Study of Scour Characteristics Downstream of Partially-Blocked Circular Culverts

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Abstract: Debris accumulations upstream and through crossing hydraulic structures such as culverts cause the upstream water level and the downstream scour depth to increase, which can lead to structure failure. This experimental study aimed to investigate the effects of various inlet blockage ratios on culvert efficiency and scour hole depth. In a non-blocked case, various submergence ratios ($S = 1.06, 1.33, 1.60, \text{ and } 1.90$) were tested with different discharge rates. In a blocked case, the effects of inlet blockage with various blockage ratios ($Ar = 10\%, 20\%, \text{ and } 30\%$) were seen as sediment blockage on the pipe bed or floating debris upstream of the culvert. The results show that as the submergence ratio increases, the maximum scour depth decreases at the same discharge rate, and the relative energy loss also decreases in the non-blocked case. In the sediment blockage ($Ar d$) case, the relative maximum depth increases with increasing densimetric Froude number and with an increasing blockage ratio. An empirical equation was developed to predict the relative scour depth under the present study conditions.

Keywords: scour; culvert; blockage; physical model; efficiency

1. Introduction

Culverts are hydraulic structures used to transport water below roads and railways. Local scour downstream of culverts involves the removal of granular bed material through the action of hydrodynamic forces. As the maximum scour depth downstream of the culvert increases, the stability of the foundation of the structure may be threatened, with a consequent risk of damage and failure [1].

Many previous studies have studied the factors affecting the scour hole characteristics downstream of the culverts. Abt [2,3] experimentally studied the effect of culvert shape on scour hole dimensions. Different culvert sections such as square, arch and rectangular culvert shapes were investigated with uniform graded sand ($D_{50}$ at 1.86 mm). The results revealed that culvert cross-section shape had a limited effect on outlet scour. Chen [4] and Ruff et al. [5] observed that under equivalent discharge conditions, a square culvert with a height equal to the diameter of a circular culvert would reduce scour. Abt [6] studied the culvert slope influence on the maximum scour depth. Experimental tests were performed on a circular pipe with various slopes (0, 2, 5, 7 and 10%), and uniform graded sand ($D_{50}$ at 1.86 mm) was used. The results showed that the maximum scour depth increased as the culvert slope increased within the range of the slopes tested.
Doehring and Abt [7] studied culvert drop height effects on the maximum scour depth. Experimental tests were performed in a 4-inch diameter circular culvert and uniform sand with $D_{50}$ at 1.86 mm. Drop heights of 0, 1, 2 and 4 times the culvert diameter above the bed were investigated. The results showed that the depth of scour was directly proportional to discharge intensity. As the relative drop height increased, the maximum scour depth increased proportionally, the width of scour increased, the scour length decreased, and scour hole volume increased. Abt et al. [8] investigated the effects of varying non-cohesive bed material on local scour geometry at circular culvert outlets. Five non-cohesive bed materials were tested downstream of a four-inch diameter circular culvert. The results produced a single expression for estimating the relative scour depth. Aderibigbe and Rajaratnam [9] investigated the effects of sediment gradation on scour hole shape deformed by wall jets. Three sediment mixtures were investigated with $D_{50}$ at 6.75, 1.32 and 1.62 mm, and geometric gradations ($\sigma$) of 1.32, 2.02 and 3.13, respectively. The results demonstrated that sediment non-uniformity had a significant effect on the scour hole dimensions deformed by the jets. There is good correlation between the effective sediment size $D_{95}$ and scour depth at more than $D_{50}$ for estimating $F_d$. Abida and Townsend [10] investigated experimentally the effects of bed material properties on scour hole patterns downstream of a box culvert. The results showed that the maximum scour in uniform sands was greater than in well-graded mixtures. Sarathi et al. [1] studied sediment grain size effects on scour hole dimensions in a non-cohesive sand bed.

Experimental tests were conducted using submerged square jets with three different values of a densimetric Froude number. Two sediment sizes were used with $D_{50}$ at 2.46, 0.71 mm and $\sigma$ of 1.24, 1.14. At a given densimetric Froude number, it was noted that the results correlated with the nozzle size-to-grain size ratio. An empirical procedure was developed to check the relationship between scour hole parameters and the densimetric Froude number ($F_d$). Abida and Townsend [10] studied the effects of tailwater depth on scour hole dimensions. The results indicated that tailwater depth had only a marginal effect on the maximum depth of scour for the submerged flow condition ($S > 1.0$) [1,10,11]. Emami et al. [12] experimentally investigated the effect of tailwater depth on scour depth. The results confirmed that scour depth decreased with increasing tailwater depth [1,10,11]. Chiwe et al. [13] investigated the local scour produced by a submerged horizontal circular jet. Azamathulla and Haque [14] used gene-expression programming for predicting scour hole dimensions at culvert outlets. Their results demonstrated that GEP was quite effective in predicting scour depth at culvert outlets. Negm et al. [15] used a vertical flow deflector to minimize the scour hole dimensions downstream of a circular culvert under different flow conditions, and developed an empirical equation to estimate the relative scour depth.

One of the problems affecting crossing structures such as culverts is debris accumulation upstream or inside them, which becomes an obstruction in the waterway. Floating or submerged debris causes higher velocities and vortices, which increase the scour depth downstream of the culvert as well as raising the upstream water level, which increases the possibility of the structure failure during a flood event. [16]. Yasser Abdallah et al. [16,17] studied experimentally the effects of partial blockage permeability on scour characteristics in front of bridge piers and found that partial blockage occurrence in front of a bridge pier had considerable interest due to its influence on the stream flow and the formed scour around the neighboring bridge supports. Sorousian et al. [18–20] experimentally investigated blockage ratio effects on scour characteristics downstream of a square culvert under steady flow. The results showed that blockage had a significant effect on the flow structure and scouring hole dimensions at the culvert outlet. The velocity distribution was rapidly increased in the culvert barrel in blocked condition and the average turbulent intensity was three times greater than the non-blocked condition.

It may be concluded from the above studies that culvert shape, culvert slope, soil properties, tailwater depth and culvert blockage are the main factors affecting downstream scour deformation. The aim of this study was to investigate the effects of different inlet blockage ratios on clear-water scour depth and culvert transport efficiency.
2. Materials and Methods

2.1. Theoretical Study

Dimensional analysis was used to correlate the different variables affecting the scour phenomenon downstream of a blocked circular culvert. Figure 1 shows a definition sketch of the physical model. The main factors affecting maximum scour depth are presented in Equation (1):

\[ d_s = f(D, L, a_c, a_b, Q, v_d, h_u, h_d, d_{50}, \rho, \rho_s, g, l_s, d_d, l_d) \]  

(1)

Using the Buckingham theory, the relative maximum scour depth \( \frac{d_s}{h_d} \) can be written as shown in Equation (2). From this equation it can be seen that relative scour depth is a function of blockage ratio, densimetric Froude number and submergence ratio:

\[ \frac{d_s}{h_d} = f(A_r, F_d, S) \]  

(2)

Culvert efficiency \( \frac{E_u}{E_d} \) is calculated as:

\[ \frac{E_u}{E_d} = f(A_r, F_d, S) \]  

(3)

2.2. Experimental Work

This experimental study was carried out in the Hydraulics and Water Engineering Laboratory, Faculty of Engineering, Zagazig University, Egypt. The physical model was put in the middle of a rectangular flume with dimensions 66 cm width, 65.5 cm depth and 16.2 m length, as shown in Figure 2. A circular culvert was used, 0.188 m in diameter and 1.60 m long, with sudden inlet and outlet as shown in Figure 1. The removable bed was elongated for about 4.0 m after the culvert outlet with 0.66 m width and a depth of 0.20 m, containing coarse uniform sand with \( D_{50} = 4.00 \) mm and standard deviation \( \sigma = 1.46 \), as presented in Figure 3. The experimental model was tested for different tailwater depths and different blockage areas with a range of discharge flows from 19.00 to 33.00 L/s. Table 1 shows the different experimental runs.

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Figure 1. Definition sketch of model elevation and plan.

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3. Analysis and Discussions

3.1. Effect of Downstream Submergence Ratio (S) on Scour-Hole Characteristics

Scour downstream of a non-blocked culvert was investigated at various submergence ratios (S) and densimetric Froude numbers ranging 4–9. The results were analyzed for both scour characteristics and culvert efficiency. Figure 4 describes the relationship between the densimetric Froude number (Fr) and the scour depth (D). The relationship shows that as the densimetric Froude number increases, the scour depth also increases, indicating a higher level of erosion.

![Particle size distribution for sediment bed.](image)

**Table 1.** Tested submergence and blockage ratios.

| Case       | S (h_d/D) | Ar | Runs |
|------------|-----------|----|------|
|            |           | X_1| X_2  |
| Non-blocked| 1.06      | 0.0| 0.0  | 22   |
|            | 1.33      | 0.0| 0.0  |
|            | 1.60      | 0.0| 0.0  |
|            | 1.90      | 0.0| 0.0  |
|            | 1.06      | 0.10| 0.0  | 15   |
|            | 1.06      | 0.20| 0.0  |
|            | 1.06      | 0.30| 0.0  |
|            | 1.06      | 0.0  | 0.10 | 15   |
|            | 1.06      | 0.0  | 0.20 | 15   |
|            | 1.06      | 0.0  | 0.3  |
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Scour downstream of a non-blocked culvert was investigated at various submergence ratios (S) and densimetric Froude numbers ranging 4–9. The results were analyzed for both scour characteristics and culvert efficiency. Figure 4 describes the relationship between the densimetric Froude number and relative scour depth for different submergence ratios. The results show that as the flow rate rises, the scour depth increases. At the same densimetric Froude number, the relative scour depth decreases with increasing downstream submergence ratio. When the densimetric Froude number equals 6.64, the relative scour depth increases at S = 1.06 by 96% more than at S = 1.90. Figure 5 shows the relationship between the relative deposition height and the densimetric Froude number, the relative deposition height being directly proportional to the densimetric Froude number. At F_d = 6.64, the relative deposition height increases at S = 1.06 by 96.7% more than at S = 1.90. Figure 6 shows bed deformation downstream of a circular culvert at different submergence ratios S = 1.06, 1.33, 1.60 and 1.90 and Ar = 0.00. The negative contours indicate that the scour region, and positive contours indicate the deposition region. It can be seen from this figure that as the submergence ratio increases, the scour hole becomes more symmetrical, with reduced maximum scour depth, scour hole width and scour area. The deposition height, area and volume decreases as the submergence ratio increases.

In the non-blocked culvert, culvert efficiency decreases with increasing densimetric Froude number, as shown in Figure 7. When the submergence ratio increases, culvert efficiency also increases at the same densimetric Froude number for the tested submergence ratios. Culvert efficiency decreases to 70% at S = 1.06 and reaches up to 80% at S = 1.90 when F_d = 6.64. This is because as the submergence ratio increases, the upstream water level rises, but not to the same degree as the downstream water level. The flow discharge is constant and the mean velocity through the culvert is constant too, so
the friction losses through the culvert are approximately the same for all submergence ratios. Thus, the difference between upstream and downstream water levels decreases as the submergence ratio increases, and thus culvert efficiency increases as the submergence ratio increases.

Figure 6. Scour contour maps downstream of circular culvert at Ar = 0.0 (a) S = 1.06, F_d = 6.64, (b) S = 1.33, F_d = 6.69, (c) S = 1.60, F_d = 6.30, (d) S = 1.90, F_d = 6.75.

Figure 7. Culvert efficiency for different S.

3.2. The Blockage Effect on Scour Characteristics and Culvert Efficiency

Figures 8 and 9 present the relationship between relative scour depth and densimetric Froude number at the same submergence ratio and different blockage ratios Ar_d and Ar_u, respectively. As shown in these figures, the relative scour depth increases with an increasing densimetric Froude number. As the blockage ratio increases, the relative scour depth also increases at the same densimetric Froude number, because as the relative blockage area (Ar_d) increases, the near-bed velocity increases compared to that in the non-blocked case. When the relative blockage area rises to 10%, 20 and 30%, the relative scour depth increases by 2.63%, 5.78% and 10.53%, respectively, compared to the non-blocked case (Ar = 0.0). The relative scour depth increases by 1.32%, 2.63% and 7.90% compared to the non-blocked case when the relative blockage area Ar_d becomes 10%, 20% and 30%, respectively. Figure 10 shows that at blockage ratio 30%, relative scour depth is greater when blockage occurs near the culvert bottom (Ar_d) than when the blockage is near the culvert upper part (Ar_u). This is...
because, when the blockage accumulates in the lower part of the culvert, the near-bed velocity increases compared to when debris accumulates in the upper part. Figure 11 demonstrates the scour contour maps for different blockage areas, showing that as the blockage ratio increases, the maximum scour depth, scour hole width, area and volume also increase proportionally. At the same blockage ratio, the maximum scour depth, scour hole width, area and volume for Ar d were greater compared to Ar u.

![Figure 8](image8.png)

**Figure 8.** Relationship between \((d_s/h_d)\) and \((F_d)\) at \(S = 1.06\) and Ar d = 10%, 20%, 30% and Ar u = 0.00.

![Figure 9](image9.png)

**Figure 9.** Relationship between \((d_s/h_d)\) and \((F_d)\) at \(S = 1.06\) and Ar u = 0%, 10%, 20%, 30% and Ar d = 0.00.

![Figure 10](image10.png)

**Figure 10.** Relationship between \((d_s/h_d)\) and \((F_d)\) at \(S = 1.06\) and different Ar.
Figure 11. Scour contour maps downstream of blocked circular culvert at $S = 1.06$ (a) $Ar = 0.00$, (b) $Ar_d = 10\%$, $Ar_u = 0.0$ (c) $Ar_d = 0.0$, $Ar_u = 10\%$ (d) $Ar_d = 20\%$, $Ar_u = 0.0$ (e) $Ar_d = 0.00\%$, $Ar_u = 20\%$ (f) $Ar_d = 30\%$, $Ar_u = 0.0\%$ (g) $Ar_d = 0.0$, and $Ar_u = 30\%$.

Figure 12 indicates culvert efficiency for different blockage ratios and its relationship with the densimetric Froude number. The figure shows how culvert efficiency decreases with increasing flow rate and increasing blockage ratio. For the same densimetric Froude number and blockage ratio, the culvert’s ability to transport water decreases when the blockage is near the culvert bottom. Culvert efficiency decreases by 15.97%, 18.06% and 23.61% when the relative blockage area $Ar_d$ increases to 10%, 20% and 30%, respectively. However, culvert efficiency decreases by 13.89%, 17.365% and 20.835% compared to the non-blocked case when $Ar_u$ increases to 10%, 20% and 30% respectively at the same $F_d = 6.00$. Lower blockage ratios ($Ar_d$) increase the relative head loss and decrease the culvert efficiency. Culvert efficiency is more sensitive to debris accumulation upstream of the culvert inlet, decreasing by about 23.6% in the case of $Ar_d = 30\%$ compared to the non-blocked case at the same $F_d = 6.00$. 
4. Location of Scouring Hole

Figure 13a,b display the scour profiles along the centerline for non-blocked and blocked cases respectively. Two estimated equations are investigated to predict the scour depth \( d_s \) at distance \( l_s \) along the \( x \)-axis downstream of a non-blocked and blocked culvert. Equation (4) is for the non-blocked case. According to Figure 13a and Equation (5), the maximum scour depth is equal to 0.41 of the culvert diameter, and is located at a distance of three times the culvert diameter from the culvert outlet.

\[
d_s = -0.0016 (l_s/D)^4 + 0.0205 (l_s/D)^3 - 0.0363 (l_s/D)^2 - 0.1753 (l_s/D) + 0.018
\]  

The maximum scour depth in the blocked case occurs at a distance of 3.20 times the culvert diameter from the culvert outlet. In the non-blocked case, the protection length is about 5.70 times the culvert diameter, while in the blocked case this distance increases to 6.10 times the culvert diameter.

\[
d_s = -0.0009 (l_s/D)^4 + 0.0117 (l_s/D)^3 + 0.0032 (l_s/D)^2 - 0.206 (l_s/D) - 0.0041
\]
The maximum scour depth in the blocked case occurs at a distance of 3.20 times the culvert diameter from the culvert outlet. In the non-blocked case, the protection length is about 5.70 times the culvert diameter, while in the blocked case this distance increases to 6.10 times the culvert diameter.

\[
\frac{d_s}{D} = -0.0009 \left( \frac{D}{D} \right)^4 + 0.0117 \left( \frac{D}{D} \right)^3 + 0.0032 \left( \frac{D}{D} \right)^2 - 0.206 \left( \frac{D}{D} \right) - 0.041
\]

(5)

5. Maximum Scour Depth Prediction

Regression analysis was used to predict maximum scour depth downstream of a circular culvert for different ratios of inlet blockage area by correlating the maximum relative scour and other variables affecting it in one formula. An equation was developed to predict maximum scour depth. As shown in the equation below, the relative maximum scour depth \( \left( \frac{d_s}{h_d} \right) \) is a function of densimetric Froude number \( (F_d) \), blockage ratios \( Ar_d \) and \( Ar_u \) and submergence ratio \( (S) \). Equation (6) clearly reveals the higher impact of downstream submergence ratio and lower effect of blockage ratio on maximum scour depth in the present study experimental conditions.

\[
\frac{d_s}{h_d} = 0.067 F_d + 0.16 Ar_d + 0.11 Ar_u - 0.245 S + 0.224
\]

(6)

The correlation coefficient (R²) is 0.97 with standard error 0.017 and residuals do not exceed 0.05. Figure 14 shows a comparison between relative maximum scour depth \( (\frac{d_s}{h_d}) \) as measured in the experimental model and estimated using the empirical equation. Figure 15 presents a comparison between residuals and estimated \( \frac{d_s}{h_d} \). It can be seen from these figures that there is very good agreement between the measured and estimated relative scour depths.

![Figure 14. Comparison between measured and estimated \( \frac{d_s}{h_d} \) in present study.](image1)

![Figure 15. Comparison between residuals and estimated \( \frac{d_s}{h_d} \).](image2)
6. Comparing with Previous Studies

Many previous empirical formulas have been investigated for estimating the relative scour depth downstream of culverts. Table 2 presents scour depth estimation formulas downstream of a circular culvert developed in the present study and in those by Sorourian et al. [20], Emami and Schleiss [12], Chiew et al. [13], Abt et al. [8] and Negm et al. [15]. Figure 16 shows a comparison of scour depth estimations between the above empirical formulas for a range of densimetric Froude numbers ($F_d = 4.00–8.00$). It can be seen in this figure that the present study formula results fall between the other scour depth estimation results. The results of Chiew et al. [13] and Abt et al. [8] exceed the results of the present study equation, with average relative errors equal to 2.25 and 1.63, respectively. The results of Negm et al. [15] are closest to those produced by the present study because their equations do not take into consideration the submergence ratio downstream of the culvert. The results obtained by Negm et al. [15] are closest to those produced by the present study formula, with an average relative error 0.12. While the present scour prediction equation includes the blockage effect, there is still good agreement between it and the mentioned researchers’ formulas.

Table 2. Summary of some scour prediction formulas.

| Researchers            | Scour Formula                                                                 |
|------------------------|-------------------------------------------------------------------------------|
| Present study          | $\frac{d_s}{D} = 0.067 F_d + 0.16 Ar_d + 0.11 Ar_u - 0.245 S + 0.224$         |
| Sorourian et al. [20]  | $\frac{d_s}{D} = 0.27 F_d + 0.29 Ar - 0.3$                                  |
| Emami and Schleiss [12]| $\frac{d_s}{D} = a \ln F_d + b$                                              |
|                        | $a = -0.6 \left( \frac{h_d}{D} \right) + 1.8$                              |
|                        | $b = 1.23 \left( \frac{h_d}{D} \right) - 2.25$                             |
| Chiew et al. [13]      | $\frac{d_s}{D} = 0.21 \times F_d$                                           |
| Abt et al. [8]         | $\frac{d_s}{D} = 3.67 F_d^{0.57} \times d_{50}^{0.4} \sigma^{-0.4}$        |
| Negm et al. [15]       | $\frac{d_s}{D} = 0.229 + 0.037 \left( \frac{b}{D} \right) - 0.603 \left( \frac{H_d}{D} \right) + 0.243 \left( D.I \right) - 0.024 \left( \frac{b}{D} \right) + 0.392 \left( \frac{H_d}{D} \right)^2$ |

Figure 16. Comparison of relative maximum scour depths estimated using the formula proposed in the present study, and using other scour formulas with the same $F_d$ range.
7. Conclusions

Blockages can be a considerable factor affecting flow structure and scour hole characteristics at culvert outlets. Notwithstanding that, the downstream submergence ratio has a higher effect on maximum scour depth from Equation (6). The present results lead to the following conclusions:

(a) For non-blocked culverts, the relative scour depth increases as the submergence ratio decreases at the same densimetric Froude number \( F_d = 6.64 \). The maximum relative depth increases by 96% at \( S = 1.06 \) compared to \( S = 1.90 \).

(b) In the blocked case, the relative scour depth is directly proportional to the blockage ratio. When the relative area of blockage \( (Ar) \) equals 10%, 20 and 30%, the relative scour depth increases by 2.63%, 5.78% and 10.53%, respectively, compared to the non-blocked case \( (Ar = 0.0) \). The relative scour depth increases by 1.32%, 2.63% and 7.90% compared to the non-blocked case when the relative blockage area \( Ar_d \) increases to 10%, 20% and 30%, respectively. In the non-blocked case, the protection length is about 5.70 times the culvert diameter, while in the blocked case, this distance increases to 6.10 times the culvert diameter. The inlet blockage has a limited effect on the maximum scour depth, but has a greater effect on culvert efficiency.

(c) From the present experimental data, an empirical equation has been created to predict the relative scour depth at a range of densimetric Froude numbers \( F_d = 4.00–8.00 \). The estimated relative scour depth shows good agreement with the measured relative scour depth with \( R^2 = 0.97 \). Good agreement was also found when the predicted scour formula was compared with five other scour estimating formulas.

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List of Symbols

- \( a_b \) inlet blockage area
- \( a_c \) culvert inlet area
- \( Ar \) blockage percentage \( (a_b/a_c \%) \)
- \( Ar_d \) blockage ratio in lower part of culvert
- \( Ar_u \) blockage ratio put in upper part
- \( D \) culvert diameter
- \( d_s \) maximum scour depth
- \( d_d \) maximum deposition height
- \( E_u \) total energy at culvert inlet
- \( E_d \) total energy at culvert end
- \( F_d \) densimetric Froude number
- \( D_{50} \) median particle size of bed material
- \( g \) gravitational acceleration
- \( h_d \) tailwater depth
$h_u$  upstream water depth  
$h_t$  tailwater depth  
$l_d$  location of maximum deposition height  
$l_s$  location of maximum scour depth  
$L$  culvert length  
$Q$  flow rate  
$S$  submergence ratio ($h_d/D$)  
$u$  flow velocity  
$v_d$  velocity just before culvert outlet  
$W$  channel width  
$\rho$  water density  
$\rho_s$  bed material density  
$\sigma$  standard deviation of soil particle size

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