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International Journal of River Basin Management

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/trbm20

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INTL. J. RIVER BASIN MANAGEMENT
https://doi.org/10.1080/15715124.2022.2064483

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RESEARCH PAPER

Blockage of box-shaped and circular culverts under flood event conditions: a laboratory investigation

Azam Miranzadeh[a], Alireza Keshavarzi [a,b] and Hossein Hamidifar [a]

[a]Water Engineering Department, Shiraz University, Shiraz, Iran; [b]Centre for Infrastructure Engineering, School of Engineering, Western Sydney University, Penrith, Australia

ABSTRACT

Culverts are used to allow runoff to pass through roads, railways, and embankments. Accumulation of debris during flood events reduces the culvert flow capacity and hence flow overtopping results in culvert failure both hydraulically and structurally. This paper presents the results of an experimental study of temporal variations of blockage upstream of culverts due to woody debris under unsteady flow conditions. To simulate flood conditions, a synthetic flow hydrograph was produced in the laboratory. Cylindrical wooden dowels with two different diameters were used to simulate the woody debris carrying during flood events. Two culvert shapes including box and circular pipe culverts are examined here. The results showed that the maximum percentage of blockage occurs during the falling limb of the hydrograph. Although the feeding rate of smaller diameter woody debris into the flow is of considerable importance in the culvert blockage, the blockage percentage is not influenced by the feeding rate of large woody debris. It was also found that the pipe culvert is more susceptible to blockage than the box-shaped culvert. Using regression analysis, predictive equations are suggested to estimate the percentage of culvert blockage during flood events.

ARTICLE HISTORY
Received 5 October 2021
Accepted 6 April 2022

KEYWORDS
Urban drainage; flood; culvert; blockage; debris

Introduction

While the structural design of the culvert is simple, evaluating its hydraulic performance is still a challenging task due to the blockage problem with the presence of various types of floating debris (Ahmed et al., 2021; Iqbal et al., 2021b; Osman & Taha, 2022). A culvert is a short-length underground drainage structure to convey flood flows from one side of infrastructures such as embankments, levees, roadways, and railroads in urban areas or in the countryside to the other side. Culverts are also designed in different shapes and for a particular purpose for example to allow the passage of fish or animals besides their main purpose as a drainage structure(Chanson et al., 2021; Li et al., 2022). While the structural design of the culvert is simple, evaluating its hydraulic performance is still a challenging task due to the blockage problem with the presence of various types of floating debris (Balkham et al., 2011; Blanc et al., 2014; Iqbal et al., 2021a; Paik & Park, 2011; Zhong et al., 2021). Three different types of debris may be considered in hydraulic engineering including floating debris (generally different types of vegetation), non-floating debris (e.g. sediments), and urban debris such as structural materials and all types of fly-tipping (Balkham et al., 2011; Weeks et al., 2009). Some studies show that there is a range of locations and conditions where the blockage may be a concern in hydraulic designs (Diehl, 1997; Friedrich et al., 2022; Furlan et al., 2018; Spreitzer et al., 2021; Streftaris et al., 2013).

The inclusion of blockage is an important part of the design for bottlenecks of a drainage network such as culverts and bridge openings (De Cicco et al., 2020; Mohammadiun et al., 2020; Steeb et al., 2017; Xia et al., 2018). In addition to the adverse effects of culvert blockage such as rising upstream water level and overtopping, animal crossings can be interrupted. In some situations, designers consider an insignificant proportion for blockages or even ignore the effects of blockage in culvert designing while some studies showed the importance of blockage and its effect on instability of the culvert with time during an unsteady flow condition (Sorourian et al., 2013, 2016).

One of the main concerns for hydraulic engineers is the reduction of culvert passage area or even obstructing the entire cross-section during the blockage conditions and hence the failure of its serviceability (Balkham et al., 2011; Chang & Shen, 1979; Okamoto et al., 2020; Schmocker & Hager, 2011). From the above studies, it has been found that the culvert failure is mostly due to blockage during a flood event. However, the degree of a culvert blockage is a function of the culvert geometry, approaching flow conditions, and debris characteristics (Barthelmess & Rigby, 2011; Weeks et al., 2009). From the literature review, it was found that the main factors affecting the flow through the culvert in the blockage mode at the entrance can be summarized as follows:

- Geometry-related parameters such as the width (or diameter) of the conduit, the shape of the conduit, the slope of the bottom of the conduit, and the width of the upstream channel,
- Flow-related parameters such as flow depth, flow velocity, and other flow characteristics, and
- Debris-related parameters such as specific mass, size, shape, and debris feeding rate, and debris velocity.

Many studies have considered blockage in culverts of different sizes and shapes, and different types of floating

CONTACT Hossein Hamidifar hamidifar@shirazu.ac.ir

debris. For example, some researchers have evaluated culvert blockage after a flood event in the Wollongong area and found that when the opening size of the culvert is less than 6 m (measured diagonally), the risk of blockage in the culverts is higher (Rigby et al., 2002; Rigby & Silveri, 2001). They recommended that a full blockage (100% blockage factor) should be applied to culverts with an opening size of smaller than six metres, while for culverts with an opening size larger than six metres a 25% blockage is expected. However, the type and availability of debris upstream of the catchment were not considered in their study. In addition, their conclusions were based on a single flood event in Wollongong city, Australia; therefore, it is hard to use their conclusions to other catchments with different morphological and climatological conditions.

Barthelmess and Rigby (2011) studied blockage in bridge and culvert structures considering the availability of debris and its ability to move with the flow. They presented a procedure for estimating the potential of debris at a site that reflects the geometry of the structure and debris quantum and geometry factors. Schmocker and Hager (2013) classified the accumulation process into two phases; including the initial debris accumulation resulting in a major backwater rise during the first phase and the formation of the debris carpet with a partial backwater rise during the second phase.

Kramer et al. (2015) conducted a laboratory study of the hydraulic effects of large-scale urban debris blockage on a 94 mm by 94 mm box culvert model. They concluded that for large-scale debris conditions, culvert hoods may be cost-effective solutions to improve the hydraulic performance of culverts. Also, they pointed out that a full blockage was not observed during their tests and suggested the necessity of further investigation.

Some studies have focused on the effect of entrance blockage on the scour hole at the culvert outlet. It has been reported that partial blockage in steady flow conditions leads to the formation of a greater scour hole downstream of culverts compared to non-blocked conditions (Karimpour & Gohari, 2020; Sorourian et al., 2016, 2013; Taha et al., 2020b, 2020a). It has also been found that the dimensions of the scour hole increase with blockage. Similar results were observed for unsteady flow conditions (Sorourian et al., 2014a, 2014b). Some other studies have pointed out the importance of blockage on flood passage capacity, structural stability, and hydraulic behaviour of culverts (for example, Barthelmess & Rigby, 2011; Diakakis et al., 2020; Mohammadiun et al., 2020; Rigby et al., 2002; Roso et al., 2002).

In a recent study, De Cicco et al. (2020) conducted laboratory experiments using different bridge pier shapes to investigate the effect of pier shape on the probability of blockage. They found that the shape of the pier has a significant impact on blockage and among the tested pier shapes, the squared pier shape resulted in the highest blockage probability. Although not all culverts and bridges are blocked by debris, this phenomenon must be investigated as the failure of these structures leads to a high risk of damages to lives and properties. Further study of culverts blockage phenomenon can provide more understanding of the problem and a broader perspective on the hydraulic design of the structure. Also, there is generally a shortage of field and laboratory data to quantify the consequences of culvert blockage to implement effective policies for the issues.

To the authors' best knowledge, no studies have been reported on the temporal dynamic transport of debris during flood events. Also, little information is still available for blockage changes during flood events with its dynamic random transport of woody debris. In addition, in most previous studies, culvert blockage and its effect on the flow around the structure have been modelled by reducing the cross-sectional area of culvert opening without live feeding of debris during flooding. Therefore, the aim of the present study is to experimentally investigate the percentage of temporal blockage at the inlet of two types of culverts, including box and pipe culverts, with the presence of woody debris transport during unsteady flow conditions in a flood event. Also, changes in upstream water level and the height of the blockage in different flood conditions are studied. Moreover, effective parameters on temporal blockage are identified and some equations are derived based on linear regression analysis to determine the blockage percentage in different flow conditions.

Materials and methods

Dimensional analysis

Blockage at the inlet of culverts can generally be represented as a functional relationship of several variables. This functional relationship can be expressed as:

$$f_1(W, S_0, D, F, T, \rho, \rho_w, V, V_w, \mu, g, H_e, H_u, L_w, h_c, L_c, X, Aw, Ac) = 0 \quad (1)$$

where W is the width of the upstream channel, S_0 is the bed slope, D is the diameter of wooden debris, F is the feeding rate of woody debris into the flow, T is the time after feeding from the falling of the first wooden debris, ρ is the fluid density, ρ_w is the wooden debris density, V is the average flow velocity at upstream, V_w is the velocity of woody debris, μ is the dynamic viscosity of water, g is the acceleration due to gravity, H_e is the flow depth at the culvert inlet, H_u is the upstream flow depth, L_w is the length of wooden debris, L_c is the culvert length, h_c is the culvert width or diameter for the box and pipe culverts, respectively, X is the distance between the accumulated wooden debris and the channel bed at the inlet, A_w is the area of the culvert opening occupied by the wooden debris, and A_c is the total area of the culvert opening. By applying Buckingham's Pi theory, Eq. (1) can be regrouped as Eq. (2):

$$B, X^* = f_2(Q^*, T^*, Re_w, Fr_u, Fr_e, \rho^*, h_c^*) \quad (2)$$

in which $B = Aw/Ac$ is called the degree of culvert blockage, $X^* = X/H_e$ is called the non-dimensional blockage height, $T^* = TV/H_e$, $Q^* = VH_e^2/F$, $\rho^* = \rho_w/\rho$, $h_c^* = H_e/h_c$, $Re_w = \rho_w V_w D/\mu$ is the Reynolds number of woody debris, $Fr_e = \frac{V}{\sqrt{gH_e}} \cdot \frac{W}{h_c} \cdot \frac{H_u}{H_e}$ is the Froude number at the culvert entrance, and $Fr_u = V/\sqrt{gH_u}$ is the upstream flow Froude number. The upstream Froude number has been used in the present study because culverts are generally under inlet control conditions during floods and the process is influenced by the upstream flow characteristics. If the culvert is outlet control, the downstream flow characteristics are important too. While downstream Fr is commonly used,

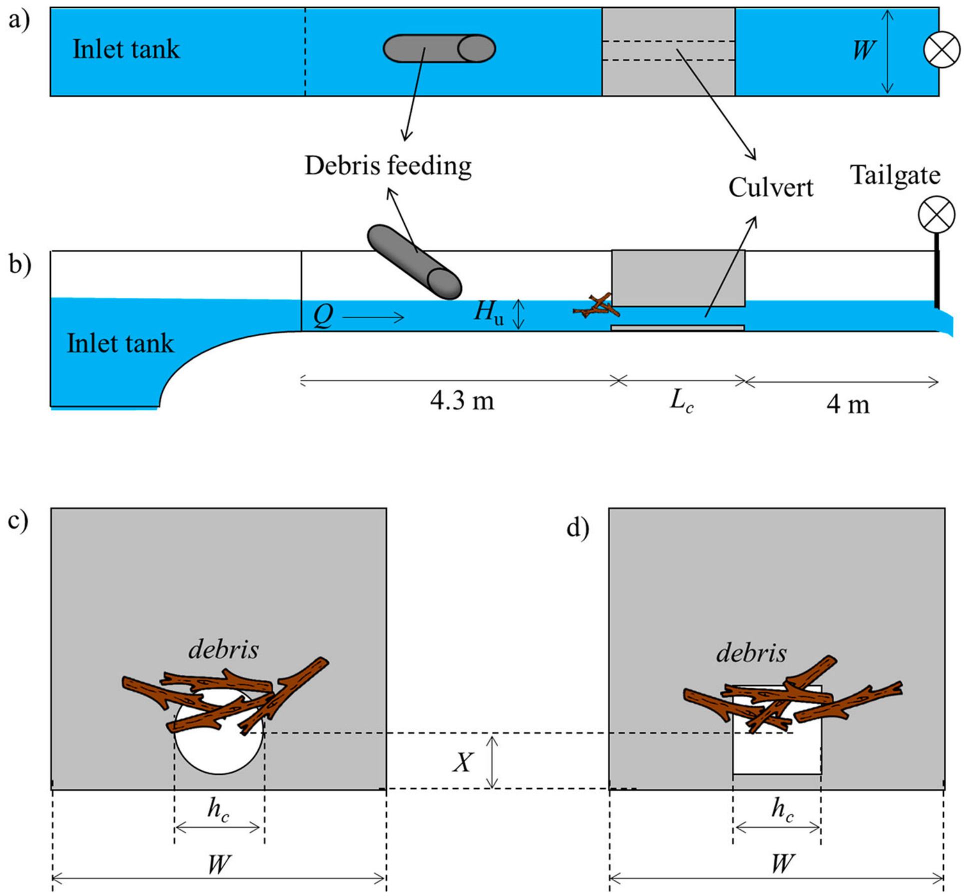

Figure 1. Schematic view of the experimental setup, (a) plan view, (b) side view, and cross-sectional view of (c) pipe, and (d) box culverts.

the process is influenced by the characteristics of the upstream flow and thus the upstream Fr is a better descriptor of flow conditions influencing the processes.

Based on the percentage of the culvert opening blocked by debris, the degree of blockage (*B*) introduced by Sorourian et al. (2014a) has been used instead of the traditionally used hydraulic blockage parameter (Kramer et al., 2015). It should be noted that some of the parameters that were kept constant in the present study, e.g. the channel bed slope, the nondimensional channel width, upstream flow Reynolds number, non-dimensional debris length, and non-dimensional culvert length, have been excluded from Eq. (2).

Experimental setup

The experiments were carried out in a rectangular glass side wall flume of 9 m length, 0.4 m width, and 0.6 m height (Figure 1). The bed slope of the flume was adjusted to 0.002 using a pivot located under the flume. Two types of culverts including box and pipe shapes were studied. The box culvert was 0.1 m ×0.1 m and the pipe culvert was 0.116 m in diameter both 0.45 m long designed for the experimental test. With a scale of 1:10, the culvert models were designed to simulate a 4.5 m wide roadway culvert. Each culvert model was individually installed in the middle of the flume. Table 1 shows the geometric and hydraulic similarities of the model and prototype.

Flow depth and water surface profile were measured at several points upstream of the culvert using a ±0.1 mm resolution point gauge. A tailgate was at the endpoint of the flume to regulate the normal depth in the case without a culvert. Discharge was measured using an electromagnetic flowmeter with a resolution of ±0.1 l/s. The discharge changed every 4 minutes to create a stepwise hydrograph. For each step, the discharge increased by 2 l/s intervals up to a peak flow of 8 lit/s (Figure 2). Hence, the hydrograph lasted 28 minutes for each test.

Woody dowels with lengths of 200 ± 0.4 mm with two diameters of 12 ± 0.3 mm and 23 ± 0.8 mm were used to resemble tree branches as floating debris in experiments. With the 1:10 scaling ratio, the woods model is similar to a prototype size diameter of 120 and 230 mm with a length of 2 metres. These dimensions are within the most common sizes of the large woody debris in field conditions (Justice,

Table 1. Scale parameters for box and pipe culverts.

Parameter	Scaling ratio	Prototype		Model	
		Box	Pipe	Box	Pipe
Culvert height (mm)	Lr = 10	1000	1160	100	116
Culvert length (mm)	Lr = 10	4500	4500	450	450
Inlet area (m^2)	$Lr^2 = 10^2$	1	1.057	0.01	0.01057
Flow rate (lit/s)	$Lr^{5/2} = 10^{5/2}$	600–2530	600–2530	2–8	2–8
Flow velocity at U/S of culvert (m/s)	$Lr^{1/2} = 10^{1/2}$	0.1-0.43	0.1-0.43	0.035-0.136	0.035-0.136
Time base of flow hydrograph (min)	(Lr/Vr)	88.6	88.6	28	28

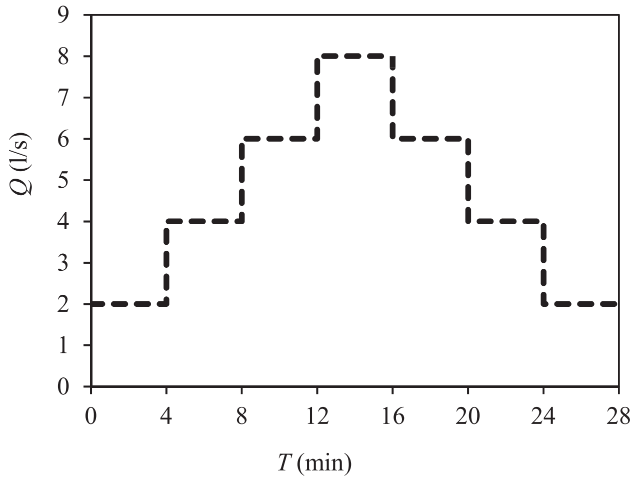

Figure 2. Idealized stepwise hydrograph simulating quasi-unsteady flow used in the experiments.

2007). Gomi et al. (2001) classified woody debris into two categories: large woody debris with 500 mm or more in length and 100 mm in diameter, and fine woody debris with a length of 500 mm or more and 30–100 mm in diameter. Based on the above criteria, the woody debris models used in this study fall into the category of large woody debris. The specific gravity of the woody debris was 0.61, representing tree species such as chestnut oak and black locust (Adams, 2001).

Floating woody dowels were fed singly in the centreline of the flume parallel to the flow. The dowels were carried downstream by the flow, with some passing through the culvert, while the remaining dowels were piled up in the culvert inlet. The accumulation of the woody dowels was monitored using two digital video cameras with a rate of 30 frames per second. The first camera was 0.5 m above the culvert entrance, while the second one was 0.2 m from the sidewall adjacent to the flume. Images were extracted for different time intervals from recordings. The images were imported into image processing software and the area occupied by the dowels was determined. Examples of extracted images are shown in Figure 3 for the pipe culvert. A summary of experimental conditions is reported in Table 2 for box and pipe culverts. In this table, scenarios 0–4 represent the feeding rate of the woody dowels into the flow ranging from 0 to 5540 mm^3/s. Scenarios 1 and 3 correspond to the feeding rate of a woody debris every 40 seconds while in scenarios 2 and 4, the dowel feeding rate is one woody debris every 15 seconds.

Results and discussion

Box culvert

Maximum percentage of blockage

Time variations of the percentage of blockage are shown in Figure 4. According to Figure 4, it is seen that the effects of the dowel's diameter are more important than those of their feeding rate. The maximum percentage of culvert blockage observed in the B2 test which is much greater than that of the B1 test. In the case of woody debris with a smaller diameter, the result shows that the percentage of blockage increases with the feeding rate. However, there is no significant variation in the percentage of blockage for the B3 and B4 tests which indicates that the effect of feeding rate is not an issue in the culvert blockage for the dowels with large diameters. The maximum percentage of blockage for the tests with smaller diameter woody dowels was 42% higher than that of larger diameter woody dowels. Also, the maximum percentage of blockage occurred at the final time step of the flow hydrograph, i.e. at the end of each test. The percentages of blockage for maximum discharge are 0.46 and 0.74 of the maximum percentage of blockage

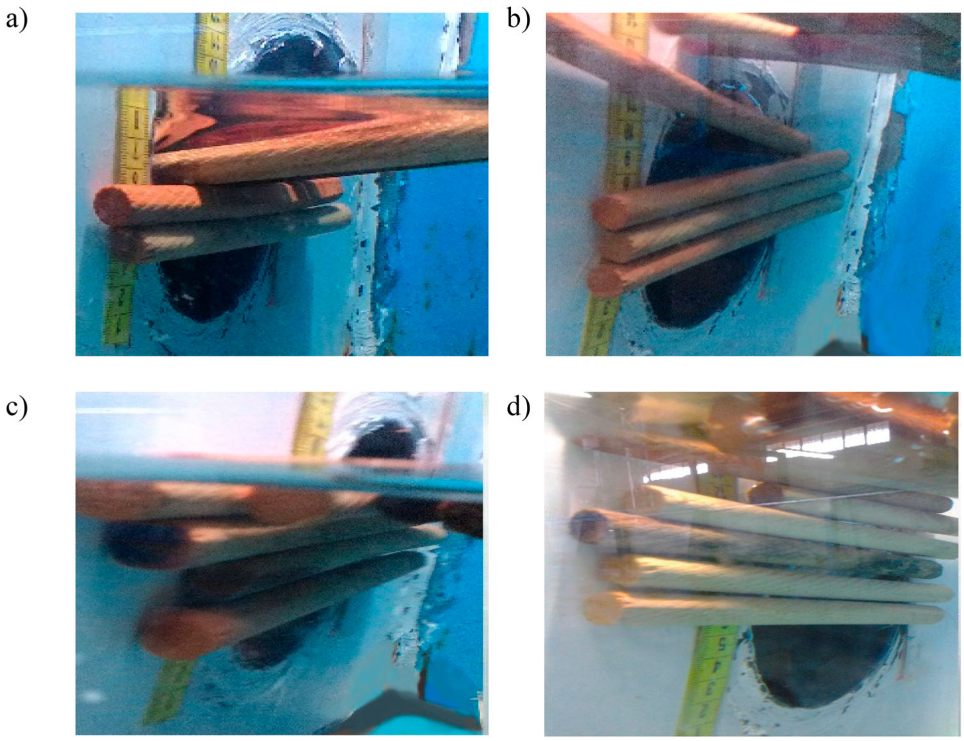

Figure 3. Images of woody debris accumulation at the pipe culvert entrance in different time steps, T = (a) 4, (b) 12, (c) 20, and (d) 28 minutes.

Table 2. Summary of the experimental conditions for the box and pipe culverts.

	Code						H_u (mm)		*X* (mm)	
Scenario (#)	*Box*	*Pipe*	*D* (mm)	*F* (mm^3/s)	*T* (min)	*Q* (lit/s)	Box	Pipe	Box	Pipe
0	B0	P0	-	0	4	2	130	140	–	–
	B0	P0	-	0	8	4	160	170	–	–
	B0	P0	-	0	12	6	185	200	–	–
	B0	P0	-	0	16	8	230	220	–	–
	B0	P0	-	0	20	6	185	200	–	–
	B0	P0	-	0	24	4	160	170	–	–
	B0	P0	-	0	28	2	130	140	–	–
1	B1	P1	12	566	4	2	130	145	28	31
	B1	P1	12	566	8	4	168	176	56	48
	B1	P1	12	566	12	6	199	216	53	48
	B1	P1	12	566	16	8	246	252	54	44
	B1	P1	12	566	20	6	206	232	53	44
	B1	P1	12	566	24	4	174	195	43	42
	B1	P1	12	566	28	2	141	160	27	31
2	B2	P2	12	1508	4	2	133	146	20	21
	B2	P2	12	1508	8	4	171	191	38	35
	B2	P2	12	1508	12	6	208	247	34	37
	B2	P2	12	1508	16	8	269	270	34	37
	B2	P2	12	1508	20	6	225	255	34	37
	B2	P2	12	1508	24	4	179	203	33	35
	B2	P2	12	1508	28	2	154	162	18	12
3	B3	P3	23	2077	4	2	130	140	44	36
	B3	P3	23	2077	8	4	166	180	69	61
	B3	P3	23	2077	12	6	191	216	80	68
	B3	P3	23	2077	16	8	240	234	65	61
	B3	P3	23	2077	20	6	200	230	77	61
	B3	P3	23	2077	24	4	169	188	48	53
	B3	P3	23	2077	28	2	140	158	31	33
4	B4	P4	23	5540	4	2	134	146	40	35
	B4	P4	23	5540	8	4	168	185	62	61
	B4	P4	23	5540	12	6	193	222	75	65
	B4	P4	23	5540	16	8	243	257	54	57
	B4	P4	23	5540	20	6	204	241	71	57
	B4	P4	23	5540	24	4	175	193	46	46
	B4	P4	23	5540	28	2	143	160	31	31

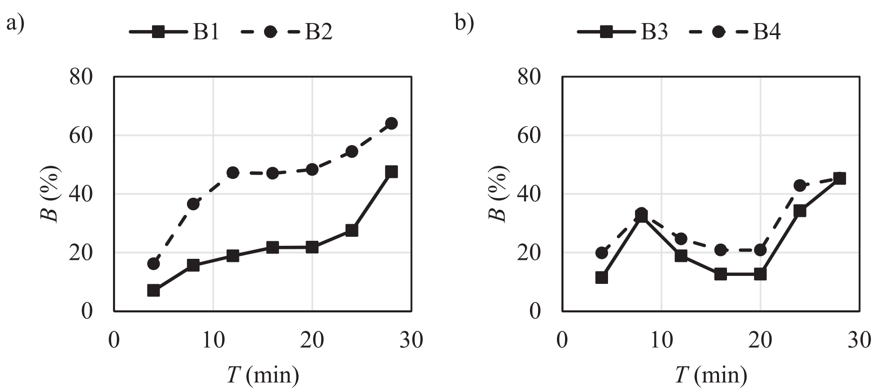

Figure 4. Time variations of the percentage of blockage for box culvert, (a) $D = 12$ mm and (b) $D = 23$mm.

for the tests B1 and B2 but the percentages of blockage for maximum flow rate are 0.28 and 0.46 of the maximum percentage of blockage in B3 and B4 tests, respectively.

Figure 5 shows the variations of the percentage of blockage (B) at the box culvert inlet versus the upstream Froude number (Fr_u). It is seen that as the Froude number of the upstream flow increases, the percentage of blockage decreases. It can be seen in Figure 5 that for low-velocity flow conditions, the percentage of blockage is greater than that of higher velocity flow conditions. In other words, as the flow velocity increases, more dowels are conveyed through the culvert and hence small blockage occurs. Based on regression, a linear equation is fitted on the data to determine the percentage of blockage (B) in box culverts with knowing the upstream flow Froude number (Fr_u) as

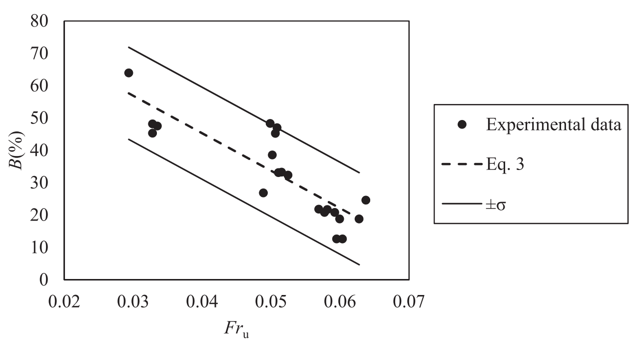

Figure 5. Percentage of blockage (B) vs. upstream flow Froude number (Fr_u) for box culvert.

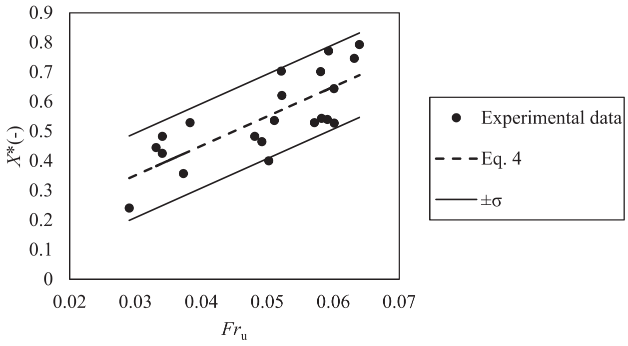

Figure 6. Height of blockage at the entrance of box culvert (X^*) vs. upstream Froude number (Fr_u).

Eq. (3). This equation with a standard deviation of σ = 14.2 is valid in the range of Fr_u values tested in the present study. All the data points fall within ±σ limits as shown in Figure 5.

$$B = -1159Fr_u + 91.65, \ R^2 = 0.73 \tag{3}$$

The height of accumulated dowels

Figure 6 shows the height of the blockage in reference to the channel bed at the culvert entrance for different flow conditions. It is seen that as the Froude number increases, the blockage height, where dowels accumulate at the culvert entrance, is also increased. Also, according to Table 2, it was found that the blockage height, X^*, reduced for 12 mm diameter of dowels when compared to 23 mm diameter of dowels. For example, the ratio X^* for the B2 test with the 12 mm diameter of woody debris is 42% less than that for the B4 test with 23 mm diameter of woody debris. The minimum value of X^* occurred at the final time step of the hydrograph. Moreover, the height of the blockage is affected by the feeding rate of woody debris into the flow. For example, X^* in the B2 test with a higher feeding rate is 60% less than that for the B1 test with a lower feeding rate of woody debris. Based on regression analysis, a linear equation is fitted on the data to determine the height of blockage (X^*) in the box culverts with knowing the upstream flow Froude number (Fr_u) as Eq. (4). This equation with a standard deviation of $\sigma = 0.14$ is valid in the range of Fr_u values tested in the present study.

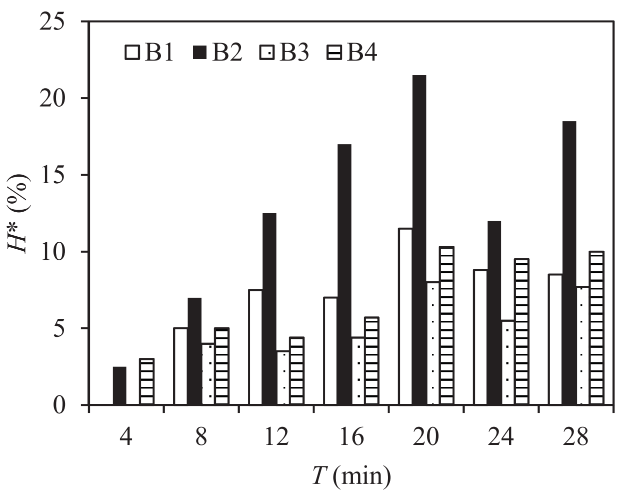

Figure 7. The time variations of $H^*$for box culvert.

All the data points fall within ±σ limits as shown in Figure 6.

$$X* = 9.96Fr_u + 0.052, \ R^2 = 0.59 \tag{4}$$

Variations of the upstream flow depth

Figure 7 shows the time variations of an increase in upstream flow depth (H^*) under different woody debris conditions compared to the case without woody debris. The results showed that the maximum value of H^* occurred at $T =$ 20 min for the $Q = 6$ lit/s and the falling limb of the hydrograph. Also, for a given diameter of woody debris, H^* increases as the feeding rate of woody debris increases. Moreover, the maximum value of H^* in each time step was observed for the B2 test which may be attributed to the higher percentage of blockage in this test.

Pipe culvert

Maximum percentage of blockage

Time variations of the blockage percentage for the pipe culvert and different debris diameters are shown in Figure 8. It can be seen in Figure 8 the effect of debris diameter on the time variations of B in the pipe culverts is less than that in the box culverts (Figure 4). Also, Figure 9 shows the percentage of blockage in pipe culvert entrance versus the upstream Froude number. The falling trend of data points shows that increasing the upstream Froude number reduces the percentage of effective blockage. During the experiments, the pipe culvert performed in submerged conditions for 6 and 8 lit/s flow rates. In experiments P1 and P2, the percentages of blockage for the maximum flow rate ($Q = 8$ lit/s) were 51% and 75% of the blockage at the final time step of the hydrograph, respectively. The maximum percentage of the blockage occurred at the final time step. Also, the blockage was high for the tests with more wood feeding rate.

In the P3 and P4 experiments, the blockage for the maximum flow rate was 32% and 50% of the blockage for final time step of the hydrograph, respectively. The maximum percentage of B in the P4 test was 16.3% higher than that of the P3 test while woods were fallen in the flow with higher rates in the P4 test when compared with the P3 test. Based on regression analysis, a linear equation is fitted on the data to determine the percentage of blockage (B) in pipe culverts with knowing the upstream flow Froude number (Fr_u) as Eq. (5). This equation with standard deviation of σ = 13.4 is valid in the range of Fr_u values tested in the present study. All the data points fall within ±σ limits as shown in Figure 9.

$$B = -1307Fr_u + 102.4, \ R^2 = 0.82 \tag{5}$$

The height of blockage

Figure 10 shows the height of blockage from the bed at the entrance of the pipe culvert versus upstream Froude number. The increasing trend of the data shows that the distance of the accumulated dowels increases with the upstream flow Froude number. This distance also increased with the increasing of the diameter of the wooden dowels. This value decreases while the sinking of the woods in the water was high. The values of X^* were high in the cases where wood with 23 mm diameter is used when compared with

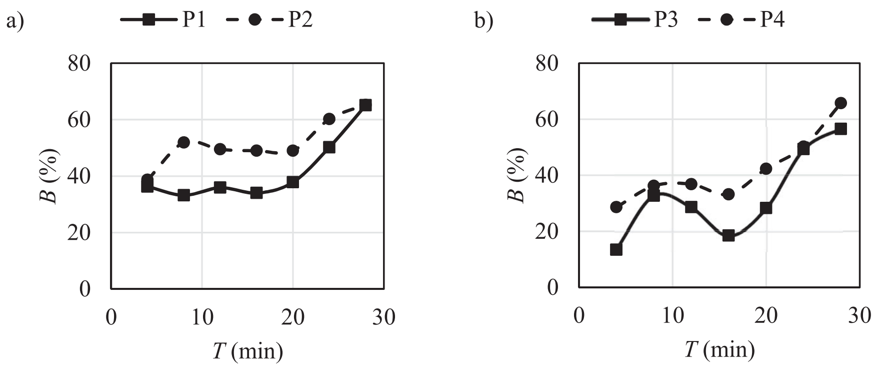

Figure 8. Time variations of the percentage of blockage for pipe culvert, (a) $D = 12$ mm and (b) $D = 23$mm.

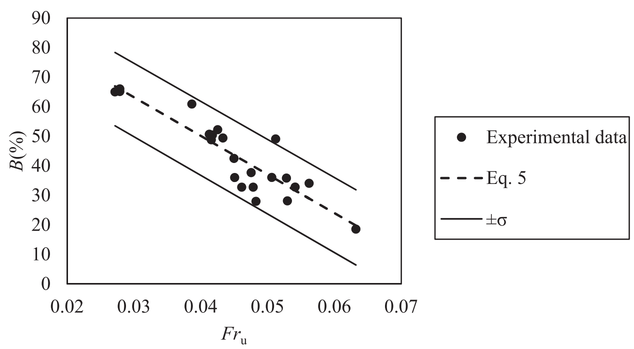

Figure 9. The percentage of blockage (B) vs. upstream Froude number (Fr_u) for pipe culvert.

the cases with 12 mm diameter wood. Based on regression analysis, a linear equation is fitted on the data to determine the height of blockage (X^*) at the entrance of pipe culvert with knowing the upstream flow Froude number (Fr_u) as Eq. (6). This equation with a standard deviation of $\sigma = 0.09$ is valid in the range of Fr_u values tested in the present study. All the data points fall within ±σ limits as shown in Figure 10.

$$X* = 11.2Fr_u - 0.079, \ R^2 = 0.52 \tag{6}$$

Variations of the upstream flow depth

Figure 11 compares the variations of the upstream flow depth at different time steps with the no-woody debris conditions. The maximum value occurred at $Q = 6$ lit/s flow rate and at the time of 20 minutes from the start of the feeding of the woods. The maximum values were obtained while the culvert entrance was submerged. Also, the results show

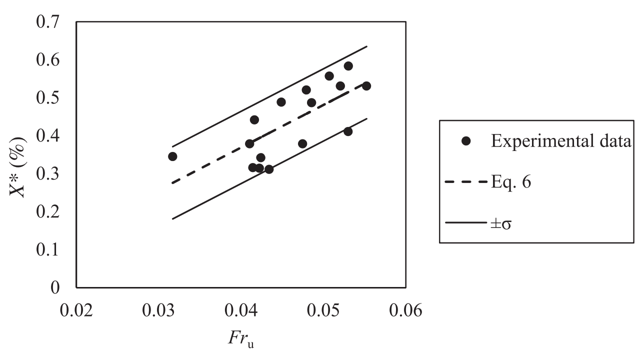

Figure 10. The distance ratio with occurrence of blockage from entrance flooring of the pipe culvert (X^*) vs. upstream Froude number (Fr_u).

that H^* increases with an increase in the woody debris diameter. The above result is consistent with the results from a study by Xia et al. (2018) who reported that blockage of the bridge opening with floating vehicles increases the upstream flow depth. However, it is expected that for a single barrel culvert, as studied here, the increase in the upstream flow depth to be greater than multi-barrel culverts or bridges due to the smaller conveyance capacity of single barrel culverts. It should be noted that the experimental flume used in the present study simulates the common culvert type located in an embankment. Hence, in the field situation, water can pond behind the embankment and increase the flow through the culvert, even if it is blocked. This can occur only if the flood hydrograph has sufficient volume. The influence of hydrograph volume has not been considered in the analysis of the present study.

Effect of culvert shape on culvert blockage

It can be seen in Figures 5–6 and 9–10 that both shapes of the culvert have similar trends with the upstream flow Froude number. However, if the culvert has multiple barrels, the effect of blockage on the upstream flow depth variations may be decreased because other barrels may pass the flow while some of them are partially or fully blocked by debris. Also, it can be seen from Figures 5–6 and 9–10 that in any stages of blockage, the effect of blockage on the upstream flow depth is positive, i.e. the upstream flow depth was greater than that if there is no blockage.

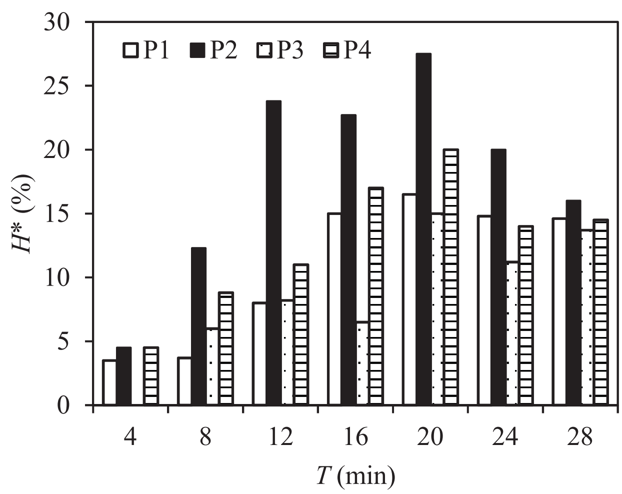

Figure 11. Percentage of increase of upstream flow depth in comparison with no woody debris conditions in pipe culvert.

Due to relatively low values of the R^2 in Eqs (3)–(6), an attempt was made to incorporate some other parameters obtained by dimensional analysis. Using linear regression analysis in the SPSS software, the most effective dimensionless parameters on the percentage of blockage and woody debris height to the channel bed have been identified. Consequently, the following equations have been obtained for the determination of B and X^* with the coefficient of determination of 0.90 and 0.81, respectively. These equations are valid in the range of the values of the parameters tested in the present study.

$$B = 46 - 785Fr_u - 38184T^* + 18.8Fr_e - 0.03Re_w - 2.24\rho^* - 0.001Q^* + 66.7h_c^* \quad (7)$$

$$X^* = 0.584 + 9.1Fr_u + 202.4T^* - 0.13Fr_e + 5.1Re_w - 0.04\rho^* - 6Q^* - 0.36h_c^* \quad (8)$$

According to the above equations, it is found that the most effective parameter on the percentage of blockage (B) and the blockage height at the inlet (X^*) is T^*. It should be mentioned that the values of B and X^* obtained by Eqs (7) and (8) may differ from those calculated by Eqs (3)–(6) because Eqs (3)–(6) correspond to the final stage of the experimental tests but Eqs (7) and (8) correspond to any stage of the flood event. It should be mentioned that the results presented in this paper were based on cylindrical woody debris. In the presence of branches and leaves and also for the other shapes of woody debris, different values may be expected. Therefore, further experimental and field information is required to generalize the above equations.

For the experimental conditions used in this study, it was found that a circular pipe culvert produces 9% more blockage than a box culvert. It is due to that woody debris accumulate at the interior top inlet of the pipe (see Figure 3). It is due to that pipes have a smaller top width when it is close to a fully filled flow. Therefore, it is practically recommended to select a box shape culvert as an alternative rather than selecting a circular shape culvert. The main advantage of the box culverts is there is a constant water surface width while the top width varies with flow depth in the culverts with a circular cross-section. Also, the spacing between the box culvert cells in multi-barrel culverts is kept to a minimum.

Finally, with the results of the present study, it is still impossible to simplify the outcomes due to the influence of other parameters like shape, spacing and direction of moving materials on the flow structure around a floating object for simulation of the problem in the natural situation. As a result, there are also challenges ahead concerning the effect of different floating material density on the rate of blockage and therefore the present work should be followed by a detailed study on a large scale as well as natural channels with different materials and various flow conditions.

Conclusion

In this study, experimental tests were carried out under unsteady flow conditions using a synthetic hydrograph during flood events to simulate blockage at the inlet of box and pipe culverts. The results show that for both culvert types, the maximum percentage of blockage (B) at the culvert entrance occurred at the final time step of the falling limb of the hydrograph. It was found that the maximum blockages for wood with 12 and 23 mm diameters were 65% and 70%, respectively. For a given wood diameter and a specific feeding rate, the percentage of blockage in the pipe culvert was higher than that of the box culvert. As a result, the percentage of blockage in the P4 and P3 tests with a 23 mm diameter wood debris were 45% and 37% higher than that in the B4 and B3 tests with the same wood debris diameter, respectively. Furthermore, it was found that the shape of the culvert influences the height of the accumulated woods. The height of the blockage in the P4 and P3 tests were 10% and 23% less than that in the B4 and B3 tests, respectively. Moreover, the maximum increase in the upstream flow depth (H^*) for both types of culverts was observed at the falling limb of the hydrograph. Also, the values of H^* in the P4, P3, P2, and P1 tests were18.3%, 15%, 13.5%, and 13% higher than corresponding values in the B4, B3, B2, and B1 tests, respectively. Finally, some empirical equations have been presented based on regression analysis for the calculation of blockage percentage and its height which can be used by hydraulic designers to increase the reliability of their designing against blockage. Also, the results may be interesting for the stakeholders in the operational phase to increase the reliability of the culvert performance.

For the experimental conditions used in this study, it was found that a circular pipe culvert produces 9% more blockage than a box culvert. It is due to that woody debris accumulates at the interior top inlet of the pipe (see Figure 3). It is due to that pipe has minimum top width when it is close to fully full flow. Therefore, it is practically recommended to select a box shape culvert as an alternative rather than a circular shape culvert. Another important advantage of the box culvert is that there is a constant water surface width at all flow levels. Also, the spacing between the box culvert cells in multi-barrel culverts is kept to a minimum. The results from this study are only for the test conditions used in this study. The debris feed into the flume represented selected sizes from a range of potential debris sizes and different effects would be expected if the debris had a wider range of sizes. Therefore, more study is required to generalize the results for practical application. Finally, a conceptual model of flow past cylindrical wood comprising the blockage would be to consider the wood as horizontal piers. Using that analogy, it can be argued that similar factors would influence the flow to those that influence the flow around a vertical pier. The wood Reynolds number, therefore, should be analogous to a pier parameter related to its size and spacing.

Notations

b	water surface width
B	percentage of effective blockage
D	diameter of wooden debris
F	feeding rate that woody debris added to the water
Fr_e	flow Froude number at the entrance of culvert
Fr_u	flow Froude number at the upstream of culvert
Fr_w	Froude number of woody debris
H^*	percent of upstream water depth increase
h_c	culvert height or culvert diameter
H_e	entrance water depth to culvert
H_u	upstream water depth
L_c	culvert length
L_w	length of wooden debris
Q	discharge
Re_w	Reynolds number of woody debris
R^2	coefficient of determination

S_0 slope of channel
T time
V_w velocity of woody debris
W upstream channel width
X space of blockage from the floor of culvert entrance
g acceleration due to gravity
μ dynamic viscosity of water
ρ water density
ρ_w woody debris density
υ kinematic viscosity of water

Acknowledgement

The authors thank the reviewers and editor for their helpful comments.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Alireza Keshavarzi http://orcid.org/0000-0001-8252-4569
Hossein Hamidifar http://orcid.org/0000-0001-9054-0120

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