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Investigation of Scour Depth at Bridge Piers using Bri-Stars Model in Iran

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***Abstract*—**BRI-STARS (BRIdge Stream Tube model for Alluvial River Simulation) program was used to investigate the scour depth around bridge piers in some of the major river systems in Iran. Model calibration was performed by collecting different field data. Field data are cataloged on three categories, first group of bridges that their rivers bed are formed by fine material, second group of bridges that their rivers bed are formed by sand material, and finally bridges that their rivers bed are formed by gravel or cobble materials. Verification was performed with some field data in Fars Province. Results show that for wide piers, computed scour depth is more than measured one. In gravel bed streams, computed scour depth is greater than measured scour depth, the reason is due to formation of armor layer on bed of channel. Once this layer is eroded, the computed scour depth is close to the measured one.

***Keywords*—**BRI-STARS, local scour, bridge, computer modeling

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I. INTRODUCTION

BRIDGE scour is a severe problem that costs millions of dollars of damage. Scour occurs during times of rapid river flow and can be exacerbated by debris when rocks, gravel, silt, etc., are transported by currents away from bridge piers and similar structures. During severe scour events, foundation material below the pier footing may be eroded, leaving the structure unsupported and jeopardy of collapse. On March 10 1995 about 9:00 p.m. the south bound and north bound bridges on Inter state over Arroyo Pasajero in California collapsed during a large flood [1]. There are many methods and studies for prediction of pier scour depth. For example, Coleman (2005) presented a methodology to predict local scour depth at a complex pier, that combines existing expressions for scouring respectively at uniform piers, caisson-founded piers, pile groups with debris rafts, and pile groups alone [2]. And Bozkus et al., (2004) investigated study, the effects of inclination of bridge piers on local scour depths around bridge piers, in an experimental [3]. Mia (2003) proposed a design method to predict the local scour depth with time. An experimental program was carried out using a cylindrical pier placed in uniform beds under clear-water flows. The pier scour depth was calculated on the basis of a sediment transport equation [4]. Sheppard (2004) Local performed clear-water scour tests with three different diameter circular piles, three different uniform cohesionless sediment diameters and a range of water depths and flow velocities. Equilibrium scour depths were found to depend on the wash load concentration [5].

A risk-based method for ranking, comparing, and choosing the most appropriate scour countermeasures is presented by Johnson et al., (2004) using failure modes and effects analysis and risk priority numbers. Risk priority numbers can provide justification for selecting a specific countermeasure and the appropriate compensating actions to be taken to prevent failure of the countermeasure [6]. A fluvial study of Brazos River near I-59 has been made with the objective to assess potential river channel changes at the bridge crossing by Chang et al., (1998) [7]. Quantitative assessment for scour of the bridge is based on mathematical modeling of the river channel using the GFLUVIAL model [7].

Richardson et al., 1995 applied a commercially available three-dimensional hydrodynamic model which was used to simulate the flow which occurs within a scour hole at the base of a cylindrical pier. The results of the numerical simulation were compared to the laboratory findings of Melville and Raudkivi (1977). Quantitative and qualitative agreement between the studies was quite good [1].

A finite volume method has been employed to discretize the governing equations by Peng et al., (1998). A K-ε model modified by Zhu-Shih is used to simulate the turbulent momentum transport [8].In this investigation, scour around bridge piers have been studied. BRI-STARS software was used for computing scour around bridge pier. Calibration of this software was performed by some of field data, then scour around bridge piers were computed, and finally scour around bridge pier were discussed.

II. METHODOLOGY FOR PREDICTION OF SCOUR DEPTH

BRI-STARS computer program was used to compute scour around bridge pier. Any numerical modeling effort of an alluvial system (such as BRI-STARS) is conducted in three basic stages: Calibration, Verification and Prediction. The first stage, calibration, aims at preparing the model of the type of system to be modeled. Calibration of BRI-STARS was performed with American field data. Data were cataloged on three categories: first group of bridges that their river beds are formed by fine material (i.e. silt and clay), second group of bridges that their river beds are formed by sandy material and finally bridges that their river beds are formed by gravel or cobbles materials. In each group, calibration of the bridge pier scour was performed through comparison with actual data using linear regression.Verification involved application and comparison of the model with a different set of field data. The results of this comparison determine the validity and quality of the calibration. Verification was performed with some field data in Fars Province. Finally, once the model is calibrated and verified, predictions may be made concerning system behavior for which there is no data. This step is the goal of the

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modeling effort, wherein design decisions are made. In this investigation three bridges in the Fars and Isfahan provinces were used for prediction. The results were modified by regression equations obtained from calibration.

III. Bri-Stars Computer Program

The development of BRI-STARS (BRIdge Stream Tube model for Alluvial River Simulation) consisted of three stages. The development of a stream tube model for alluvial channels with fixed width was documented. In the second stage of development, the theory of minimum rate of energy dissipation or its simplified version of minimum total stream power was used to incorporate the channel width as an unknown variable. Finally, in the last stage, the bridge hydraulics and local pier scour component was added. Also, in this third stage, the model's capabilities were enhanced by the inclusion of new sediment transport equations, graphical user interface, lateral water, and sediment inflow options. Both energy and momentum functions are used in the BRI-STARS model so the water surface profile computation can be carried out through combinations of sub-critical and supercritical flows without interruption. The stream tube concept is used for hydraulic computations in a semi two-dimensional way. Once the hydraulic parameters in each stream tube are computed, the scour or deposition in each stream tube determined by sediment routing. The end results will provide the variation of channel geometry in the vertical direction.

The parameters which influence scour around bridge piers can be arranged into four main groups: 1) fluid variables: density of fluid and kinematics viscosity of fluid, 2) stream flow variables: depth of approach flow, mean velocity of undisturbed flow and roughness of the approach flow, 3) stream bed materials: grain diameter and form, grain size distribution, density of the sediment and cohesive properties, 4) bridge pier variables: pier dimensions, pier shape, surface roughness, number and spacing of the piers, orientation of piers to approach flow and pier protection. Equation (1) shows the dependence of scour depth as a depended variable as a function of mentioned variable:

$$d_s = f\left(y, b, u_0, D_{50}, \sigma_g, \psi, \alpha, \gamma_s', t, g, \rho, v\right) \tag{1}$$

where y is the flow depth; b is the pier width; u_0 is the mean approach velocity; D_{50} is the mean sediment size; σ_g is the sediment gradation; ψ is the pier shape factor; α is the angle of attack; γ_s' is the submerged weight of the sediment; t is the time; g is the gravitational acceleration; ρ is the water density; and υ is the kinematic viscosity. After dimensional analysis, the following equation is obtained:

$$\frac{d_s}{b} = \kappa K_1 K_2 \left(\frac{y}{b}\right)^a \left(Fr\right)^b \left(\frac{D_{50}}{y}\right)^c \left(\frac{u_0 t}{b}\right)^d \tag{2}$$

where κ is a proportionality constant; K_1 is a shape factor; K_2 is the alignment factor; and a, b, c, and d are exponents to be determined through regression analysis.

Various investigators used laboratory data and achieved different equations by dimensional analysis. Following equations have been used in BRI-STARS computer program.

a) *Colorado State University (CSU) equation (1975) for equilibrium scours depth:*

$$\frac{d_s}{b} = 2.0 K_1 K_2 \left(\frac{b}{y}\right)^{0.65} Fr^{0.43} \tag{3}$$

Where Fr is Froude Number

b) The Laursen relationship (1960):

$$\frac{b}{y} = 5.5 \frac{d_s}{y}\left[\left(\frac{d_s}{11.5y} + 1\right)^{1.7} - 1\right] \tag{4}$$

The equation was based on an analysis using long bridge contraction hydraulics. A balance of sediment transport capacity in the normal and contracted sections was used in the derivation of this equation. It is valid for subcritical flow with a significant rate of sediment movement. This equation represents a conservative approximation of the pier scour by enveloping the available data.

c) Froehlich (1987) used multiple-linear-regression analysis to develop a prediction equation for local live-bed scour:

$$\frac{d_s}{b} = 0.32\varphi \left(\frac{b'}{b}\right)^{0.62} \left(\frac{y}{b}\right)^{0.46} Fr^{0.2} \left(\frac{b}{D}\right)^{0.08} + 1 \tag{5}$$

Where b' the pier width is projected normal to the approach flow $\left(b\cos\theta + L\sin\theta\right)$, θ is the angle of attack; and ψ is the pier shape correction factor with values of 1.3 for a square-nosed pier, 1.0 for a round-nosed pier, and 0.7 for a sharp-nosed pier. It should be noted that Froehlich's equation increases the computed depth.

d) Jain (1981), using experimental data from previous studies, formulated an equation for maximum clear-water scour around cylindrical piers for higher flow velocities $\left(Fr - Fr_c \geq 0.15\right)$:

$$\frac{d_s}{b} = 1.86\left(\frac{y}{b}\right)^{0.5} \left(Fr - Fr_c\right)^{0.25} \tag{6}$$

Where Fr_c is the critical Froude number. The equation was obtained first in a general form as a result of dimensional analysis, and then the numeric coefficients were determined with a multiple-linear regression analysis of experimental data.

IV. Calibration

The bridges that were used for calibration are located in various parts of US (www.usgs.gov). This data were cataloged on three categories: 1) first group of bridges that their river beds are formed by fine material (i.e. silt and clay); these bridges are: Brazos River at FM2004 near Lake Jackson, TX, SR 37 over James River near Mitchell, SD, US 2 over Beaver Creek Overflow 7 Miles West of Saco and MT and US 2 over Beaver Creek Overflow 9 Miles West of Saco. MT, 2) second group of bridges that their river beds are formed by sandy material; these bridges are: Pomme De Terre River at CR 22 near Fairfield, Mississippi River at I-255 (Jefferson Barracks Bridge) near St. Louis, MO, Mississippi River at Martin Luther King Memorial Bridge (S.R.799) at St. Louis, MO and Highway 25 over Minnesota River at Belle Plaine, MN 3) bridges that their river beds are formed by gravel or cobbles materials; these bridges are: SR 370 over Bitterroot River at Bell Crossing near Victor, MT, I-90 over Gallatin River near Manhattan, MT and US 93 over Bitterroot River near Darby, MT.Computed scour depth and measured scour depth from four equations that used in BRI-STARS program (i.e. CSU, Froehlich, Laursen and Jain and Fisher equations) can be seen in Fig. 1. Debris logged on a pier usually increase local scour at a pier. The debris may be increased pier width, local velocity and deflect the flow downward. This increases the transport of scour. Effect of debris on scour depth can be seen in site 74, the accumulation of woody debris centered on bent 6 was approximately 22.88 m wide, and extended about 13.72 m upstream from the nose of bent 6. The accumulations at bents 7 and 8 were submerged and could not be visually inspected. Therefore computed scour depth is less than measured scour depth (7.503 m).For each category a linear regression was performed. The correlation factor in each category and for each equation was computed by SPSS Software. And Pearson's correlation coefficient is computed from (7).

$$r = \frac{n\sum(XY) - \sum(X)\sum(Y)}{\sqrt{[n\sum X^2 - (\sum X)^2][n\sum Y^2 - (\sum Y)^2]}} \tag{7}$$

Pearson's correlation coefficient is a measure of linear association, if the relationship is not linear, Pearson's correlation coefficient is not an appropriate statistic for measuring their association and if a linear relationship is valid the Pearson's correlation coefficient is around 1. The correlation factors for four categories have been shown in Table I.

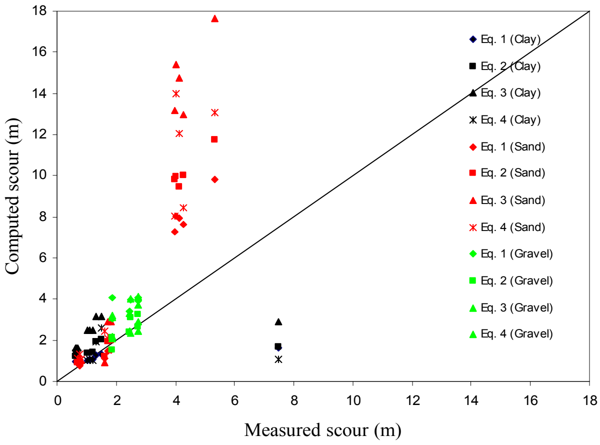

Fig. 1 Computed scour depth versus measured scour depth for data calibration

TABLE I
CORRELATION FACTORS FOR FOUR EQUATIONS

Equation	Correlation factor		
	Fine	Sand	Gravel
CSU	0.93	0.986	0.93
Laursen	0.968	0.978	0.778
Froehlich	0.871	0.983	0.794
Jain and Fisher	0.402	0.923	0.825

Pier width is an important parameter affecting on local scour depth. Fig. 2 shows the relation between pier width and relative scour depth (computed scour to observed scour). Ettema et al., (1998) stated that many scour depth equations (as they were used in BRI-STARS computer program) overestimate the scour depth for wide piers (piers that their width larger than 7.5) (Fig. 2) [9].

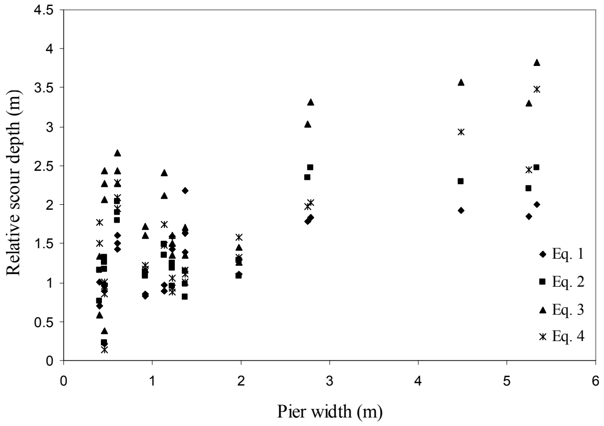

Fig. 2 Relative scour depth versus pier width for four equation

V. VERIFICATION

Verification was performed with some field data in Fars Province [10], i.e. Shirbaba, Shesh Pir, Ghotb Abad, Baghesafa, Hor, Aberepiade, Bereihan, Choghade, and Kerade. BRI-STARS' output were modified by regression equations, the results can be seen in Fig. 3.

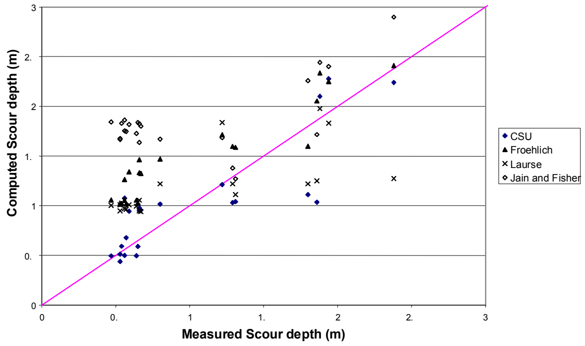

Fig. 3 Modified output by regression equation versus measured depth

The results were compared with Root Mean Square Error (RMS), as in (8):

$$e = \sqrt{\frac{1}{n}\sum(Y - X)^2} \tag{8}$$

The results can be seen in Table II, implying that CSU equation after modification by regression equation has less

RMS. Also, for other equations after modification the RMS decreases, as an evidence of calibration validity.

TABLE II
ROOT MEAN SQUARE ERROR

Equation	BRI-STARS Output	Modified Output by regression Equation
CSU	0.6314	0.3344
Laursen	0.9223	0.5064
Froehlich	1.1515	0.4678
Jain and fisher	1.0272	0.9616

VI. PREDICTION

The four bridges that were investigated are; Ghadir Bridge on Zayanderood River, Chamesohrabkhani on Kor River, Khan Bridge on Kor River. Table (3) and Table (4) show computed scour depths and the results after modification by regression equations, respectively. These results obtained without debris effect. These bridges are located in an area that covered by small trees, these trees have a shallow depth, therefore during flood these trees are felt and accumulate in front of piers, they act like voluminous piers, and scour depth will be greater than computed scour depth. In Khan Bridge, the pile foundation is near the bed, during flood the surface bed material are eroded and the piles become expose and because of this, depth of scour may be greater than computed scour.

TABLE III
COMPUTED SCOUR DEPTH FOR IRANIAN BRIDGES

Bridge Name	Pier ID	Computed scour (m)			
		CSU	Laursen	Froehlich	Jain and Fisher
Ghadir	1	2.28	4.62	3.39	4.28
	2	2.28	4.62	3.39	4.28
	3	2.53	4.68	3.68	4.45
	4	2.18	4.33	3.06	3.87
	5	2.18	4.33	3.06	3.87
Khan	1	1.95	3.45	2.64	2.86
	2	1.79	2.45	2.57	2.43
Chamesoh -rabkhani	1	1.71	2.27	2.03	2.21

TABLE IV
RESULTS AFTER INCORPORATING REGRESSION EQUATION

Bridge Name	Pier ID	Computed scour (m)			
		CSU	Laursen	Froehlich	Jain and Fisher
Ghadir	1	3.90	2.32	3.15	1.88
	2	3.90	2.32	3.15	1.88
	3	4.51	2.35	3.48	1.94
	4	3.66	2.13	2.77	1.74
	5	3.66	2.13	2.77	1.74
Khan	1	1.75	1.8	1.82	1.87
	2	1.66	1.58	1.80	1.75
Chameso hrabkhani	1	1.65	1.53	1.61	1.69

VII. CONCLUSION

- Results show that for wide piers, computed scour depth is more than measured one; the reason lies on that many equations have been established based on small pier width in laboratory flume.
- In gravel bed streams, computed scour depth is greater than measured scour depth, the reason is due to formation of armor layer in bottom of channel. When this layer will be eroded, the computed scour depth gets near measured one.
- In clay bed streams, the computed scour depth is less than scour depth for sandy bed streams; the reason is due to cohesion for clay bed that its effect has not been included in computation equations.
- Results show that BRI-STARS computer program can be used for scour depth estimations in various streams after proper calibrations.
- The results show that CSU equation compute scour depth more accurate than other equations.

Due to large debris accumulation in front of bridge pier, BRI-STARS computer program is not able to predict scour depth; it is recommended that for these cases, BPP (Bridge Pier Prediction) will be used [11].

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