Scientia Iranica A (2012) 19 (6), 1437–1444

SCIENTIA IRANICA

Sharif University of Technology

Scientia Iranica

Transactions A: Civil Engineering

www.sciencedirect.com

Local scour due to free fall jets in non-uniform sediment

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Received 12 December 2011; revised 17 July 2012; accepted 7 August 2012

KEYWORDS

Free fall jets;
Non-uniform sediment;
Jet scour;
Densimetric Froude number.

Abstract The results of experiments on the local scour due to free fall jets are presented in this paper. Experiments were conducted for various values of the densimetric Froude number, the relative tailwater depth, the relative drop height and the relative sediment size. It has been found that by increasing the sediment non-uniformity parameter the scour hole parameters decrease. Moreover, in non-uniform sediment, d_{90} can be used instead of d_{50} in the densimetric Froude number of the jet. By using the present and previous experimental data, new equations for the scour parameters were developed. The validity of the developed equations was checked by available prototype data on the scour depth.

1. Introduction

The out flow jets from dams usually have high velocity and can lead to scour of the downstream bed. For location of dam foundation and assurance of the stability of downstream valleys, the dimensions of the scour hole and its downstream ridge should be estimated with acceptable accuracy. Parameters such as tailwater depth, drop height, jet velocity, angle of jet, sediment gradation, sediment size and sediment density can affect the scour hole parameters due to a jet. Extensive studies have been done to understand the effect of some of the influencing parameters on the scour hole dimensions. Different types of equations are available for estimation of the scour hole parameters. Some of the dimensional equations were shown by Mason and Arumugam [1] with general form of Eq. (1).

$$Y_s + Y_t = p\frac{q^l H^m}{d_m^n} Y_t^o, \tag{1}$$

in which q is the unit discharge of jet (m^3/s-m), H is the drop height from upstream to downstream water level (m), Y_s is the maximum depth of the scour below original bed level (m), d_m is the sediment characteristic size (m), Y_t is the tailwater depth (m) and p, l, m, n and o are the empirical constants given by different researchers as shown in Table 1. This table shows that different values of sediment characteristic size can be used in Eq. (1) (i.e. d_{90}, d_{85} or d_{50}). Here d_{90}, d_{85} and d_{50} are the sediment size in which 90%, 85% and 50% of sediment particles are smaller than this size, respectively.

Eq. (2) was presented by Martins [7] for estimating the depth of scour. Here Q is the jet discharge (m^3/s)

$$Y_s + Y_t = 0.14\sqrt{\frac{49Q^3 Y_t^{1.5}}{d_m^2}} - 0.73\frac{d_m Y_t^2}{7\sqrt{Q^3 H^{1.5}}} + 1.7Y_t, \tag{2}$$

Eqs. (3) and (4) were derived by Mason and Arumugam [1] to estimate the maximum depth of scour using laboratory and prototype data, respectively.

$$Y_s + Y_t = 3.27\frac{q^{0.6} H^{0.05} Y_t^{0.15}}{g^{0.2} d_{50}^{0.1}}, \tag{3}$$

$$Y_s + Y_t = (4.42 - 3.1H^{0.1}) q^{(0.600-0.0033H)} \times H^{(15-0.005H) Y_t^{0.15}} g^{-0.2} d_{50}^{-0.1}, \tag{4}$$

in which g is the gravitational acceleration.

Eq. (5) was derived by Azar [8] for estimating scour hole parameters.

$$\frac{\phi}{H} = a\left(\frac{H}{Y_t}\right)^b \left(\frac{q}{d_{50}\sqrt{gH}}\right)^{c(H/Y_t)d}, \tag{5}$$

in which ϕ represents the scour parameters (i.e. the maximum depth of scour, Y_s, the length of scour hole, L_s, the width of

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Peer review under responsibility of Sharif University of Technology.

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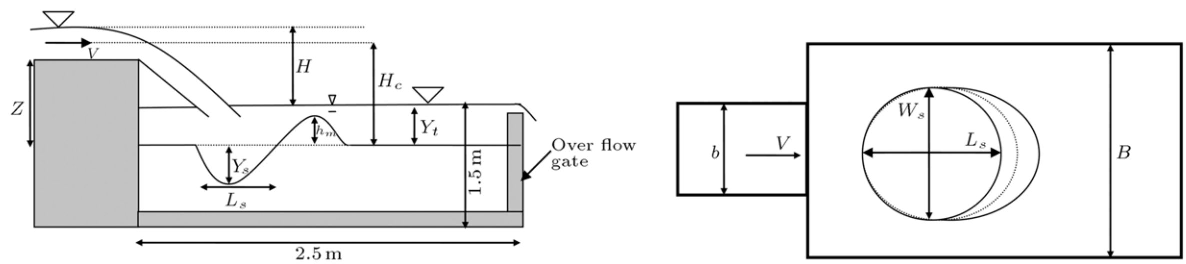
doi:10.1016/j.scient.2012.10.008



(a) Section view. (b) Plan view.

Figure 1: Schematic view of the experimental setup and scour parameters.

Table 1: Values of constants in Eq. (1).

Researcher	p	l	m	n	o	d_m
Veronese [2]	0.202	0.54	0.225	0.42	0	d_{50}
	1.90	0.54	0.225	0	0	–
Jaeger [3]	0.6	0.5	0.25	0.33	0.33	d_{90}
Eggenburger [4]	1.44	0.60	0.50	0.40	0	d_{90}
Schoklitch [5]	0.521	0.57	0.2	0.32	0	d_{90}
Hartunge [6]	1.40	0.64	0.36	0.32	0	d_{85}

Table 2: Values of constant in Eqs. (5) and (6).

Scour hole parameters	a	b	c	d	e	f	j
Y_s	1.466	−0.739	0.104	0.457	1.925	−0.61	0.3
L_s	1.749	−0.277	0.231	0.15	8.432	−0.9	1
W_s	2.52	−0.239	0.213	−0.126	10.126	−0.02	0.2
h_m	0.446	0.567	0.246	−0.647	0.549	−0.3	0.03

scour hole, W_s, and the ridge height at the downstream of the scour hole h_m) and a, b, c and d are empirical constants given in Table 2.

By using data from different sources Ghodsian et al. [9] developed the following equations for scour hole parameters due to circular and rectangular free fall jets.

$$\frac{\phi}{Y_t} = e\left(\frac{Y_t}{H_c}\right)^f \left(\frac{V}{\sqrt{gd_{50}(S-1)}}\frac{R}{H_c}\right)^j, \tag{6}$$

in which R is the hydraulic radius of the outflow jet, H_c is the drop height from center of the jet to downstream bed level, V is the jet velocity, S is the relative density of sediment and e, f and j are empirical constants given in Table 2. Eqs. (1)–(6) are applicable for uniform sediment.

D'Agostino and Ferro [10] introduced Eqs. (7) and (8) by using the data of grade control structures and free fall jets with different sediment gradations.

$$\frac{Y_s}{Z} = 0.54\left(\frac{b}{z}\right)^{0.593}\left(\frac{Y_t}{H}\right)^{-0.126} A_{50}^{0.544}\left(\frac{d_{90}}{d_{50}}\right)^{-0.856} \times\left(\frac{b}{B}\right)^{-0.751}, \tag{7}$$

$$\frac{Y_s}{Z} = 0.975\left(\frac{Y_t}{Z}\right)^{0.863}, \tag{8}$$

in which Z is the vertical distance of jet above initial bed level, b is the width of jet, B is the width of downstream channel (see Figure 1) and $A_{50} = Q/bz\sqrt{gd_{50}(S-1)}$. Dey and Raikar [11] correlated maximum depth of scour to densimetric Froude number, relative sediment size and relative tailwater depth.

According to the knowledge of the authors, no detail study was done to understand the effect of sediment gradation on the scour hole due to free fall jet. As most of sediments in the field are non-uniform, it is necessary to investigate this subject. The objectives of this paper are:

1. To investigate the effect of important parameters including sediment gradation on the scour hole parameters due to free falling jet in more detail,
2. To develop new scour predictive equations considering the effect of sediment gradation and other important parameters.

2. Dimensional analyses

Parameter ϕ represents the scour hole characteristics, including the maximum scour depth, Y_s, the scour length, L_s, the scour width, W_s, and the ridge height downstream of scour hole, h_m (Figure 1). The scour hole parameters due to free fall jet depends on many parameters including:

1. Sediment properties (the specific gravity ρ_s, the grain size d_m and the geometric standard deviations of the bed material $k = \sqrt{d_{84}/d_{16}}$),
2. Jet parameters (the velocity of jet, V, the width of jet, b, the hydraulic radius of jet, R, the drop height of jet, H_c),
3. Fluid parameters (density, ρ),
4. Downstream geometry (the tailwater depth, Y_t, and the width of downstream channel, B).

Therefore one can write:

$$\phi = f(V, R, d_m, k, \rho_s, \rho_w, g, Y_t, b, B, H_c). \tag{9}$$

Using dimensional analysis and after simplification, Eq. (9) can be written as:

$$\frac{\phi}{Y_t} = f\left(K, \frac{Y_t}{H_c}, Fr_{dm} = \frac{V}{\sqrt{gd_m\left(\frac{\rho}{\rho_s}-1\right)}}, \frac{H_c}{R}, \frac{d_m}{H_c}, \frac{B}{b}\right). \tag{10}$$

3. Experimental data

Experiments were conducted in a galvanized sediment basin 1.5 m width, 2.5 m length and 1.5 m height with an over fall gate at its downstream. A rectangular free over fall jet of 0.18 m width was established from the upstream channel. A schematic view of the experimental setup and the scour parameters is shown in Figure 1. Four types of sediment mixture were used. The median size for all the sediment mixtures was kept equal to $d_{50} = 1.28$ mm with geometric standard deviation $K = 1.3$, 2.15, 2.3 and 2.7 (Figure 2).

Table 3: Summery of data used.

Researcher	Veronese [2]	D'Agostino and Ferro [10]	Azar [8]	Saeidi Nezhad [12]	Present study
k	1.33	1.7, 2.5	1.13	1.3	1.3, 2.15, 2.3, 2.7
Fr_{d50}	0.77–1.85	1.46–10.46	0.55–2.4	1.95–9.1	5.69–9.55
Fr_{d90}	0.634–1.51	8.011–1.19	1.95–0.45	7.41–1.59	7.68–2.77
$\frac{Y_t}{H_c}$	0.048–0.21	0.878–0.11	0.5–0.097	0.61–0.32	0.45–0.344
$\frac{H_c}{R}$	13.48–32.79	21.51–5.94	13.42–8.14	46.68–17.95	38.94–23.45
$\frac{d_{50}}{H_c}$	0.005–0.023	0.005–0.027	0.027-0.273	0.0006–0.0053	0.0013–0.0053
$\frac{d_{90}}{H_c}$	0.008–0.034	0.04–0.008	0.41–0.04	0.008–0.0009	0.008–0.002
$\frac{B}{b}$	1	1.67, 3.33	3.19	7.14	8.33
No. of experiments	36	114	80	86	48
Measured parameter	Y_s	Y_s, h_m	L_s, Y_s, W_s, h_m	L_s, Y_s, W_s	L_s, Y_s, W_s, h_m

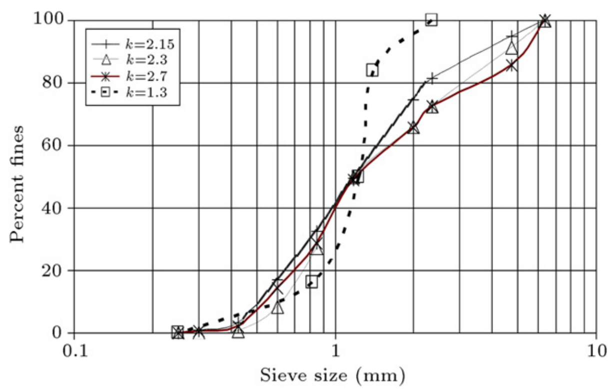


Figure 2: Grain size distribution curves of bed material used.

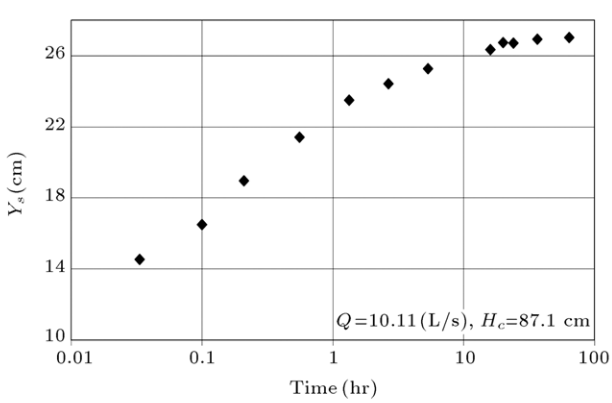


Figure 3: Time variations of scour depth.

Experiments were conducted for three values of discharge ($Q = 4.36, 7.4$ and 10.11 L/s) and four values of drop height ($H_c = 66.47, 77.1, 82.1$ and 87.1 cm). The tailwater depth was equal to 30 cm in all the experiments. Discharge was measured by a calibrated sharp-crested triangular weir. The depth of the flow at the upstream of the weir and the bed profile were measured using a digital point gauge with an accuracy of ± 0.001 mm. Initially, a thin protective metal sheet was placed on the bed at the downstream of the jet. The flume was slowly filled until the desired tailwater level was reached. The jet scour experiments were started when the protective sheet was removed. The removal of protective sheet was in such a manner that the disturbance of the bed was avoided. At the end of the experiments, the scour profile was measured by using a point gauge.

Table 4: Values of *MRD* and *R* due to some of previous scour depth equations.

Researcher	R	*MRD*	Equation no.
Veronese [2]	0.254	112	1
	0.111	112.7	1
Jaeger [3]	0.1	110	1
Schoklitsch [5]	0.152	122	1
Eggenburger [4]	0.22	112	1
Hartunge [6]	0.05	102	1
Martins [7]	0.438	359	2
Mason and Arumugam [1]	0.22	188	3
	0.371	312.3	4
Azar [8]	0.21	73	5
Ghodsian et al. [9]	0.4	106	6
D'Agostino and Ferro [10]	−0.023	44	7
	−0.03	56	8

In order to obtain the equilibrium state of the scour, a long time experiment (64 h) was performed (Figure 3). It is evident that after about 20 h, almost 90% of the scour depth is achieved. Therefore, it was decided to limit the duration of the experiments to 20 h.

In addition to the present experimental data, an extensive set of available data (Table 3) was used to study the influence of important parameters on the dimensions of the scour hole and the ridge height downstream of the scour hole.

4. Assessment of previous equations

By using the available data and considering the statistical parameters including the mean relative deviation *MRD* and the correlation coefficient R as defined by Eqs. (11) and (12), the accuracy of Eqs. (1)–(8) was checked.

$$MRD = \frac{1}{n}\Sigma\left[100\frac{|O-C|}{O}\right], \tag{11}$$

$$R = \frac{\sum(O-\bar{O})(C-\bar{C})}{\sqrt{\sum(O-\bar{O})^2(C-\bar{C})^2}}. \tag{12}$$

Here O and C represent the observed and computed values of the scour parameters, respectively, and symbol $^{-}$ shows their mean values. The values of *MRD* and R due to Eqs. (1)–(8) for all the data are given in Table 4. None of the equations predict the scour depth correctly because these equations do not consider the effect of sediment gradation.

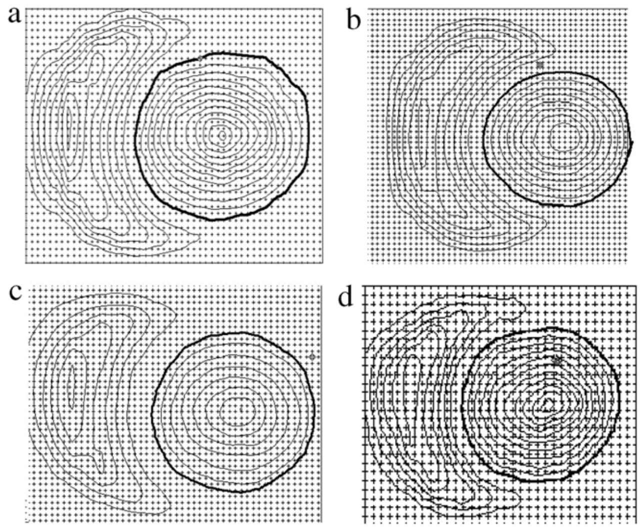
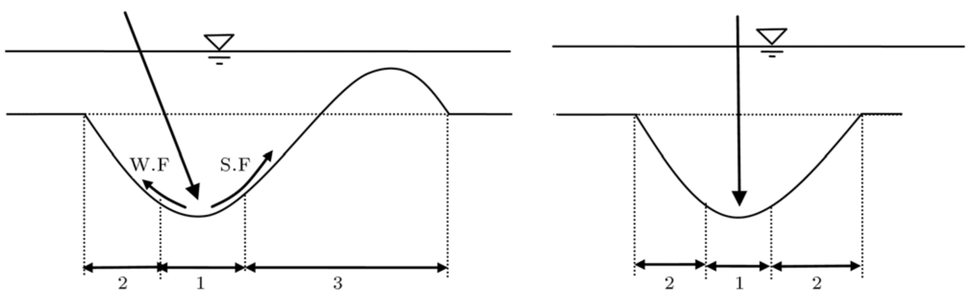


Figure 4: Scour hole and its downstream ridge: (a) $K = 1.3$ (b) $K = 2.15$, (c) $K = 2.3$, and (d) $K = 2.7$.



(a) Longitudinal scour profile.

(b) Lateral scour profile.

Figure 5: Schematic view of the scour hole profiles.

5. Results and discussion

At the beginning of all the experiments the scour hole expands in all dimensions with high rate. Most of the finer sediment particles transport to the downstream as suspended load while the coarser sediment particles transport to the downstream as bed load. The scour hole is roughly circular in plan, with most of the eroded material being deposited as a ridge downstream from the scour hole (Figure 4). After impinging on the bed, the jet is divided into two portions. The main portion of the jet which moves toward the downstream is named here as strong flow (S.F in Figure 5). The other portion of the jet which is diverted toward the upstream is named here as weak flow (W.F in Figure 5). Scour profile at the equilibrium state consists of three regions (regions 1–3 in Figure 5). The coarser sediments form an armor layer on the lowest part of the scour hole (region 1 in Figure 5). The median size of the sediment in this region d_{50} approximately corresponds to d_{90} of the original sediment mixture. Regions 2 and 3 (Figure 5) are covered mostly with finer sediments and d_{50} in these regions approximately corresponds to d_{50} of the original sediment mixture.

The influence of the geometric standard deviation of the bed material K on the longitudinal and lateral scour profiles is shown in Figure 6. It is clear that by increasing K, the scour hole parameters decrease. The scour hole length and width decrease by about 30% as the geometric standard deviation K varies from 1.3 to 2.7. Moreover, decrease in the maximum depth of scour and the height of downstream ridge by increasing the geometric standard deviation is about 32% and 45%, respectively. At higher values of the geometric standard deviation, due to formation of armor layer, the rate of change in the dimensions of the scour hole decrease.

Due to the existence of S.F., the potential of sediment transport by the jet to the downstream is larger in the downstream portion of the scour hole. As a result, the downstream slope of the scour hole is flatter than the upstream slope of scour hole.

Figure 7 shows variations of the scour parameters with H_c for various sediment mixtures. It is clear that the scour depth and the ridge height increase by increasing H_c, while the scour length and the scour width decrease by increasing H_c. Ervin and Falvey [13] stated that as the size of the core of the free falling jet decrease and the velocity of the jet increase by increasing the drop height, the scouring potential of the jet increase in vertical direction (i.e. the scour depth and the ridge height increase) and decrease in lateral direction (i.e. the scour length and the scour width decrease).

The influence of K on the scour parameters for various values of H_c/R and Y_t/H_c is shown in Figure 8. This figure again shows that by increasing K, the scour parameters decrease. The decreasing trend of the scour parameters by increasing K is attributed to the formation of the armor layer at higher values of K. This behavior of non-uniform sediments was also observed by previous researchers [14,15]. Increasing H_c/R increases Y_s/Y_t and h_m/Y_t while decreases W_s/Y_t and L_s/Y_t. Moreover, increase of Y_t/H_c is associated by decreasing Y_s/Y_t and h_m/Y_t and increasing W_s/Y_t and L_s/Y_t.

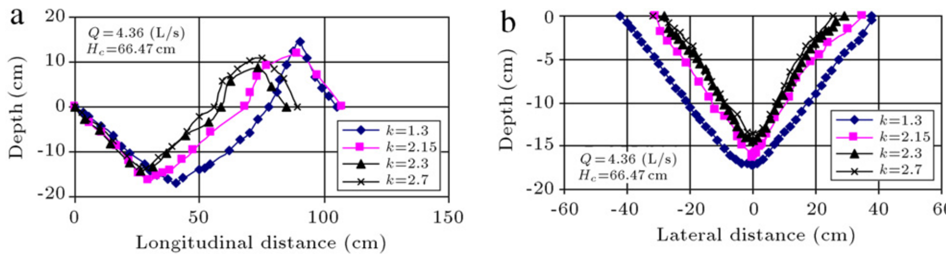
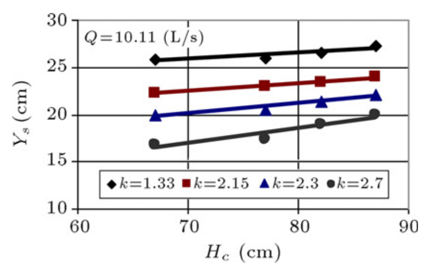
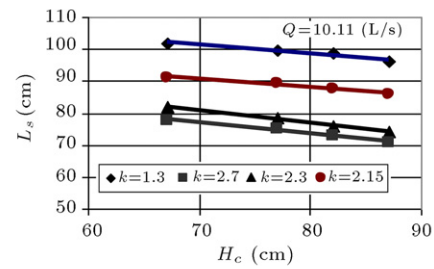


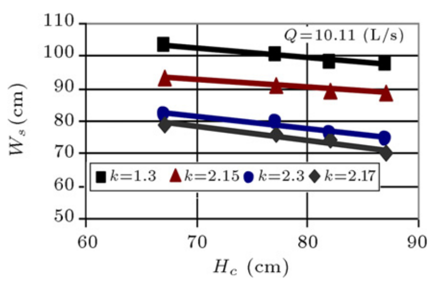
Figure 6: Scour profiles for different values of K: (a) Longitudinal, and (b) lateral profiles.



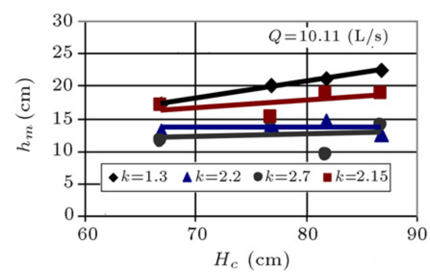
(a) Scour depth.



(b) Scour length.



(c) Scour width.



(d) Ridge height.

Figure 7: Variations of scour parameters with H_c and K.

Figure 9 shows the influence of the densimetric Froude number $Fr_{50} = V/\sqrt{gd_{50}(s-1)}$ and K on the relative scour hole dimensions and the relative ridge height. As the densimetric Froude number of the jet represents the ratio of the drag force of the flow to submerged sediment weight, hence by increasing the densimetric Froude number, the scour parameters increase for all values of K. By considering $Fr_{d90} = V/\sqrt{gd_{90}(\rho_s/\rho - 1)}$ instead of $Fr_{d50} = V/\sqrt{gd_{50}(\rho_s/\rho - 1)}$, a single curve could be fitted to all the data (Figure 10). This means that Fr_{d90} sufficiently considers the effect of sediment gradation. Therefore, it is preferred to use d_{90} instead of d_{50} in the densimetric Froude number of the jet for non-uniform sediment. Previous researchers also used d_{90} in scour predictive equations for uniform sediment [3–5].

Previous researches such as D'Agostino and Ferro [10] and Amanian [16] have shown that B/b affects the scour hole parameters due to free fall jet. Ghodsian et al. [9] showed the influence of H_c/R and Y_t/H_c on the scour hole parameters due to free fall jet.

However, there is a contradiction about the effect of H_c/d_m on the scour. Whittaker and Schleiss [17] have shown that this parameter does not have an effect on the scour hole dimensions for $H_c/d_m > 200$, while Ghodsian and Azar [15] have shown that this parameter influences the scour hole dimensions even for $H_c/d_m > 200$.

Eq. (10), by considering $d_m = d_{90}$, can be written as:

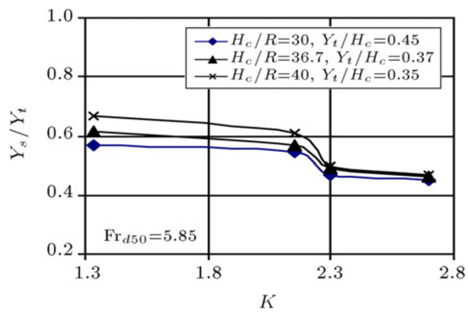
$$\frac{\phi}{Y_t} = x_1 k^{x_2} Fr_{d90}^{x_3} \left(\frac{H_c}{R}\right)^{x_4} \left(\frac{d_{90}}{H_c}\right)^{x_5} \left(\frac{B}{b}\right)^{x_6} \left(\frac{Y_t}{H_c}\right)^{x_7}, \quad (13)$$

where coefficient x_1 and exponents x_2, x_3, x_4, x_5, x_6 and x_7 are empirical constants. By using all the data, the values of constants in Eq. (13) were obtained using the least squares methods as given in Table 5. This table shows that the effects of K and d_{90}/H_c are not significant. This means Fr_{d90} considers the effect of the sediment gradation. After eliminating K and d_{90}/H_c, Eq. (13) can be written as:

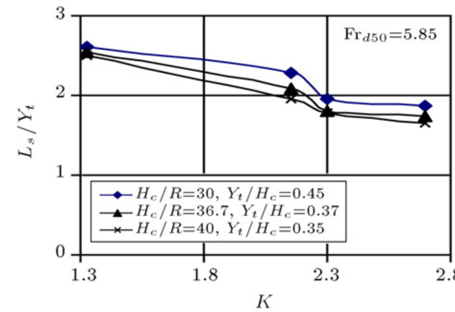
$$\frac{\phi}{Y_t} = x_8 Fr_{d90}^{x_9} \left(\frac{H_c}{R}\right)^{x_{10}} \left(\frac{B}{b}\right)^{x_{11}} \left(\frac{Y_t}{H_c}\right)^{x_{12}}, \quad (14)$$

where coefficient x_8 and exponents x_9, x_{10}, x_{11}, and x_{12} are empirical constants. The values of constants in Eq. (14) were obtained by using the least squares methods as given in Table 6. Table 7 compares the values of R and MRD due to Eqs. (13) and (14). Figure 11 shows the comparison of the measured and computed values of the scour parameters due to Eq. (14) for all the data (Table 3). It is clear that Eq. (14) gives acceptable results for estimation of the scour parameters.

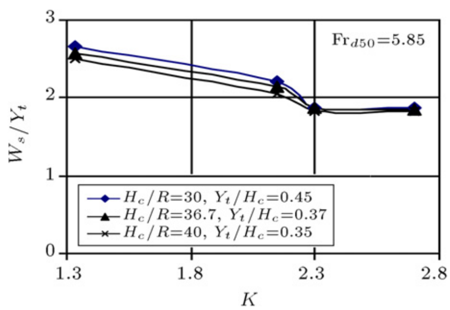
In order to check the validity of Eq. (14), the prototype data as reported by previous researches [2,17–19] were used (Table 8). The data of maximum scour depth downstream of 29



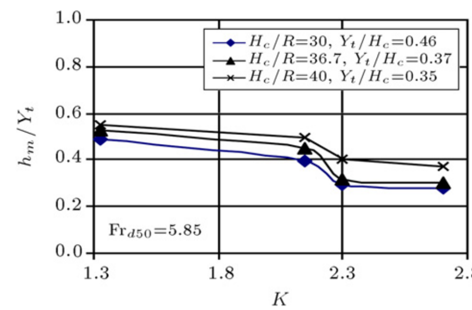
(a) Scour depth.



(b) Scour length.

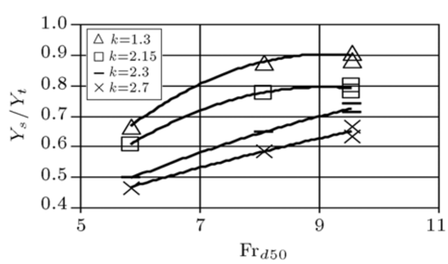


(c) Scour width.

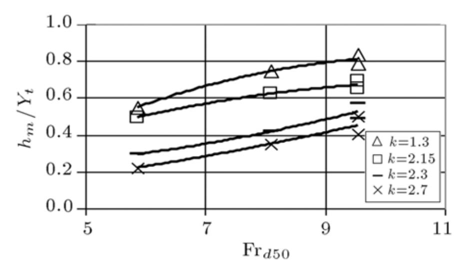


(d) Ridge height.

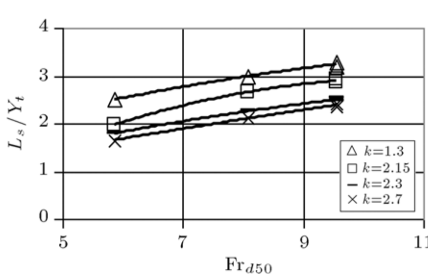
Figure 8: Variations of scour parameters with K, H_c/R and Y_t/H_c.



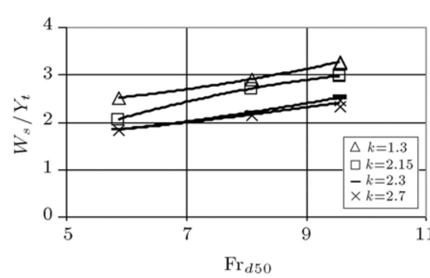
(a) Scour depth.



(b) Ridge height.



(c) Scour length.



(d) Scour width.

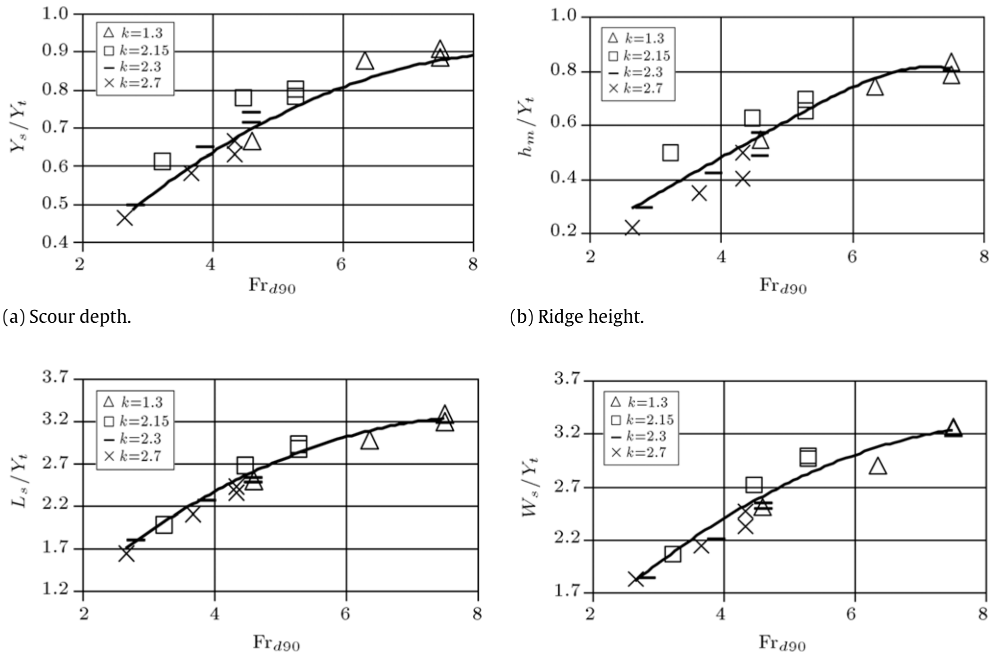
Figure 9: Effect of K and Fr_{d50} on scour hole dimensions and ridge height $0.34 < Y_t/H_c < 0.36$, $28 < H_c/R < 33$, $0.004 < d_{90}/H_c < 0.008$, $B/b = 8.33$.

Table 5: Values of constants in Eq. (13).

Parameter	Constants							No. of experiments
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	
$\frac{Y_s}{Y_t}$	0.76	−0.05	0.22	−0.83	−0.01	0.59	−1.06	374
$\frac{W_s}{Y_t}$	8.67	−0.08	0.2	−1	−0.05	0.35	−1	216
$\frac{L_s}{Y_t}$	5.22	−0.03	0.3	−0.67	−0.012	0.2	−0.91	216
$\frac{h_m}{Y_t}$	0.67	−0.06	0.1	−0.65	−0.02	0.5	−0.65	244

Table 6: Values of constants in Eq. (14).

Parameters	Constants					No. of experiments
	x_8	x_9	x_{10}	x_{11}	x_{12}	
$\frac{Y_s}{Y_t}$	0.54	0.42	−0.96	0.68	−1.27	376
$\frac{W_s}{Y_t}$	8.44	0.25	−0.77	0.1	−1.01	216
$\frac{L_s}{Y_t}$	2.22	0.27	−0.54	0.38	−1.13	216
$\frac{h_m}{Y_t}$	0.69	0.2	−0.7	0.45	−0.76	244



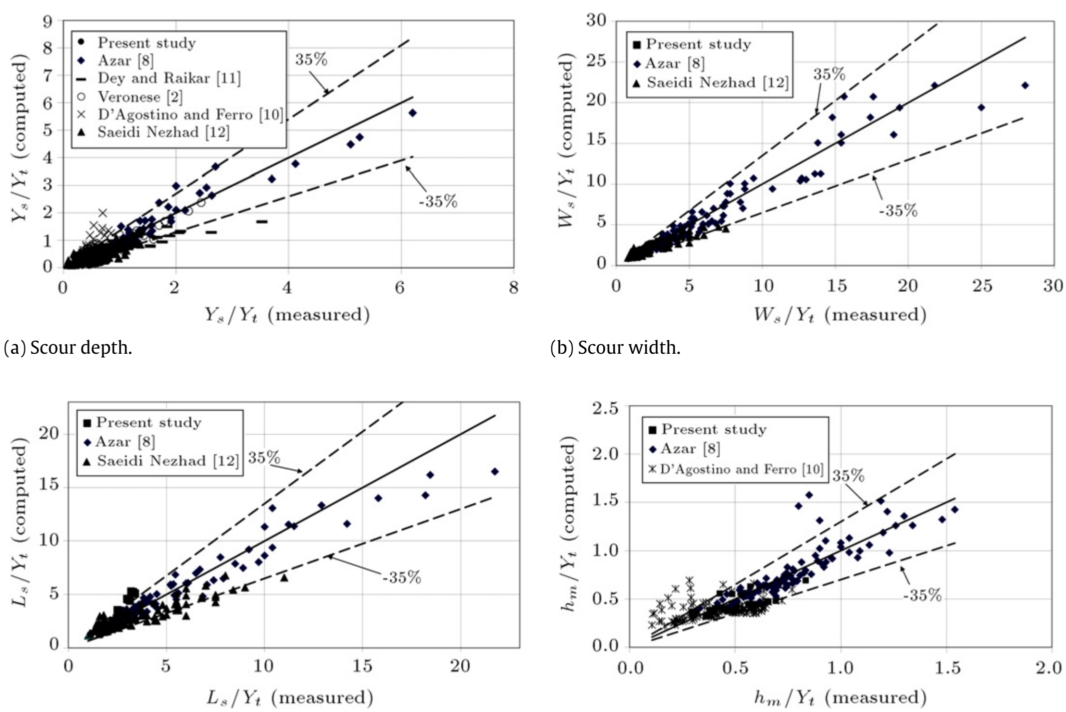
(a) Scour depth.

(b) Ridge height.

(c) Scour length.

(d) Scour width.

Figure 10: Effect of Fr_{d90} on scour hole dimensions and ridge height: $0.34 < Y_t/H_c < 0.36$, $28 < H_c/R < 33$, $0.004 < d_{90}/H_c < 0.008$, $B/b = 8.33$ m.



(a) Scour depth.

(b) Scour width.

(c) Scour length.

(d) Ridge height.

Figure 11: Comparison of computed (Eq. (14)) and measured values of scour hole parameters.

check dams in Italy were reported by Falicia and Giacomin [18]. Veronese [2] reported the scour depth for Rochatta dam in Italy.

Whittaker and Schleiss [17] reported the scour hole profile for Cabora–Bassa dam in Zimbabwe. Scimeimi [19] reported the scour depth downstream of the Conowingo dam in USA.

Table 9 compares the values of *R* and *MRD* due to Eqs. (1)–(8) and (14) for the above-mentioned prototype data. It is clear that Eq. (7) gives better result for prototype data as compared to Eqs. (1)–(6) and (8). Figure 12 shows the comparison of measured and computed values of the relative scour depth using Eq. (14) and some of the earlier equations. The values of *MRD* and *R* due to Eq. (14) are 34 and 73, respectively. Therefore, Eq. (14), which also considers the effect of the sediment gradation, is more accurate as compared to other equations.

Table 7: Values of R and MRD due to Eqs. (13) and (14).

Scour parameter	Eq. (13)		Eq. (14)	
	R	MRD	R	MRD
$\frac{Y_s}{Y_t}$	0.91	24	0.891	38
$\frac{L_s}{Y_t}$	0.95	19	0.94	21
$\frac{W_s}{Y_t}$	0.98	13	0.95	15
$\frac{h_m}{Y_t}$	0.84	21	0.84	24

Table 8: Range of prototype data used.

Parameter	Fr_{d90}	$\frac{Y_t}{H_c}$	$\frac{H_c}{R}$	$\frac{B}{b}$
Range	0.35–1.95	0.31–1.286	0.59–8.44	1–1.33

Table 9: Values of R and MRD due to different equations for prototype data.

Research	R	MRD	Equation no.
Veronese [2]	−0.23	135	1
	−0.02	140	
Jaeger [3]	−0.2	62	
Schoklitsch [5]	−0.23	84	
Eggenburger [4]	−0.17	672	
Hartunge [6]	−0.19	467	
Martins [7]	−0.06	57	2
Mason and Arumugum [1]	−0.13	270	3
	−0.13	276	4
Azar [8]	−0.02	166	5
Ghodsian et al. [9]	−0.92	429	6
D'Agostino and Ferro [10]	0.66	54	7
	−0.07	73	8
Present study	0.73	34	14

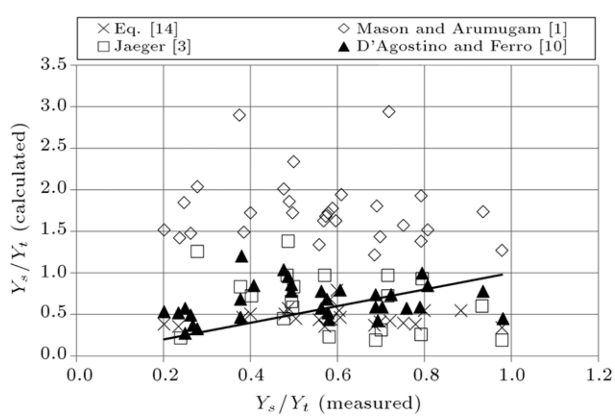


Figure 12: Comparison of measured and computed (Eq. (14)) values of scour depth for prototype data.

6. Conclusion

The results show that by increasing the geometric standard deviation of the sediment, the scour hole parameters and the ridge height decrease. At the equilibrium state, the median size of sediment d_{50} in the armor layer in the scour hole is about the same as d_{90} of the original sediment. By using d_{90} instead of d_{50} in the densimetric Froude number of the jet, better correlations with scour hole parameters were obtained. This means that Fr_{d90} considers the effect of sediment gradation. By increasing the drop height, the maximum scour depth and the ridge height increase while the length of scour and the width of scour hole decrease. The scour parameters were correlated to the densimetric Froude number, the relative drop height, the relative tailwater depth and relative tailwater width. Sensitive analysis showed that the effect of the relative drop height on the scour hole parameters is marginal as compared to other parameters. New equations are obtained for estimation of the scour parameters. The accuracy of developed equations was examined with the available prototype data.

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