Scour at partially blocked box-culverts under steady flow

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Culverts are built at locations where a waterway crosses a road or railway and creates a limitation to flow passage. Furthermore, blockage commonly occurs during flood events with accumulation of debris at the culvert inlet. The inlet blockage changes the flow structure at the outlet and may result in culvert failure. Despite this, the impacts of blockage on culvert hydraulics and downstream waterways have not received consideration in the literature. The purpose of this paper is to mitigate this deficiency by reporting on an investigation into scouring at the outlet of partially blocked culverts. Experimental tests were conducted under steady flow to investigate a relationship between the maximum scour depth, blockage ratio of the culvert and the flow characteristics. Both non-blocked and partially blocked conditions were considered. Consideration of the results obtained showed that the scoured area and maximum scour depth increased with partially blocked culverts conditions compared with equivalent non-blocked culverts.

Notation

A	cross-sectional area of culvert outlet
A_s	scoured area
B	blockage ratio
d_s	scoured depth
d_{sm}	maximum scour depth
d_0	outlet diameter in circular-shaped culverts
d_{50}	median grain size of bed material
F_d	densimetric Froude number
F_r	flow Froude number
$\boldsymbol{g}$	acceleration of gravity
H	culvert height
h_B	height of blockage plate
h_d	depth of water at culvert outlet
h_t	tail water depth
h_u	upstream depth of water
KE_x	kinetic energy in x direction
L_t	total length of scouring hole
Q	flow rate
R^2	coefficient of correlation
RSS	Reynolds shear stress
S	culvert slope
S_E	standard error of estimate
TI_x	turbulence intensity in x direction
t	time of experiment
U_*	shear velocity at culvert outlet
V_x	flow velocity in x direction
v'_x	turbulent fluctuations of flow velocity in x direction
W	culvert width
W_t	maximum scour width
X	horizontal axis (flow direction)
x_s	horizontal distance from the outlet
x_{sm}	location of maximum scour depth along horizontal axis
y_s	width of scour hole at any location along Y-axis
z	depth of water from culvert invert
ρ	water density
ρ_s	sediment density
σ_g	sediment geometric standard deviation

1.   Introduction

Culverts are locations in water courses where a flow constriction occurs and therefore where blockage of some type may occur. Consideration of the number of culverts highlights the importance of culvert structures and their functional requirements. Weeks *et al.* (2009) reported on the damage resulting

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from blockage of culverts and waterways. In terms of functionality, blockage of culverts and bridges during floods is an important issue for many road authorities and local councils. Furthermore, blockage at culverts creates a risk of damage to private properties and public assets (Weeks *et al.*, 2009). An analysis of the literature indicates that the two different research fields important in understanding this topic are

- culvert blockage
- scouring downstream of the culvert, that is, scour at the culvert outlet.

The first category generally consists of research based on field data collected after major floods. In these studies the main focus has been on the factors leading to blockage and the consequences of blockage on the downstream flow paths. For instance, Rigby *et al.* (2002) collected field data after a flood event and reported that, when the opening size of culverts is less than 6 m (measured diagonally) there is a high risk of culvert blockage, while Barthelmess and Rigby (2011) estimated culvert and bridge blockage based on availability, mobility and transportability of debris. Rigby and Barthelmess (2011) also explored culvert blockage mechanisms and their impact on flood behaviour. They reported that one of the consequences of blockage was flow diversions during flood events. They reported that even small blockages created diversions that would not usually occur and considerably changed flood behaviour.

The second group of research studies comprises those considering the scouring phenomena at the outlet of culverts. Several equations have been developed to estimate the maximum scouring depth at culvert outlets when the culvert is not blocked. Results from some of the more recent studies are presented herein for the purpose of comparison with the experimental data collected as part of the present study. In particular the data of the studies Lim (1995), Ade and Rajaratnam (1998), Sarathi *et al.* (2008) and Emami and Schleiss (2010) were used for this purpose.

There are many factors that influence scour downstream of a culvert outlet, including flow velocity, flow discharge, sediment size, tail water depth, culvert shape and culvert slope. While there have been numerous studies considering this problem, no reported study has considered all the influencing factors.

Bohan (1970) investigated scour dimensions at the culvert outlet using scale models. Bohan developed an equation based on the flow Froude number and experimental duration. Additionally, Bohan reported that culvert shape did not have a significant effect on scour hole geometry. However, Abt *et al.* (1987) concluded the opposite when they investigated the influence of culvert shape on scouring depth at the culvert outlet, and determined that scour dimensions developed at the outlet of circular-shaped culverts are significantly different from those arising from culverts with other shapes. Abt *et al.* also developed an equation to correlate the maximum scour depth to a modified discharge intensity where the discharge intensity is a modified form of the Froude number and is defined by

1. $$DI = \frac{Q}{A(\boldsymbol{g}R_{\mathrm{H}})^{0.5}}$$

where Q is discharge, A is cross-sectional area; $\boldsymbol{g}$ is acceleration due to gravity and R_{H} is the culvert hydraulic radius.

Abt *et al.* (1986) studied the effect of culvert slope on the scour depth at the outlet of a culvert and noted that a steep culvert can increase the maximum scour depth by 10–40% over the scour dimensions for a horizontal culvert. Abida and Townsend (1991) developed an equation for local scour downstream of box-culverts relating flow Froude number and sediment size. Abt *et al.* (1996) estimated the dimension of outlet scour in relation to culvert discharge, hydraulic radius, time and material gradation. The effect of culvert slope and outlet drop was considered also. Although this formula was quite comprehensive, it lacked simplicity.

Some researchers – see Rajaratnam and Berry (1977), Ali and Lim (1986), Lim (1995), Day *et al.* (2001), Liriano *et al.* (2002), Sarathi *et al.* (2008) and Emami and Schleiss (2010) – used the densimetric Froude number to estimate the scouring depth at the outlet of culverts and wall jets. The densimetric Froude number, which incorporates many of the influencing factors, is defined as

2. $$F_{\mathrm{d}} = \frac{u}{\sqrt{[(\rho_{\mathrm{s}}/\rho) - 1]\boldsymbol{g}d_{50}}}$$

where u is mean flow velocity, ρ_{s} is sediment density, ρ is water density, $\boldsymbol{g}$ is acceleration due to gravity and d_{50} is median grain size of the sediment.

From consideration of Equation 2, it can be seen that velocity of flow, sediment size and sediment density are the primary influencing parameters. Factors that influence the flow velocity include the culvert slope, shape, flow rate and the tail water level.

Rajaratnam and Berry (1977) studied erosion at the outlet of circular wall jets both in non-cohesive sand and polystyrene. They concluded that the main characteristics of the scour hole, such as maximum scour depth and the location of deepest scour depth from the outlet, are functions of the densimetric Froude number. Ali and Lim (1986) investigated the effects of changing tail water depth on scouring downstream of the culvert outlet. They pointed out that tail water depths significantly affected the scour depth at the culvert outlet. They also noted that there is a critical tail water depth beyond which any changes in tail water will result in increase of scour depth.

Lim (1995) conducted experimental tests on a circular un-submerged culvert and compared his work with that of Abt *et al*. (1984) and Breusers and Raudkivi (1991). Lim highlighted the limitations of the formulations proposed by Abt *et al*. (1984) and Breusers and Raudkivi (1991) compared with his work and proposed equations to encompass the data based on the sediment densimetric Froude number. Day *et al*. (2001) investigated the effects of tail water depth and model scale on the maximum depth of scouring using the data collected from experimental testing of circular culverts. Liriano *et al*. (2002) studied scour at the outlet of culverts influenced by turbulent flow and pointed out that the peak values of turbulence intensities over the fixed bed coincided with the location of the maximum scour depth for a fully developed scour hole. Sarathi *et al*. (2008) studied the effect of nozzle size to sediment diameter at the downstream of square wall jets and noted that, for a certain value of densimetric Froude number, the evolution of scour depends on the ratio of nozzle size to grain size. However, they concluded that, for the equilibrium condition, the scour hole is independent of nozzle size to grain size. Emami and Schleiss (2010) conducted some experimental tests to evaluate the natural mobile bed erosion without any protection. They compared their work with some previous studies and proposed an equation for maximum scour depth based on their experimental tests.

From consideration of these previous studies, it can be concluded that the main factors influencing the maximum scour depth downstream of a culvert are sediment properties such as median grain size and geometrical standard deviation, flow conditions and depth of tail water. Some research has indicated that the geometry of the culvert and its slope also affects the formation of the scour hole. Most formulas proposed in this regard are functions of densimetric Froude number, median grain size of bed material, depth of water downstream from the culvert and size of culvert opening. In previous studies, blockage was not considered as a factor influencing the development of a scour hole; hence the focus has been on the scouring pattern at the outlet of the culvert in a non-blocked condition. However, culverts may be partially blocked and there is a need for a systematic study on partially blocked culverts. Hence, the focus of this study was to investigate the flow characteristics and scouring pattern of a partially blocked culvert.
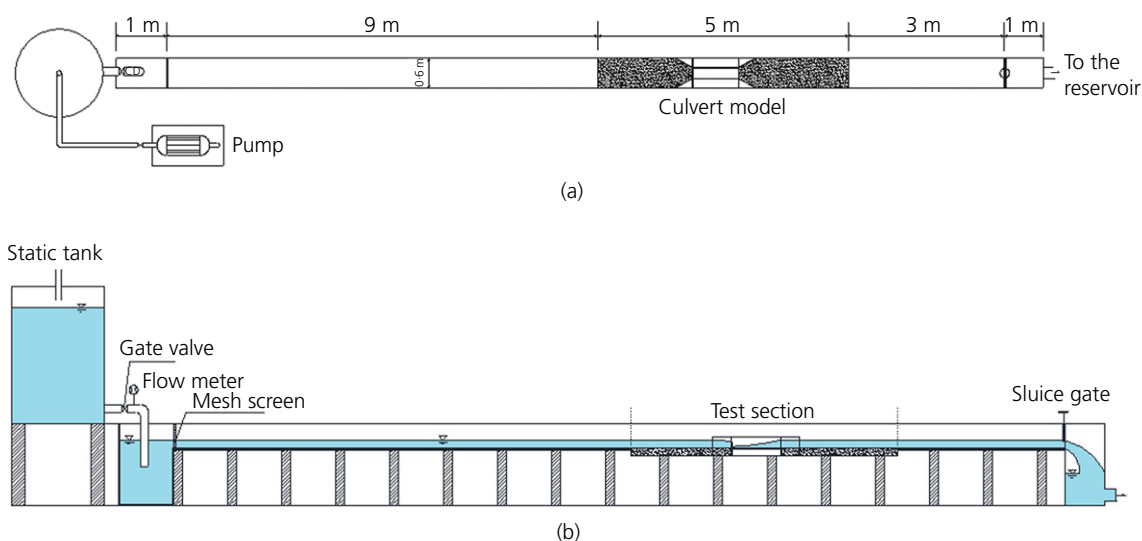
2. Experimental set-up

An experimental programme was designed to investigate the relationship between the maximum scour depth, blockage ratio of the culvert and flow characteristics. The experimental tests were conducted for two different conditions
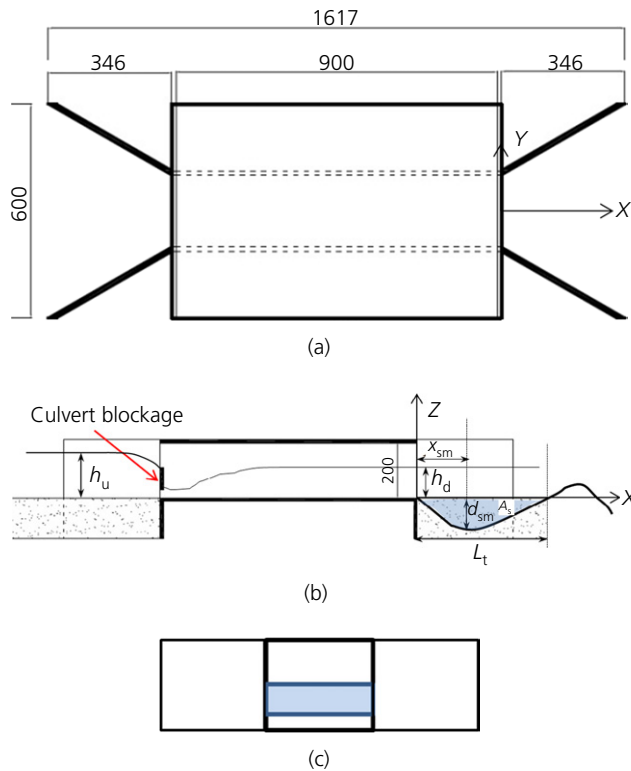
- non-blocked
- partially blocked.

The experimental set-up was located in the UTS hydraulics laboratory and consisted of a rectangular flume fed by a static tank. The plan view and longitudinal profile of this flume are shown in Figure 1. The concrete flume is 19 m long with a width and depth of 605 and 600 mm, respectively. The test section was located 9 m from the inlet of the flume to ensure a fully developed flow would reach the test section. The test section was a 4 m long, 150 mm deep sand basin with the same width as the flume. Water flow in the flume is controlled through a valve, while, at the downstream end of the flume, a sluice gate was installed to adjust the downstream water depth.

The box-culvert model being tested was placed in the flume on a sand bed. The culvert model details are shown in Figure 2.

Figure 1. Experimental test facility in hydraulics laboratory: (a) plan view; (b) section view

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Figure 2. Culvert model and coordinate system: (a) plan view;
(b) section view; (c) inlet view (units: mm)

The opening of the culvert is 200×200 mm and the length of the culvert barrel is 900 mm. There are transitions with 30° flare at the inlet and outlet of the culvert. To simulate blockage at the inlet, a plate was installed at the opening of the culvert. Two sizes of plates (200×80 and 200×120 mm) were used to obtain variable blockage ratios in the experimental tests. The sediment materials used in this study were uniform non-cohesive sand with median grain sizes (d_{50}) of 0·85 and 2·0 mm.

To measure bed profile and velocities in the x, y, and z dimensions, a Nortek Vectrino Profiler, was used. This device is an Acoustic Doppler Velocimeter which is generally known as ADV. This instrument has four receive transducers set 90° apart, mounted inside a receiver arm. The transmit transducer is in the centre of the probe. The ADV Profiler can take a velocity profile of a layer. The measuring volume is in a distance of 40 to 70 mm below the probe to get a full profile and 45 t0 55 mm below the probe for point measurement. Operating temperature for this ADV Profiler is −4° C to +40° C. The ADV Profiler measures velocities from 0·1 to +3 m/s and is accurate to ±0·5% within this velocity range. It collected up to 6000 samples per point with a sampling rate of 100 Hz. These samples were then processed to determine average velocities. The ADV Profiler installed on a cart allowed for the movement of the instrument in all directions. The coordinate system

was set with the origin at the culvert outlet (Figure 2). The positive X dimension was measured downstream of the culvert, the Y dimension laterally across the flume and the Z dimension upward. As shown in Figure 2 h_d refers to the water depth at the outlet of the culvert and the average velocity through the culvert is u. The maximum scour depth along the centreline is d_{sm} and the axial scour length downstream of the culvert is L_t. In this text the culvert height is denoted by H.

Prior to each test the sand was levelled with the culvert inlet and outlet in the sand basin. Experimental tests were conducted in a steady-state condition. The range of flow rate varied from 5 to 25 l/s, while the test durations were sufficient to ensure that an equilibrium condition for the scouring process was achieved.

Tests were conducted under free surface flow conditions. Each individual run is referred to, by the sand type (S), blockage condition (B) and experiment number for each set. For example, S1 represents sand type 1 ($d_{50} = 0.85$ mm) and S2 represent sand type 2 ($d_{50} = 2$ mm). B0 is used for tests in non-blocked condition and B40 and B60 are for partially blocked conditions. Tests where the nomenclature starts with V had velocity measurement in the culvert barrel as well.

Table 1 shows the test classifications. In this table σ_g is the sediment geometric standard deviation, h_d is the depth of water at the outlet of the culvert, h_u is the upstream water level, h_t represents the tail water depth and F_d is the densimetric Froude number. The blockage of a culvert is represented by B, which is defined as (h_B/h_u), where h_B is the height of the plate used as the blockage in the inlet of the culvert (see Figure 2(b)).

3. Dimensional analysis
As discussed earlier, scouring at the culvert outlet is related to

- flow discharge, Q
- culvert width, W
- culvert height, H
- height of blockage, h_B
- upstream water level, h_u
- downstream water level at the culvert outlet, h_d
- tail water depth, h_t
- median grain size of sediments, d_{50}
- water density, ρ
- sediment density, ρ_s
- culvert slope, S
- acceleration due to gravity, $\boldsymbol{g}$

Using these parameters, scouring at the outlet of a culvert can be expressed as

3. $f(d_s, Q, W, H, h_B, h_u, h_d, h_t, d_{50}, \rho, \rho_s, S, \boldsymbol{g}) = 0$

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Test	d_{50}: mm	σ_g	h_d: mm	h_t: mm	h_u: mm	Q: l/s	B	F_d
S2B01	2	1·23	125	125	125	10·1	0·0	2·2
S2B02	2	1·23	155	155	155	12·3	0·0	2·2
S2B03	2	1·23	100	105	105	12·8	0·0	3·6
S2B04	2	1·23	120	120	120	8·6	0·0	2·0
S2B05	2	1·23	100	105	100	6·6	0·0	1·8
S1B01	0·85	1·37	200	197	198	14·6	0·0	3·1
S1B02	0·85	1·37	157	157	160	15·0	0·0	4·1
S1B03	0·85	1·37	170	170	174	18·7	0·0	4·7
S1B04	0·85	1·37	138	145	150	13·2	0·0	4·1
S1B05	0·85	1·37	95	108	95	14·2	0·0	6·4
S1B06	0·85	1·37	90	95	90	4·9	0·0	2·3
S1B07	0·85	1·37	55	50	75	7·0	0·0	5·5
VS1B08	0·85	1·37	90	100	130	15·1	0·0	7·2
VS2B01	2	1·23	140	143	140	10·0	0·0	2·0
S2B401	2	1·23	140	145	170	10·7	0·5	2·1
S2B402	2	1·23	155	160	185	12·3	0·4	2·2
S2B403	2	1·23	105	105	175	12·8	0·5	3·4
S2B404	2	1·23	110	115	145	8·8	0·6	2·2
S2B405	2	1·23	105	110	125	6·6	0·6	1·7
S1B401	0·85	1·37	195	195	210	14·7	0·4	3·2
S1B402	0·85	1·37	165	168	196	14·6	0·4	3·8
S1B403	0·85	1·37	60	60	195	15·1	0·4	10·7
S1B405	0·85	1·37	210	213	230	19·8	0·3	4·0
S1B406	0·85	1·37	150	145	200	20·7	0·4	5·9
S1B407	0·85	1·37	80	70	230	25·0	0·3	13·3
S1B408	0·85	1·37	70	70	120	4·9	0·7	3·0
S1B409	0·85	1·37	80	95	160	10·1	0·5	5·4
VS2B401	2	1·23	135	140	215	10·5	0·8	2·2
VS2B402	2	1·23	140	145	185	14·3	0·6	2·8
VS2B403	2	1·23	150	160	180	14·1	0·4	2·6
VS2B404	2	1·23	165	175	185	14·1	0·4	2·4
VS2B405	2	1·23	165	170	185	10·7	0·5	1·8
S2B601	2	1·23	130	130	190	10·3	0·6	2·2
S2B602	2	1·23	170	170	210	12·5	0·6	2·0
S2B603	2	1·23	130	130	195	12·8	0·6	2·7
S2B604	2	1·23	110	115	160	8·8	0·8	2·2
S2B605	2	1·23	90	105	135	6·6	0·9	2·0
S1B601	0·85	1·37	60	70	150	7·0	0·8	5·0

Table 1. Experimental test classification

In this study the effect of W and H can be excluded, as the dimensions of the culvert were constant. Also, the culvert slope S, the water density ρ and the sediment density ρ_s were constant and, therefore, could be disregarded in this dimensional analysis. Hence, suitable non-dimensional terms in the relationship become

$$4. \quad \frac{d_s}{h_d} = f\left(\frac{Q}{Wh_d\sqrt{gd_{50}}}, \frac{h_B}{h_u}\right)$$

The first non-dimensional parameter $\left(Q/Wh_d\sqrt{gd_{50}}\right)$ is known as the densimetric Froude number (F_d), while the second parameter (h_B/h_u) is defined as the blockage factor (B) for this research.

The densimetric Froude number has been used to accurately predict the sediment discharge by Aguirre-Pe *et al.* (2003). Ade and Rajaratnam (1998) collected data from 13 different sources and concluded that the densimetric Froude number (F_d) was the main parameter influencing the local scouring. While Ade and Rajaratnam considered the densimetric Froude

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number, the effects of culvert blockage were not considered in their study.

The major non-dimensional parameters considered herein are the densimetric Froude number and the blockage factor; it is the inclusion of the blockage factor that is unique to this study.

4. Results and discussion

4.1 Flow structure
The longitudinal, lateral and vertical velocity components through the culvert centreline were measured for all tests. Figure 3 shows the distribution of streamwise velocity in a 50 mm layer of flow from the bed in non-blocked (VS1B05) and blocked conditions (VS1B405). Both tests were run under similar flow conditions.

The maximum velocity in the non-blocked condition was 0·28 m/s, but in the partially blocked condition the maximum velocity increased to a maximum of 0·75 m/s, which is 2·7 times greater than the non-blocked condition. Furthermore, as shown in Figure 3, the change in velocity near the culvert invert differs significantly between the partially blocked and non-blocked conditions.

The velocity components in all directions were measured for four tests and the turbulence intensity, turbulent kinetic energy

and Reynolds shear stress were calculated. Two of these tests were for a partially blocked culvert (VS1B403, VS1B405) and two were for a non-blocked condition (VS1B04, VS1B05). Figure 4(a) shows the depth-averaged velocity along the horizontal axis in the culvert barrel, normalised with shear velocity at the outlet of the culvert (U_*). In the non-blocked condition the depth-averaged velocity remains constant along the culvert, while for the partially blocked condition the depth-averaged velocity decays from a maximum of 16 at the inlet to about 7 at the outlet.

Normalised turbulence intensity along the horizontal axis in the culvert barrel is shown in Figure 4(b). The turbulence intensity increases from 1·5 at the inlet to about 3·5 in the mid barrel and from there decreased to 2·5 at the outlet. In the non-blocked condition the turbulence intensity was around 0·8.

Figure 4(c) depicts the normalised turbulent kinetic energy along the horizontal axis in the culvert. As can be seen from this figure, the variation in turbulent kinetic energy along the culvert barrel was the same as the turbulence intensity at the culvert outlet. In partially blocked culvert, the normalised turbulent kinetic energy is about 2 at the culvert inlet, it increases to about 5 in mid-barrel and decays to 3 at the outlet. The maximum kinetic energy occurs at the middle of culvert barrel. While in non-blocked culvert, this parameter is about 0·7–1 at the inlet and decreases to 0·5–7 at the outlet. The normalised kinetic energy ay the outlet of partially blocked culvert is about 6 times greater compare to non-blocked condition. This value is about six times greater than the normalised turbulent kinetic energy at the outlet for non-blocked flow conditions. Normalised Reynolds shear stress along the culvert barrel is shown in Figure 4(d). The normalised Reynolds shear stress (termed RSS) is defined as

5. $$\frac{\text{RSS}_{xz}}{U_*^2} = \frac{\overline{v_x' v_z'}}{U_*^2}$$
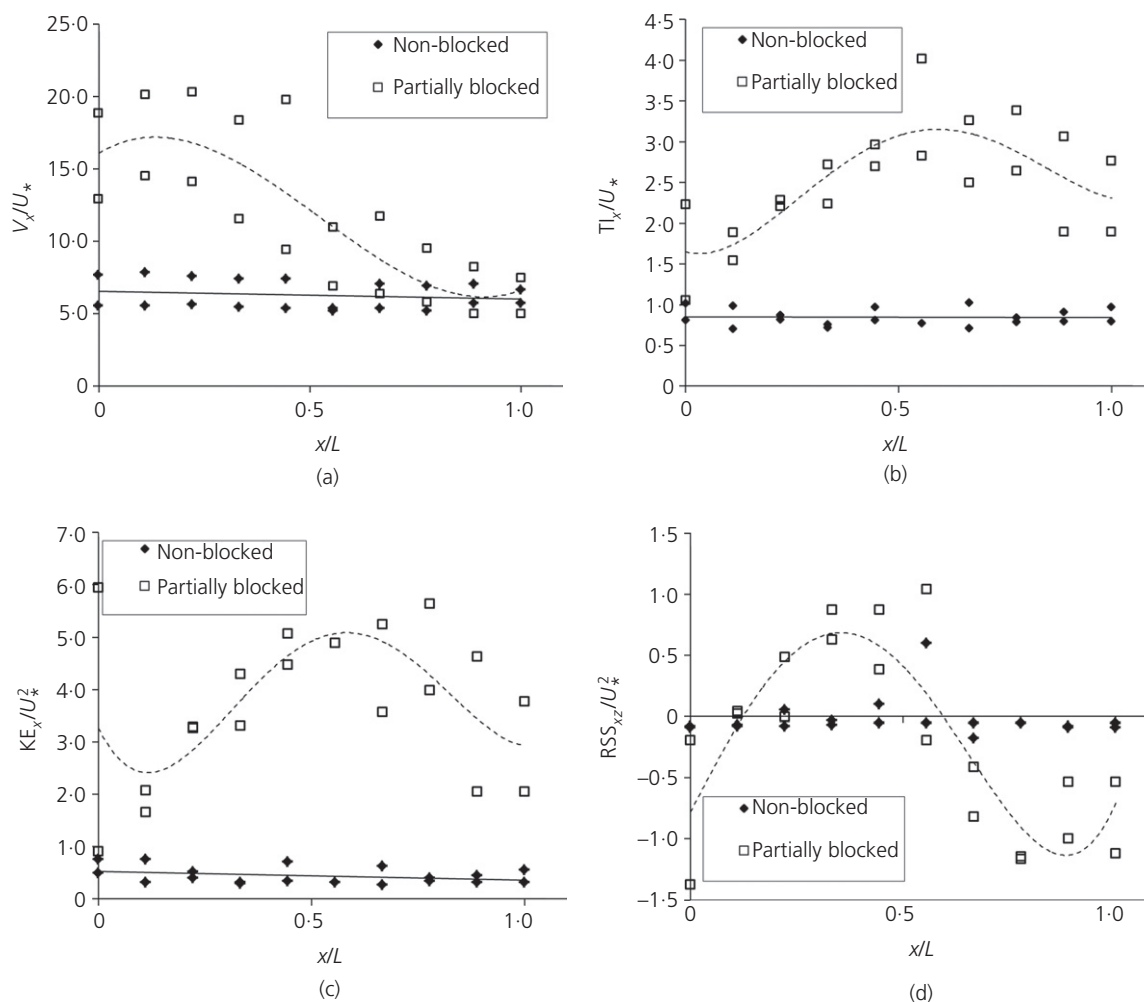
In Equation 5, v_x' is the longitudinal turbulent velocity component and v_z' is the vertical turbulent velocity component. For non-blocked conditions, the depth-averaged values for normalised Reynolds shear stress remain constant and generally around $-0·08$. For the partially blocked condition, the normalised Reynolds shear stress increases from zero at the inlet to about 1 at a location 0·4 along culvert. From the middle of the culvert the normalised shear stress becomes negative with a value of about $-1·1$ at a location of 0·7 along the barrel and to a value of -1 at the outlet of the culvert.

Although the depth-averaged velocity of the partially blocked condition at the outlet of the culvert decreased to reach the velocity of the non-blocked condition (Figure 4(a)), other flow characteristics such as turbulence intensity, turbulent kinetic
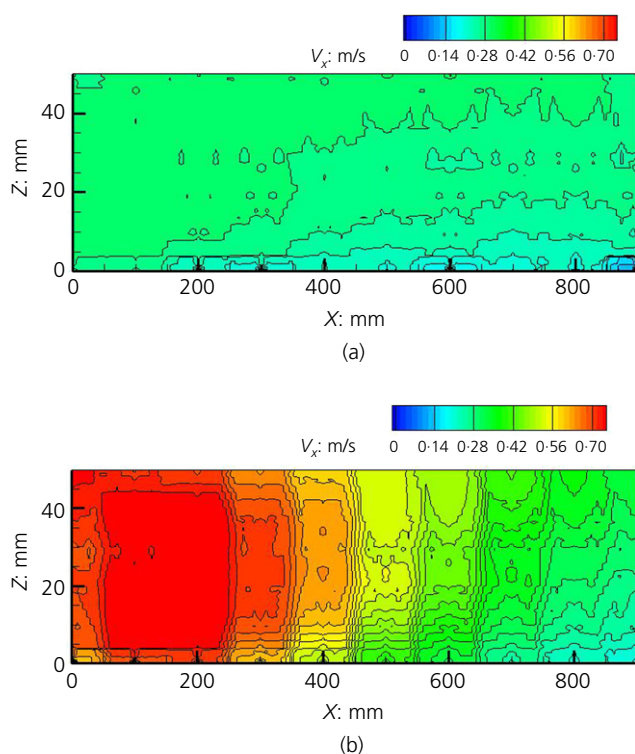
Figure 3. Velocity distribution in horizontal direction along the culvert barrel: (a) non-blocked; (b) partially blocked

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Figure 4. Non-dimensional flow characteristics of blocked and non-blocked conditions in culvert barrel: (a) velocity along horizontal axis depth averaged (V_x); (b) turbulence intensity depth averaged (TI_x); (c) kinetic energy depth averaged (KE_x); (d) Reynolds shear stress depth averaged (RSS_{xz})

energy and Reynolds shear stress were much greater in the partially blocked condition.

Figure 5 shows the variation in the turbulence parameters with normalised depth at the culvert outlet for two sets of experimental tests. Set 1 includes test VS1B04 (non-blocked) and VS1B403 (blocked) and the set 2 includes VS1B05 (non-blocked) and VS1B405 (blocked). Each set of tests was conducted in the same flow condition (Table 1).

Figure 5(a) shows the normalised turbulence intensity (TI_x/U_*) in the X direction at the outlet of the culvert ($x = 900$ mm) plotted against normalised depth (z/h_d). z is the depth of water from the bed, h_d is the total water depth at the outlet of the culvert and U_* is the shear velocity at the outlet. The normalised turbulence intensity at the outlet of the culvert for the blocked condition is more than for the non-blocked condition in both sets of tests. The normalised turbulence intensity of the

blocked condition equals 1·90 and 2·7 for set 1 and set 2, respectively. This parameter decreases to 0·76 and 1·15 in the non-blocked condition (Figure 5(a)).

The normalised turbulent kinetic energy (KE_x/U_*^2) of the flow in the non-blocked condition of set 1 is around 0·3 and not much change was observed. Likewise, the non-blocked condition of set 2 was around 0·7. Comparing the normalised kinetic energy in the blocked with the non-blocked condition, there is a 6·7 and 5·3 times increase for set 1 and set 2, respectively (Figure 5(b)).

Figure 5(c) shows the normalised Reynolds shear stress plotted against normalised water depth at the outlet of the culvert. Normalised Reynolds shear stress for the non-blocked condition of both sets is around −0·1, while it reaches to −0·9 in the blocked condition for set 1, and to −1·22 in the blocked condition for set 2 (Figure 5(c)).

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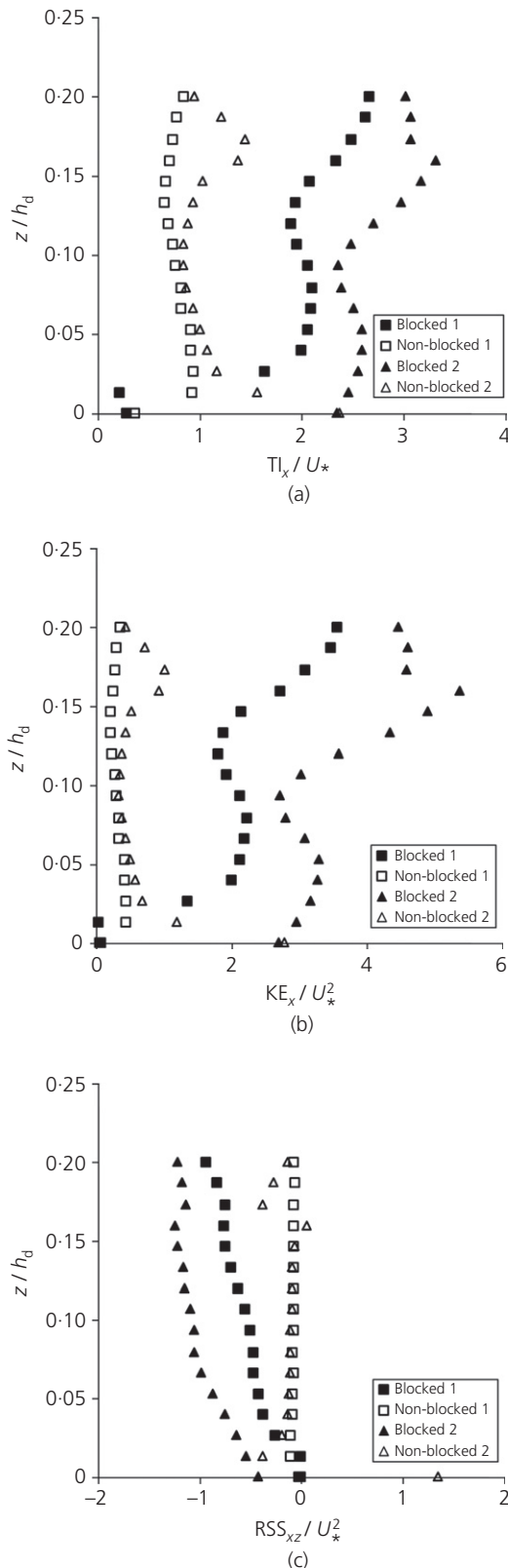
Figure 5. Variation of non-dimensional flow characteristics in depth at the outlet of the culvert: (a) turbulence intensity (TI_x); (b) kinetic energy (KE_x); (c) Reynolds shear stress (RSS_{xz})
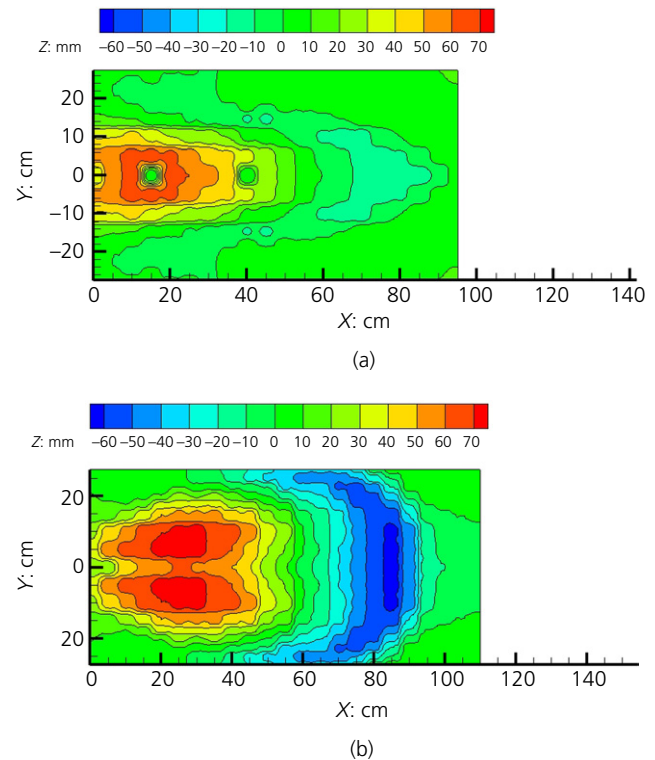
Figure 6. Contour results: (a) non-blocked; (b) partially blocked conditions (Sorourian et al., 2012)

4.2 Scouring hole geometry

4.2.1 Equilibrium condition
For each test, the sediment was set initially to the same level as the outlet of the culvert. Each individual test was run until no significant change in the bed profile was observed. Test durations were for 72 h.
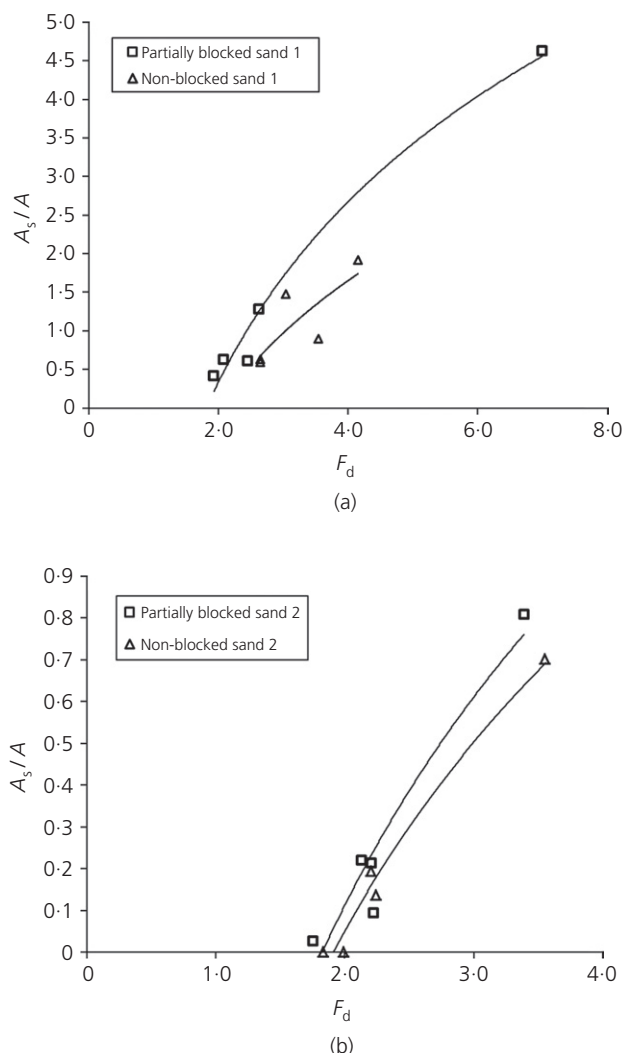
4.2.2 Scour hole extent
Figure 6 shows the development of the scour hole for two experimental tests, S1B01, which was a non-blocked condition (Figure 6(a)), and S1B401, which was a partially blocked condition (Figure 6(b)). Contour plots were used to determine the scouring depth, length and width. The contour plots locate the scour hole in a sand basin and show the mound location in each test. Positive depths indicate the erosion and negative depths show where aggradation occurs. A comparison between these two conditions shows that the scour hole for a partially blocked culvert generally is larger than for a non-blocked culvert. Figure 6(a) illustrates that the scour width for the non-blocked condition was 400 mm, whereas the scour width for the blocked condition, as shown in Figure 6(b), was 500 mm, which is a 25% increase in scour width.

4.2.3 Scouring area
In the present study, the scoured area (A_s) is defined as an area below bed level along the centreline which is eroded by water
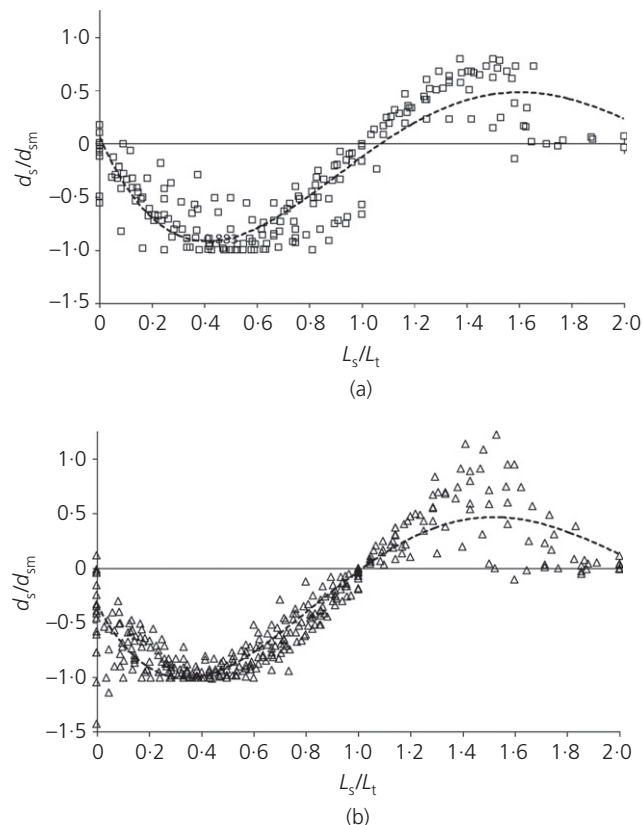
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Figure 7. Scoured area plotted against densimetric Froude
number: (a) sediment median size ($d_{50} = 0.85$ mm); (b) sediment
median size ($d_{50} = 2.0$ mm)

Figure 8. Normalised scouring profile along centreline:
(a) non-blocked condition; (b) partially blocked condition

(Figure 2(b)). The scoured area is normalised by the area of
the culvert outlet (A). Figure 7 shows the normalised scoured
area for partially blocked and non-blocked culverts for two
sediment types. As can be seen, the scoured area increases with
densimetric Froude number. Although the general trend of the
scoured area (A_s) for the partially blocked and non-blocked
conditions is the same, for each densimetric Froude number
the value of A_s in the partially blocked condition is greater
than in the non-blocked condition. It is also demonstrated that
the increase in the scoured area between partially blocked and
non-blocked conditions increases with the rise of densimetric
Froude number (Figure 7).

4.2.4 Scouring profile along centreline
Centreline bed profiles were measured after equilibrium
conditions were obtained. Figure 8 depicts the normalised

bed profile scouring for partially blocked and non-blocked
conditions. The bed profiles were normalised by the maximum
scouring depth (d_{sm}). In the horizontal direction, a non-dimen-
sional length was achieved by normalising the distance of any
point from the culvert (x_s) to the total length of the scour (L_t).

Both profiles were estimated by a fourth-order polynomial. For
a non-blocked condition (Figure 5(a)), the estimated bed
profile is given by

$$6. \quad \left(\frac{d_s}{d_{sm}}\right) = 0.82 \left(\frac{x_s}{L_t}\right)^4 - 4.97 \left(\frac{x_s}{L_t}\right)^3 + 9.43 \left(\frac{x_s}{L_t}\right)^2 - 5.46 \left(\frac{x_s}{L_t}\right) - 0.06$$

In this equation, d_s is the scouring depth at any location along
the X direction; d_{sm} is the maximum scouring depth; x_s is the
distance of any point from the culvert outlet along the X direc-
tion; and L_t is the total length of scouring hole. The location
of maximum scouring depth can be reached by taking the
derivative of the scouring profile and making it equal to zero.
From Equation 6 the maximum scouring depth occurs at a
location equal to 0.41 of the total scouring length (L_t). Also,
at the outlet of the culvert, the scouring depth for the

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non-blocked condition is equal to 0·05 of maximum scouring depth.

For the blocked condition (Figure 5(b)), the estimated bed profile is given by

7.
$$\left(\frac{d_s}{d_{sm}}\right) = 0.93\left(\frac{x_s}{L_t}\right)^4 - 5.24\left(\frac{x_s}{L_t}\right)^3 + 9.14\left(\frac{x_s}{L_t}\right)^2 - 4.51\left(\frac{x_s}{L_t}\right) - 0.33$$

The maximum scouring depth for this condition occurs at 0·33 of the total scouring length, which is 25% closer to the culvert outlet compared to the non-blocked condition.

Additionally, the scouring depth at the outlet of a partially blocked culvert is equal to 0·33 of maximum scouring depth. This is 5·5 times greater than the depth of scouring at the outlet of the culvert in a non-blocked condition.

4.2.5 Transverse scouring profile

Figure 9 shows the non-dimensional transverse bed profiles for partially blocked and non-blocked conditions. The transverse profiles were measured in the Y direction at the maximum scour point for each test. The horizontal axis in Figure 9 is the normalised scour width (y_s/W) where the culvert width (W) was used as the normalising transverse length. Similarly to the longitudinal scour profile, a polynomial regression equation was developed for non-blocked and partially blocked conditions. For the non-blocked conditions, the transverse profile is given by

8.
$$\left(\frac{d_s}{d_{sm}}\right) = 0.154\left(\frac{y_s}{W}\right)^2 - 0.853$$

From Equation 8, the maximum non-dimensional scouring width for the non-blocked condition can be obtained by setting (d_s/d_{sm}) equal to zero. In this case, the non-dimensional scouring width for the non-blocked condition is 4·7.

For a partially blocked culvert the transverse profile (Figure 9(b)) is given by

9.
$$\left(\frac{d_s}{d_{sm}}\right) = 0.125\left(\frac{y_s}{W}\right)^2 - 0.952$$

Using a similar logic as for the non-blocked condition, the maximum scouring width for the partially blocked condition would be 5·5, which is 17% more than the scouring width in the non-blocked condition.
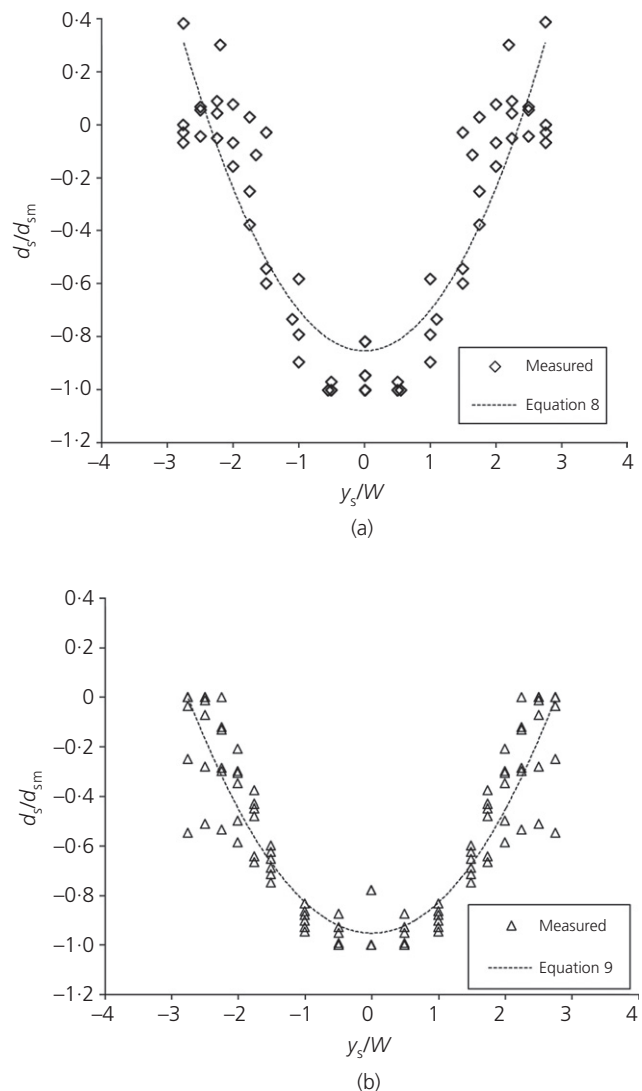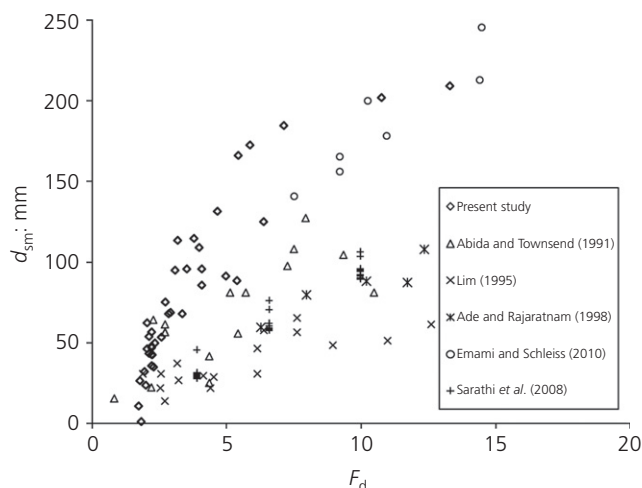

Figure 9. Non-dimensional transverse scouring profiles for sand 1: (a) non-blocked condition; (b) partially blocked condition

The preceding analysis has shown that blockage has a significant effect on the scouring geometry at the outlet of culverts. When the culvert is partially blocked, the extent of the scouring hole, including its depth, width and length, would be longer than in the non-blocked condition. Therefore, predicting the maximum scouring depth of culverts in the partially blocked condition has significant importance.

4.3 Scouring depth prediction

Over past decades several equations have been proposed to estimate the maximum scouring depth at the outlet of culverts in non-blocked conditions. Figure 10 shows a comparison of the maximum scouring depth for a partially blocked condition with some of the recent equations for non-blocked conditions. As shown in this figure, for the same range of F_d, the maximum scouring depth for a partially blocked condition is greater than

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Figure 10. Comparison of maximum scouring depth for present study of the same densimetric Froude number with some of the recent works

Figure 11. Comparison between measured and estimated d_{sm}/h_d for the proposed equation

that for a non-blocked condition. Therefore, the previously proposed equations for non-blocked conditions are not suitable to estimate the partially blocked conditions accurately.

Based on the results of about 40 experiments, an equation was developed to estimate the maximum scouring depth downstream of a partially blocked culvert; this equation is

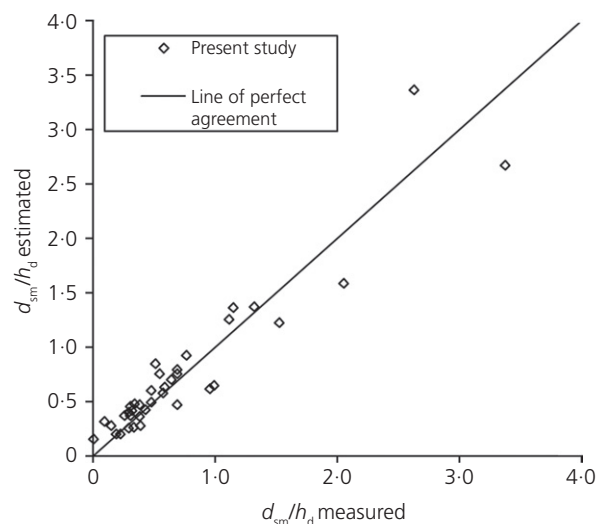10. $$\frac{d_{sm}}{h_d} = 0{\cdot}27F_d + 0{\cdot}29B - 0{\cdot}35$$

In this equation the maximum scouring depth is a function of the densimetric Froude number (F_d) and degree of blockage (B). Parameter B is defined by

11. $$B = \frac{h_B}{h_u}$$

In this equation, h_B is the height of the blockage at the culvert inlet and h_u is the upstream water level. The coefficient of correlation (R^2) for Equation 10 is 0·887 and the standard error of estimate (S_E) equals 0·259. Figure 11 shows a comparison of the measured maximum scour depth with the scouring depth estimated using the proposed equation. As shown in this figure, a reasonable correlation was achieved.

5. Comparison with previous scour equations

Several equations have been proposed to predict the maximum scour depth. Table 2 provides a summary of experimental works conducted by Lim (1995), Ade and Rajaratnam (1998),

Sarathi *et al.* (2008) and Emami and Schleiss (2010), including the condition in which the tests were conducted. As depicted in Table 2, all of these equations considered densimetric Froude number as a main parameter to predict the scouring depth. Some of them, such as Sarathi *et al.* (2008) and Emami and Schleiss (2010), included the effect of tail water depth in the predictive equation. However, this causes the predictive equation to lack simplicity. All of these experimental tests were conducted in the non-blocked condition and, as a result, the predictive equations are not suitable to estimate scouring downstream from a partially blocked culvert.

Figure 12 shows the data from four experimental studies. A perfect match between predicted and recorded value would occur on a 45° line. Also shown in this figure are the ± 30% error lines; this value was previously used by Lim (1995) in a similar comparison.

Independent sets of data from the present study, Lim (1995), Ade and Rajaratnam (1998), Sarathi *et al.* (2008) and Emami and Schleiss (2010) were used to compare with the data calculated using Equation 10 and plotted in Figure 12. As shown in the figure, most of the data are predicted within the ± 30% line. Consideration of the results suggests that the proposed equation in this study has a good agreement with the other data sets. Although the proposed equation includes the blockage ratio (B), it can be used for non-blocked conditions by setting B equal to zero.

6. Conclusions
Blockage has not been considered as a key element in studying and estimating the scour at culvert outlets. Hence, the study reported herein focuses on flow structure and sediment

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Researchers	F_d	Culvert shape	d_{50}: mm	Proposed equation	Flow condition
Present study	1·5–13·3	Box	0·85 2	$\dfrac{d_{sm}}{h_d} = 0\cdot27F_d + 0\cdot29B - 0\cdot35$	Unsubmerged Partially full
Lim (1995)	2·5–24·6	Circular	1·65	$\dfrac{d_{sm}}{d_0} = 0\cdot45F_d \quad 1 \leq F_d \leq 10$ $\dfrac{d_{sm}}{d_0} = 4\cdot5 \quad F_d > 10$	Unsubmerged Full flow
Ade and Rajaratnam (1998)	6·3–88·2	Circular	0·24 7·2	$\dfrac{d_{sm}}{d_0} = 0\cdot5F_d + 0\cdot5$ $\dfrac{d_{sm}}{d_0} = 0\cdot5F_d \quad 0\cdot6 \leq F_d \leq 10$ $\dfrac{d_{sm}}{d_0} = 4\cdot75 + 0\cdot025F_d \quad 10 < F_d < 100$	Submerged Unsubmerged
Sarathi et al. (2008)	3·9–10	Circular	2·46 0·71	$\dfrac{d_{sm}}{d_0} = 2\cdot55\ln(F_d) - 2\cdot44 \quad \dfrac{h_t}{d_0} \geq 4$ $\dfrac{d_{sm}}{d_0} = a\ln(F_d - b) \quad 0\cdot5 \leq \dfrac{h_t}{d_0} \leq 3$ $a = -0\cdot66(h_t/d_0) + 2\cdot34$ $b = 1\cdot31(h_t/d_0) - 1\cdot73$	Submerged Unsubmerged
Emami and Schleiss (2010)	7·5–14·5	Circular	0·8	$\dfrac{d_{sm}}{d_0} = a\ln(F_d) + b$ $a = -0\cdot6(h_t/d_0) + 1\cdot8$ $b = 1\cdot23(h_t/d_0) - 2\cdot25$	Submerged Unsubmerged

Table 2. Summary of range of experimental tests and proposed equations for recent researchers
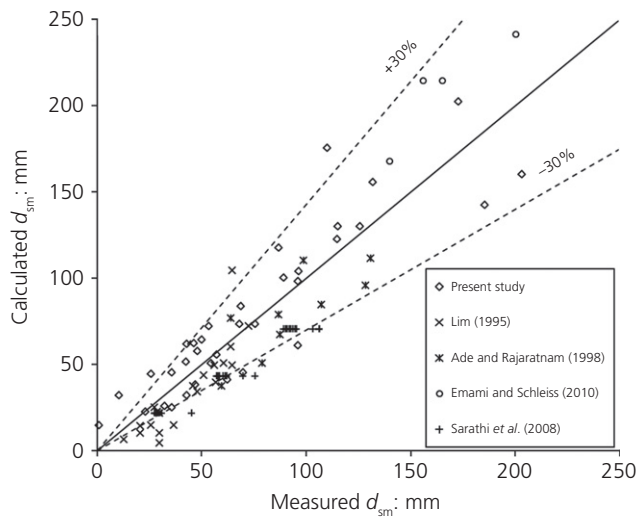
Figure 12. Comparison between values predicted by equations in the present study and measured values for recent experimental equations

transport downstream of a box-culvert for partially blocked and non-blocked conditions. For the experimental tests two different non-cohesive sediment sizes were used.

Results show that blockage has a considerable effect on the flow structure and scouring hole geometry at the outlet of the culvert. The velocity distribution rapidly changes in the culvert barrel for the blocked condition and the average turbulence intensity was found to be three times greater than the non-blocked condition. The scoured area at the blocked culverts was 20–60% more than non-blocked conditions and scouring width and length increased up to 17% in the partially blocked conditions. Two equations were proposed to estimate the scouring profile along the centreline and transverse profile, respectively. Results of the maximum scouring depth for the present study were compared with some recent studies in non-blocked conditions and it was noted that maximum scouring depth in the partially blocked condition was greater than the results obtained in a non-blocked condition. Therefore, previously developed formulas in non-blocked conditions are not suitable to estimate outlet scour at partially blocked culverts.

As a result, an equation was proposed to estimate the maximum scouring depth considering the blockage effect. The proposed equation was used to predict the maximum scouring depth in the non-blocked condition using some data from recent studies and could predict the results reasonably accurately.

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