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Experimental study of local scour around a vertical pier in cohesive soils

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Bridge pier;
Froude number.

Abstract. Estimation of maximum scour depth is an important factor in designing structures that are embedded in rivers. Using a hydraulic model, the mechanism of local scour around bridge piers embedded in cohesive soils has been studied. Experiments were performed in a flume; 22 m long, 0.77 m wide and 0.60 m deep, with a pier of 0.1 m in diameter. Also, three types of cohesive soil with different percent clay were used. While changing parameters, such as current velocity, flow depth, initial moisture content, clay percentage, and undrained shear strength, in each experiment, the scour depths were measured. The measured data were adjusted by hyperbolic law. Using dimensional analysis, a relationship between the ultimate scour depth and effective parameters was developed. Finally, the ultimate scour depths obtained by the experiments were compared with those calculated by empirical equations.

1. Introduction

Accomplished investigations into the mechanism of local scour around bridge piers show that the approaching flow to piers produces a stagnation pressure gradient, due to the generation of a vertical velocity profile. This approaching flow, which acts as a down flow, is responsible for local scour around bridge piers. Partheniades [1], Partheniades and Paaswell [2], and Christensen and Das [3] carried out experiments on cohesive soils and found that the rate of scour in these soils depended on the percent of clay and initial compaction, initial water content and shear strength. Clark et al. [4] and Melville [5] reported that the equilibrium scour depth is about 1 to 2.4 times the diameter of the bridge piers. Investigations by Kamphuis and Hall [6] and Herobich et al. [7] made it clear that the existence of electro-chemical and chemical forces among the colloid particles of clay causes the scour phenomena to be complicated. According to Parchure and Mehta [8], salinity has a major influence on resistance, and, for a higher salinity, a higher resistance to erosion can be expected. Ting et al. [9] used a physical model, which included five piers of different diameter, three cohesive and two sandy soils, in order to investigate the local scour around bridge piers. Results showed that at a low Reynolds number, scour depths around piers are the same. However, at a large Reynolds number, the resulted scour depths at the side of the piers were deeper than those in front of the piers. Ansari et al. [10] used the results of experiments on cohesive soils of different clay percentages, and presented a mathematical model as a function of the physical properties of soils to evaluate scour depth. Rambabu et al. [11] investigated the ultimate local scour in a cohesive soil with 44% clay and found that the ultimate local scour depth depends on many parameters, including Froude number, pier Reynolds number, critical shear stress, and saturated undrained shear strength. Recently, Debnath and Chaudhuri [12] investigated the effects of different parameters on depth scour in cohesive soils. They

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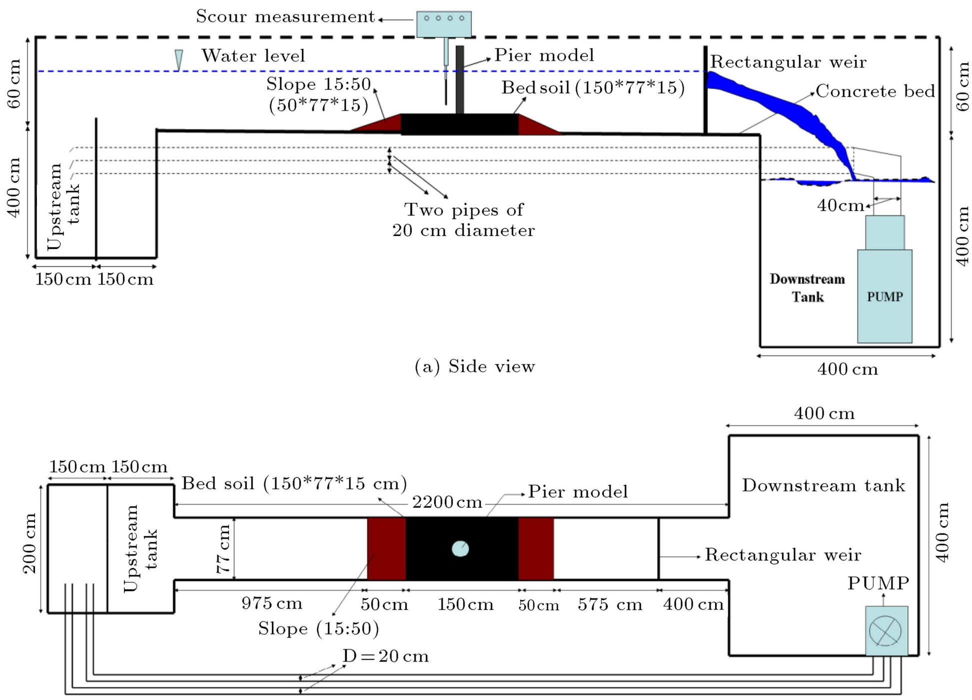

(b) Top view

Figure 1. General view of experimental model (not to scale).

presented empirical equations based on the properties of cohesive soils. In this study, laboratory experiments were carried out using three types of cohesive soil to investigate the influence of undrained shear strength, flow characteristics, and initial moisture content on the ultimate scour depth. Finally, using measured data, linear and non-linear models were developed to estimate the ultimate scour depths. Comparisons were made with eight equations, which were presented in two groups of empirical equation. The first group, related to the pier scour in cohesive soils, includes Ansari et al. [10], Rambabu et al. [11], Debnath and Chaudhuri [12], and the other group of equations, applied to pier scour in non-cohesive soils, includes Shen et al. [13], Johnson [14], USDOT [15], and Melville [16].

2. Model description

Experiments were performed on a rectangular cemented channel measuring 22 m in length, 0.77 m in width, 0.6 m in depth and a longitudinal slope of 0.005, located in the hydraulic lab of the Civil Engineering Department at Shahid Bahounar University, Kerman, Iran. Two storage tanks were located at two ends of the channel. The first tank with $4 \times 3 \times 2$ m^3 capacity and the second tank with $4 \times 4 \times 4$ m^3 capacity were located at the upstream and downstream of the channel, respectively. A centrifugal pump was installed in the second storage tank to recirculate water through two pipes, 0.2 m in diameter, to the upstream tank. Discharge control was performed by gate valves which were installed on the pipes. The first tank was divided into two sections, which were connected to each other from the bottom. Pumped-water discharged to the first section of this tank and entered the second section from the bottom to achieve uniformity of flow (Figure 1). The model pier, built of cement, 0.1 m in diameter and 0.6 m in height, was installed in the center of the channel. Discharge was measured using a calibrated rectangular weir, which was installed at the downstream end of the channel.

3. Preparation of soil sample

Two types of soil were collected from two regions of Kerman, Mohyabad and Shahid Bahonar University Farm. The hydrometer model, 152 H, was used to determine the texture of these soils. Results showed 52 percent clay from Mohyabad soil and 12 percent from the university farm soil. These soils were mixed with 100, 90 and 80 percent of Mohyabad soil and 0, 10 and 20 percent of university farm soil, respectively. Eventually, three types of soil were generated with 52, 41 and 34 percent clay. The first clay soil, with 52 percent clay, had a specific gravity, $\gamma = 20.1$ kN/m^3, natural moisture content, NMC = 37.1%, liquid limit, $W_L = 45\%$, plastic limit, $W_P = 19\%$, plasticity index, $PI = 26\%$, consistency index, $I_C = 0.3$, and mean diameter, $D_{50} = 5.5 \times 10^{-3}$. The other properties of clay soils are presented in Table 1.

Table 1. Physical properties of soils.

Soil properties	**Soil types**		
	No. 1	**No. 2**	**No. 3**
Specific gravity (kN/m^3)	20.1	18.5	17.3
Sand (%)	21	30	41
Silt (%)	27	29	25
Clay (%)	52	41	34
D_{50} (mm)	0.0055	0.012	0.037
Natural moisture content (%)	37.1	30.4	24.3
Plastic limit (%)	19	15	13
Liquid limit (%)	45	35	27
Plasticity index (%)	26	20	14
Consistency index	0.3	0.23	0.19

4. Experiments

To prepare the model for experiments, some water was added to each soil sample and covered by a plastic sheet for 24 hours to supply the required moisture content. The channel bed was covered with the moist soil, 1.5 m long and 1.5 m thick, and compacted. A hole was dug at the middle of the channel and a pier of 0.1 m diameter was installed in this hole. Later, the surface of the bed soil was compacted by a metal plate to remove air voids. Two ends of the compacted bed were regulated for a slope of 0.15 to 0.5 m (V&H) to prevent flow turbulence during experiments. Before each experiment, a small mass of moist soil was cut and the initial moisture content was measured. Also, the undrained shear strength of this was measured using a direct shear test. For each experiment, a steady flow condition was established. Current velocity and bed elevation were measured by the current meter (Kenek VOA-101 type) and scour sensor (Kenek WH-406 type), respectively.

Using the Kenek VOA-101 current meter, flow velocity was measured at two depths (0.2 and 0.8 flow depth), two meters upstream of the pier. The average of these two measured velocities was considered as the flow velocity. The maximum scour depth around the pier was measured 4 hours past the beginning of the experiment. To access more accurate results, each experiment was carried three times under constant flow depth and approach velocity.

The average of the three measured data was used in further computations. In cohesive soils, ultimate scour depth occurred after a long time. Briaud et al. [17] carried out their experiments in a flume test with a circular pier and continued for 400 hours. They had not observed the ultimate scour depth around the pier. Ting et al. [9] performed their experiments in clay soils and continued in the range of 16 to 227 hours; they could not reach the ultimate scour condition. Rambabu et al. [11] carried out their experiments in cohesive soil for 4 hours and measured the scour depth; they used the hyperbolic law for correction of the measured local scour depths. Hence, in the present study, the duration of each experiment was considered to be 4 hours, then, the maximum scour depths were measured and corrected using the hyperbolic law. Similar approaches can be found in many fields of engineering. For example, in geotechnical science, Junhwan and Jongwan [18] estimated the bearing capacity for multiple footing in sand using hyperbolic law, under the assumption that unit load and settlement typically follow a power or an exponential equation, as described by Ghionna et al. [19] and Fonseca [20].

Based on the hyperbolic law, the relationship between measured local scour depth (d_s) and time (t) is:

$$d_S(t) = \frac{t}{a + bt}, \tag{1}$$

and the ultimate scour depth (d_{su}) is:

$$d_{su} = \lim_{t \to \infty} (d_s) = \frac{1}{b}, \tag{2}$$

where $d_s(t)$ is the scour depth at instant time (t) from the beginning of the experiment, $1/a$ is the rate of initial scour ($t = 0$), which depends on hydraulic conditions and soil texture, and $1/b$ is the ultimate scour depth. Development of scour as a function of time for soil no. 1 and four experiments are presented in Figure 2. For each curve of Figure 2, time values (t) are divided by their correspond scour depths (d_s) to obtain (t/d_s) at each time (t). The relation between t/d_s and t is illustrated in Figure 3. In each line of Figure 3, the inverse slope is the ultimate scour depth and the intercept of the y-axis is the initial rate of scour. The validity of rectangular hyperbola between scour depth (d_s) and time (t) was checked by Rumbabu et al. [11]. Results show that the relationship between t/d_s and t is essentially a straight line, thus, confirming the application of a rectangular hyperbola formula.

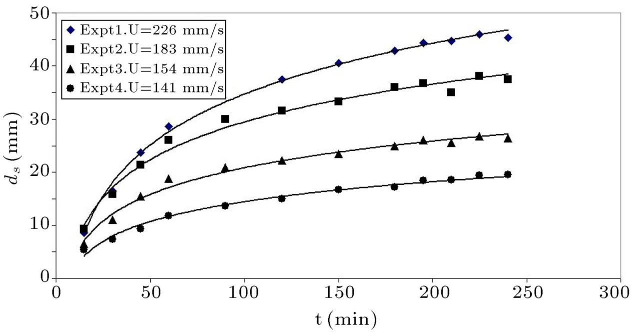

Figure 2. Time development of the scour depth in the first type soil (52% clay).

Table 2. Experimental results.

Type soil	Experiment no.	Flow depth y_0 (mm)	Flow velocity U (mm/s)	Initial moisture content IMC (%)	Undrained shear strength S_u(kPa)	Observed scour depth d_s (mm)	Ultimate scour depth d_{su} (mm)
1	1	300	226	29.3	15	45	60
1	2	350	183	20.4	21.2	37	45.5
1	3	400	154	17.3	27.8	26	32
1	4	450	141	12.3	35.6	19	23.85
2	1	300	226	23	11.2	54	77.1
2	2	350	183	20.2	16.1	48	65.1
2	3	400	154	15	18.5	33	40.8
2	4	450	141	13.7	24.2	25	34.2
3	1	300	226	33.1	8.3	62	93
3	2	350	183	25.9	11.5	56	77
3	3	400	154	17.8	17.2	45	64
3	4	450	141	10.7	21.5	40	49.5

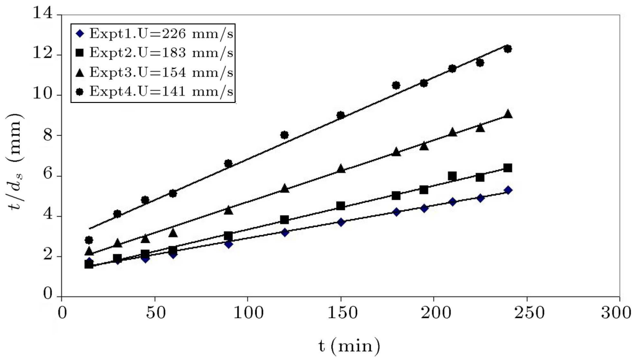

Figure 3. Estimation of the ultimate scour depth based on hyperbolic law.

5. Dimensional analysis

The parameters that affect scour include the properties of the flow and the physical properties of soil. Laursen [21], Bata [22], Chitale [23], Johnson [14], and the United States Department of Transportation [15] suggest that the scour depth can be stated as a function of d_{su}/y_0 with related parameters. From the experiments, the following function can be defined for ultimate scour depth:

$$F(\rho_w, \rho_m, y_0, \mu, D, C, \text{IMC}, S_u, U, g, d_{su}) = 0, \tag{3}$$

where ρ_w, ρ_m, y_0, μ, D, C, IMC, S_U, g, and d_{su} are density of water, density of bed soil, flow depth, fluid dynamic viscosity, pier diameter, clay percentage, initial moisture content, undrained shear strength, flow velocity, accelerated gravity, and ultimate scour depth, respectively.

Using dimensional analysis and selecting U, D, and ρ_m as repeating variables, we get Eq. (4):

Table 3. Results of non-dimensional parameters.

$S_u/\gamma.y_0$	C (%)	Re	Fr	d_{su}/y_0
2.48	52	22600	0.131	0.2
3.01	52	18300	0.098	0.13
3.45	52	15400	0.077	0.08
3.93	52	14100	0.067	0.05
2.01	41	22600	0.131	0.26
2.48	41	18300	0.098	0.19
2.5	41	15400	0.077	0.1
2.9	41	14100	0.067	0.07
1.6	34	22600	0.131	0.31
1.9	34	18300	0.098	0.22
2.48	34	15400	0.077	0.16
2.76	34	14100	0.067	0.11

$$f(\text{IMC}, \frac{d_{su}}{y_0}, \frac{S_U}{\gamma.y_0}, \text{Fr}, \text{Re}, C) = 0, \tag{4}$$

where d_{su}/y_0, $S_U/\gamma.y_0$, Fr, and Re are the dimensionless ultimate scour depth, dimensionless undrained shear strength, Froude number and Pier Reynolds number, respectively. Results of scour experiments are shown in Table 2. In addition, Results of non-dimensional parameters are presented in Table 3.

The Re number ($\rho_w VD/\mu$) is not an important parameter if the viscous effects are taken into consideration, but the Re influences the frequency of vortex shedding [24]. The Re number is not a significant parameter if the flow around the pier is fully turbulent and is generally neglected in pier scour studies [25]. In the present study, the range of Re is from 22600 to 14100, which is located in Debnath, and, in Chaudhuri [12], the range of the Re number is from 59722 to 94272. As a result, the Re number may not be an important parameter in local scour in cohesive materials.

$$\frac{d_{su}}{y_0} = f(\frac{S_u}{\gamma \cdot y_0}, \mathrm{Fr}, C, \mathrm{IMC}). \quad (5)$$

6. Discussion on parameters affecting the scour

In this section, effects of different parameters on scour depth are investigated based on dimensional analysis.

6.1. Undrained shear strength (S_u) of bed soil

Some of the physical properties of soil, such as consistency index, plastic and liquid limits, and moisture content, can be an important factor in estimating shear strength [26,27]. Ting et al. [9] and Rambabu et al. [11] used soft clay soils with a consistency index smaller than 0.5 in their local experiments. Hence, in this study three soft clay soils, with consistency indexes of 0.3, 0.23 and 0.19, were used. Variations of initial moisture content at the beginning of each experiment caused the undrained shear strength to change. Variations of ultimate scour depth (d_{su}/y_0) against the undrained shear strength (S_u) of bed soil are shown in Figure 4. From this, it can be found that increasing the undrained shear strength of soil causes a decrease in the ultimate local scour depth. Using data of Figure 4, by regression analysis, the following equation resulted:

$$\frac{d_{su}}{y_0} = 5.29\,(S_u)^{-1.27}. \quad (6)$$

This equation can be applied to soft clay soils with a consistency index smaller than 0.5. Rambabu et al. [11] experiments resulted in a power equation for these

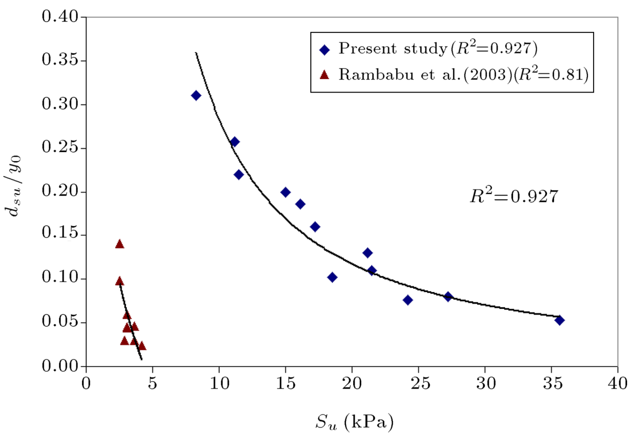

Figure 4. Comparison of d_{su}/y_0 as a function of S_U based on present data (unsaturated soil) and Rambabu et al. (2003) (saturated soil).

two parameters in saturated clay soil. The resulted correlation coefficient was 0.81, while, in the present study, it is 0.927. Further, using the experimental data of Debnath and Chaudhuri [12], Rambabu et al. [11], and Molinas et al. [28], the dimensionless scour depth is plotted against dimensionless undrained shear strength in Figure 5. As illustrated in this figure, Molinas et al. [28], and Debnath and Chaudhuri [12] equations, which are proposed for unsaturated clay soil conditions, are in general agreement with the present study. These comparisons show that plots can be used for the validation of field data from similar types of unsaturated bed material.

6.2. The Froude number (Fr)

Two parameters that affect the scour include the current velocity and the flow depth, which are known as the Froude number. Figure 6 demonstrates the variation of ultimate scour depth as a function of the Froude number for all three soils. This figure shows that scour depths increase by increasing the Froude number. Also, for a specified Froude number, the scour depth decreases by increasing the clay percentage of the soil. Comparison of d_{su}/y_0 as a function of Fr, based

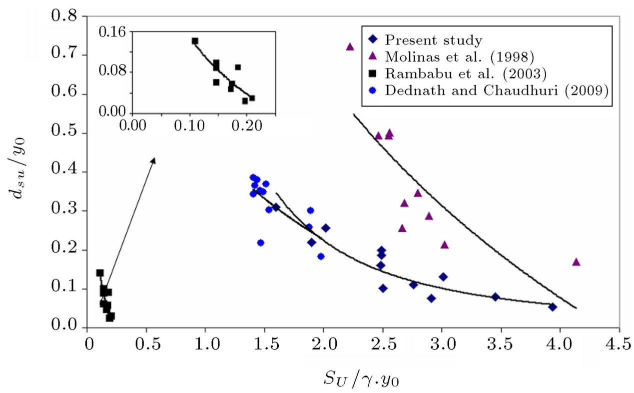

Figure 5. Comparison of d_{su}/y_0 as a function of $S_U/\gamma.y_0$ based on present data and data from Molinas et al. (1998), Rambabu et al. (2003), and Debnath and Chaudhuri (2009) (clay soil of river Ganges) (35% $< C <$ 100%).

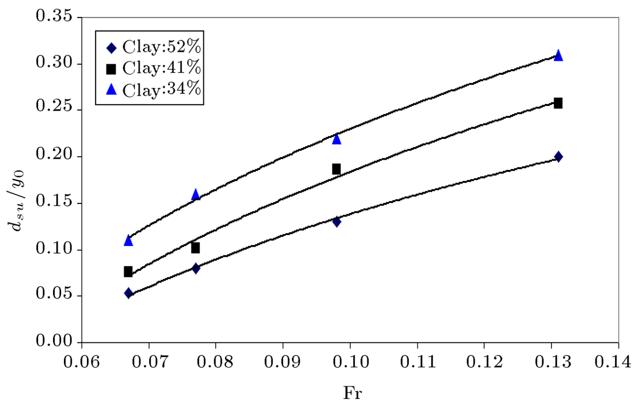

Figure 6. Variation of d_{su}/y_0 with Fr.

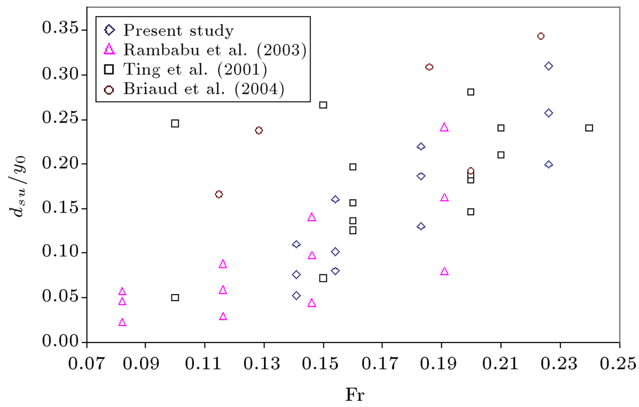

Figure 7. Comparison of d_{su}/y_0 as a function of Fr based on present data, and data from Ting et al. (2001), Rambabu et al. (2003) and Briaud et al. (2004).

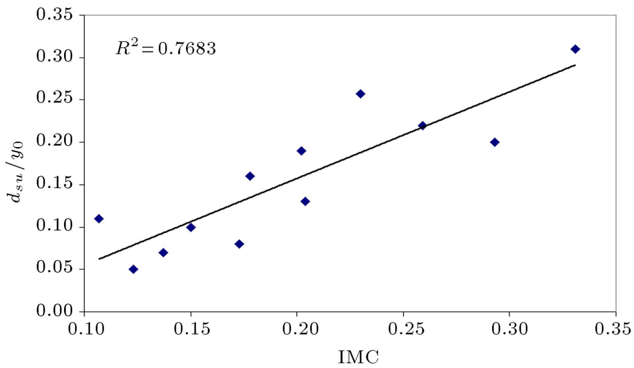

Figure 8. Variation of d_{su}/y_0 with IMC.

on pier scouring experiments on a clay bed, is made between the present data and that reported by Ting et al. [9], Rambabu et al. [11], and Briaud et al. [29] for 25% < C < 65%, 0.061 < D < 0.273 m, and $y_0/D > 2$ (Figure 7). It is seen that the data of the present study is in general agreement with that observed by Ting et al. [9], Rambabu et al. [11], and Briaud et al. [29]. The scattering in the data was possibly due to the variations in parameter between experiments such as initial moisture content and clay percent.

6.3. Initial soil Moisture Content (IMC) and Clay percentage (C)

The effect of initial soil moisture content on ultimate scour depth is shown in Figure 8. It is clear that by increasing the IMC of unsaturated soil with different clay percentages, the ultimate scour depth increases. Using the data of Figure 8 and regression analysis, the following equation can be obtained:

$$\frac{d_{su}}{y_0} = 1.023 \text{ IMC} - 0.0471. \tag{7}$$

For soil nos.1-3, with clay percentages of 52, 41, and 34, by changing initial moisture content from 29.3% to 12.3%, 23% to 13.7%, and 33.1% to 10.7%, the ultimate scour depths decrease to 60%, 55%, and 46%, respectively. Honsy [30], through some experiments on different clay soils, concluded that the scour depth decreases by decreasing the IMC of the soil. Also, Debnath and Chaudhuri [12] experiments showed that for a moisture content ranging from 33.6% to 45.92%, the ultimate scour depth depended on the initial moisture content, and that for IMC < 24%, the ultimate scour depth decreased by increasing the clay content of the soil. Also, according to Molinas et al. [28], and Debnath and Chaudhuri [12] experiments, when the initial moisture content is less than 30%, dimensionless ultimate scour depth does not depend on the initial moisture content.

Based on the mentioned investigations, there are various suggestions regarding the effects of initial moisture content on scour depth in cohesive soils. In this study, the range of the IMC varies between 10.7% and 33.1%. Variation of d_{su}/y_0 with IMC shows the low coefficient correlation of 0.76 using plot scatter (Figure 8). This coefficient correlation is the lowest coefficient correlation compared to the d_{su}/y_0 with $S_U/\gamma.y_0$ and the d_{su}/y_0 with Fr. Finally, it is suggested that it is better for IMC to be eliminated from dimensional analysis.

7. Experimental results

Rambabu et al. [11] based their findings on the combination of some effective parameters of scour depth, and introduced a combined dimensionless parameter (α_c), which is a function of the Froude number (Fr), the model Reynolds number (Re), and the ratio of erosive critical shear stress, to undrained shear strength in saturated mode (τ_c/C_u). Hence, in this investigation, by multiplying, three combined dimensionless parameters resulted (α_c), such as in Rambabu et al. [11]:

$$\alpha_c = \text{Fr.Re.}\frac{\tau_c}{S_u}. \tag{8}$$

Therefore, the Rambabu et al.'s [11] combined dimensionless equation can be written as below:

$$\frac{d_{su}}{D} = K(\alpha_c). \tag{9}$$

The variation of dimensionless ultimate scour depth was plotted against the variation of the combined dimensionless parameters in Figure 9. The following equation obtained from the curves is based on clay soil properties and the hydraulic condition in the pier upstream:

$$\frac{d_{su}}{D} = 3.675(\alpha_c)^{0.355}. \tag{10}$$

The coefficient of relation is 0.97. Hence, the above equation is suggested for the prediction of the ultimate scour depth based on the Rambabu et al.'s [11] com-

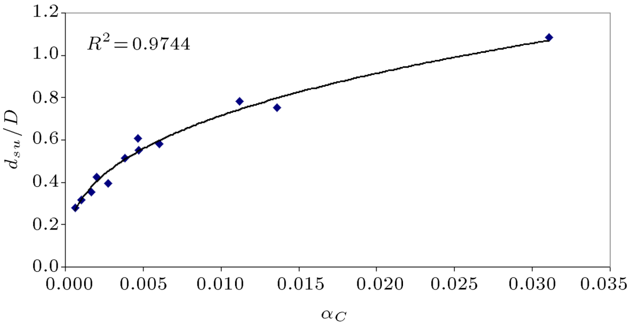

Figure 9. Relationship between d_{su}/D and combined dimensionless parameter (α_c).

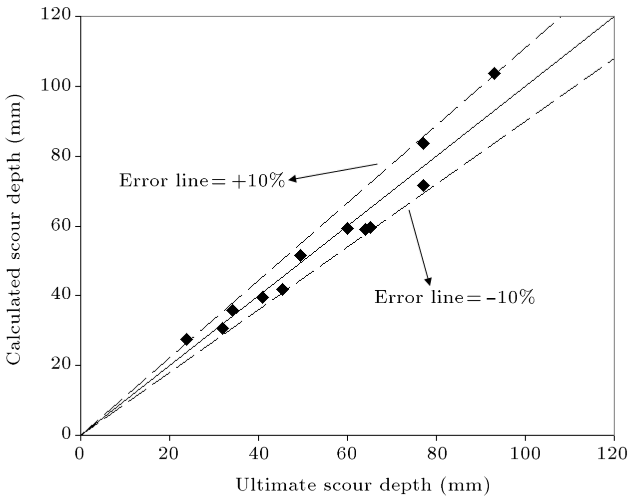

Figure 10. Plotting the result for Eq. (11).

bined dimensionless equation. After eliminating the IMC and Re number from Eq. (5), with dimensionless parameters, a regression equation was obtained as follows:

$$\frac{d_{su}}{y_0} = 5565.05(\frac{S_u}{\gamma \cdot y_0})^{0.83}.(C)^{-2.179}.(\mathrm{Fr})^{2.306}. \qquad (11)$$

The calculated values of the ultimate scour depths (d_{su}/y_0), using Eq. (11), versus the ultimate scour depths obtained through experiments, are presented in Figure 10. The resulted correlation coefficient is $R^2 = 0.97$. Similar equations around a vertical pier have been suggested by Herbich et al. [7] in coarse materials for unsteady and varied conditions of flow, and by Molinas et al. [28], Rambabu et al. [11], and Debnath and Chaudhuri [12] in cohesive soil under steady flow.

8. Comparison of regression equation with empirical equations

The results of Eq. (2) have been compared with many empirical equations. These equations are applied to estimate the scour depth in cohesive and non-cohesive soils.

Ansari et al. [10], Rambau et al. [11], and Debnath and Chaudhuri [12] equations were used for comparison with Eq. (2) in cohesive soils, and Shen et al. [13], Johnson [14], USDOT [15], and Melville [15] equations were used in non-cohesive soils.

The empirical equations used in cohesive soils are:

1. Ansari et al. [10]:

$$\frac{dsmc}{dsms} = \frac{6.02 - 10.82(\frac{W}{W_*}) + 5.41(\frac{W}{W_*})^2}{(\frac{C_*}{\phi_*})^{0.2}}, \qquad (12)$$

where:

$$C_* = \frac{C.C_U}{(\gamma_s - \gamma_w).d_a}, \qquad (13)$$

and:

$$\phi_* = \frac{C\tan(\varphi_C) + (1-C)\tan(\varphi_S)}{\tan(\varphi_S)}. \qquad (14)$$

In this equation, $dsmc$, $dsms$, W, W_*, C_U, φ_C, φ_S, and d_a are maximum scour depth below the bed level for pier scour in cohesive soils, maximum scour depth below the bed level for pier scour in non-cohesive soils, antecedent moisture content (%), antecedent moisture content required to saturate the soil sample, cohesion, angle of repose or internal friction for sand, angle of repose or internal friction for cohesive sediment, and arithmetic mean size of the sediment used for sand-clay mixture, respectively.

2. Rambau et al. [11]:

$$\frac{S_{UC}}{D} = (\frac{U}{\sqrt{g \cdot y_0}})^{0.641}.(\frac{U.D}{\nu})^{0.64}.(\frac{C_U}{\gamma_s \cdot y_0})^{-0.976}, \qquad (15)$$

where S_{UC}, C_U, D, U, y_0, γ_s, and ν are ultimate scour depth due to currents, undrained shear strength of soil, diameter of obstruction, current velocity, flow depth, unit weight of soil, and kinematic viscosity of water, respectively.

3. Debnath and chaudhuri [12]:

$$\frac{d_S}{D} = 2.05(\frac{U}{\sqrt{g.D}})^{1.72}.C^{-1.29}.(\frac{\tau_S}{\rho.U^2})^{-0.37}, \qquad (16)$$

where d_s, D, U, C, ρ and τ_S are maximum scour depth, pier diameter, approach velocity, clay percent, mass density of water, and undrained shear strength, respectively. Also, the ranges of related parameters in Eqs. (12) and (15)-(17) are presented in Tables 4 and 5.

Empirical equations used in non-cohesive soils are:

Table 4. Range of physical properties of bed soils used by Debnath and Chaudhurs (2009), Rambabu et al. (2003), Ansari et al. (2002), and Ting et al. (2001).

Researchers	IMC (%)	C (%)	S_U (kN/m^2)
Debnath and Chaudhurs (2009)	20-45.92	20-100	5.7-12.7
Rambabu et al. (2003)	32.94	44	2.6-4.2
Ansari et al. (2002)	8.5-48.1	10-60	0-240
Ting et al. (2001)	26.18-39.28	25-65	12.51-39.56

Table 5. Range of hydraulic and geometry parameters due to piers and flow condition uesd by Debnath and Chaudhurs (2009), Rambabu et al. (2003), Ansari et al.(2002), and Ting et al. (2001).

U (m/s)	D (m)	y_0 (m)	d_{su} (mm)
0.514-0.818	0.12	0.35	58-222
0.199-0.328	0.05-0.11	0.3-0.6	14.2-72.46
0.21-0.48	0.1125	0.05-0.18	11-179
0.204-0.608	0.025-0.11	0.16-0.4	8.4-134

1. Shen et al. [13]:

$$\frac{d_s}{b} = 3.4(\frac{V_0^2}{gb})^{0.67}(\frac{d_0}{b})^{1/3}, \tag{17}$$

where g, V_0, d_0, b, and d_s are gravity acceleration, current velocity, flow depth, pier diameter and scour depth, respectively.

2. Johnson [14]:

$$\frac{d_s}{d_0} = 2.02F_0^{0.21}(\frac{b}{d_0})^{0.98}\sigma^{-0.98}, \tag{18}$$

where d_s, σ, F_0, d_0, and b are scour depth, standard deviation of sediment particle size distribution ($\sigma = \sqrt{D_{84}/D_{16}}$), the Froude number, flow depth, and diameter of pier, respectively.

3. USDOT [15]:

$$\frac{d_{se}}{y_o} = K_3(\frac{y_0}{D})^{-0.63}\text{Fr}^{0.43}, \tag{19}$$

where K_3, Fr, D, y_0 and d_{se} are equilibrium scour depth, flow depth, diameter of pier, Froude number, and a constant value that is between 1.1 to 1.3.

4. Melville [16]:

$$\frac{d_{se}}{D} = K_l K_d K_{yD}, \tag{20}$$

where $K_l = V/V_C$ if $V/V_C < 1$ and $K_l = 1$, otherwise, $K_d = 0.57\log(2.24D/D_{50})$ if $D/D_{50} \leq 25$ and $K_d = 1$, otherwise and $K_{yD} = 2.4$ if $D/y_0 < 0.7$, $K_{yD} = 2\sqrt{y_0/D}$ if $0.7 \leq D/y_0 \leq 5$, and $K_{yD} = 4.5\ y_0/D$ if $D/y_0 > 5$.

Applying the measured data to the above empirical equations, scour depths are calculated. To compare the ultimate scour depths with results of empirical equations, Theil's coefficient statistical test has been used.

$$U = \frac{\left[\frac{1}{n}\sum_{i=1}^{n}\left\{(d_{sc})_i - (d_{su})_i\right\}^2\right]^{0.5}}{\left[\frac{1}{n}\sum_{i=1}^{n}\left\{(d_{sc})_i\right\}^2\right]^{0.5} + \left[\frac{1}{n}\sum_{i=1}^{n}\left\{(d_{su})_i\right\}^2\right]^{0.5}}, \tag{21}$$

where U is the Theil coefficient ($U = 0$ for model of perfect prediction and $U = 1$ for unsuccessful model), d_{sc} is the scour depth, which resulted from each empirical equation, and n is the number of experiments.

The results of the statistical test show that the Debnath and Chaudhuri [12] equation is successful in predicting scour depth in cohesive soils ($U = 0.148$). This equation is proposed for the unsaturated soil condition. It seems that the high difference in the Theil coefficients is due to the effects of soil properties in the empirical equations. Ansari et al. [10] proposed an equation based on moisture content, clay percent, plasticity index, angle of repose of the sediment, and bed sediment shear strength, whereas the Rambabu et al. [11] equation was presented under conditions of initial moisture, saturated soil, and clay percent constant. Based on Theil's coefficient, Ansari et al. [10] and Rambabu et al. [11] equations were unsuccessful in the prediction of scour depths ($U = 0.47$ and 0.74, respectively) because they are only valid for saturated soils. In this study, these equations were used for saturated cohesive soils, while applying them for the prediction of scour depth in unsaturated cohesive soils (Figure 11).

The other group of equations include Eqs. (17)-(20), which are applied often for the prediction of scour depths in non-cohesive soils. Results of statistical tests show that the Johnson [14] equation, with $U = 0.12$, has the best prediction compared to Shen et al. [13], US DOT [15], and Melville [16]. The Johnson [16] equation has parameters that include soil (bed sediments) properties, model geometry, flow depth and velocity, whereas the Shen et al. [13] equation has no soil (bed sediments) properties (Figure 12). As a result, it is not valid enough for scour depth, and the maximum value of Theil's coefficient is related to the Shen et

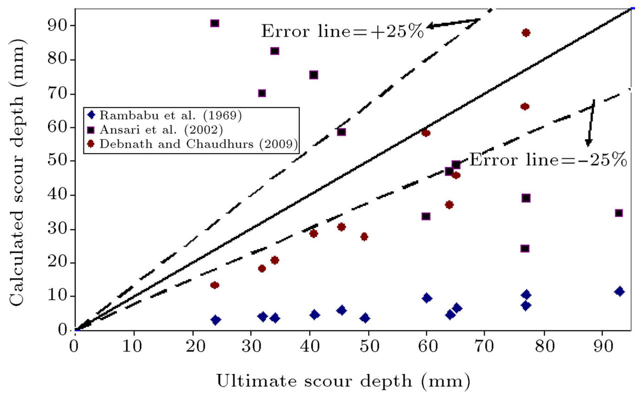

Figure 11. Comparison with calculated scour depths obtained from Ansari et al. (2002), Rambabu et al. (2003), and Debnath and Chaudhurs (2009) formula and the ultimate scour depths using hyperbolic law.

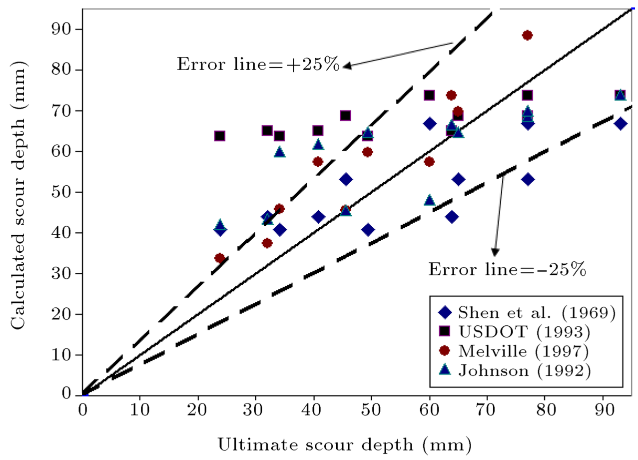

Figure 12. Comparison with calculated scour depths obtained from Shen et al. (1969), Johnson (1992), USDOT (1993), and Melville (1997) formula and the ultimate scour depths using hyperbolic law.

al. [13] equation ($U = 0.34$). Also, the Melville and USDOT equations have the main three parameters (soil properties, model geometry, and hydraulic conditions) and the values of their Theil coefficients are 0.17 and 0.18, respectively. These Theil coefficients indicated the effects of soil properties on scour depth.

9. Conclusion

Scour depth around bridge piers can be affected by several parameters, such as undrained shear strength, Froude number, initial moisture content, and clay percentage. The ultimate scour depth decreases by increasing the undrained shear strength of unsaturated soils, while it increases by increasing the Froude number. Also, at a constant Froude number, the ultimate scour depth increases by decreasing clay percentage and the percentage of moisture content of the soil.

Combining the flow Froude number, Reynolds number and dimensionless undrained shear strength, a general equation for calculating the ultimate scour depth was resulted, based on the Rambabu et al combined dimensionless parameter. In this study, through experimental tests, the effect of current velocity, flow depth, initial moisture content, clay percentage and undrained shear strength on scour around a bridge pier has been investigated. Using dimensional analysis, a relationship between the ultimate scour depth and effective parameters was developed. The ultimate scour depths were compared with calculated scour depths that were calculated, using two groups of empirical equations. In this study, the Theil's coefficient statistical test was used to determine the accuracy of each group of equations. The results of the comparisons show that Debnath and Chaudhuri, and Johnson empirical equations have better agreement with ultimate scour depth gained from experiments than from other equations in each group. It can be concluded from comparisons of empirical equations in cohesive soils that saturated and unsaturated conditions are significant factors in predicting scour depth. Also, empirical equations in non-cohesive soils can be used for predicting scour depths in cohesive soils, which are sometimes more accurate.

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