Geotech Geol Eng (2018) 36:2505–2516
https://doi.org/10.1007/s10706-018-0479-x

ORIGINAL PAPER

Effect of Gradation of Bed Material on Local Scour Depth

Bintul Huda Mir · Mohd Akbar Lone · Javeed Ahmad Bhat · Nasir Ahmad Rather

Received: 29 May 2017 / Accepted: 26 January 2018 / Published online: 5 February 2018

Abstract The paper presents a study on local scour with respect to bed material gradation, flow depth and the Froude number. In the study, bed materials collected from five different rivers were used separately for four different shapes of the obstructions. The water discharge was also varied for each run. The experimental results obtained, reveal the dependence of local scour on the overall bed material gradation, and shape of the obstruction, especially the upstream interface. The models developed on basis of the experimental findings for different shapes are more realistic than the widely adopted criteria which mainly consider only effective size, d_{50} of the bed material, ignoring the other gradation parameters. Moreover, it was found that the obstruction shape also affects the scour phenomenon considerably.

Keywords Gradation · Local scour · Bed material · Sediment · Obstruction · Flume · Froude number · Flow depth

B. H. Mir (✉) · M. A. Lone · J. A. Bhat · N. A. Rather
Department of Civil Engineering, National Institute of Technology, Srinagar, Jammu and Kashmir, India
e-mail: huda_07phd13@nitsri.net

1 Introduction

Local Scouring is a complex phenomenon and involves a spectrum of parameters which affect its development. Local Scour is identified as one of the most prominent cause of failure of hydraulic structures (Landers and Mueller 1996; Melville and Coleman 2000; Hong et al. 2012). It is the removal of sediment from around bridge piers or abutments or an obstruction. The sediment removal is caused mainly due to formation of both horse vortex and down flow in front of the piers or obstruction (Moncada-M et al. 2009). Both the obstruction, as well as, the bed material parameters affects the local scouring besides the fluvial properties of the water (Raudkivi and Ettema 1983). The complex nature of the scouring process involves a wide range of theories such as sediment transport, fluvial hydraulics, boundary layer theory, time-dependence, etc. (Fakhri et al. 2014; Mohammadzade Miyab et al. 2017) which hinder the exact quantification of the process. The waterways under consideration, whether it is a natural stream in which the hydraulic structures are laid or the man made channels which also support various structures while dealing with the water resources engineering show a varied scouring pattern. Based on experience from the study of the existing hydraulic structures and the researches available (Laursen and Toch 1956; Chiew and Melville 1987; Melville 1992a, b; Johnson 1995; Heza et al. 2007; Akib and Rahman 2013), it is clearly evident that the bed material of the water way is an important governing feature while computing local scour depths. A complete gradation analysis of the soil or the bed material needs to be done for determining the scouring in that particular setup. The present study was conducted to formulate the detailed effect of the gradation parameters of bed material on the local scour depth.

Most of the local scour studies are accomplished by means of physical modelling (Raudkivi and Ettema 1983; Chiew 1984; Chiew and Melville 1987; Mohammed et al. 2007; Mir et al. 2017; Mir et al. Forthcoming). Physical Modelling along with numerical techniques are an effective means of understanding the local scour mechanism.

The present study was conducted with an aim to study the variation of local scour with bed material characteristics and develop an empirical solution to the identified problem.

2 Dimensional Analysis

Scour depth around the obstruction depends on a number of parameters. These parameters in case of bridge piers can be identified easily as pier size, sediment characteristics, flow conditions and fluid properties (Breusers et al. 1977; Hong et al. 2012). The relationship describing the equilibrium local scour depth for an obstruction may be expressed as follows:

$$d_s = \phi(\mu, \rho, V, y, d_5, d_{30}, d_{85}, f, C_u, D, g, S, b) \quad (1)$$

where d_s = maximum equilibrium scour depth, μ = fluid dynamic viscosity, ρ = water density, V = average velocity of approach flow, y = flow depth, d_5 = particle diameter for 5% passing, d_{30} = particle diameter for 30% passing, d_{85} = particle diameter for 85% passing, f = silt factor, C_u = uniformity coefficient, D = obstruction size, g = gravitational acceleration, S = bed slope, b = channel width, Fr = Froude number, φ = function of, ψ = function of, ϕ = function of.

Taking repeating variables as ρ, V and D, the functional relationship obtained is given as:

$$\frac{d_s}{D} = \psi\left(Fr, \frac{\mu}{\rho VD}, \frac{y}{D}, \frac{d_5}{D}, \frac{d_{30}}{D}, \frac{d_{85}}{D}, f, C_u, S, \frac{b}{D}\right) \quad (2)$$

The dependent parameter is d_s/D i.e. normalised scour depth and its variation was studied with the normalized gradation parameters. Froude number was varied on account of allowing varying discharges to pass through the flume and slope of the flume adjusted

Fig. 1 Glass sided tilting flume used in the experimental study

as per the commonly found slope of the rivers in the region.

Also, D, b, μ and ρ for the given experiments were constant. Similarly, for open channel flow, Reynolds number ($R_e = \mu/\rho VD$) can be ignored. Hence, the functional relationship applicable for this study was reduced to:

$$\frac{d_s}{D} = \phi\left(\frac{d_5}{D}, \frac{d_{30}}{D}, \frac{d_{85}}{D}, f, C_u, Fr, \frac{y}{D}\right) \quad (3)$$

3 Experimental Work

The experimental set-up for the experiments, material used and the procedure adopted is given in the proceeding sections.

3.1 Experimental Setup

The aim of present study was to assess the gradation effect of the bed material on local scour by physical modelling. The experimental set-up used for the purpose consisted of a tilting flume 24 m long having a height of 0.6 m and a width of 1 m, located in the Fluid Mechanics Laboratory of Water Resources Department, National Institute of Technology, Srinagar. Figure 1 shows the glass flume used in the study. The flume had glass side walls and a metallic base with necessary arrangements for water supply regulation and measurements.

3.2 Test Material

The obstructions used were modelled in four different shapes of concrete material. The width of the obstructions were modelled as 1/10th of the channel

Fig. 2 Obstructions used in the experimental study

Table 1 Gradation parameters of the bed material (M_1–M_5) used in the study

Parameters	Material				
	M_1	M_2	M_3	M_4	M_5
d_5 (mm)	0.21	0.225	0.105	0.12	0.12
d_{10} (mm)	0.37	0.373	0.142	0.161	0.155
d_{30} (mm)	0.9	0.8	0.2	0.24	0.24
d_{50} (mm)	1.399	1.2	0.258	0.506	0.39
d_{60} (mm)	1.588	1.54	0.293	0.94	0.567
d_{85} (mm)	4.11	4.2	0.469	2.88	2.07
C_u	4.29	4.12	2.06	5.83	3.658
f	2.08	1.97	0.89	1.25	1.09

width i.e. the dimension of each obstruction facing the direction of flow was modelled to be about 10 cm. Chiew and Melville (1987) recommended on the basis of their studies that the obstruction diameter should not exceed 10% of the flume width. In the present study, this aspect of the Chiew and Melville study has been taken into account for more reliability of the results. A pictorial view of these shapes is shown in Fig. 2. The shapes selected for this study have been chosen keeping in view the most commonly encountered obstruction shapes in real life hydraulic structures e.g. Bridge piers, view-points constructed in the water bodies, etc.

Five types of bed material having varying gradation parameters were used. The bed material used represents the existing natural soil of actual river sites of Kashmir region. The soils were non-cohesive though a negligible amount of cohesive material may have been present. Study of the soils of a large number of river sites of the Kashmir valley was conducted, out of which five were selected on the basis of their gradation parameters variation. Five different sites selected were Khor (Sherabad); Sumbal; Ganderbal, Kunzer Nallah (Tangmarg), and Pampore of the Kashmir valley and were designated as M_1–M_5 respectively. The gradation

Fig. 3 Experimental set-up of the study

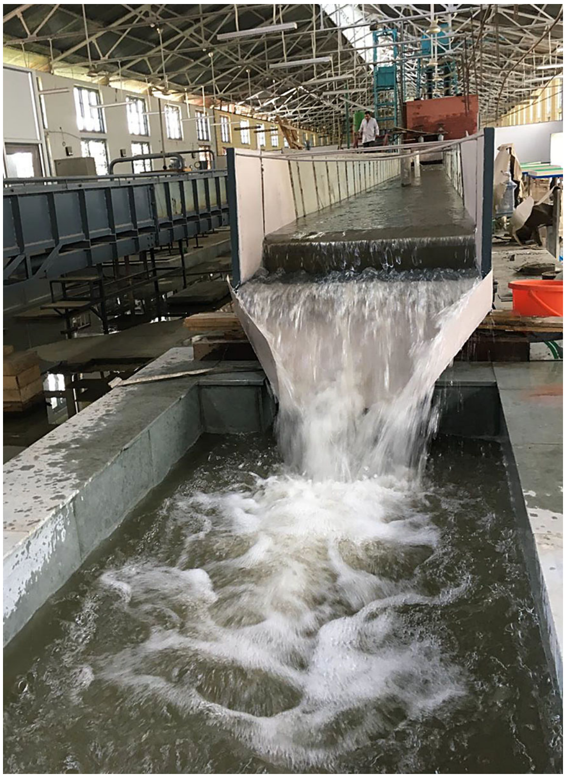

Fig. 4 Discharge measurement at the downstream using Sharp Crested Weir

Fig. 5 Experimental run for circular obstruction

parameters of the bed material used are given in Table 1.

3.3 Experimental Procedure

The experiments were carried out in the tilting flume described under the experimental set-up sub-heading. The middle section was chosen for placement of the obstructions so as to minimize the effect of inlet disturbances and tail gates. The flume was then filled with the above described bed material, up to a depth of 18 cm. The obstructions were fully penetrated in the bed material up to the flume floor so that the obstructions aren't destabilized with the increasing discharges and the local scour depth measurements are done accurately. The material was properly levelled in order to achieve results nearer to natural conditions of the river sites. At the entrance section of the flume boulders were placed on the sand bed to still the flow so as to add stability to the bed material and prevent it from getting washed away due to inlet turbulence. Figure 3 shows the experimental set-up used in the study. Water supply to the flume was regulated with the help of valves located in the supply line fed by a constant head tank. The slope of the flume was fixed at

Table 2 Values of the various flow parameters of the experimental study

S. no.	Head over weir h (m)	Discharge coeff. C_d	Discharge Q (m^3/s)	Flow depth y (m)
1	0.01	0.655	0.002495	0.018
2	0.02	0.655	0.006938	0.0275
3	0.03	0.655	0.012676	0.038
4	0.04	0.655	0.019493	0.048
5	0.05	0.655	0.02727	0.059

Fig. 6 Experimental run for hexagonal obstruction

Fig. 7 Experimental run for rectangular obstruction

Fig. 8 Experimental run for rounded obstruction

1 in 200 m which is one of the commonly found slopes in the study area.

3.4 Data Collection

The variables of the study include bed material, obstruction shapes and the discharge through the flume, the discharge was varied and scouring was measured for all discharges along the boundaries of the obstructions. Discharge was measured at the downstream end of the flume as shown in Fig. 4 with the help of a Sharp Crested Weir. Table 2 gives the values of the various flow parameters for the given experimental runs. After allowing the discharge through the flume, the scour process starts around the obstructions. Over the period of time, the scour hole gets filled with water along with the sediments and it appears opaque and hinders the scour hole measurement. This shortcoming was overcome by use of a laser meter which gives relatively more accurate values of scour depth with the varying discharges over the period of experimenting time. Scour depth was measured along the periphery of the obstructions and the maximum scour depth was considered. Figures 5, 6, 7 and 8 show a few experimental runs.

Table 3 Experimental results of local scour depth for varying shapes and bed material

Material	Discharge (cumecs)				
	Q_1	Q_2	Q_3	Q_4	Q_5
Local scour depths for circular obstruction for different discharges (m)					
M_3	0.041	0.079	0.093	0.122	0.124
M_5	0.034	0.059	0.084	0.105	0.122
M_4	0.014	0.042	0.071	0.08	0.1
M_1	0.008	0.03	0.066	0.073	0.094
M_2	0.007	0.03	0.057	0.076	0.089
Local scour depths for hexagonal obstruction for different discharges (m)					
M_3	0.025	0.042	0.088	0.118	0.128
M_5	0.021	0.047	0.062	0.108	0.099
M_4	0.017	0.041	0.057	0.091	0.086
M_1	0.017	0.035	0.052	0.072	0.082
M_2	0.017	0.029	0.055	0.083	0.059
Local scour depths for round-nosed obstruction for different discharges (m)					
M_3	0.045	0.075	0.078	0.086	0.087
M_5	0.022	0.046	0.072	0.092	0.093
M_4	0.017	0.045	0.059	0.062	0.068
M_1	0.008	0.03	0.041	0.052	0.067
M_2	0.006	0.011	0.023	0.038	0.055
Local scour depths for rectangular obstruction for different discharges (m)					
M_3	0.04	0.038	0.109	0.132	0.164
M_5	0.02	0.046	0.084	0.1	0.131
M_4	0.019	0.046	0.078	0.089	0.11
M_1	0.011	0.027	0.063	0.082	0.097
M_2	0.004	0.012	0.054	0.041	0.066

Table 4 Regression results for the models developed

Shape of obstruction	R^2 (%)	*p* value	Error (%)
Circular	98	6.818×10^{-16}	4.6
Hexagonal	89	1.456×10^{-7}	12.8
Rectangular	91	8.278×10^{-9}	14
Round-nosed	94	3.078×10^{-10}	7.4

4 Results and Discussion

The present study was conducted with an aim to relate the gradation parameters of the bed material with the local scour depth. The type of bed material has a prominent effect on the scouring. The bed material is differentiated on the basis of gradation parameters. Data collected from the experimental runs is given in Table 3.

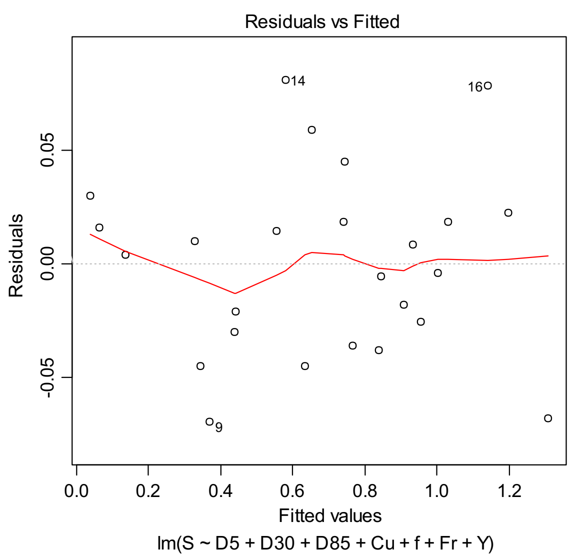

Fig. 9 Residuals versus fitted plot for circular obstruction

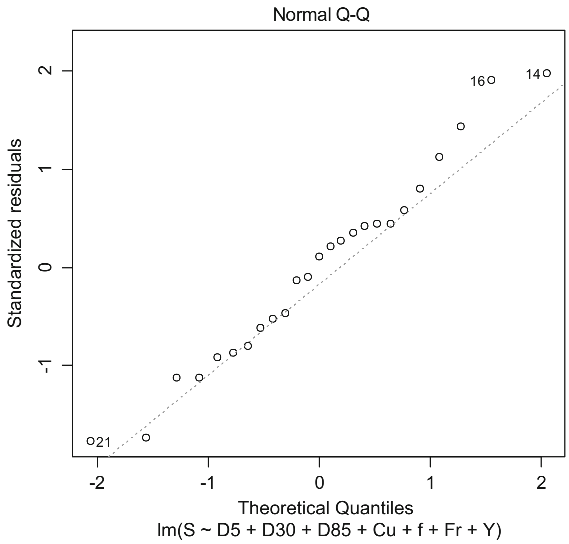

Fig. 10 Normal Q–Q plot for circular obstruction

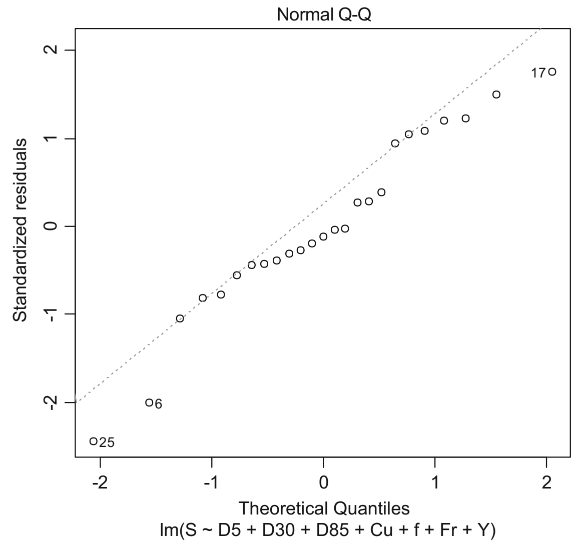

Fig. 12 Normal Q–Q plot for hexagonal obstruction

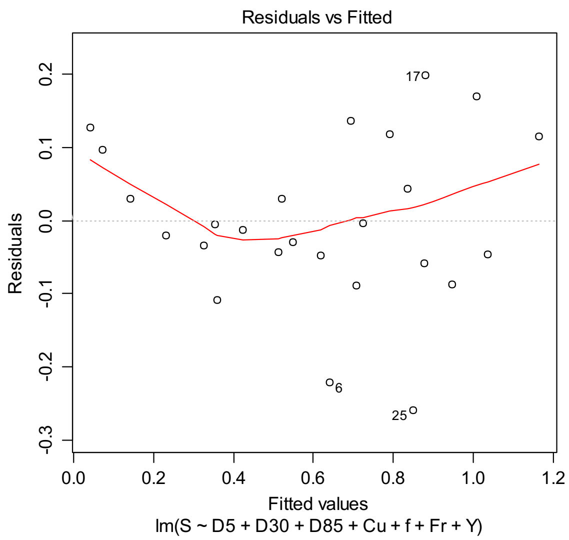

Fig. 11 Residuals versus fitted plot for hexagonal obstruction

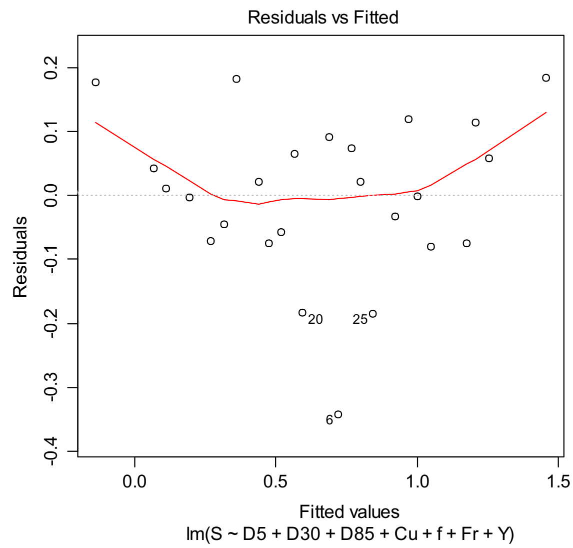

Fig. 13 Residuals versus fitted plot for rectangular obstruction

4.1 Models Predicted

The variables of the study include bed material, obstruction shapes and the discharge through the flume; the discharge was varied and scouring was measured for all discharges along the boundaries of the obstructions. Table 3 gives the experimental values of scour depths for combinations of five different bed materials (M_1–M_5), five discharges and four obstruction shapes (circular, hexagonal, rectangular and rounded). The experimental data was regressed to obtain the inter-relationships between the local scour depths and bed material parameters (d_5, d_{30}, d_{85} and C_u). For different shapes, multiple regression using "R" software yielded different models given in the following section. For circular obstruction, the model developed is given as Eq. (4).

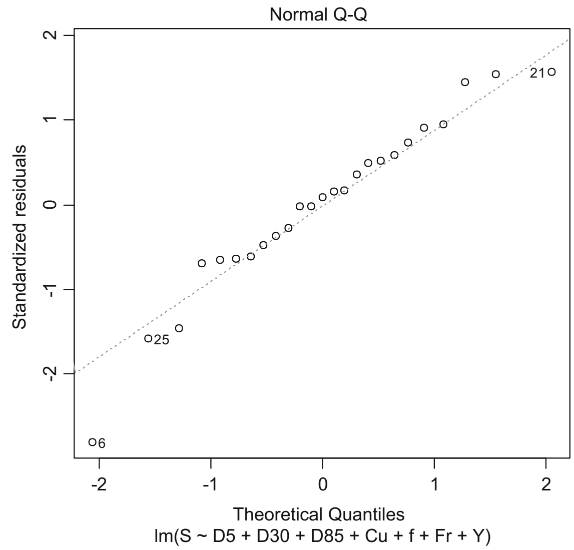

Fig. 14 Normal *Q–Q* plot for rectangular obstruction

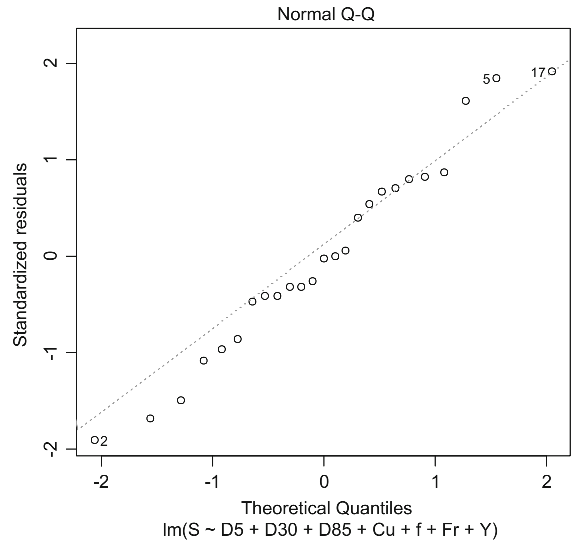

Fig. 16 Normal *Q–Q* plot for rounded obstruction

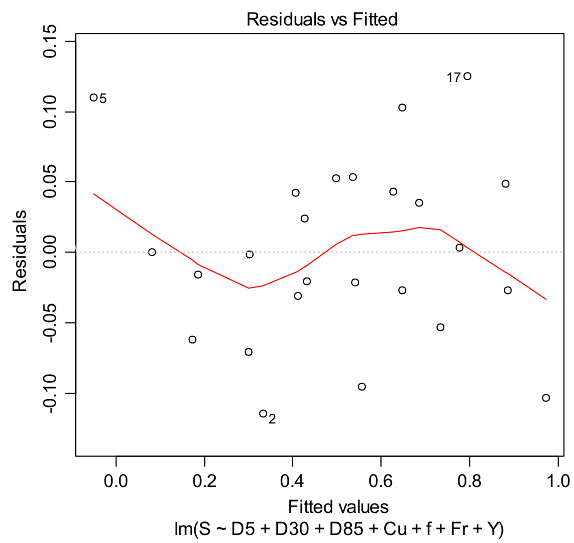

Fig. 15 Residuals versus fitted plot for rounded obstruction

$$\frac{d_s}{D} = 0.261 - 171.166\frac{d_5}{D} - 27.262\frac{d_{30}}{D} + 6.896\frac{d_{85}}{D} - 0.115C_u + 1.136Fr + 0.134\frac{y}{D} \quad (4)$$

In the equation, d_s is local scour depth in metres, d_5, d_{30} and d_{85} are the gradation parameters of the bed material in mm, y is flow depth in metres and D is obstruction diameter/width perpendicular to the direction of flow in metres. Similarly, Eqs. (5), (6) and (7) give the models for hexagonal, rectangular and rounded obstructions respectively.

Table 5 Parameters of the bed material used for validation

Material	d_5	d_{10}	d_{30}	d_{50}	d_{60}	d_{85}	C_u	f
M_v	0.19	0.35	0.77	1	1.2	4	3.43	1.76

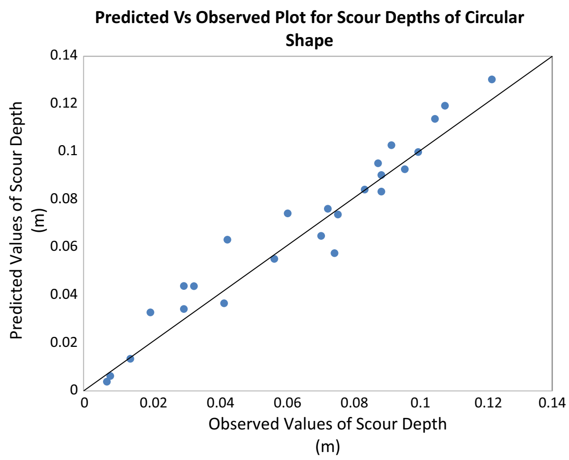

Fig. 17 Predicted versus observed plot for scour depths of circular shape

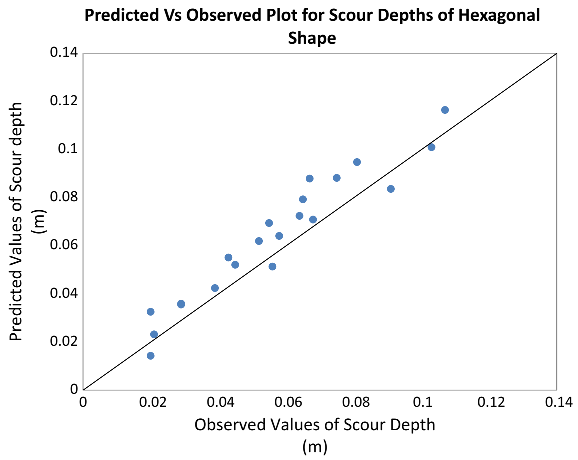

Fig. 18 Predicted versus observed plot for scour depths of hexagonal shape

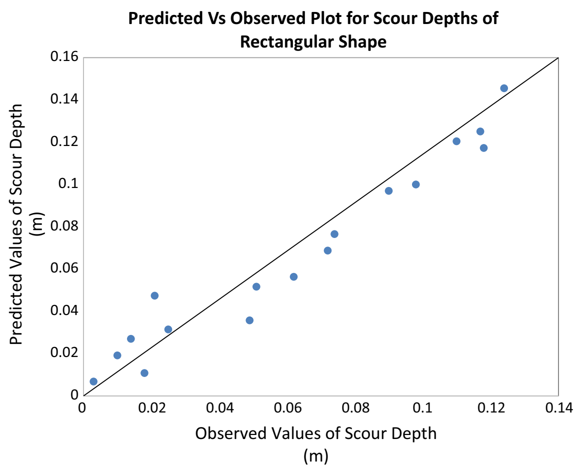

Fig. 19 Predicted versus observed plot for scour depths of rectangular shape

$$\frac{d_s}{D} = -0.086 - 58.022\frac{d_5}{D} + 2.669\frac{d_{30}}{D} - 5.387\frac{d_{85}}{D} - 0.0213\text{Cu} + 1.039Fr + 0.126\frac{y}{D} \tag{5}$$

$$\frac{d_s}{D} = 0.280 - 322.8\frac{d_5}{D} + 48.88\frac{d_{30}}{D} - 11.72\frac{d_{85}}{D} + 0.00777Cu + 0.210Fr + 0.225\frac{y}{D} \tag{6}$$

$$\frac{d_s}{D} = 0.504 - 346.99\frac{d_s}{D} - 3.808\frac{d_{30}}{D} + 7.010\frac{d_{85}}{D} - 0.094Cu + 1.034Fr + 0.063\frac{y}{D} \tag{7}$$

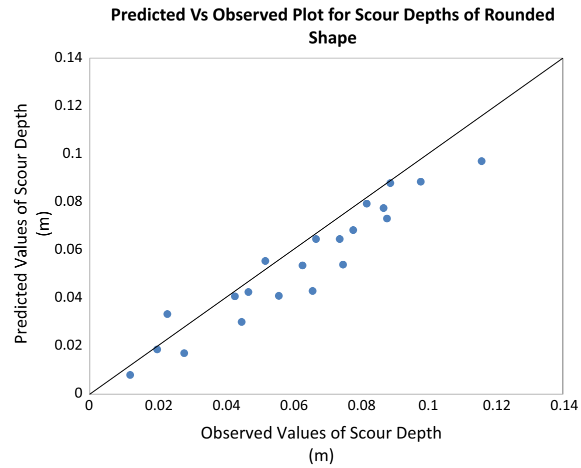

Fig. 20 Predicted versus observed plot for scour depths of round nosed shape

The summary of the models are tabulated in Table 4. The characteristics given in the table are clearly in the acceptable ranges. Figures 9, 10, 11, 12, 13, 14, 15 and 16 give the graphical presentations of the regression results for the four shapes; where, S represents d_s/D, D_5 is d_5/D, D_{30} is d_{30}/D, D_{85} is d_{85}/D, f is silt factor, Fr is Froude Number, C_u is Uniformity Coefficient and Y is y/D.

The results clearly indicate a substantive effect of d_5 on the local scour depth. Lesser the d_5 of the bed material for a constant obstruction width, greater is the local scour. Greater the d_5 of the bed material, lesser is the local scour. Similarly, an increase in the uniformity coefficient will decrease the local scour. Also, results indicate the effect of flow depth and Froude number; greater the flow depth, greater is the local scour; greater the Froude number, more is the local scour and vice versa.

4.2 Validation

The obtained regression models were tested for a separate set of experimental data collected in the laboratory with a different bed material (M_v) and compared to validate the models put forth. The gradation parameters of the bed material used for validation purpose are given in Table 5.

Figures 17, 18, 19 and 20 give the predicted versus observed plots for the models developed in the present study. The results were found in close approximation

Table 6 Variance and efficiency of the developed models

Shape	Mean observed d_s	Initial variance $\sum\left(d_{s(obs)} - d_{s(mean)}\right)^2$	Final variance $\sum\left(d_{s(obs)} - d_{s(pred)}\right)^2$	Efficiency %
Circular	0.06452	0.02777624	0.001963952	92.92
Hexagonal	0.046384	0.005373077	0.001085315	80
Rectangular	0.059869	0.023712471	0.001364563	92.24
Round-nosed	0.058444	0.011876444	0.001409293	88.13

and hence, the models put forth were inferred to be acceptable.

4.3 Efficiency

The models obtained in this study were further investigated for their efficiency and are given in Table 6. The efficiency was calculated as per Eq. (8).

$$Efficiency = \frac{(Variance_{Initial} - Variance_{Final})}{Variance_{Initial}} \times 100 \tag{8}$$

where, $d_{s(obs)}$ = observed local scour; $d_{s(mean)}$ = mean of observed local scour; $d_{s(pred)}$ = predicted local scour

5 Conclusions

On the basis of the study presented in this paper, four models were developed for four different shapes of the obstructions for estimation of their local scour depth with respect to the bed material gradation, Froude number and the flow depth. Exhaustive experimental runs were carried out to study the in-depth effect of gradation parameters on local scour depth while keeping other parameters such as slope (S), obstruction width/diameter (D), and channel width (b) constant for a given range of Froude number.

The experimental findings showed the dependence of local scour depth not only on the widely used d_{50} size of the bed material but also to its other gradation parameters, like d_5, d_{30}, d_{85}, C_u. The flow depth and the Froude number were also found to play an important role in the local scour phenomenon.

Equations (4)–(7) gives the models for four different obstruction shapes used in the study. The models presented were further investigated to check their efficiency which ranged between 80 and 92%. Also, these models were validated for a different bed material in the laboratory. The experimental results for this bed material were compared with those obtained using the above models for the said material and the shapes. It was found that the experimental and the calculated results for the said bed material were quite in tune with each other.

It is highly recommended to increase the scope of present study, by extending it to more variations of bed material and obstruction shapes. Another recommendation that is suggested is to check the effect of the ratio of obstruction length to its width.

Acknowledgements The paper presents part of the research work carried out by the author*, who receives a Doctoral Fellowship from the Ministry of Human Resources Development (MHRD), Government of India. The experimental work was carried out in the Fluid Mechanics Laboratory, National Institute of Technology, Srinagar, Jammu and Kashmir.

References

Akib S, Rahman S (2013) Time development of local scour around semi integral bridge piers and piles in Malaysia. World Acad Sci Eng Technol 79:2221–2226

Breusers HNC, Nicollet G, Shen HW (1977) Local scour around cylindrical piers. J Hydraul Res 15(3):211–252

Chiew WM (1984). Local scour at bridge piers. Ph. D. Dissertation, School of Engineering, New Zealand, Department of Civil Engineering, Report No. 355

Chiew YM, Melville BW (1987) Local scour around bridge piers. J Hydraul Res 25(1):15–26

Fakhri M, Dokohaki H, Eslamian S, Fazeli Farsani I, Farzaneh MR (2014) Flow and sediment transport modeling in rivers. In: Eslamian S (ed) Handbook of engineering hydrology, Ch. 13, Vol. 2: modeling climate changes and variability. Francis and Taylor, CRC Group, BocaRaton, pp 233–275

Heza YBM, Soliman AM, Saleh SA (2007) Prediction of the scour hole geometry around exposed bridge circular-pile foundation. J Eng Appl Sci 54(4):375–392

Hong J-H, Goyal MK, Chiew YM, Chua LHC (2012) Predicting time-dependent pier scour depth with support vector regression. J Hyrol 468–469:241–248

Johnson PA (1995) Comparison of pier-scour equations using field data. J Hydraul Eng 121(8):626–629

Landers MN, Mueller DS (1996) Channel scour at bridges in the united states. FHWA Report

Laursen EM, Toch A (1956) Scour around bridge piers and abutments, vol 4. Iowa Highway Research Board, Ames

Melville BW (1992a) Local scour at bridge abutments. J Hydraul Eng 118(4):615–631

Melville BW (1992b) Local scour at bridge sites. Report No. 117. University of Auckland, New Zealand

Melville BW, Coleman SE (2000) Bridge scour. Water Resources Publications, LLC, Colorado

Mir BH, Lone MA, Bhat JA (Forthcoming) Laboratory Investigation for development of local scour depth model for varying shapes of obstruction. Int J Hydrol Sci Technol

Mir BH, Lone MA, Bhat JA (2017) Effect of obstacle material type on local scour. Int J Adv Struct Geotech Eng 6:114–119

Mohammadzade Miyab N, Eslamian S, Dalezios NR (2017) River sediment in low flow condition, Ch. 21. In: Eslamian S, Eslamian F (eds) Handbook of drought and water scarcity, vol. 2: environmental impacts and analysis of drought and water scarcity. Francis and Taylor, CRC Group, BocaRaton, pp 387–408

Mohammed AT, Noor MJ, Ghazali AH, Yusuf B, Saed K (2007) Physical modelling of local scouring around bridge piers in erodible bed. J King Saud Univ Eng Sci 19(2):195–207

Moncada-M AT, Aguirre-Pe J, Bolivar JC, Flores EJ (2009) Scour protection of circular bridge piers with collars and slots. J Hydraul Res 47(1):119–126

Raudkivi AJ, Ettema R (1983) Clear-water scour at cylindrical piers. J Hydraul Eng 131(2):338–350