Engineering and Technology Journal Vol. 37, Part A, No.12 , 2019
DOI: http://dx.doi.org/10.30684/etj.37.12A.436

Zahraa F. Hassan
Civil Engineering
Dep.,,University of Warith Al-Anbiyaa-Iraq, Karbala, Iraq.
zahraaf@uowa.edu.iq

Ibtisam R. Karim
Civil Engineering
Dep.,,University of Technology-Baghdad, Iraq

Abdul-Hassan K. Al-Shukur
Civil Engineering
Dep.,,University of Babylon-Iraq.

Received on: 09/09/2018
Accepted on: 27/02/2019

Evaluation of Predictive Equations for Local Pier Scour in Cohesive Soils

Abstract- *Wavelet-analysis has become a powerful tool for denoising images. It represents a new way to achieve better noise reduction and increased contrast. Here, experimentally demonstrate abilities of discrete wavelet transform with Daubechies basis functions for improving the quality of noisy images.in this research two methods has been compaired for modify the coefficients using soft and hard threshold to improv the visual fineness of noisy image depend on Root-Mean-Square error (RMS). The low RMS value and better noise reduction find in soft threshold method which is based on Daubechies wavelet (db8) for first example image RMS=0.101 and second example RMS= 0.109.*

Keywords- *image processing, wavelet-analysis, noise , Root-Mean-Square error*

How to cite this article: Z. F. Hassan, I. R. Karim and A. K. Al-Shukur , “Evaluation of Predictive Equations for Local Pier Scour in Cohesive Soils,” *Engineering and Technology Journal*, Vol. 37, Part A, No. 1, pp. xx-yy, 2019.

1.Introduction

The local scour of the bed of rivers at the piers and abutments is one of the major problems with bridge hydraulics. Such type of problems causes undermining of the bridge foundation and failure. The turbulence flow structures that result from the interaction between the river flow and the bridge supports are responsible for the formation of scour holes around these supports. It is vital to get an accurate estimate of the depth and extent of these scour holes for design purposes. Many studies had been conducted in the past investigating the local scour at a bridge pier and to developing predictive equations for the scour depths correctly. Evaluation of the scour depths at bridge piers in the cohesionless riverbed is well achieved at present. The scour depth at a pier in cohesionless soil depends on the flow characteristics that are depth and velocity of river flow, soil characteristics, size, and shape of the pier [1]. The process of scouring is more complex at piers in cohesive soil beds. In cohesive soils, bonding forces are represented by Vaan der Waals and electrostatic resistant of the scouring and they control the scour rate [2]. However, the riverbed sediment consists of cohesionless along with cohesive soils, in a mixture of sand and clay. Usually, the sand and clay soils are observed in the lower stages of a river and in marine areas [3, 4]. A few research works were conducted on the cohesive soil scouring, where the existing pier scours equations were mainly developed on the bases of laboratory tests for pier scour in cohesionless soils. These methods are considered conservative when applied to scour in cohesive soils. This action may result in the use of undeserved costly foundations and/or scour countermeasures [5]. Experimental studies on the scouring around a pier placed in cohesive sediment have been conducted by many researchers. Hosny [6] proposed a set of empirical equations based on flume experiments on the local scour of a pier in a bed of cohesive and cohesionless sediment mixture and unsaturated and saturated cohesive soils. The developed equations related the scour depth to the pier diameter, clay percent, soil compaction, water content, and the Froude number. Gudavalli [7] conducted 43 flume tests on cylindrical pier scour using medium sand, fine sand and three clays of different plasticity as bed materials. Gudavalli [7] proposed a simple equation to predict circular pier scour depth in a deep flow condition ($y/D \geqslant 1.43$). Although five types of soil were investigated by Gudavalli [7], a parameter for the soil properties was not included in his equation. Briaud et al. [8] developed a method to predict the scour depth and rate of scouring in a cohesive bed at a circular bridge pier. It is called “Scour Rate in Cohesive Soils (SRICOS)” and it involves testing soil samples in a laboratory device named (EFA) and it was developed for this purpose to get the rate of scouring versus the bed shear stress. This enables the prediction of the maximum scour depth and the time curve of scour depth. Ting et al. [9] introduced data sets for scouring measurements in the laboratory that were carried out to study local scouring at circular piers in clay beds. Their study aimed at figuring the differences in scouring process between sand and clay. The results "indicated that the scour rate in clay was much slower than in the sand, but the maximum scour depth was similar to that obtained in sand". Their established formula for the scour depth had a similar form to the form that was developed by Gudavalli [7]. Li [10] developed a predictive equation for the pier scour depth at complex piers geometry in a cohesive bed. In his experiments, porcelain clay was used as bed sediment. The flow shallowness, pier nose shape, attack angle, and pier-side by side arrangement were all investigated and addressed in the equation. The effect of these parameters was added in the form of correction factors to be multiplied by the scour equation developed by Gudavalli [7] to arrive at an accurate estimate of the pier scour depth.

Kho et al [11] developed a predictive equation for the scour depth at a bridge pier based on regression for experimental data conducted in beds of the sand-clay-silt mixture. The equation addressed the impact of the pier Reynolds number and clay content on the scouring depth. Debnath and Chaudhuri [12, 13] studied the effects of clay content, water content, Froude number and applied shear stress on the maximum scour depth around a circular pier in sand-clay mixtures at velocities near to the critical velocity of sand particle movement in bed mixture. They developed an empirical formula for the estimation of the pier scour depth considering these effects. Debnath and Chaudhuri [14] conducted another study to include the estimation of local scour at a noncircular bridge pier in clay-sand sediments. They included round-nose, square, and rectangular pier shapes in the proposed scour equations. Link et al [15] examined the influence of soil compaction on the local scouring at a bridge pier founded in a bed containing 72% sand and 28% clay. Scour depths were measured at the pier and data was reported. Kothyari et al [16] studied the scour development in the wake of a bridge pier installed in a cohesive bed made up of gravel, sand, and clay in different proportions. Based on the experimental data, equations were proposed to estimate the scour depth at the wake of the pier. Najafzadeh and Barani [17] examined the effect of undrained shear strength, flow characteristics, and water content on the maximum scour depth at a pier using flume experiments on three cohesive soil mixtures. They conducted short-time duration tests and the maximum pier scour depth was extrapolated by a hyperbolic law as used by previous researchers. They developed a regression formula for the pier scour depth involving the effective parameters. Briaud [18] proposed a general predictive method for the bridge scour termed the TAMU scour method, and this method incorporates the soil erosional properties so that a proper estimation could be acquired when estimating the scour depth in low and in high erodibility soils. The TAMU method could be applied to estimate the maximum scour depth or to estimate the temporal scour depth. It was verified with 10 independent data bases of scouring measurements, some of them represent laboratory data and the other represent field measurements. Muzzammil et al. [19] implemented the gene express programming GEP, an evolving AI tool, for the derivation of a scour depth predictive equation at a pier in cohesive soil making use of laboratory data from the literature. They found that "the performance of GEP is better than a nonlinear regression-based formula for the prediction of scour depth at piers in cohesive beds".

No study has been conducted yet to evaluate those predictive equations that were proposed for the estimation of the scour depth at a pier placed in cohesive sediment. Therefore, this study attempts to satisfy this research gap. A detailed data search was carried out to examine the previous research works for the subject of local scour around the pier in cohesive sediment. The search led to the collection of 437 sets of laboratory equilibrium local pier scour data points and 100 extrapolated data points. The dimensionless parameters that represent the flow characteristics, sediment transport and structure geometry were were plotted to help in the classification of the covered experimental conditions of the collected data. The search also examined 9 predictive equations that were established for the estimation of the local pier scour depth. The evaluation of these equations was done by using the local scour laboratory data and comparing the results.

2. Data Acquisition and Analysis

A set of equilibrium local pier scour data that was published in the literature (437 laboratory data points and 100 extrapolated data points) has been collected. Table 1 lists the source and number of the sets of data points. The collected data were derived from flume tests on local scouring at piers in the laboratory where the bed sediment is either cohesionless, a mixture of cohesive and cohesionless, or only cohesive sediments. No database for field measurements of local scour in fine-grained soils could be found in literature, the most field databases are mainly related to coarse-grained soils [18]. The ranges of the dimensionless parameters which are influenced by the local scour associated with the collected data sets are presented in Table 2. The independent parameters that influence the local scouring in clay and sand mixed bed are plotted in histograms in Fig. 1 which helps to illustrate the distribution of the collected data and the range of the variables covered in the laboratory data sets extracted for this study. Figure 1 consists of seven plots. Starting from the histogram that shows the distribution of laboratory data of depth of flow, it can be found that most of the data correspond to a flow depth of less than 0.4 m with a few data points to a depth larger than 0.45 m.

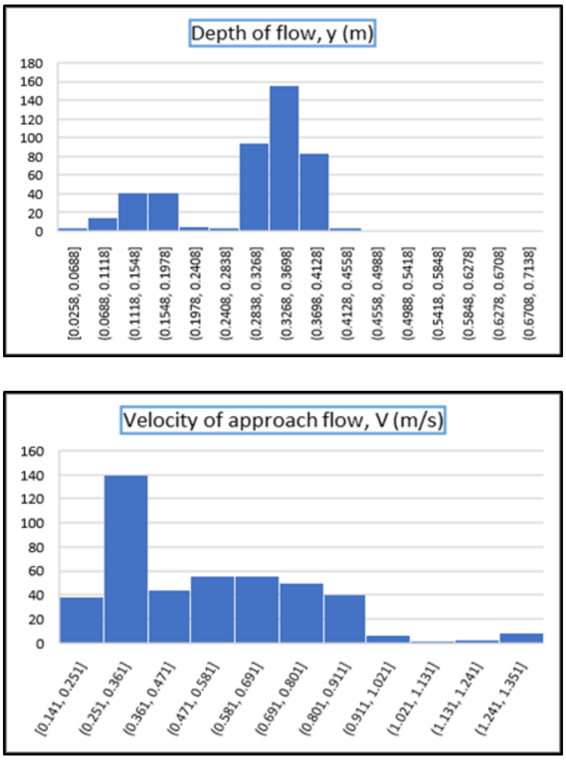


Figure 1: Histograms (a-g) for local scour variables based on laboratory values.

The second plot shows the values of the average velocity of approach flow covered by the data. The range 0.25-0.36 m/s was the most used in laboratory experiments with some of them conducted at higher velocities. The third plot in Figure 1 shows the values of pier sizes used in the laboratory experiments, where most of the experiments used piers of size less than 0.125 m and a few experiments used piers of a width beyond 0.125 to about 0.285m. The fourth plot shows the values of sediment size, and the tests concerned with fine-grained soils mixed with mainly fine sand. The next plot shows the values of cohesive soil content as a percentage of sediment mixture, and the laboratory experiments covered a wide range of cohesive soil content from 0% (non-cohesive soil only) to 100% (pure cohesive soil). The plot of Figure1 that displays the distribution of soil mixture undrained shear strength, illustrates that the 19 KPa was the upper limit except for few tests that used soil of undrained shear strength as high as 39 KPa. Finally, the duration of tests was displayed in the last plot in Figure 1. The considered time duration to reach an equilibrium stage of local scour was variant. The lower range was 15 hr. and the upper was 60 hr. with some tests lasted a longer time.

Figure 2 shows the distribution of dimensionless local scour variables, normalized scour depth ys (pier)/b, flow intensity V/Vc, flow shallowness y/b and sediment coarseness b/d50 for the collected data points. It can be concluded from the plots in Fig.2 (the horizontal axis) that the largest value of dimensionless scour depth is nearly 5. The values of the V/Vc ratio involved clear water scour and live bed scour (V/Vc range in Fig.2 is from 0.14 to 1.35), however, most of the experimental runs were conducted at near the threshold condition for sediment motion, and a small number of experiments were conducted at relatively high flow velocity. In the collected data set, flow shallowness y/b was more than 2 for most hydraulic conditions (deep flow condition) excluding the conditions investigated by Li et al (2002) [10] where the shallow flow was the target of some experiments. The reported scour data corresponds to b/d50 >> 50 (Fig.2).

Figure 3 displays plots for the cohesive soil content in sediment mixtures and the resulted scour depth, test duration and flow intensity. In the plot of cohesive soil content vs. scour depth (Fig.3), it was found that for different percentages of cohesive soil content that was tested in the literature the local scour depth was mainly near to that recorded in zero content of cohesive soil. Although some researcher works showed a decline in the local scour depth with an increase in cohesive soil content [6, 12, 13, and 14]. These findings may be attributed to the fact that in those investigations usually the scour test duration was not long enough to reach the equilibrium state and record the maximum scour depth. The plot of cohesive soil content versus test duration in Fig. 3 illustrates the different time durations that were used for different experimental runs in the literature. It is evident that most of the experiments that were reported in the literature were conducted at the time durations of less than 60 hr (as an average). Some of the reported experiments were carried out for longer time durations (such as more than 200 hr). In fact, the scour rate of cohesive soil is considerably slower than that of a cohesionless soil and the time to equilibrium scour depth is longer in cohesive soil and increases for increased clay/silt content in the sediment mixture [5]. Moreover, Brauid et al. [8], Ting et al. [9] and Li [10] conducted very long-duration scour experiments that lasted more than 220 hr and they stated the measured scour depth that was not the maximum. Brauid [18] considered the scour depth that is measured after a specific time duration of being subjected to a constant flow velocity as the final scour depth, and this depth is useful to extrapolate the maximum scour depth using a time-scour curve. From Figure 3, the laboratory experiments on different cohesive soil content mixtures were carried out at different velocities and some of them were close to the critical velocity of the sand fraction in the sediment mixture, while some studies used flow greater than flow velocity.

3. Equilibrium Local Pier Scour Predictive Equations

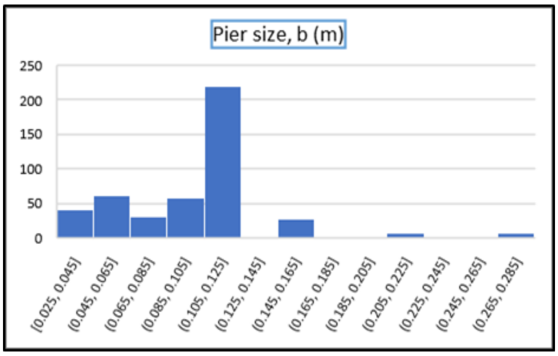
Several researchers conducted laboratory experiments on equilibrium local pier scour in cohesive and in mixtures of cohesive and non-cohesive soil beds. These investigations aimed to develop formulations used for estimating the pier scour depth. Many of these formulations were derived from dimensional analysis and regression of the laboratory data. By reviewing the literature of the prediction equations, it has been found that only Braiud [18] method was tested against both laboratory data and field database. He selected 10 data bases independent from those that were used to develop the scour equations. Other scour equations that are available in the literature were tested only against the same laboratory data that were used to derive the equations and resulted in fairly good correlation factors methods.

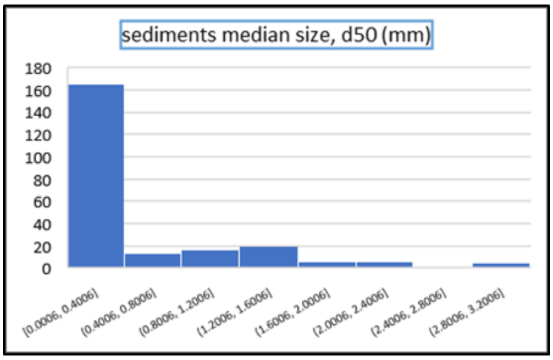
I.Screening of Equilibrium Local Pier Scour Predictive Equations

A selection of the equations that involve soil properties from the published literature is given in Table 3. Nine equations were selected to be used for the evaluation. The screening of the equations was done by solving all the equations for a specific experimental condition of input values and comparing the results of the prediction process. The output of this evaluation process is introduced in bar charts as shown in Figure 4. Also, the input parameters used in the evaluation are given in the charts of Fig 4. Several other predictive equations exist in the literature, but we did not consider them in the evaluation process due to the insufficient information for the required parameters. This left 9 equations for the evaluation.

II.Evaluation of Equilibrium Local Pier Scour Predictive Equations

The predicted local pier scour depths versus the equations used in the prediction are displayed in Fig. 4. The local pier scour depth was evaluated in four laboratory cases that represent different mixtures of the bed sediment and subjected to similar hydraulic conditions. The predicted local scour depths also had been compared to the laboratory measurements; the predicted pier scour depth should not be less than the measured values. It can be concluded from Fig. 4 that the equilibrium local pier scour depths predicted by the cohesive sediment equations (Eq. 1-9) are variant, and this discrepancy may be attributable to the reasons that those equations were developed based on laboratory data regression, scouring mechanism in cohesive soils is complicated and there are too many interrelated factors that affect scour in cohesive beds.





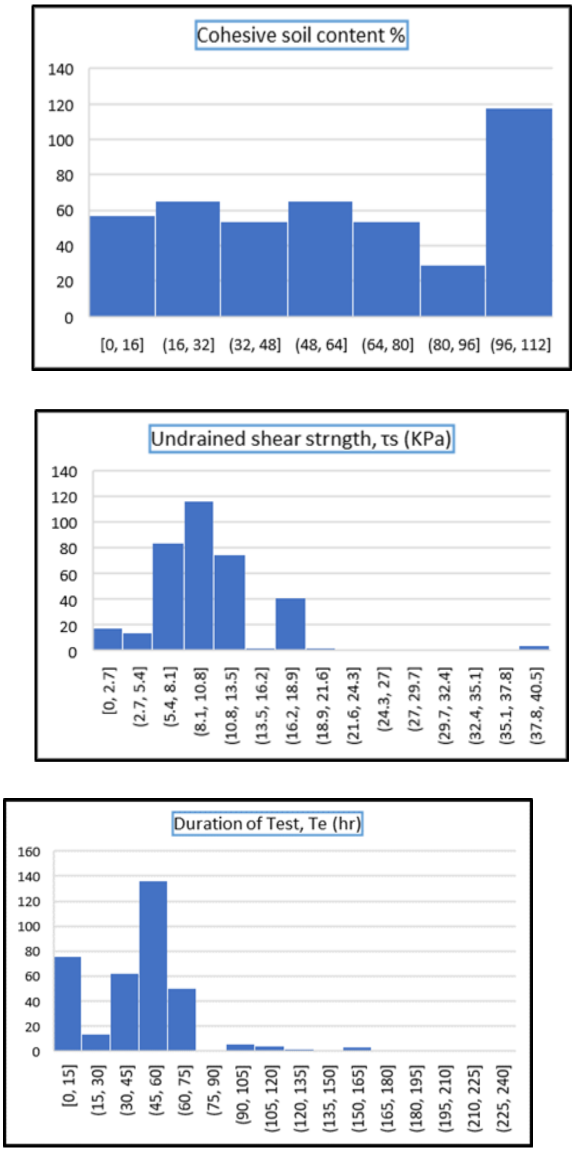
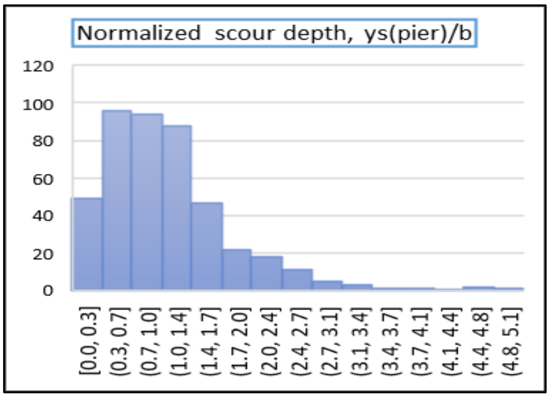


Figure 2: Histograms (a- g) for local scour variables based on laboratory values (continued). The vertical axis in these plots represents the number of repetitions of each variable value in the collected laboratory data. The horizontal axis is the range of values of the local scour influencing parameters related to the collected laboratory data.



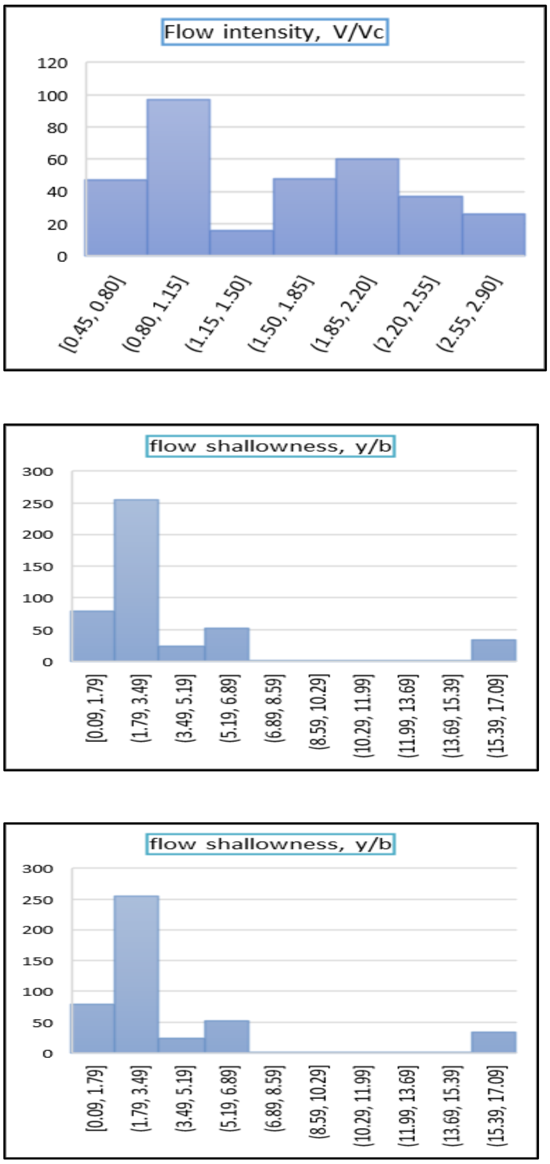
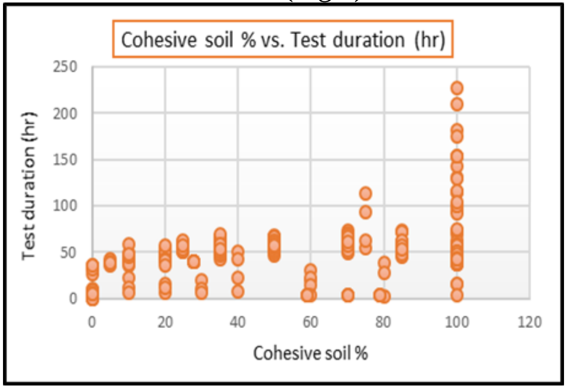
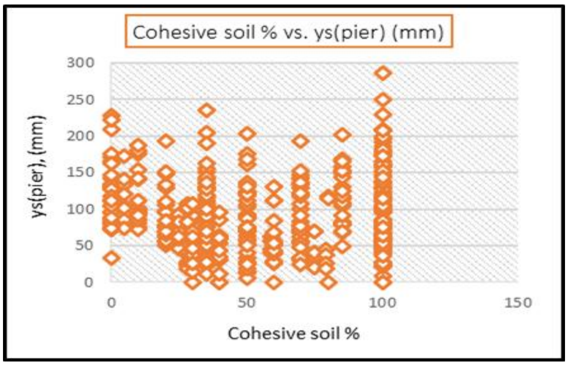


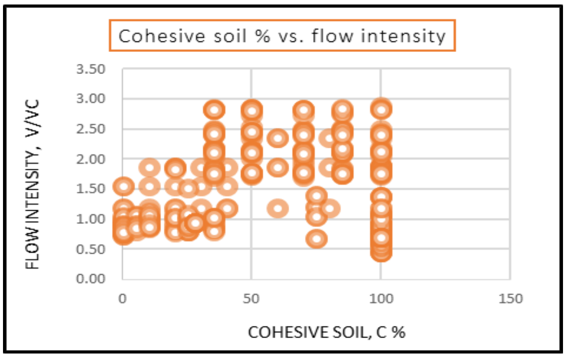
Figure 3: Dimensionless plots of local scour characterizing variables. The vertical axis in these plots represent the number of repetitions of each dimensionless variable value in the collected laboratory data. The horizontal axis is the range of values of the dimensionless local scour characteristics related to the collected laboratory data.

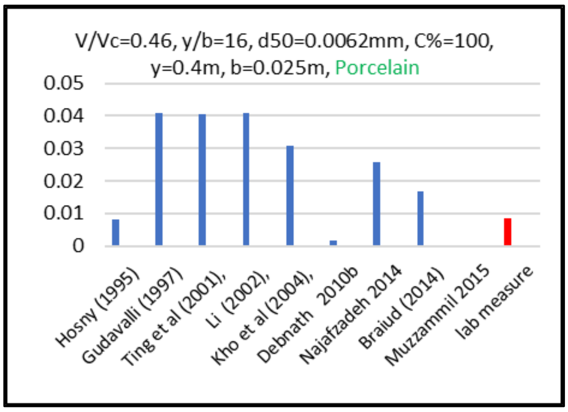
Comparison of the predicted values of the scour depth ys(pier) by Hosny, Gudavalli, Ting, Kho, and Briaud equations shows that they give similar predictions in the case of sand bed which are near to the measured value in the laboratory (Fig. 4). When the porcelain clay was used as bed material, the equation by Najafzadeh approximates the scour depth predicted by Briaud equation while other cohesive sediment equations overpredict the value.

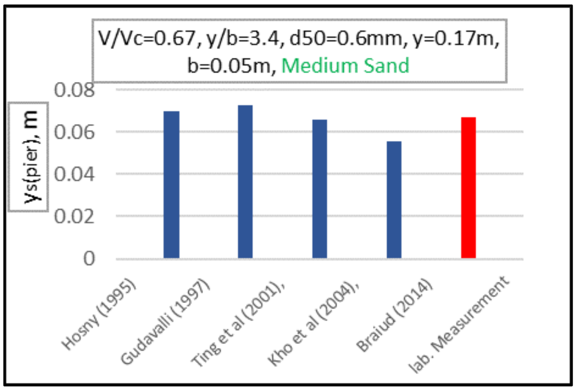
In the plot of sand-clay mixture, the sediment is assumed to have cohesive soil content of 50% by weight. The prediction of local scour depth by Najafzadeh was the closest one to the flume measurement. Briaud equation gives a result close to that of cohesionless sediments without clay content,and the equation predicts scour based on a parameter that represents the erodibility of the soil which is the critical Froude number. This parameter requires the knowledge of sediment mixture critical velocity that initiates particles motion. Yet there is no accepted method to estimate the critical velocity of cohesive soils other than measuring it by laboratory or field devices. In this evaluation study, critical velocity for the sand fraction and the in clay-sand mixture was utilized for the estimation of the pier scour depth by Briaud (2014) equation and it resulted in a scour depth value near to that predicted for cohesionless sediments (Fig.4)

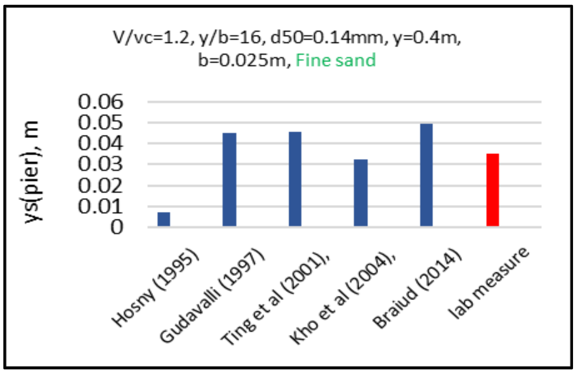












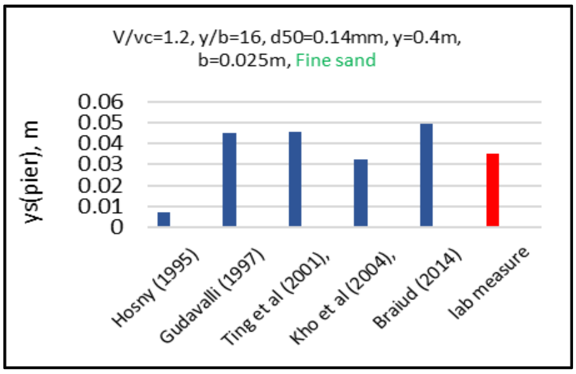


Figure 4: Plots of cohesive soil content % in sediments vs. some local scour characterizing variants of the collected data set

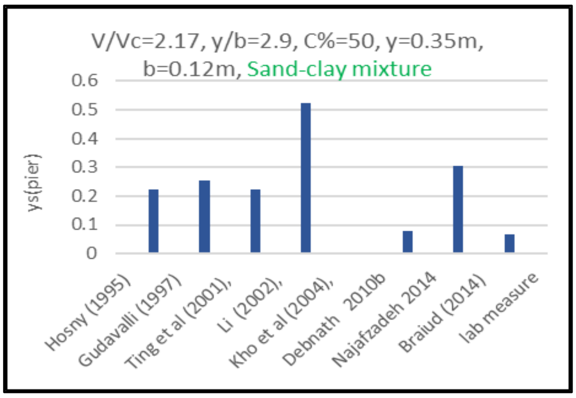


Figure 5: Comparison of pier scour depth predictions using 9 different equations for different laboratory conditions. The vertical axis indicates the values of scour depth and the horizontal axis the corresponding equation used to predict the values

Comparison of the predicted values of the scour depth ys(pier) by Hosny (1995), Gudavalli (1997), Ting (2001), Kho (2004) and Briaud (2014) equations show that they give similar predictions in the case of sand bed which are near to the measured value in the laboratory (Fig. 4). When the porcelain clay was used as a bed material, the equation by Najafzadeh (2014) approximates to the scour depth predicted by Briaud (2014) equation while other cohesive sediment equations overpredict the value. In the plot of sand-clay mixture, the sediment assumed to have cohesive soil content of 50% by weight. The prediction of local scour depth by Najafzadeh (2014) was the closest one to the flume measurement. Briaud (2014) equation gives a result close to that of cohesionless sediments without clay content, the equation predicts scour based on a parameter represents the erodibility of the soil which is the critical Froude number. This parameter requires the knowledge of sediment mixture critical velocity that initiate particles motion. Yet there is no accepted method to estimate the critical velocity of cohesive soils other than measuring it by laboratory or field devices. In this evaluation study, critical velocity for sand fraction in clay-sand mixture was utilized for the estimation of the pier scour depth by Briaud (2014) equation and it resulted in a scour depth value near to that predicted for a cohesionless sediments (Fig.4).

Table 1: Observed pier scour depths from the literature, references and number of data points.

Data References	No. of Measured datapoints	No. of Extracted datapoints
Gudavalli (1997) [7]	43	-
Ting et al. (2001) [9]	43	37
Li (2002) [10]	30	-
Kho et al (2004) [11]	23	-
Debnath, Chaudhuri(2010a) [12]	64	51
Debnath, Chaudhuri(2010b) [13]	71	-
Debnath, Chaudhuri (2012) [14]	79	-
Link et al (2013) [15]	14	-
Najafzadeh, Barani (2014) [17]	12	12
Kothyari et al (2013) [16]	58	-
Total laboratory data	437	100

Table 2: Ranges of the influential parameters on local scour associated with the collected data sets

Property	Range of laboratory data
Flow intensity V/Vc	0.45 - 2.364
Sediment coarseness b/d50	41.67 - 350000
Flow shallowness y/b	0.095 - 16
Pier Reynolds number Vb/ν	5000 - 84840
Froud number V/√gy	0.067 - 0.42
Sediment nonuniformity σg	1.37 - 2.1
Cohesive soil content (silt and/or clay) %	0 - 100
Clay mineral type	Kaolinite - montmorillonite - armstone - illite
Soil undrained shear strength (KPa)	1.1 - 112
Pier shape	Circular – rectangular – square – round nosed
Pier alignment (°)	0 - 90
Pier group	Single – two piers in row
Duration of tests (hr)	6 - 227.3

Table 3: Equilibrium local scour predictive equations for Cohesive Sedimen

Reference	Equation	Comments
(1) Hosny(1995) [6]	$y_{s(pier)} = 18.9b\left(\frac{Fr}{1+C}\right)^2$ $y_{s(pier)} = 0.9b(IWC)^{-2/3}Fr^{2/3}Comp^{-2}$	0.58<Comp<1) (0.15<IWC<0.5) (0.18<Fr<0.51)
(2) Gudavalli(1997) [7]	$y_{s(Pier)} = 0.00018\left(\frac{bV}{\nu}\right)^{0.635}$	
(3) Ting (2001) [9]	$y_{s(pier)} = 0.00012R_p^{0.682}$	
(4) Li (2002) [10]	$y_{s(pier)} = 0.18 \cdot K_w \cdot K_{sp} \cdot K_{sh}(\frac{b`V}{\nu})^{0.635}$	K = correction factors
(5) Kho et al. (2004) [11]	$y_{s(pier)} = 0.0044R_p^{1.0234}\ (1 + C/100)^{0.5}$	
(6) Debnath, Chaudhuri (2010) [13]	$\hat{y}_s = 2.05F_{rp}^{1.72}C^{-1.29}\hat{\tau}_s^{-0.37}$ $\hat{y}_s = 3.64F_{rp}^{0.22}C^{-1.01}\hat{\tau}_s^{-0.69}$ $\hat{y}_s = 20.52F_{rp}^{1.28}C^{0.19}\hat{\tau}_s^{-0.89}$ $\hat{y}_s = 3.32F_{rp}^{0.72}C^{-0.62}W_c^{0.36}\hat{\tau}_s^{-0.29}$ $\hat{y}_s = 8F_{rp}^{0.61}C^{0.58}W_c^{1.24}\hat{\tau}_s^{-0.19}$	$W_c = 20 - 23.22$ $20\% \le C \le 80$ $W_c = 27.95 - 33.55\%$ $20\% \le C \le 50\%$ $50\% \le C \le 100\%$ $W_c = 33.60\% - 45.92\%$ $20\% \le C \le 70\%$ $70\% \le C \le 100\%$
(7) Najafzadeh, Barani (2014) [17]	$\frac{y_{s(pier)}}{y} = 5565.05\left(\frac{\tau_s}{\gamma \cdot y}\right)^{0.83} \cdot (C)^{-2.179} \cdot (Fr)^{2.306}$	
(8) Braiud (2014) [18]	$\frac{y_{s(pier)}}{\grave{b}} = 2.2K_{pw}K_{psh}K_{pa}K_{psp}\left(2.6 \cdot F_{r(pier)} - Fr_{c(pier)}\right)^{0.7}$	K = correction factors
(9) Muzzammil, Danish (2015) [19]	$\hat{y}_s = 0.656 + 2Fr_p - 3C + W_c + \frac{1}{\hat{\tau}_s}$	
Total equations		9

Conclusion

Numerous predictive methods were developed for local pier scour in cohesionless sediments. On the other hand, fewer methods considered the local scouring at a bridge pier founded on a bed of cohesive soil. Most of the predictive methods relate the scour depth with the flow characteristics and pier geometry without considering the different erosion resistance of different soils. While some researchers associated the scour depth with important cohesive soil characteristics. In this study, the pier scours depths were predicted for different experimental conditions using recently developed methods for cohesive sediments for evaluation purposes. The existing methods of local pier scour in cohesive sediments involve a lot of limitations for the soil conditions covered. Hence, from reviewing the literature, it is concluded that more investigation is needed to incorporate more parameters that affect soil erodibility and scouring.

Notation

b, b* or b`= pier diameter.
C = Cohesive soil content in sediment mixture.
Comp = compaction of cohesive soil.
d_{50} = median particle size of the sediment.
Fr, Fr_c = Froude number, critical Froude number.
IWC or W_c = Initial water content of soil mixture.
V, V_c = velocity of approach flow, critical velocity for sand movement.
V_{lp} = live-bed peak velocity of flow.
y = depth of flow.
$Ys_{(pier)}$, $\hat{y}_s$ = equilibrium local scour depth, normalized scour depth.
ν = water kinematic viscosity.
σ_g = geometrical standard deviation of sediment particles.
τ_s = undrained shear strength of cohesive soil.

References

[1] B. W. Melville, The physics of local scour at bridge piers. In Proceedings 4th International Conference on Scour and Erosion (ICSE-4). Tokyo, Japan, (2008) 28-40.

[2] A.S. Lodhi, R.K. Jain, and P.K. Sharma. Influence of Cohesion on Scour Around Submerged Dike Founded in Clay–sand–gravel Mixtures. ISH Journal of Hydraulic Engineering 22, (2015) 70–87.

[3] U. C Kothyari, and R. K. Jain, Influence of cohesion on the incipient motion condition of sediment mixtures. Water resources research 44,(2008).

[4] R. K. Jain, and U. C. Kothyari, Cohesion influences on erosion and bed load transport. Water resources research 45, (2009).

[5] J-L. Briaud, Pier and contraction scour in cohesive soils. 516. Transportation Research Board, (2004).

[6] M. M. Hosny, Experimental study of local scour around circular bridge piers in cohesive soils. Ph.D. thesis, Civil Engineering Dept., Colorado State Univ., Fort Collins, CO, 177. (1995).

[7] Gudavalli, R., F. Ting, J. L. Briaud, H. C. Chen, S. Perugu, and G. Wei. Flume tests to study scour rate of cohesive soils. Res. Rep. Prepared for Texas Dept. of Transp (1997).

[8] J. L. Briaud, Francis CK Ting, H. C. Chen, Rao Gudavalli, Suresh Perugu, and Gengsheng Wei. SRICOS: Prediction of scour rate in cohesive soils at bridge piers. Journal of Geotechnical and Geoenvironmental Engineering 125, (1999) 237-246.

[9] F.C. Ting, J.L. Briaud, H.C. Chen, R. Gudavalli, S. Perugu and G. Wei, Flume tests for scour in clay at circular piers, Journal of hydraulic engineering, 127(11), (2001) 969-978.

[10] Y. Li, Bridge pier scour and contraction scour in cohesive soils on the basis of flume tests.Ph. D. Dissertation, Texas A&M University, College Station, TX. USA. (2002).

[11] K. T. Kho, E. Valentine and S. Glendinning, An experimental study of local scour around circular bridge piers in cohesive soils, 2nd ICSE Singapore, (2004).

[12] K. Debnath and S. Chaudhuri, Bridge pier scour in clay-sand mixed sediments at near-threshold velocity for sand, J. Hydraul. Eng. 136 (2010) 597-609.

[13] K. Debnath and S. Chaudhuri, Laboratory experiments on local scour around cylinder for clay and clay–sand mixed beds,J. Eng. Geo. 111(1-4) (2010) 51-61.

[14] K. Debnath and S. Chaudhuri, Local scour around non-circular piers in clay–sand mixed cohesive sediment beds, J. Eng. Geo., 151, (2012) 1-14.

[15] O. Link, K. Klischies, G. Montalva and S. Dey, Effects of bed compaction on scour at piers in sand-clay mixtures, Journal of Hydraulic Engineering, 139(9) (2013)1013-9.

[16] U. C. Kothyari, A. Kumar and R. K. Jain, Influence of cohesion on riverbed scour in the wake region of piers, Journal of Hydraulic Engineering, 140(1) (2013)1-3.

[17] M. Najafzadeh and G. A. Barani, Experimental study of local scour around a vertical pier in cohesive soils, Scientia Iranica, Transaction A, Civil Engineering, 21(2) (2014) 241.

[18] J. L. Briaud, Scour depth at bridges: Method including soil properties. I: Maximum scour depth prediction, J. Geo. and Geoen. Eng., 141(2) (2014), 04014104.

[19] M. Muzzammil, J. Alama, M. Danish, Scour prediction at bridge piers in cohesive bed using gene expression programming, Aquatic Procedia, 4 (2015)789-96.