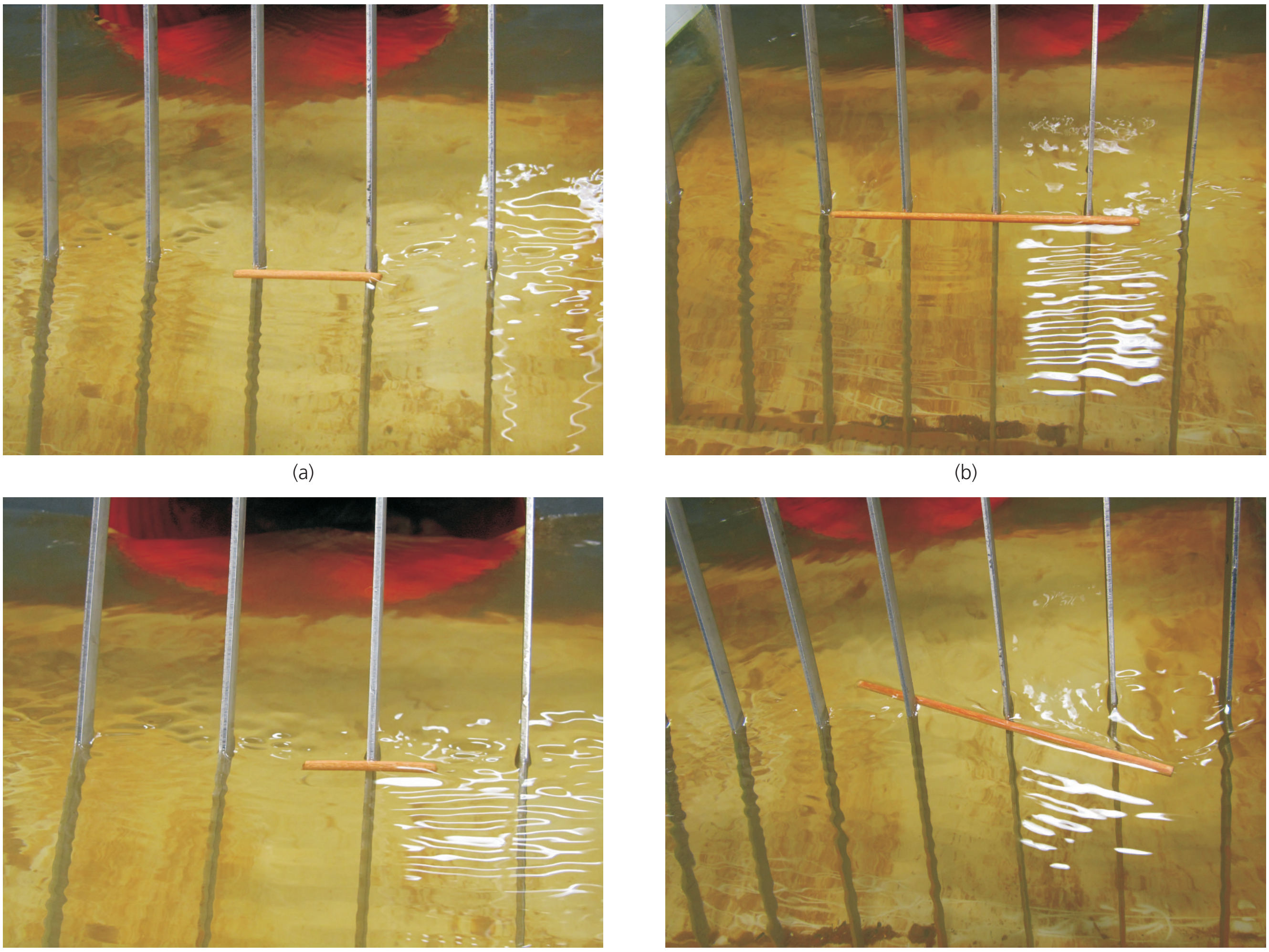
(a)
(b)
(c)
(d)

Figure 2. Methods of blocking debris: (a) bridged over two bars: (b) bridged over more than two bars; (c) balanced over a single bar; (d) wedged between bars

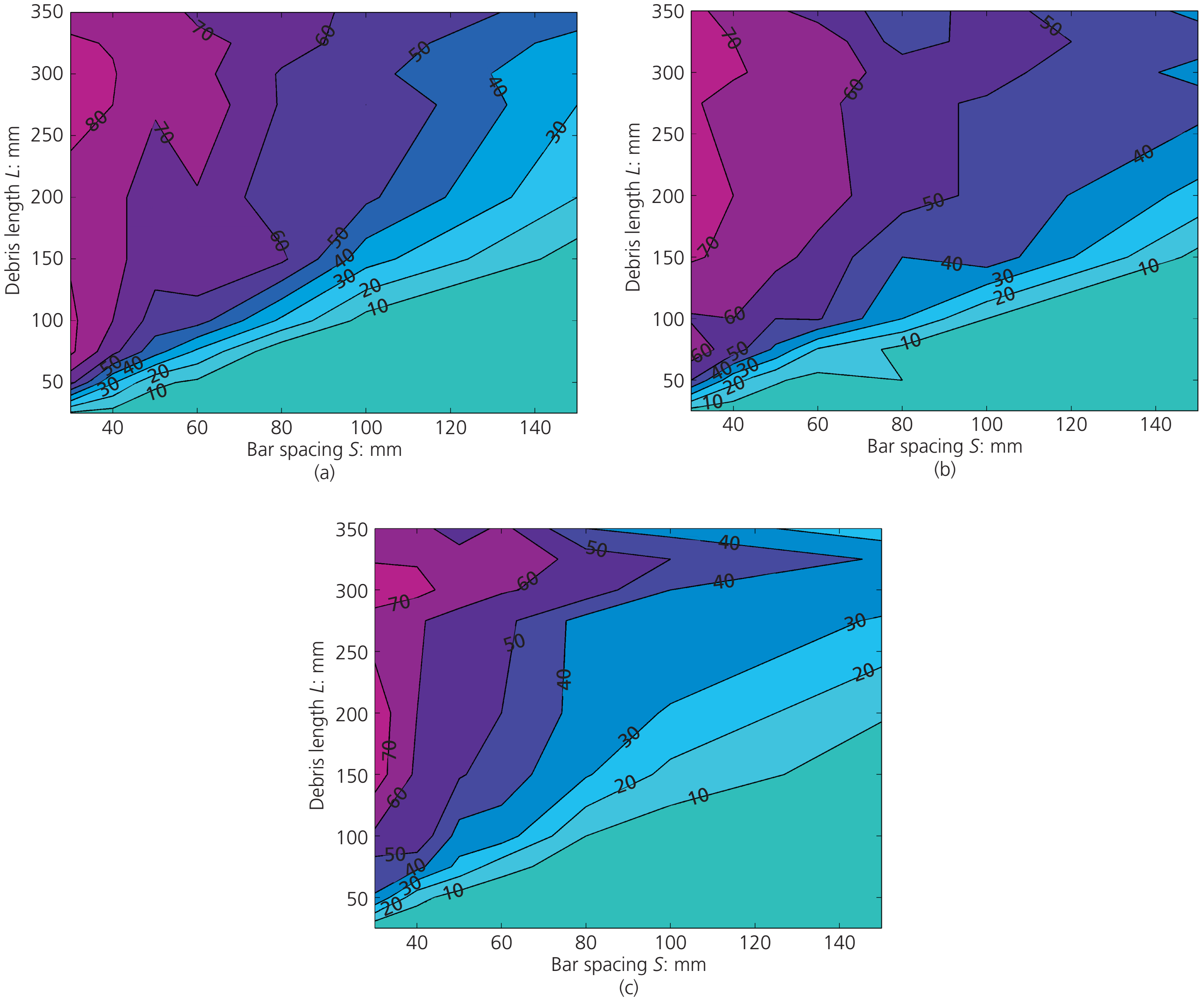

Figure 3. Contour graphs showing percentage of debris pieces blocked at discharge of 0·035 m^3/s for screen angles of (a) 30°, (b) 45° and (c) 60°

and debris length *L* on the *y*-axis. The contoured surface represents the relationship of *S* and *L* with the percentage of debris pieces blocked *D*.

Interpolated isolines of equal *D* at 10% intervals are marked as contour lines. The surface was generated using a smoothing algorithm. Figure 3 shows plots produced from results generated while testing a discharge of 0·035 m^3/s. Plots produced for the results from other tested discharges (see Table 2) showed similar trends.

As can be seen in Figure 3, the use of contour graphs offers a useful visualisation tool for independently assessing the influence of bar spacing and debris length. However, to facilitate the comparison of results across all angles and discharges, the proportion of debris pieces blocked was also assessed directly against the ratio of debris length to bar spacing (*L*:*S*) (Table 4) as this allows a visual comparison of the trends of blockage between different discharges or screen angles (see Figures 4 and 5).

For all the screen angles and discharges assessed, Figures 4 and 5 show a clear relationship between the percentage of debris pieces retained and *L*:*S*. As *L*:*S* increases, more pieces of debris are likely to become blocked – a finding that is perhaps not unexpected. These relationships were best fitted by logarithmic functions and had high R^2 regression coefficients (0·85–0·89), indicating a good fit to the experimental test data. The functions and R^2 regression coefficients associated with these graphs are detailed in Table 5.

Where the ratio of debris length to bar spacing (*L*:*S*) is less than or equal to 1, the major influencing factor at these debris lengths

S: mm	*L*: mm									
	25	50	75	100	150	200	275	300	325	350
30	0·83	1·67	2·50	3·33	5·00	6·67	9·17	10·00	10·83	11·67
40	0·63	1·25	1·88	2·50	3·75	5·00	6·88	7·50	8·13	8·75
50	0·50	1·00	1·50	2·00	3·00	4·00	5·50	6·00	6·50	7·00
60	0·42	0·83	1·25	1·67	2·50	3·33	4·58	5·00	5·42	5·83
80	0·31	0·63	0·94	1·25	1·88	2·50	3·44	3·75	4·06	4·38
100	0·25	0·50	0·75	1·00	1·50	2·00	2·75	3·00	3·25	3·50
150	0·17	0·33	0·50	0·67	1·00	1·33	1·83	2·00	2·17	2·33

Table 4. Debris length (*L*) to bar spacing (*S*) ratios used during testing for screen angles of 30°, 45° and 60°

is the bar spacing relative to the full length of the debris. Where *L*:*S* is greater than 1, the orientation of the debris is more significant. A number of factors appear to influence orientation, including debris length and buoyancy, position of the debris in the channel, initial orientation of the debris, flow depth and velocity, and flow patterns (upstream and at the screen).

During testing, the larger lengths of debris had a greater tendency to align parallel with the flow direction and to travel mid-stream, both of which facilitated debris passage through the screen. This is particularly apparent in Figure 3(c) where fewer blockages occur for debris lengths of 0·35 m than for lengths of 0·3 m. This may be owing to the longer lengths becoming aligned parallel to the flow direction more rapidly than the shorter pieces that were still rotating as they reached the screen.

However, the results may also have been influenced by the 0·35 m lengths having a greater tendency to enter the water parallel to the flow direction.

3.2 Screen angle

Experiments were conducted for a range of screen angles (30°, 45° and 60°). The angle was adjusted by having the point of contact of the screen fixed at the culvert headwall and the change in angle was achieved by sliding the screen base in and out along the channel bed resulting in steeper angled screens positioned closer to the culvert inlet. The results of these tests are shown in Figure 4. Similar trends and goodness of fit were found to exist for the full range of discharges studied.

It is evident from Figure 4 that, while the relationship between *D* and *L*:*S* varies with screen angle; it is more marked at higher discharges. The difference in the predictive trends is quite small over the range of angles investigated, particularly at low discharges. However, as can be seen from Figure 4, higher screen angles result in a consistently lower percentage of debris pieces blocked for any given value of *L*:*S*.

Observation of the experimental runs indicated that this effect may have been owing to the fact that, at higher screen angles, the bars intersected the water surface closer to the culvert inlet and therefore closer to the zone of flow acceleration into the narrower structure. This is important as debris elements that are initially randomly orientated tend towards aligning parallel with the flow as it accelerates and are therefore more likely to pass between the screen bars.

In addition, at lower screen angles, a potentially higher bar surface area is likely to be in contact with the floating debris. As well as resulting in an increased area to trap the debris, this also means the debris must overcome a greater resistance to move clear of the bars after initial contact. However, with the screen at 60°, which represented the closest position to the culvert inlet, some of the larger pieces of debris cleared the screen with their leading end only to then become lodged against the headwall as they attempted to rotate into the culvert entrance. Increasing the distance from the headwall by lowering the screen angle to 45° or 30° reduced the number of times this occurred.

3.3 Discharge

Experiments were also conducted under a range of discharges. Figure 5 shows relationships between *D* and *L*:*S* at screen angles of 30°, 45° and 60° for discharges of 0·005, 0·021 and 0·035 m^3/s, which represent a wide range of hydraulic environments that a prototype culvert might exhibit during routine operation. It is evident from these results that as discharge (and therefore approach flow velocity and depth) increases, the proportion of debris pieces that become trapped at the screen falls. This is more pronounced at higher screen angles. This effect is shown to be significant between discharges of 0·005 and 0·021 m^3/s, but is quite minor between 0·021 and 0·035 m^3/s. Two factors appear to be contributing to this. Firstly, at higher flow velocities, more pieces of debris rotate to align parallel to the flow direction as they approached the screen, thereby facilitating their passage through the screen. Secondly, at lower flow rates, the debris had a greater tendency to reach a balance point across a single bar. At higher flows the debris may be stopped initially by a single bar but would then rotate round the bar and clear the screen.

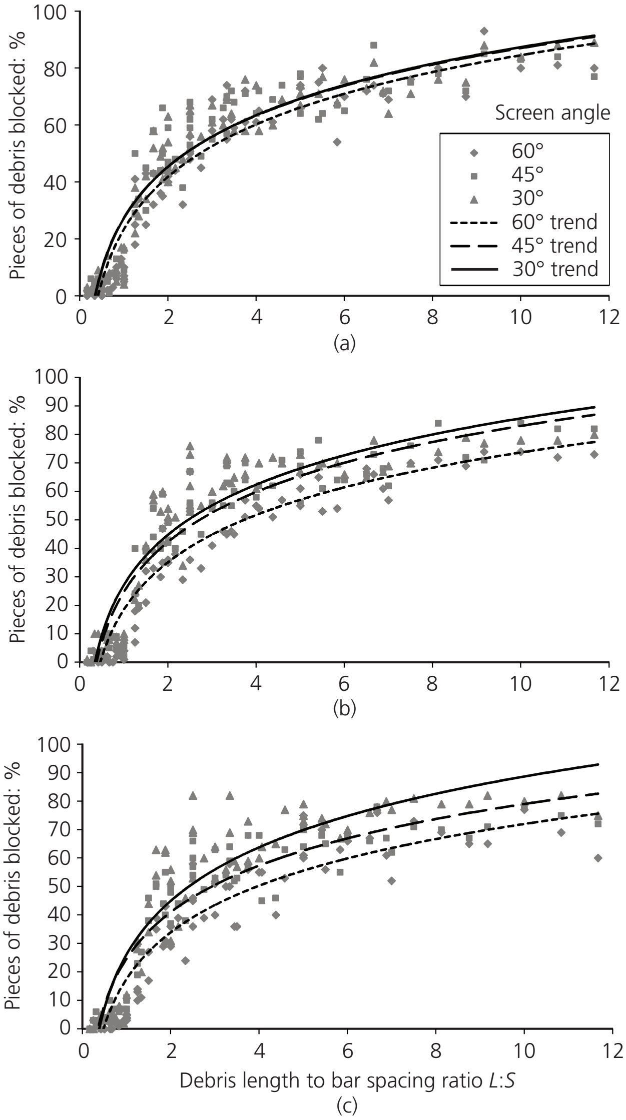

Figure 4. Percentage of debris pieces blocked at different screen angles for discharge of (a) 0·005 m^3/s, (b) 0·021 m^3/s and (c) 0·035 m^3/s. Symbols represent experimental data with each point representing percentage blockage for 100 pieces of debris

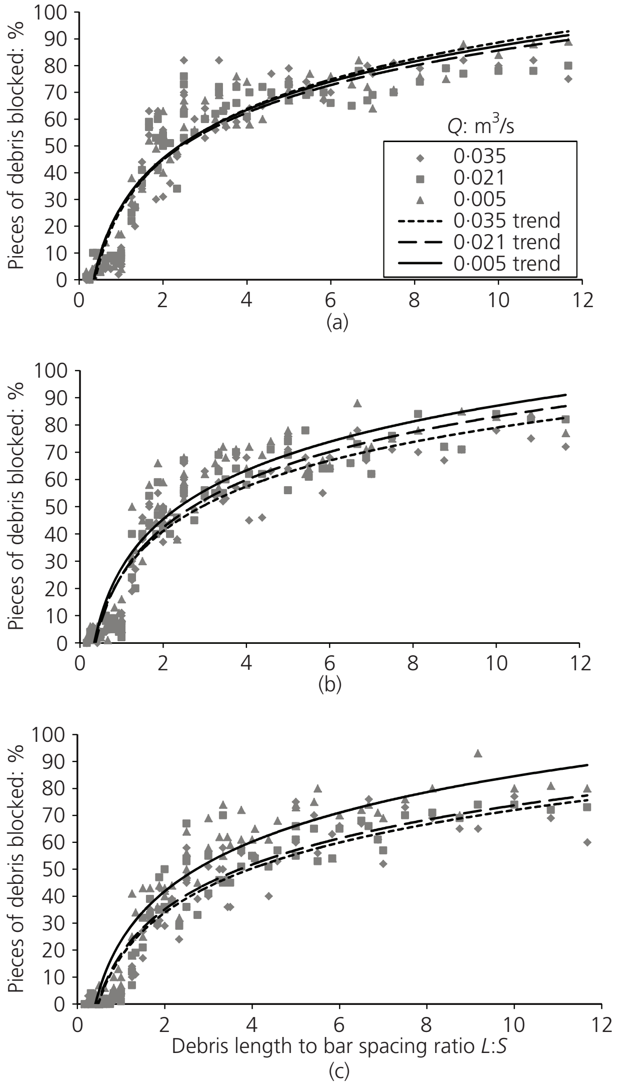

Figure 5. Percentage of debris pieces blocked for different discharges for screen angle of (a) 30°, (b) 45° and (c) 60°. Symbols represent experimental data with each point representing percentage blockage for 100 pieces of debris

4. Influence of screen position relative to culvert inlet

A further phase of testing was undertaken to investigate how the location of the debris screen relative to the entrance of the culvert influences potential blockage. Observations made during initial testing suggested that as flow accelerates towards the culvert entrance it exerts forces on the debris that affect its orientation relative to the flow direction. Therefore, it appeared that the location of the screen relative to the zone of flow acceleration, generated as the effective flow area decreases as it approaches the culvert, may influence the amount of debris blocked by the screen. In order to assess the influence of screen position independently of screen angle, two different assessments were undertaken

- assessment of the blocking potential of screens at different angles that intersected the water surface at the same point upstream of the culvert inlet
- assessment of the blocking potential of a screen with an angle of 60° at different positions upstream of the culvert inlet.

The bar spacing's and bed slope tested were as described in Section 3 for the initial testing. As observed previously differences in blockage were more marked at higher discharges, the highest discharge used during the initial testing (0·035 m^3/s) was used for the follow-up analysis.

Q: m^3/s	A: degrees	D: %	R^2
0·005	30	26·089ln(L:S) + 27·308	0·89
0·005	45	25·875ln(L:S) + 27·460	0·87
0·005	60	26·538ln(L:S) + 23·445	0·90
0·021	30	25·400ln(L:S) + 27·214	0·86
0·021	45	25·311ln(L:S) + 24·755	0·87
0·021	60	23·955ln(L:S) + 18·550	0·87
0·035	30	27·144ln(L:S) + 26·160	0·85
0·035	45	23·605ln(L:S) + 24·650	0·87
0·035	60	23·658ln(L:S) + 17·513	0·86

Table 5. Equations and corresponding R^2 regression coefficients for trends shown in Figures 4 and 5

4.1 Different screen angles at one position

Initially, one screen position was tested with screens at different angles (30°, 45° and 60°). The screens were placed so that the point of intersection of the screen with the water surface was the same for all screen angles.

As can be seen from Figure 6, no substantial difference was found in the percentage of debris blocked by different screen angles, suggesting that the difference found in blockages for different screen angles during initial testing (Figure 4) may have been influenced more by the position at which the screen intersected the water surface than the actual screen angle: if a screen is positioned so that the top of the screen is attached to the headwall, a screen of 60° intersects the water surface closer to the culvert than a screen of 30°.

4.2 One screen angle at different positions

Four positions upstream of the culvert inlet (Table 6) were tested for a screen at 60°. The distance upstream was measured from the culvert inlet to the point at which the screen intersected the water surface.

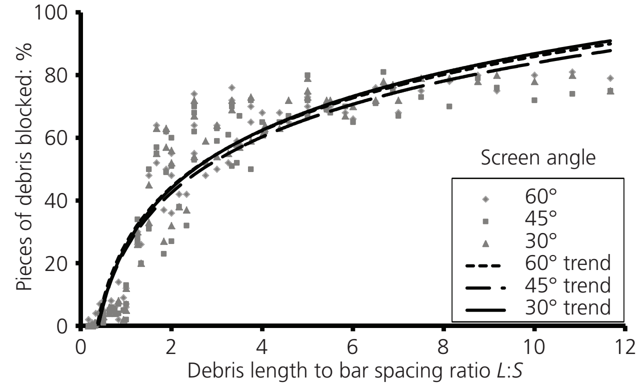

Figure 6. Percentage of debris pieces blocked at different screen angles when screens intersect the water surface at the same position

Position	Distance upstream from culvert inlet: m
P1	0·350
P2	0·250
P3	0·150
P4	0·100

Table 6. Screen positions assessed during the final phase of testing

Figure 7 shows the percentage of debris pieces blocked at each screen position tested. As can be seen, the percentage of debris pieces blocked increases as the distance of the screen from the culvert inlet increases. The greatest increase occurs between positions P3 and P4, with the least difference in blockage between screens at P1 and P2. The differences in blockages correspond to the differences in the mid-stream flow velocity at the screen.

Figure 8 shows that as the flow approaches the culvert inlet, the mid-stream depth-averaged velocity increases. At screen position P4, the velocity is approximately 90% of the maximum velocity reached by the flow before entering the culvert, while at P1 the velocity is only 60% of the maximum velocity. The greatest difference in blockage occurs where there is also the greatest difference in flow velocity, suggesting that flow velocity has a major influence on blockage potential.

Positioning of a screen further upstream from the actual culvert inlet is often considered a practical approach to allow horizontal working platforms to be positioned between the headwall and screen for ease of maintenance or to increase the available surface area of the screen. However, given the above results, this approach may increase the likelihood of the screen becoming blocked. While many factors contribute to the best setup for a particular trash screen, its position relative to the zone of flow

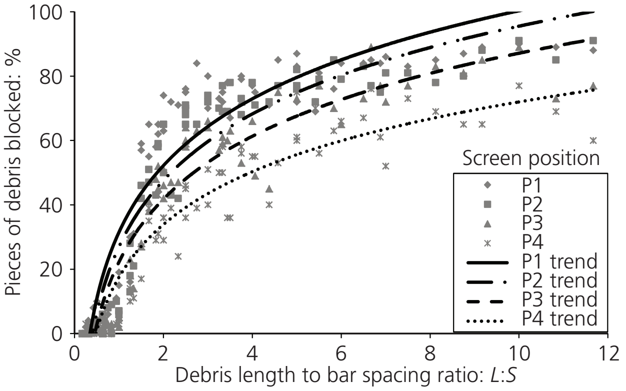

Figure 7. Percentage of debris pieces blocked at different screen positions (screen angle 60°)

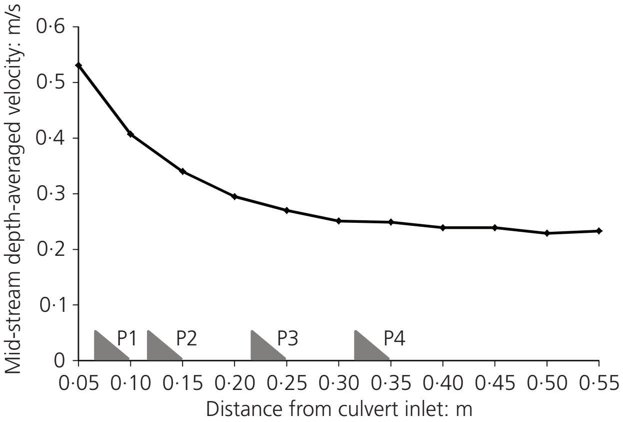

Figure 8. Variation of mid-stream depth-averaged longitudinal velocity with distance from culvert inlet, showing the positions of tested screens (P1 to P4) as listed in Table 6

acceleration should be considered at the design stage alongside other factors such as access, maintenance and safety requirements. All other things being equal, a screen with a reduced overall area positioned closer to a culvert inlet may offer a better solution with a reduced potential for blockage and therefore reducing the flood risk associated with screen installation.

5. Development of an empirical relationship

Bar spacing, debris length, screen angle, discharge and screen position have been identified as potential influencing factors in determining the amount of debris blocked at a culvert screen. Based on the results of the model test runs, regression analysis was used to establish an empirical relationship between these contributing factors and blockage potential. The relationship can be formalised by

$$D = f(A,\ S,\ L,\ Q,\ P) \tag{1}$$

where D is the percentage of debris pieces blocked, A is screen angle (in degrees), S is bar spacing (m), L is debris length (m), Q is discharge (m^3/s) and P is screen position. As the major influence on blockage at the different screen positions appears to be flow velocity, the P values were calculated as the ratio of flow velocity at the point of screen intersection with the water surface to a base (reference) upstream flow velocity measured at a distance equal to three channel widths upstream of the culvert inlet.

A log transformation was used during the regression analysis to allow limits to be set on the dependent variable D. As D represents the percentage of pieces blocked, the limits were set at 0 and 100. After transformation, a stepwise multiple regression analysis was performed using a 95% probability significance limit. A quadratic function was found to provide the best solution

$$\begin{aligned}\ln[D/(100-D)] = {} & 0{\cdot}84 + 28{\cdot}90L - 49{\cdot}64S + 0{\cdot}01A \\ & - 16{\cdot}91Q - 1{\cdot}54P + 63{\cdot}76LS \\ & + 0{\cdot}07LA - 0{\cdot}09SA - 68{\cdot}54L^2 \\ & + 106{\cdot}71S^2 + 412{\cdot}75Q^2\end{aligned} \tag{2}$$

The model generated had a high adjusted R^2 value of 0·87, indicating that it was a good fit to the test generated data, and a high prediction R^2 value of 0·87, indicating it had good predictive capabilities. A plot of the measured versus predicted blocked debris pieces is shown in Figure 9.

Debris length L, bar spacing S, screen angle A and relative velocity (position P) were found to be significant predictive factors, with all factors having $p < 0{\cdot}0001$. Discharge was only found to be significant as its squared term (Q^2) and Q was added into the final model for hierarchical completeness. Although, perhaps surprisingly, discharge was not found to be a major significant contributing factor, this finding was similar to the results reported by Wallerstein and Arthur (2011) who found that discharge was generally not a significant contributing factor in a study of the extent of debris accumulation at screens.

Equation 2 shows that the coefficients for S, P and Q are negative. As would be expected, more blockage occurs as bar spacing decreases. The negative value for P suggests that as the ratio of the velocity at the screen to the average upstream velocity increases, the potential blockage will decrease. This is illustrated for the gathered results in Figures 7 and 8. Although not considered a statistically significant contributing factor, the negative coefficient for Q in Equation 2 indicates that lower discharges will lead to higher blockages; this might be expected as lower discharges tend to result in lower flow velocities. The

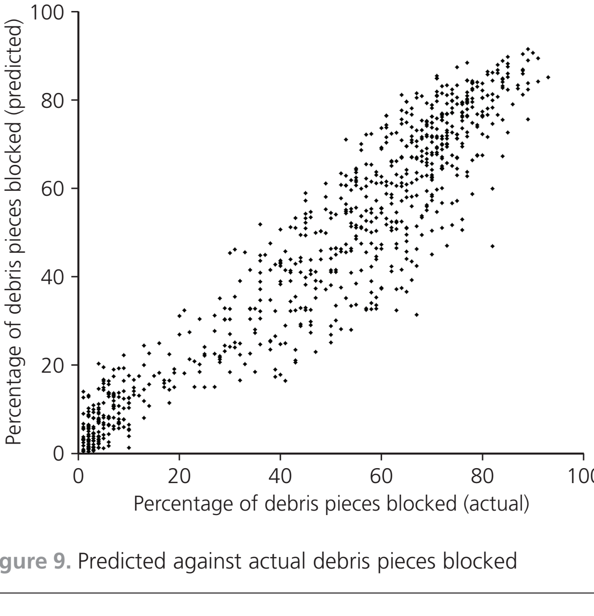

Figure 9. Predicted against actual debris pieces blocked

coefficients for L and A are positive, confirming that blockage increases as debris length increases. In addition, the positive coefficient for A suggests that higher screen angles will also result in more blockage, apparently contradicting the blockage patterns found during the testing. However, the results from the initial testing will have been influenced by the position of screen intersection with the water surface, as well as the angle itself.

A sensitivity analysis was undertaken to assess the impact of each of the contributing elements. The predicted blockage percentage D was calculated from the derived function for mid-values from the range tested ($D = 41\%$, $L = 0{\cdot}15$ m, $S = 0{\cdot}06$ m, $A = 45°$, $Q = 0{\cdot}021$ m^3/s, $P = 1{\cdot}5$). Predicted blockage values were then calculated when one element was increased and then decreased by 25% of its initial value while the other element values remained unchanged. As can be seen from Figure 10, debris length L and bar spacing S had a significant impact. Screen position P is shown to have substantially more influence on potential blockage than screen angle A, while discharge Q has very little impact.

6. Conclusions

Inflow to culverts can be restricted owing to internal blockage by debris. Screens to prevent debris entering a culvert may also cause blockages, heightening flood risk. The research outlined in this paper made use of a Froude-scaled model to investigate how blockage by debris is influenced by the geometry and positioning of a screen. Several key elements of screen design and installation that contribute towards a screen's potential for blocking debris have been identified. Debris length, bar spacing, screen position and screen angle have been shown to significantly influence blockage potential. While the use of results based on simplified debris geometries may underestimate blockage, the detailed analysis (based on 105 000 debris passes) is a significant step towards a better understanding of how blockage, and therefore potential flood risk, of culvert debris screens is influenced by screen geometry and position.

This research has developed a methodology that can be used to assess the efficiency of different trash screen configurations. Further research assessing the impact of additional aspects of screen design, such as bar shape and size, the design of working platforms, the use of different screen materials and the angle of the screen relative to the direction of flow, will further enhance understanding of blockage processes. While the analysis of the gathered empirical data has defined blockage in terms of specific contributing factors, the focus of this initial research was on individual debris pieces. To build upon the analysis from this initial research and continue working towards the development of a predictive model that can aid future screen design, the research needs to be extended to look at the process of cumulative debris build up at screens under both normal and extreme operating conditions.

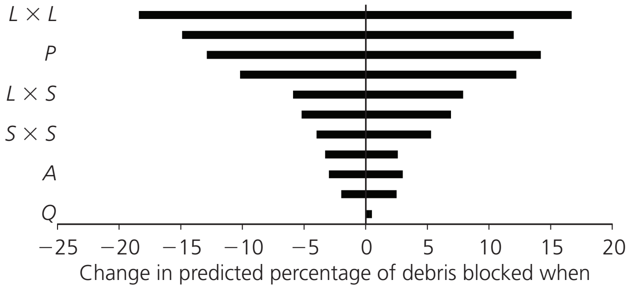

Figure 10. Change in predicted percentage of debris blocked when varying predictor variables by ±25%

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