Local Scour Near Sluice Gate in Clay–Sand Mixtures

T. Divya, A. Sarkar, and S. N. Kuiry

Abstract Local scour near the hydraulic structures is a practical problem of engineering design. The foundation can be damaged due to excessive scour, which may lead to the failure of the structure. One such problem is the local scour in the vicinity of a sluice gate due to the formation of the water jet. Scour downstream of the sluice gate due to submerged jet has been well understood experimentally in cohesionless sediments. However, in the real life, the riverbed materials are not necessarily cohesionless. There are chances that it can be a mixture of cohesive and non-cohesive soils. The experiments were conducted for different proportions of clay–sand mixture in a laboratory flume. In each experiment, clay proportions were varied as 0, 15, 20, 25, 30, 35, and 40 percent by total weight of sediment mixture while other parameters were kept constant. Scour processes, parameters of maximum scour were presented. An attempt was made to propose the equation for maximum scour depth in clay–sand mixture bed by using dimensional analysis.

Keywords Clay–sand mixtures · Scour · Sluice gate · Wall jet · Sediments

1 Introduction

Local scour of the mobile sediment beds downstream of hydraulic structures is a problem of practical importance. The foundation can be undermined due to excessive scour, leading to the failure of the structure. When a jet of water issues through sluice gate over a sediment bed, the local shear stress increases that exceed the critical

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shear stress for incipient motion, which results in local scour downstream of the sluice gate [1]. Scour downstream of the sluice gate due to a submerged jet has been well-investigated experimentally due to its applicability in the design of hydraulic structures. Much work has been done on scour due to plane jets of cohesionless soil by [1–7]. Rajaratnam [3] and Rajaratnam and Macdougall [2] investigated the scour characteristics due to plane wall jet in sand bed using dimensional analysis. Hassan and Narayanan [4], Chatterjee et al. [1], and Dey and Sarkar [6] investigated the scour caused by wall jets issuing from the sluice gate for different lengths of the apron, sluice gate openings, and efflux velocities. Kells et al. [5] studied the effect of grain size on scour. Dey and Sarkar [6, 8] studied scour characteristics and similarity of scour profiles. Melville and Lim [7] investigated the factors influencing the scour and proposed equation for maximum scour depth. However, in the actual scenario, the riverbed material is not only sand but also a mixture of cohesive and non-cohesive soils [9]. Few investigations are available on scour by plane wall jets in cohesive soils [10–12]. Hamidifar and Omid [13], Rustiati et al. [14] studied the scour in clay–sand mixtures. They conducted experiments in clay–sand mixtures and concluded that increase of clay content significantly reduces the scour. Kho et al. [15] were seen an increment in the scour with increase of clay content. Very recently Jain et al. [16] Lodhi et al. [17] have studied the influence of cohesion on scour in clay–sand-gravel mixtures. It was seen in both the studies that the scour depth decreases drastically with the increase of percentage of clay from 10 to 50%.

In this context, it can be said that the research on scour due to horizontal wall jets over clay–sand mixtures beds is more emphasized to decide the clay behavior while scouring. In this paper, the experimental investigation of local scour in clay–sand mixture due to a 2D submerged horizontal wall jet issuing from a sluice opening is investigated. Observations of scour were made with respect to clay content. A simple relation for maximum scour depth is proposed based on dimensional analysis.

2 Materials and Methods

2.1 Flume Setup

Experiments were performed in a flume of dimensions 10m × 0.4m × 0.8 m. The schematic of the experimental setup is shown in Fig. 1. A sluice gate was used to produce a 2D horizontal submerged wall jet. The sluice gate opening was kept to 2.5 cm for all the runs. Apron length was kept zero. A sediment recess of 0.12 m deep and 1 m long was constructed in the middle of the flume at the downstream of sluice-gate. Tailwater depth in the flume was adjusted using a tailgate at the downstream end of the flume. The water supply into the flume was regulated using a valve. A flow meter was used to measure the discharge entering the flume. Flow depths were measured using a point gauge with an accuracy of ± 0.1 mm installed on a rail system over the side walls of the flume.

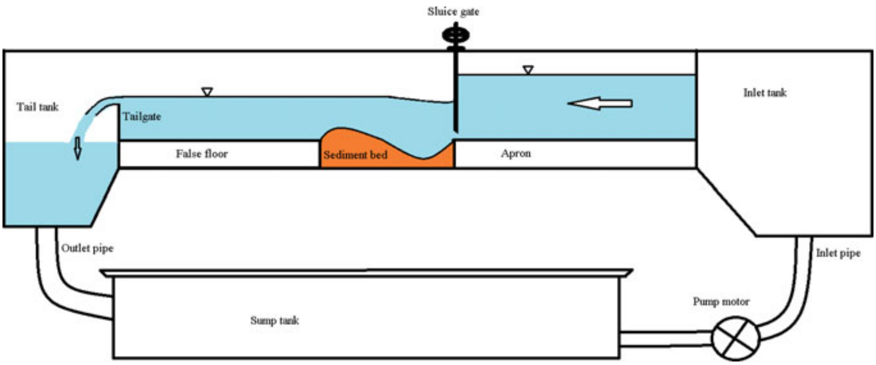

Fig. 1 Schematic side view of experimental setup (not to scale)

2.2 Sediment Bed Preparation

River sand and Kaolinite clay were used as sediments and their properties were tested as per Indian standard methods. The different properties of sediments found are listed in Table 1.

The median sizes of sand and clay were determined by sieve analysis and hydrometer analysis, respectively. The particle size of sand was determined by using sieve analysis, whereas hydrometer analysis was used for clay. Sediment beds were prepared by mixing water with clay and sand in the required proportions. The mixture was kept covered over 16 h to ensure the uniform distribution of moisture. The mixture was placed near the apron in three layers of approximately 0.04 m. Each layer was uniformly compacted throughout using the modified proctor hammer of weight 4.89 kg by with a free fall of 450 mm. The extra portion was trimmed off and leveled to a plain surface. Before starting of each run, the density, water content of the were determined for the compacted bed. A Hardson soil sampler was used to determine the bulk density with diameter of 5.4 cm and height 6 cm. The same soil

Table 1 Sediment properties

Property	Sand	Kaolinite
Median size, d_{50} (mm)	0.519	0.012
Geometric standard deviation, σ_g	1.78	–
Specific gravity, G	2.57	2.4
Plastic limit, PL (%)	–	32
Liquid limit, LL (%)	–	46
Plasticity Index, PI (%)	–	14
OMC (%)	–	31
$\gamma_{d\max}$ (κN/μ^3)	–	14.2

sample was used to determine the water content using the oven-dry method to ensure the water added while mixing process.

2.3 Experimental Schemes

Initially, the flume is filled with the water that will avoid undesirable erosion due to sudden non-uniform jet. A tailgate was operated to maintain a desired tailwater depth. The water was slowly issued to the flume to a desired discharge value. As soon as the flow reached the sluice gate, the bed geometry started changing, and the scour was initiated near the edge of the apron. The profiles of scour were drawn on a transparent graph sheet that is attached to the flume with glass wall at different times. The scour profiles were overserved to be two-dimensional. After 9 h of the scour initiation, the change in maximum scour depth was noticed to be insignificant. Therefore, the experiments were run for period of 12 h. Table 2 presents the observed experimental flow conditions, and maximum scour depths. The nomenclature KISxx represents xx% of kaolinite clay in sand.

3 Results and Discussions

3.1 Evolution of Scour

During the scour process, the qualitative observations were made visually. When the water issues through sluice opening, the conversion of potential energy to kinetic energy takes place, a part of this energy gets dissipated on the apron through the hydraulic jump, and the other part causes the flow separation at the edge of the apron due to which sediment particles lift up. The scour initiation was observed at the edge of the apron, where the jet's action created a hole. Cohesionless bed achieved 90% of maximum scour depth after 1 h; but in clay–sand mixtures, it was observed between 3 and 6 h.

3.2 Equilibrium Bed Profiles

Figure 2a–d shows the quasi-equilibrium bathymetry of equilibrium scour profiles. It is well known that the scour profiles are two-dimensional in cohesionless sediments across the width of the flume ([4–6, 18]), which is also seen in the present study (Fig. 2a). Scour profiles in clay–sand sediments are also observed to be two-dimensional for clay content range used. Dune height formed is not very uniform

Table 2 Experimental data

Run no.	Soil type	w %	d (g/cc)	γ (g/cc)	τ (N/cm^2)	Q (L/s)	U_o (m/s)	$F_{r,jet}$	T_w (cm)	h (cm)	y_{meq} (cm)
1	Sand	–	1.608	1.907	0.8	5.64	0.56	1.08	11.0	12.1	9.30
2	KIS15	10.08	1.347	1.609	1.33	5.38	0.54	1.07	11.1	12.2	10.15
3	KIS20	9.53	1.586	1.892	4.13	5.38	0.54	1.08	11.0	12.0	9.98
4	KIS25	9.69	1.579	1.936	11.4	5.22	0.52	1.08	11.0	11.9	11.08
5	KIS30	11.63	1.522	1.601	6.33	5.36	0.53	1.08	11.0	12.0	11.00
6	KIS35	10.97	1.586	1.921	4.20	5.28	0.53	1.08	11.1	12.3	11.45
7	KIS40	11.85	1.926	2.190	4.33	5.35	0.53	1.07	11.1	12.3	11.86

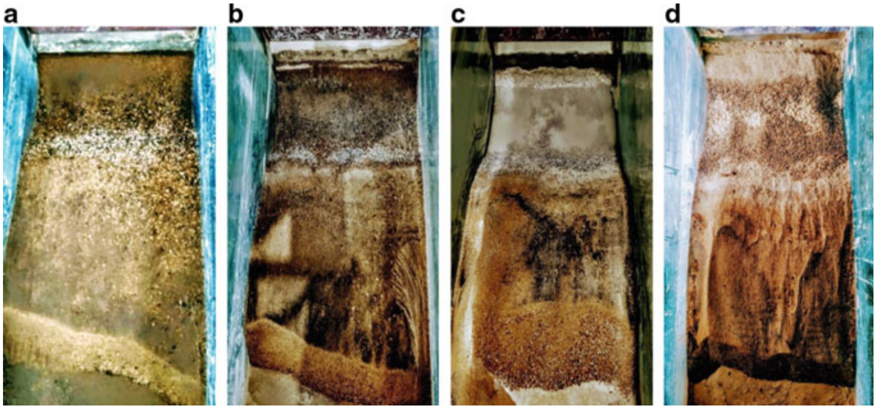

Fig. 2 Equilibrium scour profiles **a** sand **b** KIS15 **c** KIS25 **d** KIS40

across the width. However, the scour behavior after 40% clay is not investigated herein.

3.3 Effect of Clay Properties on Scour

Figure 3 shows the effect of clay content (cc) on dimensionless maximum equilibrium scour depth ($\hat{y}_{\mathrm{me}}$). A linear behavior was seen in scour depth with the increment of clay proportion in the present study (Fig. 3a), which was similar to the observation of Kho et al. [15] for the case of bridge pier in clay–sand mixtures of kaolinite clay (Fig. 3b). It was explained that the lattice structure of the clay expands, and bonds between the clay particles breakdown with passage of time in the water, that causes dispersion. Hamidifar and Omid [19] carried similar study downstream of an apron for clay–sand mixtures using kaolinite clay. Their study reported that up to 15% of clay, the scour depth increases, then decreases subsequently (Fig. 3c). It was seen that at 40% clay, reduction in maximum scour depth is 80% at equilibrium compared to cohesionless sediments. It was said that the initial increment of scour depth for low percentages of clay is due to the lubrication effect of clay particles. The clay plates break and move farther due to dispersion, which increases scour. The linear regression equations obtained for the present study as well as for Kho et al. [15] and Hamidifar and Omid [19] study, respectively, are

$$\hat{y}_{\mathrm{me}} = 0.026\mathrm{CC} + 3.67 \tag{1}$$

$$\hat{y}_{\mathrm{me}} = 0.031\mathrm{CC} + 1.53 \tag{2}$$

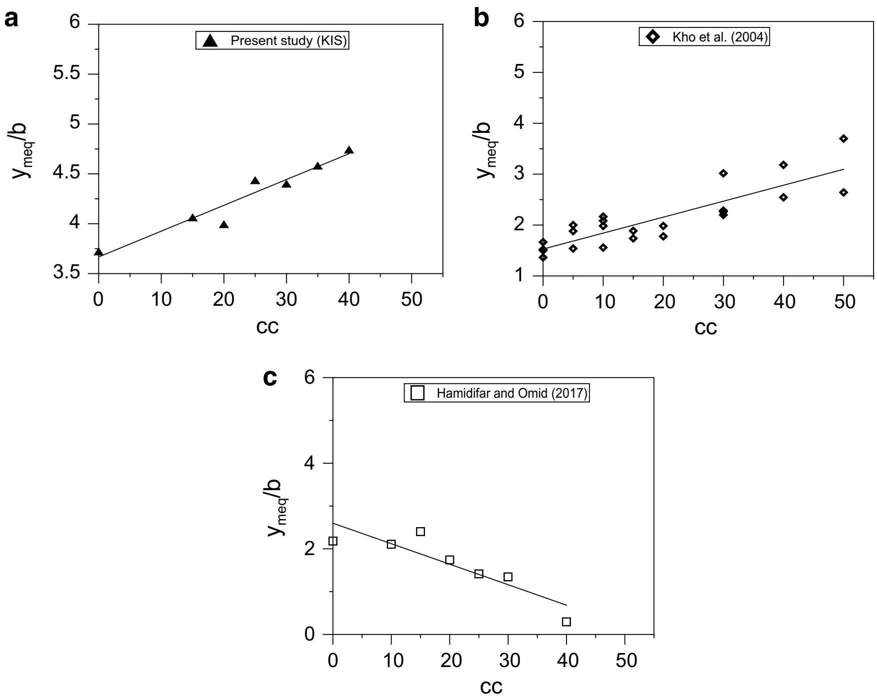

Fig. 3 Variation of dimensionless maximum equilibrium scour depth with clay content **a** present study **b** Kho et al. [15] and **c** Hamidifar and Omid [19]

The coefficients of determinations (R^2) 0.93 and 0.74 are given in Eqs. (1) and (2), respectively. However, the data points are minimal in the present study. Ansari et al. [20] observed that there is no resistance to scour up to 20% clay in which cohesion and clay particles are easily washed away. The results in the present study were coinciding with Kho et al. [15] observations but they were contradicting the observations made by Hamidifar and Omid [19]. However, for lower clay contents near to 20% overall behavior of clay is same. We cannot justify the behavior of clay in these ranges as the sand content dominates. The properties of clay play a different role in eroding the bed. Numerous properties can characterize the behavior of scour in sediments with cohesive soils. The bonding between the particles can vary depending on clay mineral present and it increases with the plasticity of clay ([18, 19]). Erosion of clay particles is less in case of clay with low sodium absorption ratio [23]. The high cation exchange capacity of clay possesses high cohesion [24]. Also, the increase in salinity levels increases erosion rates [25]. Further investigation is required to relate these parameters with scour.

3.4 Time Variation of Scour Depth

The maximum scour depth is considered to be affected by the following independent variables

$$y_m = f(U_0, \text{cc}, T_w, b, d_{50}, \rho, \rho_s, \tau_b, g, \mu, w, t) \quad (3)$$

Here, y_m is maximum scour depth, U_0 is velocity of jet coming from sluice opening, cc is clay content, T_w is tailwater depth, b is sluice gate opening, d_{50} median size of sediment, r is density of water, r_s is sediment density, t_b is bed shear stress, g is acceleration due to gravity, w is initial water content, μ dynamic viscosity of water, and t is time.

Applying Buckingham π-theorem with repeating variables as b, U_0, and r, the following set of dimensionless parameters are obtained.

$$\hat{y}_m = \left(\frac{L}{b}, \frac{T_w}{b}, \frac{d_{50}}{b}, \frac{\tau_b}{\rho U_0^2}, \frac{1}{F_r^2}, \frac{\rho_s}{\rho}, \frac{1}{R_e}, \text{cc}, w, \hat{t}\right) \quad (4)$$

where F_r is jet Froude number, R_e is jet Reynolds number. Since the parameters L, T_w, b, and w were kept constant, the terms L/b, T_w/b, and w are eliminated. The median size is dominated by sand, and the effect of clay size is ignored considering the constant size of sediment. As the same size of sand is used for all the runs, the term d_{50} is eliminated. Also, from the analysis there is no correlation found between shear, clay content, and scour depth. The bed shear variation with time is unknown after issuing the flow, and the effect of shear stress is neglected for the present study. F_r is maintained constant. The effect of r_s is negligible as uniform compaction was given for all the runs. R_e, effect is negligible for turbulent flows in open channels and is eliminated. The final equation reduced to

$$\frac{y_m}{b} = \left(\text{cc}, \hat{t}\right) \quad (5)$$

Nonlinear regression analysis is performed using the experimental data to obtain the time variation of maximum scour depth. Equation (5) yields the following relation for non-dimensional maximum scour depth for the present study.

$$\hat{y}_m = 0.57\text{cc}^{0.22}\hat{t}^{0.27} \quad 15 \le \text{cc} \le 40 \quad (6)$$

R^2 value of 0.76 obtained for Eq. (6). Figure 4 shows the line of agreement between the observed and predicted data. The standard error of 0.69 obtained for Eq. (6). Therefore, the above equation can satisfactorily describe the experimental data. The influence of clay content alone is considered from 15 to 40% for the given flow conditions. The scour prediction equations generally yield conservative estimates. Thus, Eq. (6) can be used for the estimation of time variation of scour depth for given flow conditions and properties of sediments applied.

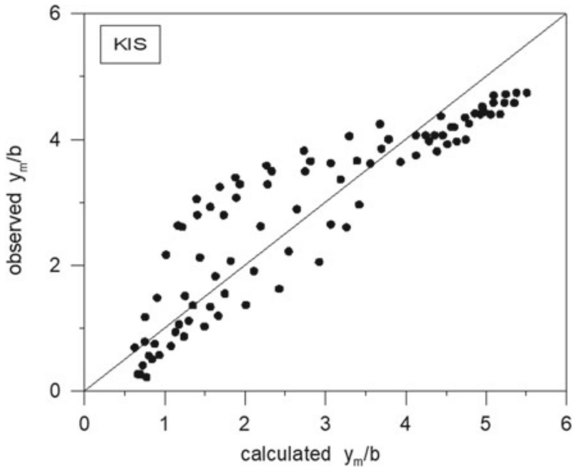

Fig. 4 Comparison of maximum scour depth observed and calculated using Eq. (6)

4 Conclusions

The experiments on scour producing by a submerged plane wall jet in clay–sand mixtures downstream of a sluice gate were performed using various clay contents (varied from 15 to 40%) using kaolinite clay as a mixture with sand. The presence of clay considerably influences the magnitude of scour. The following conclusions are drawn from the analysis of the results of the present study:

- For clay–sand mixtures, erosion characteristics differ in several ways in comparison with cohesionless sediments. However, for clay contents near to or around 20%, the properties of scour are similar in comparison with non-cohesive soils.
- The scour profiles obtained are two-dimensional for both cohesionless soils and clay–sand mixtures.
- The presence of clay can increase or decrease the scour depth depending on chemical reaction of the clay property with water. The variation of maximum scour depth with clay content was seen which is agreeing the results of Kho et al. [15] study but contradicting the results of Hamidifar and Omid [19] case. The attention is more emphasized on chemical properties of clay which plays very important role.
- The equation based on the dimensional analysis to determine the temporal variation of scour depth in two clay minerals is proposed to have a general understanding of clay behavior, although it is valid for the provided features of soil and flow conditions.
- However, it is recommended that experiments need to be conducted in natural clays obtained from the fields. The electrochemical properties and mineralogical composition affecting the scour in cohesive soils require greater attention.

Notations

b Sluice opening size.
cc Clay percentage.
d_{50} Median size of sediment.
F_j Jet Froude number.
Q Discharge.
t Time.
T_{w} Tailwater depth.
h Upstream water depth.
U_{o} Mean jet velocity at vena contracta.
y Vertical dimension of scour at time t.
y_{m} Maximum scour depth at time t.
y_{me} Maximum scour depth at semi-equilibrium state.
$\hat{y}_{\mathrm{me}}$ y_{me}/b.
$\hat{y}_{\mathrm{m}}$ y_{m}/b.

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