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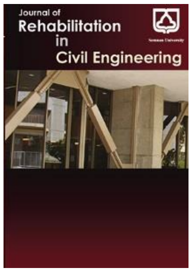

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An Experimental Study on the Effects of Debris Accumulation at the Culvert Inlet on Downstream Scour

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ABSTRACT

The major damage of hydraulic structures at river crossing occurs during floods and culverts is the structure which use as a part of drainage system in ephemeral streams. Failure in structures is caused for different reasons but pier and abutment scour is the main reason. The presence of debris causes larger scours and sediment removal compared to the absence of debris accumulation. In this study, the common problem of the flow blockage at culvert inlets is investigated applying a hydraulic model set in laboratory. Experiments were performed to understand the changes and interaction of scour depth over a range of downstream flow depths, h_t and densimetric Froude number, F_o. The debris accumulation is modelled by rectangular plates of constant width (30 cm) and various heights (4, 8, 12, 16 cm) set at the culvert entrance. When culvert inlet area decreased by the smallest solid debris accumulation - which covered 20% of inlet area-, the upstream water level raised up to 12% and by the biggest solid debris size- which covered 80% of inlet area- water level increased up to 60%. Debris accumulation causes larger scours and sediment removal, so the scour hole area extended extremely in flow direction. A new maximum scour depth predictor equation has been proposed to predict the effects of debris accumulation at culvert inlet on downstream scour. This equation is well fitted with the experimental results of the current study and the results of experiments from the previous studies used to analyze presented formula.

1. Introduction

Culverts are closed conduits passing water flowing through natural or man-made open-channels at crossings with roads. They are typically designed as single or multiple barrel culverts operating most of the time as open channels. Practically, they are similar in role with bridges but are different through cost, hydraulics, structural aspects and maintenance requirements. While the initial and operating costs of culverts are considerably less than that of bridges but the maintenance costs of culverts –especially

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those with long barrels- are higher than the maintenance costs of bridges. The main reason for such a deficiency in culverts is the vulnerability of these conduits for debris accumulation in the entrance and within the barrel.

Many factors influence sediment deposition at culverts including the size and characteristics of available debris in flow region (e.g. the presence of vegetation or urban facilities), the hydrologic event intensity and hydraulic characteristics of the channel, design of the culvert geometry and the design of channel transition [1]. Debris accumulation in culvert alters flow pattern, decreases entrance and barrel area and increases velocity. This situation affects upstream water level and downstream scouring geometry. There is a great literature review on hydraulics and design of culverts [2-4] and the culvert design method for both inlet and outlet control culverts proposed by AASHTO [5].

In the case of culvert scouring, there are valuable researches [6-12] which stated scour downstream of culverts depends on many factors, including flow discharge, flow velocity, tailwater depth, sediment size, barrel shape, and slope. Effect of these parameters on downstream scour hole geometry was studied directly in previous researches such as culvert slope and culvert shape effect on scouring depth explored by Abt et al. [8,9] and Zhang and Wu[10]. The influence of downstream water depth and sediment size on scour by submerged square wall jets presented by Sarathi et al. [11] and Zhao et al. [12]. Some studies investigate the influence of the mentioned parameters on scouring phenomena indirectly, including researches on turbulent structure and densimetric Froude number impression on scour hole geometry. Ade and Rajaratnam [13] based on 13 different sources proposed that densimetric Froude number (F_o) was the most effective parameter on local scouring.

Debris, foliage and waste material presence in hydraulic structures vicinity could be one of the blockage reasons. According to Weeks et al. [1], the mechanism of debris accumulation relates to a combination of parameters such as debris type, location, porosity, and timing. Collecting Wollongong floods data, Rigby et al. [14] reported that for culverts with less than 6 m opening, there is a high risk of culvert blockage, indeed culverts with a diagonal opening greater than 6 m had no significant debris accumulation after flood events. Australian Runoff and Rainfall (ARR) Project 11 [1] represented the damage resulting from culvert and waterway blockage. For many road authorities and local councils, blockage in culverts and bridges during floods is an important issue, since it leads to a high risk of damage to communication paths, private properties and public assets [1]. Ho [16] presented results of a field surveying in Iowa for assessing the extent of culvert sedimentation. The culverts have 25% sedimentation and 26% debris accumulation problems which in 76% of these cases there was no solution to sedimentation problems. In fact, their main issue to concern was sedimentation and they did not investigate the sudden blockage and scour problem in the vicinity of culvert. Based on their investigation on previous filed study, Ho et al. [16] presented a design procedure for multi-barrel culverts to prevent sedimentation problems. They used both numerical and experimental models to perform their presented culvert model called self- cleaning culvert. Barthelmess and Rigby stated that the main factors in culvert and bridge blockage are availability, mobility, and transportability of debris [17]. Sorourian et al. [18] investigated debris accumulation effect with sudden solid blockage in downward of box culvert entrance in unsteady flow. They reported that about 88% to 98% of scour holes were formed during rising hydrograph limb and in all steps of the hydrograph, the maximum scour depth and the scoured area were significantly more in partially blocked condition. Also, Park et al. [20] studied debris accumulation effect in sacrificial piles on bridge pier scour. They studied this phenomenon experimentally for several flow intensity and presented a suitable equation for maximum scour depth.

A deep understanding of the flow passing through culverts with debris accumulation might provide a wider perspective on hydraulic design of culverts and justify more initial costs in situations where there is a high probability of debris accumulation. In the case of culvert downstream scouring progress affected by debris accumulation in the inlet of culverts, there is not a great literature review as the other culvert problems except Sorourian et al.'s [18 and 19] studies in this filed. In their studies, downstream water level effect on the scouring progress in the partially blocked inlet did not investigated. This paper, report the results of a laboratory investigation on debris accumulation in culvert inlet and its influence on downstream scouring considering downstream submergence conditions. Two models have been studied in which the first has a single barrel and the other one has two barrels with W/D=1.5,0.75 where W and D are culvert width and height, respectively so that the total area of the double culvert is equal to the single barrel culvert. Furthermore, the inlet obstruction is considered as sudden obstruction like a two dimensional simulation of large woody debris or urban waste material. Debris accumulation simulated with four different solid plates with no slit and a porous plate which used in the highest flow discharge. All tests conducted in certain preliminary conditions - e.g. discharge and downstream water level- with densimetric Froude number F_o=1.5-6 and outlet submergence ratio- tailwater depth to culvert height- Ht/D=0.4- 0.7, then debris accumulation effects on downstream scour hole geometry have been investigated.

2. Methods

Experiments were conducted at the Hydraulic Laboratory of Water Engineering Department, Bu-Ali Sina University of Hamedan, Iran. Tests were performed in 10 m length, 0.5 m width and 0.55 m deep flume with smooth bed and glass walls. Discharge was controlled by an inverter and measured by an ultrasonic flow meter and tailwater was controlled by a tailgate installed flume downstream and a triangular weir that calibrated volumetric and located between the gate and the tank. A glass box culvert model with 20cm×30cm cross-section and 90 cm barrel length was made with 30o wing wall flares (Fig. 1). For modeling two-barrel culvert, the single barrel culvert was divided by using a thin glass plate with 5 mm thickness and all the other properties were the same as the single barrel culvert.

The experiments have been performed on an erodible bed in the culvert downstream with 2.20m length, 0.5 width, and 0.15m deep. Erodible bed contains uniform sand with d50= 2mm and σg =1.35. A sediment trapper with 0.15m deep and 0.015m length was placed at the end of the erodible bed to trap washed sediments. A gauge point was mounted on a traveling bridge to measure water surface profile and Leica Disto 810 laser meter applied for bed profiling. Four different heights of solid plates have been used for solid accumulation modeling which have the same width of culvert entrance and placed inlet downward with 1 cm distance from the bottom of culvert barrel. To avoid the unwanted erosion of the sediment bed, in all tests at first, the flume was filled with water from the downstream side of the test section.

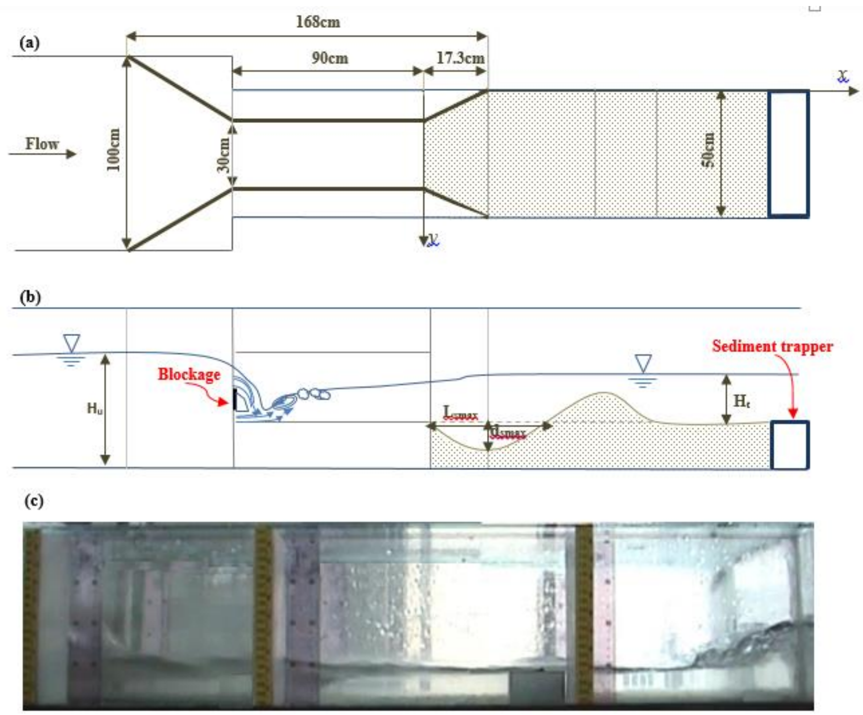

Fig. 1. Specification of experimental setup (a) Plan view, (b) Side view, and (c) Photo of Culvert operation with Q=10.5 lit/s and B=40% ,

As soon as the water level reached the required level, the experiments were run with adjusting the desired discharge value and controlling the slice gate opening. Scouring started in first moments and changed rapidly over time, but after about 30 minutes the scouring went on slowly until it came to equilibrium time, then the changing rate of scouring hole geometry significantly reduced. Culverts designed with inlet control or outlet control situation. In culverts with inlet control, the barrel hydraulic capacity is higher than that of the inlet. In fact, when a culvert operates in the inlet flow condition, critical depth occurs near the inlet and flow regime in the barrel is supercritical and the barrel geometry and roughness have no direct influence on the hydraulic characteristics of the culvert. Because of the critical constriction of the flow at the culvert entrance, the inlet configuration has a considerable effect on hydraulic performance [19]. In the current study all parameters that are effective on the hydraulic of culverts and culvert downstream scouring considered constant in each test and blockage presence with different size, is the only parameter changes entrance geometry. According to ARR report about debris accumulation in hydraulic structures, solid blockage in culvert entrance remain situation that an obstacle stuck in entrance and absolutely reduces inlet area and porous blockage predicate condition that there is an apparent material (like the accumulation of lumber and foliage) and water can flow through it with obstruction [12]. In tests for simulating debris accumulation in culvert inlet used rectangular plates have used with the same width and different height without any gap for solid blockage and rectangular plate with some horizontal splits for porous blockage. Whereas debris accumulation in culvert entrance changes the inlet condition and the effect of it on inlet control culverts must be major, the culvert model constructed in laboratory, designed and operated under inlet control condition. Table 1 shows the experimental test conditions.

Table 1. Characteristics of Experiments.

Test	B (%)	Q(lit/s)	F_r	F_o	H_u(cm)	H_d(cm)	H_t(cm)
R1Q10B0	0	10.5	0.6	2.8	10.4	7.0	7.9
R1Q10B20	20	10.5	1.3	4.5	13.5	4.3	7.9
R1Q10B40	40	10.5	1.6	5.3	16.6	3.7	8.8
R1Q10B80	80	10.5	1.4	4.9	25.5	4.0	9.0
R1Q16B0	0	16.0	0.5	3.0	13.4	10.0	11.0
R1Q16B20	20	16.0	1.1	4.7	16.4	6.3	9.8
R1Q16B40	40	16.0	1.3	5.4	19.3	5.5	9.0
R1Q16B80	60	16.0	1.5	5.9	23.5	5.0	11.5
R1Q27.5B0	0	27.4	0.5	3.4	19.8	15.0	15.5
R1Q27.5B20	20	27.4	0.5	3.4	21.5	15.0	15.5
R1Q27.5B40	40	27.4	0.5	3.2	23.8	16.0	16.9
R1Q27.5B60p	60p	27.4	0.5	3.2	24.4	16.0	17.2
R2Q10B0	0	10.5	0.6	2.8	10.5	7.0	8.0
R2Q10B20	20	10.5	1.2	4.3	13.5	4.5	7.6
R2Q10B80	80	10.5	1.3	4.6	24.3	4.2	8.0
R2Q16B0	0	16.0	0.5	2.9	13.6	10.3	10.3
R2Q16B20	20	16.0	0.9	4.2	16.4	7.0	11.0
R2Q16B60	60	16.0	1.5	5.9	23.0	5.0	11.5
R2Q27B0	0	27.4	0.4	3.1	19.8	16.2	17.0
R2Q27B20	20	27.4	0.5	3.2	21.5	16.0	17.0
R2Q27B60p	60p	27.4	0.5	3.2	25.5	16.0	17.0

3. Derivation of Empirical Equation

To obtain a suitable equation for downstream scour estimation in a culvert with debris accumulation in the inlet, first the effect of debris accumulation on scouring progress must be investigated. Then an appropriate equation based on previous studies and the current experimental study can be presented.

3.1. Scour mechanism

When flow passed through the culvert with inlet obstruction, the local velocity of the flow increased, flow depth in barrel decreased and hydraulic jump moved downstream, presence of hydraulic jump at the culvert outlet caused the sediments to be rapidly washed out and the scouring hole extended in all direction and just dragged to the sides of the channel. According to F_o values for jet in outlet (Table 1), maximum densimetric Froude number is 5.9 when 60% of inlet area covered with solid debris accumulation (Q= 16 lit/s and$h_t/D = 0.4$), which has the most affected scour area in blocked inlet situation (Fig. 2 (a) and Fig. 2 (c)).

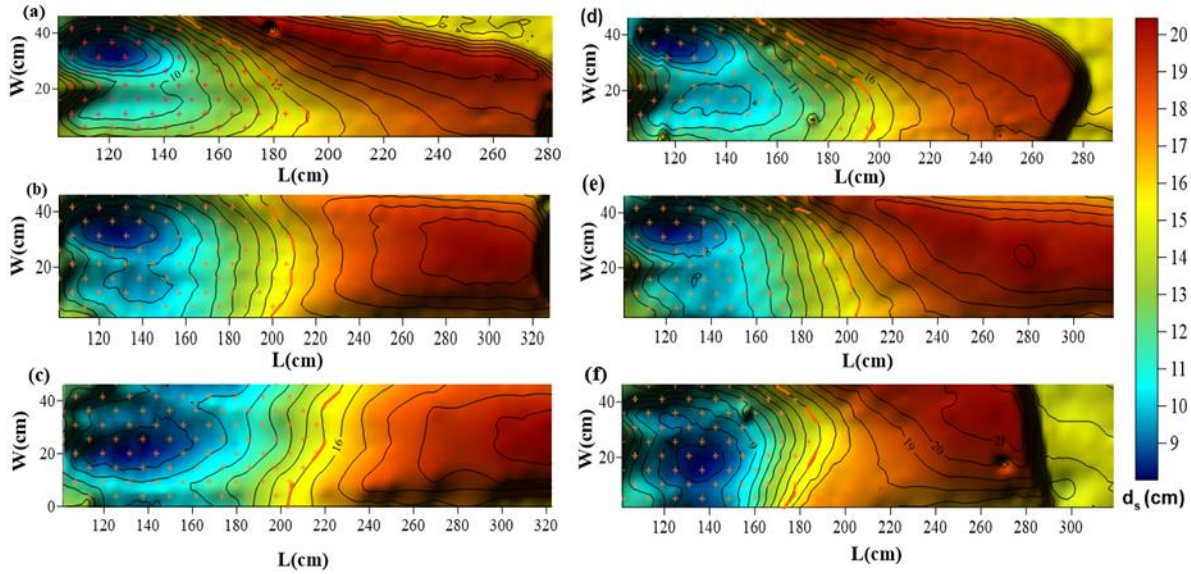

Fig. 2. Scour hole area extension: a) low tailwater depth and no debris, b) low tailwater depth and 40% solid blockage and c) low tailwater depth and 60% solid blockage, d) high tailwater depth and no debris, e) high tailwater depth and 40% solid blockage and f) high tailwater depth and 60% porous blockage.

Considering prior investigations about hydraulic jump, when tailwater depth is greater than conjugate depth hydraulic jump moves upstream as well [21]. In the case of Q=27.5 lit/s which has the highest initial h_t/D value, because of the higher tailwater depth value, hydraulic jump cannot form in outlet. So scour hole area wasn't affected so much especially when inlet covered with porous debris (Fig. 2(d) and Fig. 2(f)).

In all the tests as time passed and the scour hole depth increased, the hydraulic jump dragged into the barrel and speed of the scour hole extension got slow down. However, due to increased turbulence intensity and velocity component in the flow direction, sediment particles moved more rapidly in flow direction and the scour area more extended along stream and ridge of scour hole dune gets thinner and rapidly moved forward compared to non-blocked inlet condition. According to primary researches on the issue, h_t/D is another important effective parameter in culvert downstream scour. So debris accumulation affected scour indirectly, in fact the influence of debris on downstream scour hole geometry is complicated and dependent on downstream condition or tailwater depth too. So the effect of debris accumulation size on densimetric Froude number alteration in different tailwater depths has been investigated in conducting experiments, according to the results of Day et al. [22] about the effect of scale and tailwater depth on culvert outlet scouring, the level of downstream water was considered to be more than 70 mm. They reported in tailwater values less than 15 mm and Reynolds number in barrel fewer than 10^4, experiments have been affected by model scale. Also in $0.5 < h_t/D < 2.0$ and for $2.5 < F_o < 10$ which include all of current study tests condition, tailwater has been affected the maximum scour depth. In this study, tailwater depth remained constant for tests with the same discharge in non-blocked and blocked states, so the changes observed in scour hole geometry were the result of debris presence effects on outlet jet, but in rare cases the adjusted depth would be affected by the outlet jet. Hence, with respect to the experimental tests, after excluding constant parameter effects and considering covered percentage effect as B_p, which contains the effect of debris size and porosity. Finally, dimensionless function for scour depth will be derived as:

$$d_s/D = \varphi(F_o, B_P, h_t/D).$$

To get a better perception of how debris presence in culvert inlet affects maximum scour depth in hole and across the walls, Fig. 3(a) and Fig. 3(b) show how these parameters change with the size of accumulated debris. Scouring near walls is extended in the blocked inlet in both culvert models which shows scour hole extension in canal width and it became wider (Fig. 3(a)).

In order to define how exactly debris accumulation affect culvert downstream data it is needed to define the way it impressed main effective parameters such as F_o and h_t/D. Fig. 4 (a) and Fig. 4(b) demonstrate a direct relation between non blocked inlet area $(1 - B_p)$and F_o in different values of h_t/D.

In the case of current study culvert outlet was unsubmerged in all tests which influence scour progress directly. Although there is a little difference in h_t/D values, the way F_o changes in each downstream condition is absolutely different, especially for $h_t/D > 0.5$ values, in high values of h_t/D obstruction presence in inlet cannot affect the value of F_o considerably, and as have been seen, scouring characteristics change fewer in comparison with the cases which have $h_t/D < 0.5$.

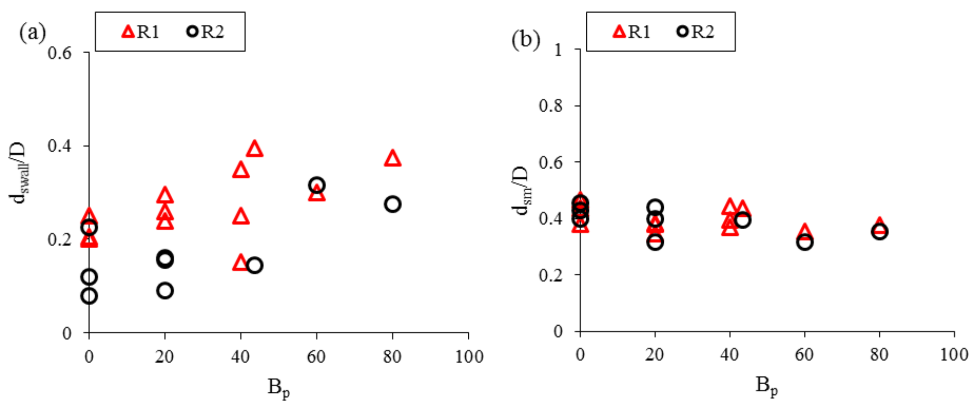

Fig. 3. Blockage effect on maximum scour depth, (a) near wall and (b) in centerline.

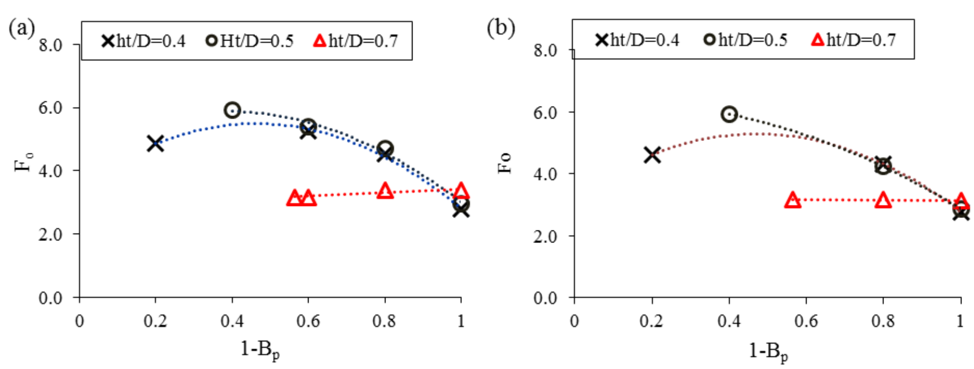

Fig. 4. F_o relation with unblocked inlet area; (a) in single barrel culvert and (b) in two-barrel culvert.

Now we can derive maximum scour depth relation according to this results which is in consistency with previous studies in unsubmerged outlet scouring process. Regards to the experimental results, the function of maximum scour depth becomes to: $d_s/D = \varphi(F_o)$. Have a glance at prior proposed equations for maximum scour depth (e.g. Table 2) support it. Some of prior scour prediction formulas were chosen to compare with result of our study and the Root Mean Square Error (R.M.S.E) test has been calculated for each prediction formula versus the laboratory data (Table 3).

Table 1. Prior equations for maximum scour depth in culvert downstream.

Researcher(s)	Equation	Remarks	
Rajaratnam and Diebel(1981)	$\frac{d_{sm}}{D} = 0.41F_o - 0.067$	Circular jet D=12.7-25.4mm	d_{50}=1.05mm $\frac{H_t}{D} = 0.2 - 3.39$
Abt et al. (1984)	$\frac{d_{sm}}{D} = \frac{3.65}{\sigma_g^{0.4}}\left[\left(\frac{Q}{\sqrt{gb_o^5}}\right)\left(\frac{d_{50}}{D}\right)^{0.2}\right]^{0.57}$	Circular jet D=102-254 mm	d_{50}=0.22-7.62mm $\frac{H_t}{D} = 0.45$
Lim (1995)	$\frac{d_{sm}}{D} = 1.45F_o$ (1) $\frac{d_{sm}}{D} = 4.5F_o$ (2)	Derived from the equation proposed by Breusers and Raudkivi(1991) for circular jets	$F_o = 2.5 - 24.6$ $d_{50} = 1.65\ mm$ $1 \le F_o \le 10$ (1) $10 < F_o$ (2)
Ade and Rajaratnam (1998)	$\frac{d_{sm}}{D} = 0.5F_o + 0.5$ (1) $\frac{d_{sm}}{D} = 0.5F_o$ (2) $\frac{d_{sm}}{D} = 4.75 + 0.025F_o$ (3)	Circular jet $F_o < 0.6$ (1) $0.6 \le F_o \le 10$ (2)	$10 \le F_o \le 100$ (3) $d_{50} = 0.24 -$ 7.2 mm
Sarathi et al.(2008)	$\frac{d_{sm}}{D} = 2.25\ln(F_o) - 2.44$ (1) $\frac{d_{sm}}{D} = a\ln(F_o - b)$ (2) $a = -0.66\left(\frac{H_t}{D}\right) + 2.34$, $b = 1.31\left(\frac{H_t}{D}\right)$-1.73	Circular jets F_o=3.9-10 $d_{50} = 0.71 - 2.46$	$\frac{H_t}{D} = 4$ (1) $0.5 \le \frac{H_t}{D} \le 3$ (2)
Emami and scheliss(2010)	$\frac{d_{sm}}{D} = a\ln(F_o) + b$ $a = 0.6\left(\frac{H_t}{D}\right) + 1.8$, $b = 1.23\left(\frac{H_t}{D}\right)$-2.25	Circular jets F_o=7.5-14.5	$d_{50} = 0.8$ mm
Sorourian et al.(2014)	$\frac{d_{sm}}{h_d} = 0.27F_o + 0.29B - 0.35$	Box culvert F_o=1.5-13.3	$d_{50} = 0.85,2\ mm$

Considering comprehensive study of Emami and Scheliss [23] on culvert downstream scouring and reasonable results of their equation, we assumed a logarithmic trend for d_s/D with F_o as: $d_s/D = \alpha\ln(F_o) + \beta$, and modified it for debris accumulated culvert inlet by applying blockage effect with B_P. Considering this point, then α and β derived as:

$\alpha = \psi(B_P, h_t/D)$ and $\beta = \omega(B_P, h_t/D)$

Using the data from the maximum scour depth for unsubmerged outlet with debris accumulation and non- blocked inlet situations, α and β values extracted as have been shown in Table 4.

Table 3. Comparison between prior equations and present study data

Research	Rajaratnam and Diebel(1981)	Abt et al.(1984)	Lim (1995)	Ade and Rajaratnam (1998)	Sarathi et al.(2008)	Emami and Scheliss(2010)	Sorourian et al. (2015)
Root mean square error (RMSE)	0.25	0.12	0.30	0.34	0.54	0.22	0.14

Table 4. The presented equation coefficients definition according to flow and blockage conditions.

Presented equation coefficients	Remarks
$\alpha = 1.4,\ \beta = -0.4$	$\frac{h_t}{D} < 1,\ F_o < 9,\ B_P = 0$
$\alpha = -0.3\ ,\ \beta = 0.07\ln(B_p) + 1$	$\frac{h_t}{D} < 1,\ F_o < 9,\ B_P \neq 0$

These equation can be applied in unsubmerged culvert outlet for all B_P values. Compared to prior studies which used logarithmic trend for d_s/D, α and values β values have a different behavior due to blockage (Fig. 5(a)).

Now d_s/D equation can be derived in blocked inlet situation. In single barrel culvert and $h_t/D = 0.7$ for $B_P > 40\%$, d_s/D equation becomes to:

$$\frac{d_s}{D} = -0.33\ln(F_0) + 0.98 \quad (1)$$

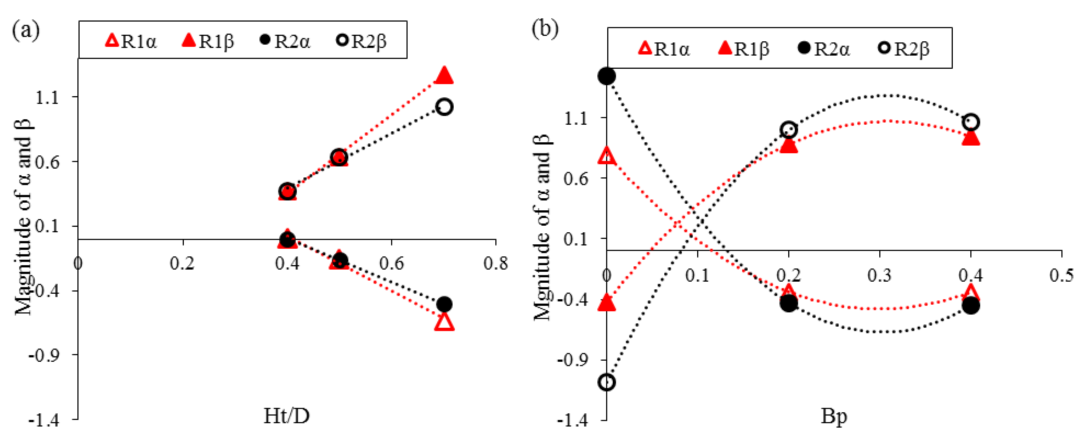

Fig. 5. Magnitudes of α and β (a) in different tailwater depths and (b) for different blockage sizes.

Fig. 6 shows how scour hole area changes according to H_t/D and F_o values. It is clear to see that F_o have a major effect than H_t/D especially in $\frac{H_t}{D} > 0.5$(Fig. 6(a) and Fig. 6(b)). In fact, it is the cause of how debris accumulation increases scouring, it increases F_o values so the scour possess got higher speed and sediments washed out rapidly (Fig. 6(c) and Fig. 6(d)). So comparing to maximum scour depth, scour area increase more directly because of debris accumulation.

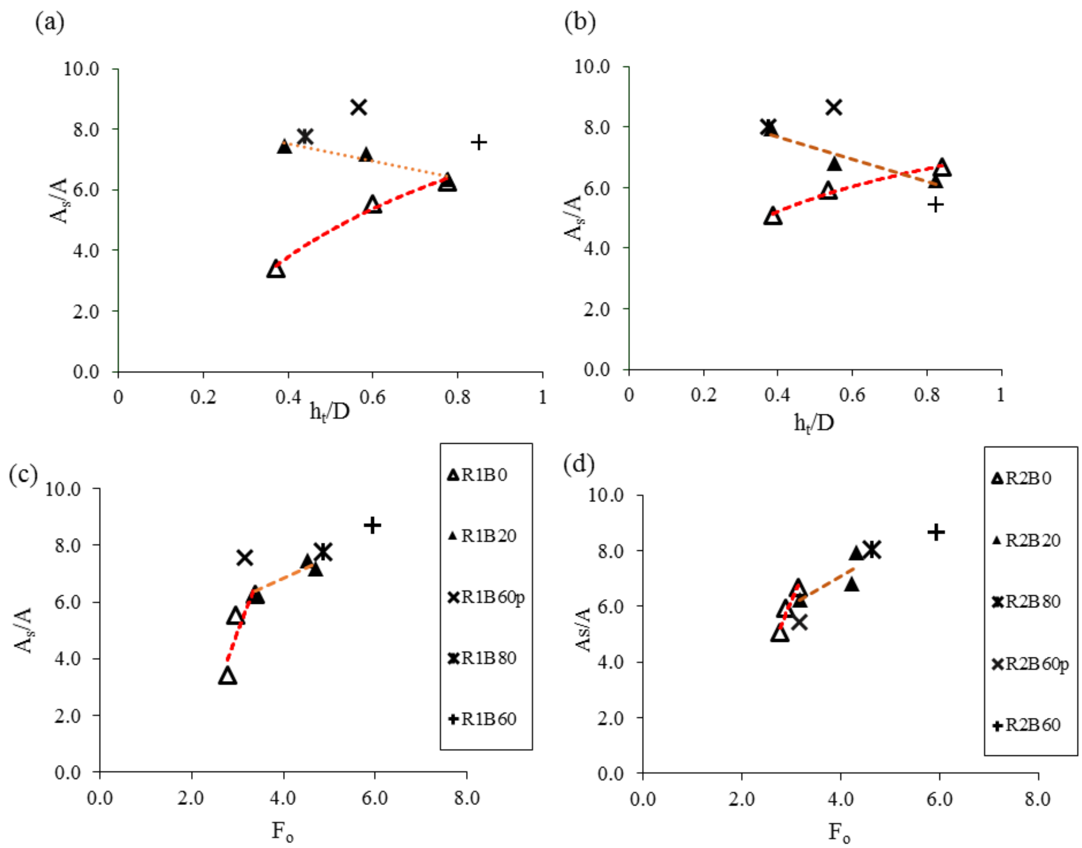

Fig. 6. Normalized scour hole area changes respect to tailwater depth changes; a) respect to tailwater depth in single barrel culvert, b) respect to tailwater depth in two-barrel culvert, (c) respect to densimetric Froude number in single barrel culvert and (d) respect to densimetric Froude number in two- barrel culvert.

Fig. 7(a) shows the longitudinal scour profiles along the centerline of culvert outlet for non-blocked inlet in single barrel culvert and 7(d) shows them for two- barrel culvert in exactly the same flow conditions. To avoid cluttering, only some of the profiles is shown. In single barrel culvert $W/D = 1.5$ with $F_o = 3.5$, it's clearly seen that scour hole scour profile is more dragged to the downstream and scour elongation is more than other flow conditions with lower F_o values but in culvert with two-barrel $W/D = 0.75$, scour hole dose not dragged as much as one barrel culvert in the same flow condition. In blocked inlet situations the ridge crest is thinner and profile is more extensive but alteration of scour along flow direction in $B_p = 20\%$ (Fig.7 (b), and Fig. 7(e)) and $h_t/D = 0.7$, is less than other cases.

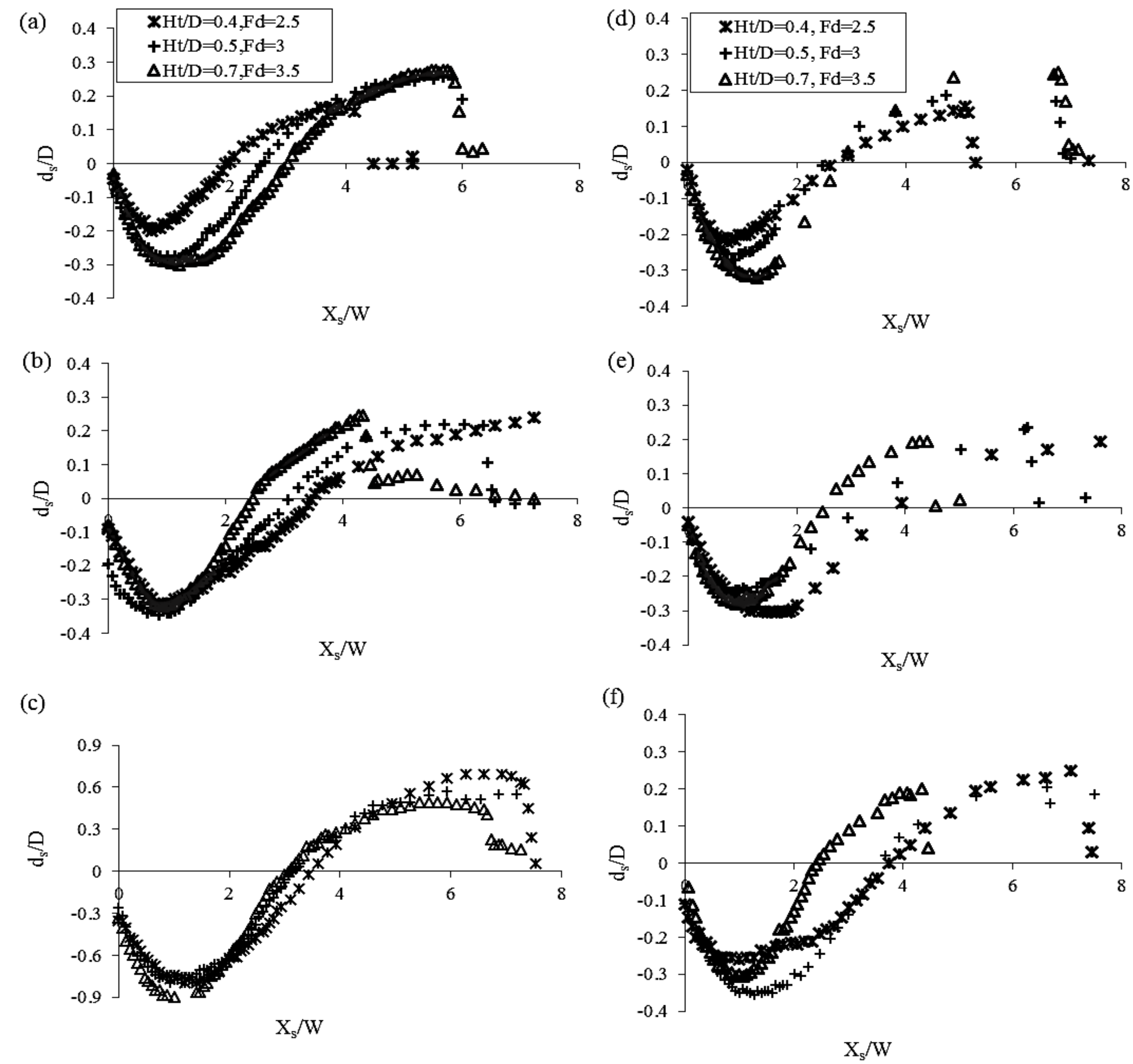

Fig. 7. Longitudinal scour profile in centerline; a) R1B0, b) R1B20, C) R1B>40, d) R2B0, e) R2B20, f) R2B>40.

In fact, the effect of blockage size on scour hole changes in flow direction relies on the initial condition. However, when the change in F_o value is not considerable, the scouring process will be affected by other parameters (e.g. h_t/D). Fig. 7(a) to Fig.7(c) show this changes for single barrel culvert and Fig. 7(d) to Fig. 7(f) show it for two-barrel culvert. One of the scour hole characteristics that changes remarkably and can be observed during flow in obstructed inlet, is the maximum length of hole. Fig. 8(a) shows the various maximum scour hole length in different blockage sizes and different $F_o$values. The difference in data for each model is almost the same. The smallest difference in scour hole length values is observed when $h_t/D = 0.7$, so tailwater depth affected longitudinal extension of scour hole.

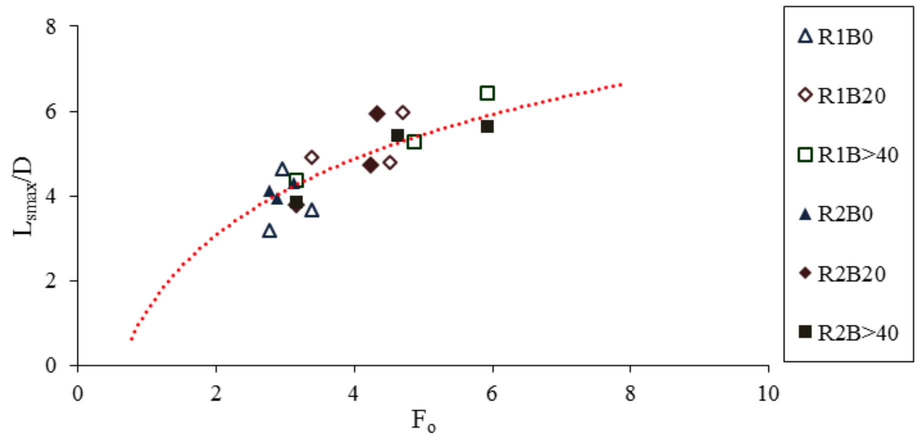

Fig. 8. Maximum length of scour hole changes with F_o.

According to the previous studies longitudinal extension of scour hole in culvert downstream, is a function of F_o(e.g. see Sarathi et al. [11] in which the longitudinal extension of scour hole is calculated by a linear equation); but in the case of the current investigation, a logarithmic relation could be the best fitted trend line with data.

$$\frac{L_{smax}}{D} = 2.6 \ln(F_o) + 1.3 \tag{2}$$

The other considerable parameter in scouring characteristics is the amount of moved sediment in scouring progress. During experiments increased rate of sediment move in debris presence was considerable. The scouring process difference between blocked and non-blocked culvert was not only about amount of washed sediments but also how and where they moved from. In culvert with debris accumulation, scour progress initiate in larger area compared to clean culvert scouring which almost initiates in a limited smaller area. It must be considered that all the tests designed respect to the critical initial motion condition, and satisfied $\mathbf{0.6} < \boldsymbol{U/U_c} < \mathbf{1}$. In fact debris accumulation cause decrease in scour but the rate of moved sediments is totally different compared to debris absence (Fig. 9). In some cases such as R1B>40 the F_o value increases but volume of moved sediments doesn't show considerable changes or in some cases (e.g.R1B20) it deceases while F_o increases. This happen because of difference in $\mathbf{h_t}/\boldsymbol{D}$, in fact maximum V_s in the same debris accumulation situation occurs in lower value of $\mathbf{h_t}/\boldsymbol{D}$.

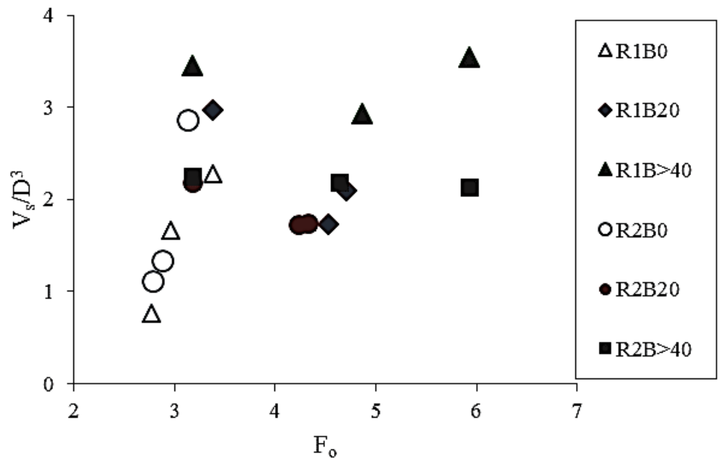

Fig. 9. Washed sediments volume changes respect to F_o.

Finally using the present experimental data and those obtained in prior studies, a relative assessment of the prediction of maximum depth of scour was fulfilled. All of these data included non-blocked inlet situations except those that belong to Soruorian et al. [19]. Using the current experimental data and those obtained in prior studies, a relative assessment of the prediction of maximum depth of scour was carried out.

Fig. 10 illustrates comparison of the different experimental data sets and predictor equations presented by several researchers. Catching a glimpse at Fig. 10 illustrates some over-predicted or under-predicted data by presented equations in some cases. The first point that must be noted about predictor equations is about the calibration data. Refer to Table 2 all of the other relations obtained for circular water jets except Sorourian et al.'s equation. Fig. 10(b) to Fig. 10(d) show over-predict data evolution by Lim's equation which considered only F_o in the presented equation and data set included $2.5 < F_o < 24$(Fig. 10(a)). Ade and Rajaratnam also presented predictor equation based on $F_o$values but they used a wider range of F_o and D_{50} for evaluating data, those data have been used in Fig. 10(b). Sarathi et al.[11] and Emami and scheliss [23] considered F_o and H_t/D as effective parameters. They used a logarithmic relation for predicting d_{smax}/D , but Emami and Scheliss's [23] equation has a better prediction in most of cases. Debris accumulation is considered in Sorourian et al.'s [19] equation which based on a linear trend of $F_o$but did not considered downstream condition as well and show over-predicted and under- predicted results in most of data series. The equation presented in this study which used a logarithmic trend of $F_o$and considered $H_t/D$and debris accumulation effect in d_{smax}/Dprediction, illustrate good agreement even in submerged outlet and high $F_o$values, which were not part of its evaluation condition. Comparison between several predictor relations with the current study data set (Fig. 10(f)) demonstrate over-prediction in most of them in debris accumulated inlet data but in other cases there is a good agreement between experimental and predicted data. As part of this comparison result, the effect of debris accumulation in culvert inlet on downstream scour hole is clear, but the way that its act needs more research to compare.

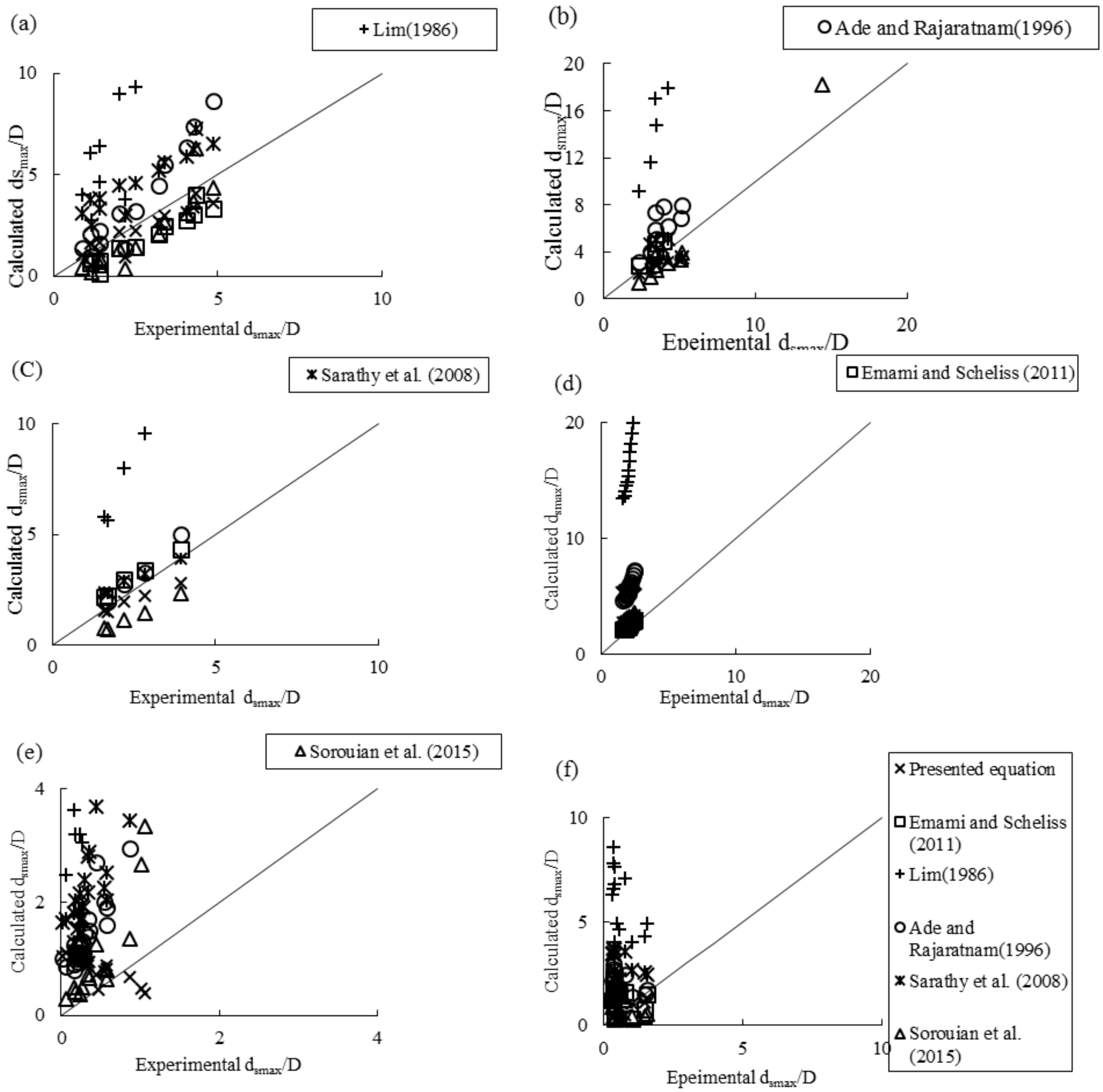

Fig. 10. Comparison between experimental data and predicted values of maximum scour depth.

4. Conclusion

Debris accumulation, even if when it exists only in inlets like large wooden debris, can alter flow condition and structure performance in culverts. In this study debris accumulation in rectangular culvert examined in different blockage sizes and hydraulic conditions: ($\frac{h_t}{D} = 0.4 - 0.9$, $Q = 10, 16,$ and 27.5 lit/s, and $F_o = 2.5 - 6$). In the cases with debris presence in inlet while Q and h_t/D were constant for each test, F_o values rises up severely due to the presence of debris in inlet while outlet condition in all tests were unsubmerged and constant for each case. In the case of hydraulic performance of the structure, blockage has a great influence, so it extremely makes culvert out of service which make it as a serious danger in practice and can made a flood to a real disaster in vicinity of urban runoff system catchment area.

Protecting downstream bed is one of the most important matters in hydraulic structure design procedure. In current study, solid and porous blockage effects on culvert downstream scour has been investigated. The main effect of obstruction in culvert inlet was on scour area and moved sediment volume, the maximum scour depth was not increased strikingly but near wall scouring growth considerably. In fact, the scour hole in blocked culvert extended along flow direction not just deeper. Because of the blockage presence in inlet, the trend of scour parameters is totally different compared to non-blocked conditions. The results show d_s/D is a function of $F_o, \mathrm{h_t}/D$ and B_p. In fact, in blocked culvert scour progress, downstream tailwater depth is important as densimetric Froude number in unsubmerged outlet condition. So it is considered in data analyzing and a practical equation has been presented to predict scour downstream culverts in blocked inlet situation. The empirical equation was compared to experimental results and prior predictor equations. The presented equation showed reasonably good agreement for maximum scour depth prediction in a wide range of experimental data. As an important result of study it is remarkable that debris accumulation causes significant increase in near wall scouring which directly threatens the stability of the structure.

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Notations

A:	Culvert inlet Area(cm^2)
B:	Debris accumulation height(cm)
B20:	Debris accumulation which covers 20% of inlet area
$B60_p$:	Porous debris accumulation which covers 60% of inlet area
B_p:	Debris accumulation size
D:	Culvert height(cm)
d_s:	Scour depth(cm)
d_{smax}:	Maximum scour depth(cm)
F_r:	Froude number
F_o:	Densimetric Froude number
g:	Acceleration of gravity(m/s^2)
h_t:	Tail water Depth(cm)
h_u:	Upstream water level(cm)
L_s:	Scour hole length(cm)
L_{smax}:	Scour hole length(cm)
R1:	One barrel culvert
R2:	Two barrel culvert
Q:	Discharge(l/s)
σ_g:	Sediment geometric standard deviation
W:	Culvert width(cm)

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