Iranian Journal of Science & Technology, Transaction B, Engineering, Vol. 30, No. B4
Printed in The Islamic Republic of Iran, 2006

INVESTIGATION OF SCOUR DEPTH AT BRIDGE PIERS USING BRI-STARS MODEL[*]

N. TALEBBEYDOKHTI[**] AND M. ASADI AGHBOLAGHI

Dept. of Civil Engineering, Shiraz University, Shiraz, I. R. of Iran
Email: taleb@shirazu.ac.ir

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. The first group of bridges having river beds formed by fine material (i.e., silt and clay), the second group of bridges having river beds formed by sand material, and finally, bridges having river beds formed by gravel or cobble materials. Verification involved application and comparison of the model to different known real-life cases. The results of this comparison determine the validity and quality of the calibration. Verification was performed with some field data in Fars Province. The scour depths of various bridges located in Iran during significant floods were calculated. The bridges are located in three different locations with different bed materials such as: the Ghadir Bridge on the Zayanderood River, the Khan Bridge River and the Chame Sohrabkhani Bridge on Kor.

Results show that for wide piers, computed scour depth is more than the measured depth. In gravel bed streams, the computed scour depth is also greater than measured scour depth, the reason is due to the formation of the armor layer on the bed of the channel. Once this layer is eroded, the computed scour depth is close to the measured one.

Keywords – BRI-STARS, local scour, bridge, computer modeling

1. INTRODUCTION

Bridge scour is a severe problem that costs millions of dollars in 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 in jeopardy of collapse. The catastrophic failure of the Schoharie Creek Bridge on the New York State Thruway in April, 1987 occurred during a near flood in which 10 people died. Two years later, the failure of the U.S. 51 Bridge over the Hatchie River in the Tennessee River broadened the concern to stream stability problems as well. Eight people died in the collapse, which occurred slowly over a rapid in about an hour during a moderate flood. In 1993 the damage and economic cost of the Mississippi River floods underscored the vulnerability of the nation's transportation system to bridge scour and system instability. Another example, on March 10, 1995, around 9:00 p.m. the southbound and northbound bridges on the Interstate over Arroyo Pasajero in California collapsed during a large flood [1].

There are many methods and studies for the prediction of pier scour depth. Some of them are as follows:

A new methodology to predict local scour depth at a complex pier is presented by Coleman, which combines existing expressions for scouring respectively at uniform piers, caisson-founded piers, pile

---

[*] Received by the editors April 30, 2005; final revised form November 5, 2005.

[**] Corresponding author

groups with debris rafts, and pile groups alone. For design purposes, the present method highlights respective pile-cap elevations that maximize (i.e., to be avoided over the pier life) and minimize local scour at complex piers [2].

In an experimental study, the effects of inclination of bridge piers were investigated on local scour depths around bridge piers. The results of this study indicate that the local scour depth decreases as the inclination of the pier increases [3].

Mia 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].

Local clear-water scour tests were performed with three different diameter circular piles (0.114, 0.305, and 0.914 m), three different uniform cohesionless sediment diameters (0.22, 0.80, and 2.90 mm) and a range of water depths and flow velocities by Sheppard *et al*. The tests were performed in the 6.1 m wide, 6.4 m deep, and 38.4 m long flumes. These tests extend local scour data obtained in controlled experiments to prototype size piles and ratios of pile diameter to sediment diameter to 4,155. Equilibrium scour depths were found to depend on the wash load concentration [5].

Confidence in a given countermeasure depends on prior experience in using the measure, cost, and maintenance, as well as the ability to detect failure. The use of countermeasures often introduces uncertainty due to a lack of systematic testing and unknown potential for failure. A risk-based method for ranking, comparing, and choosing the most appropriate scour countermeasures is presented by Johnson et al., using failure modes and effects analysis and risk priority numbers (RPN). Failure modes and effects analysis incorporates uncertainty in the selection process by considering risk in terms of the likelihood of a component failure, the consequence of failure, and the level of difficulty required to detect failure. 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].

Since scour computation is complicated and time consuming, software was developed and applied to compute scour around bridge piers. Many researchers have applied various computer programs to compute scour around bridge piers. A fluvial study of the Brazos River near I-59 in southeast Texas has been made with the objective of assessing potential river channel changes at the bridge crossing. Quantitative assessment for scour of the bridge is based on mathematical modeling of the river channel using the GFLUVIAL model [7].

A sensitivity analysis is often required for a bridge crossing a stream to estimate the potential scour depths referred to as a contraction scour, abutment scour and pier scour. Bridge Scour Sensitivity Analysis (BRSC) is a user-friendly spreadsheet program developed to perform a series of calculations to provide the data base for such an analysis [8]. Muller, in 1993, developed a computer program to extract hydraulic information required for bridge-scour computations from a Water-Surface Profile computation model (WSPRO) [9].

A fluvial study of the Trinity River near US-59 in southeast Texas evaluated potential river-channel changes at the bridge crossing. Quantitative assessment of general scour in the downstream channel is based on simulation using a FLUVIAL-12 model and a 10-year record of daily discharges [10].

The Finite Element Surface Water Modeling System (FESWMS) is a two-dimensional computer program that is employed in the horizontal plane to complete a hydraulic analysis on the Baltimore Street Bridge Rehabilitation Project, located in Baltimore, Maryland [11].

Walton *et al*., planned to make HEC more useful for bridge scour studies, and to streamline the process of evaluating hundreds of bridges. They have made the following modifications: (1) modified HEC-2 to calculate the cross-sectional distribution of velocities (2) added an 'SP' card to calculate pier scour based on CSU or Froehlich's clear water and live bed equation, and (3) added an 'SN' card to calculate contraction scour using Laursen's clear water and live bed equations [12].

Richardson *et al*., 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. Quantitative and qualitative agreement between the studies was quite good [1].

A finite volume method is employed to discretize the governing equations by Peng *et al*. A K-ε model modified by Zhu-Shih is used to simulate the turbulent momentum transport. The numerical results show the flow pattern at the tip and behind the groins possess a strongly three-dimensional feature [13].

In this investigation, scour around bridge piers have been studied. BRI-STARS software was used for computing scour around bridge piers. The calibration of this software was performed by some of the field data, then scour around bridge piers were computed and then discussed.

2. METHODOLOGY FOR PREDICTION OF SCOUR DEPTH

A BRI-STARS computer program was used to compute scour around bridge piers. 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. Since lack of data on scour around bridge piers in Iran, calibration was performed with some of the available field data from the US. Data were cataloged on three categories: the first group of bridges with river beds formed by fine material (i.e. silt and clay), the second group of bridges with river beds formed by sandy material, and finally bridges with river beds 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. These were substituted in regression equation and modified values were obtained. The calculated value from BRI-STARS and the modified value were then compared with the observed scour.

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

3. 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 a fixed width by Molinas was documented earlier [14]. That model was successfully applied to simulate local scour and deposition processes at the Mississippi River Lock and Dam No. 26 replacement site near St. Louis. In the second stage of development, the theory of a 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 is determined by sediment routing. The end results will provide the variation of channel geometry in the vertical direction.

In order to generate a data file for a BRI-STARS simulation, the following data is needed: title information, geometric, hydraulic, roughness, bottom elevations, energy losses (optional), stream tubes and flow distribution, computational time step, stage-discharge, sediment (optional), sediment equation, sediment inflow hydrograph, sediment size, bridge scour (optional), screen output control (optional), output file control data and minimization (optional).

In the absence of a data group, engineering analysis may be required to extrapolate data from similar watersheds in the geographic region and/or estimations from similar flows.

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 the mentioned variable

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

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:

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

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

Various investigators have used laboratory data and achieved different equations by dimensional analysis. The following equations have been used in the 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 [15], 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. This 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.

4. CALIBRATION

The bridges that were used for calibration are located in various parts of the US (www.usgs.gov). Since geometric data is required for BRI-STARS modeling, the bridges with geometric cross sections that were available were selected for modeling. This data was cataloged on three categories: 1) the first group of bridges with river beds formed by fine material (i.e., silt and clay); these bridges are: the Brazos River at FM2004 near Lake Jackson, TX, SR 37 over the James River near Mitchell, SD, US 2 over the Beaver Creek Overflow 7 Miles West of Saco and MT, and US 2 over Beaver Creek Overflow 9 Miles West of Saco. MT, 2) the second group of bridges have river beds formed by sandy material. These bridges are: Pomme De Terre River at CR 22 near Fairfield, the Mississippi River at I-255 (Jefferson Barracks Bridge) near St. Louis, MO, the Mississippi River at Martin Luther King Memorial Bridge (S.R.799) in St. Louis, MO and Highway 25 over the Minnesota River at Belle Plaine, MN, 3) bridges with river beds formed by gravel or cobbles materials. These bridges are: SR 370 over the Bitterroot River at Bell Crossing near Victor, MT, I-90 over the Gallatin River near Manhattan, MT and US 93 over the Bitterroot River near Darby, MT. Table 1 shows the characteristics of these bridges.

Table 1. Stream data for model calibration

Site ID	State	Stream name	Stream size	Slope	Bed material
73	MN	Pomme De Ter	Small	0.0006	Sand
74	NA	Brazos River	Medium	0.0003	Clay
75	NA	Mississippi River	Wide	0.0001	Sand
76	NA	Mississippi River	Wide	-	Sand
82	NA	Minnesota River	Medium	0.000063	Sand
83	SD	James River	Medium	0.000104	Silt
84	SD	James River	Medium	0.000104	Sand
86	MT	Bitterroot River	Medium	0.0017	Gravel
87	NA	Beaver Creek	Unknown	0.000145	Silt
88	NA	Beaver Creek	Small	0.000145	Silt
89	MT	Gallatin River	Medium	0.0046	Gravel

Important data that affects scour depth are presented in Table 2.

Table 2. Effective bridge and stream parameters on scour depth

Site ID	Pier ID	Pier station	B (m)	θ	L (m)	Pier Type	Pier shape	Protection	D_{50} (mm)	Flow depth (m)	Q_{peak} (m^3/s)
73	1	203	0.4	15	-	Group	Round	Unknown	0.15	4.57	409
	2	190	0.4	15	-	Group	Round	Unknown	0.15	4.57	
74	2	352	0.46	30	-	Group	Square	None	0.1	9.15	2380
	3	314	0.46	30	-	Group	Square	None	0.1	9.15	
	4	276	0.46	30	-	Group	Square	None	0.1	9.15	
	5	233	0.46	30	-	Group	Square	None	0.1	9.15	
	6	191	0.46	30	-	Group	Square	None	0.1	9.15	
	7	148	0.46	30	-	Group	Square	None	0.1	9.15	
	8	105	0.46	30	-	Group	Square	None	0.1	9.15	
	9	63	0.46	30	-	Group	Square	None	0.1	9.15	
	10	24	0.46	30	-	Group	Square	None	0.1	9.15	
	11	-14	0.46	30	-	Group	Square	None	0.1	9.15	
75	7	159	2.62	0	9	Single	Square	Unknown	0.7	10.68	
	8	234	2.75	0	9	Single	Square	None	0.7	10.68	
	9	309	2.79	0	9	Single	Square	None	0.7	10.68	
	10	384	2.88	0	9	Single	Square	Unknown	0.7	10.68	
	11	461	2.93	0	9	Single	Square	Unknown	0.7	10.68	
	12	536	3.68	0	18.15	Single	Square	Unknown	0.7	10.68	
76	9	448	4.48	0	19.98	Single	Sharp	None	0.88	18.3	29000
	10	742	5.25	0	20.74	Single	Sharp	None	0.88	18.3	
	11	886	5.34	0	20.74	Single	Sharp	None	0.88	18.3	
82	1	0	1.98	0	11.21	Single	Sharp	Riprap	0.7	12.2	147
	2		1.98	0	11.21	Single	Sharp	Riprap	0.7	12.2	
83	1		1.14	35	-	Group	Round	Unknown	0.7	6.1	713
	2		1.14	35	-	Group	Round	Unknown	0.7	6.1	
84	1		0.92	0	-	Group	Cylinder	Unknown	0.027	7.62	491
	2		0.92	0	-	Group	Cylinder	Unknown	0.027	7.62	
86	2	30	1.37	30	12.96	Single	Sharp	Unknown	15.8	3.68	497
	3	61	1.37	30	12.96	Single	Sharp	Unknown	15.8	3.68	
	4	91	1.37	30	12.96	Single	Sharp	Unknown	15.8	3.68	
87	1	8.84	0.61	0	-	Single	Cylinder	Unknown	0.001	3.52	497
	2	13.72	0.61	0	-	Group	Cylinder	Unknown	0.001	3.52	
	3	18.6	0.61	0	-	Group	Cylinder	Unknown	0.001	3.52	
89	1	15.56	1.22	27	39.65	Single	Sharp	None	35	4.3	239
	2	31.42	1.22	27	39.65	Single	Unknown	Unknown	35	4.3	
	3	46.97	1.22	27	39.65	Single	Unknown	Unknown	35	4.3	

Input files were created from the above data. Daily hydrograph flood was applied for scour computation. Computed scour depth and measured scour depth from four equations that were used in the 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 that pier. The debris may increase pier width, local velocity and deflect the flow downward. This increases the transport of scour. The effect of debris on scour depth can be seen in site 74. During the flood of October 23, 1994, 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).

A linear regression was performed for each category. The correlation factor in each category and for each equation was computed by SPSS software, and Pearson's correlation coefficient is computed from Eq. (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 3.

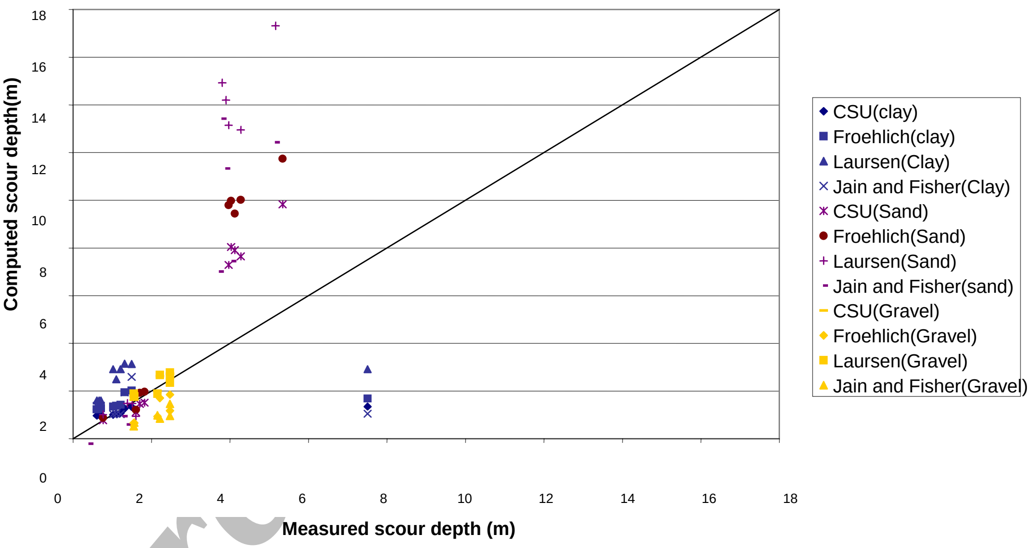

Fig. 1. Computed scour depth versus measured scour depth for data calibration

Table 3. 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

The value of the correlation coefficient for the second sandy river bed is around 1, which shows that the regression is valid. For a silt and clay river bed, and for the Jain and Fisher equation, the correlation coefficient is 0.402, which means that linear regression is not valid. For other cases, the correlation coefficient is in an acceptable range. The regression lines can bee seen in Figs. 2-4.

Pier width is an important parameter affecting local scour depth. Figure 5 shows the relation between pier width and relative scour depth (computed scour to observed scour). Ettema *et al*. mentioned that many scour depth equations (as they were used in BRI-STARS computer program) overestimate the scour depth for wide piers (piers having widths larger than 7.5 meters) (Fig. 5) [16].

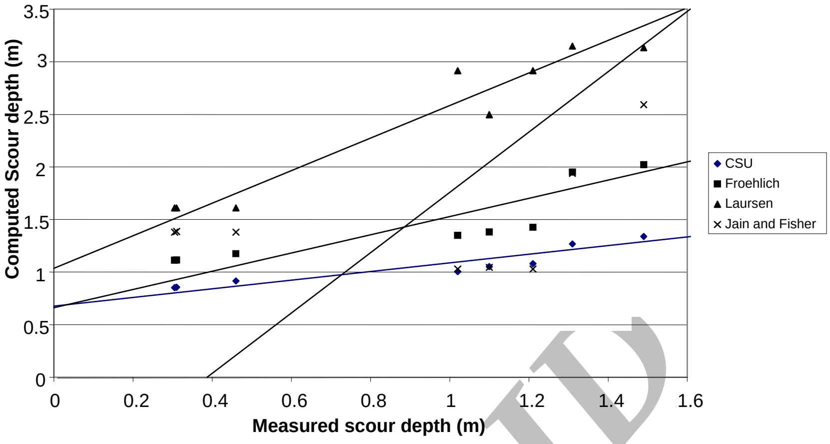

Fig. 2. Regression lines for fine materials for four equations

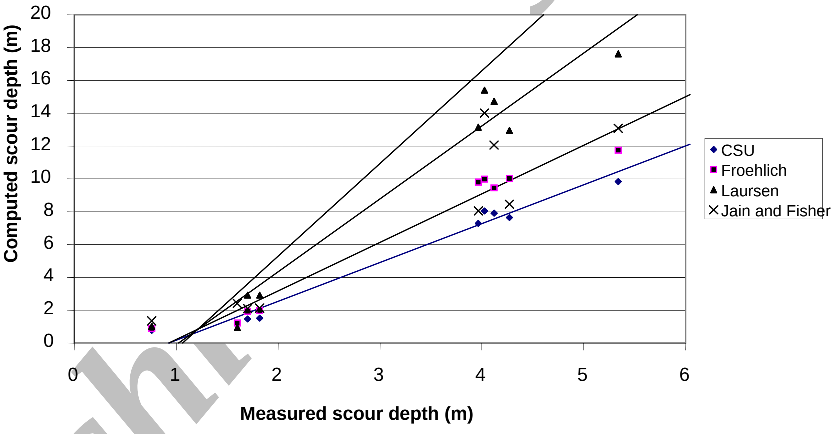

Fig. 3. Regression lines for sandy bed rivers for four equations

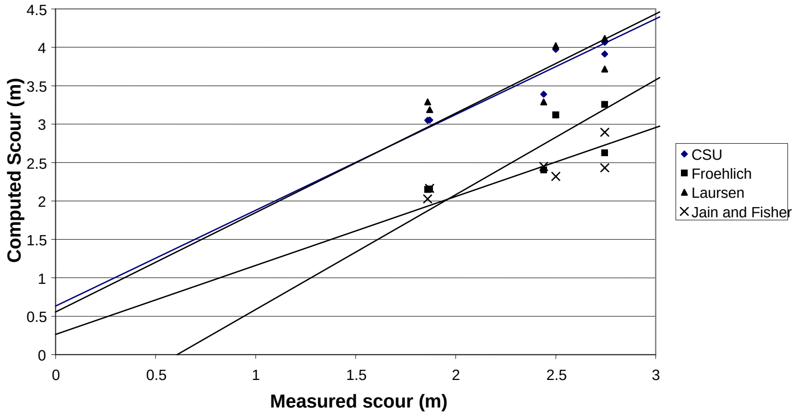

Fig. 4. Regression lines for sandy gravel and Cobble rivers for four equations

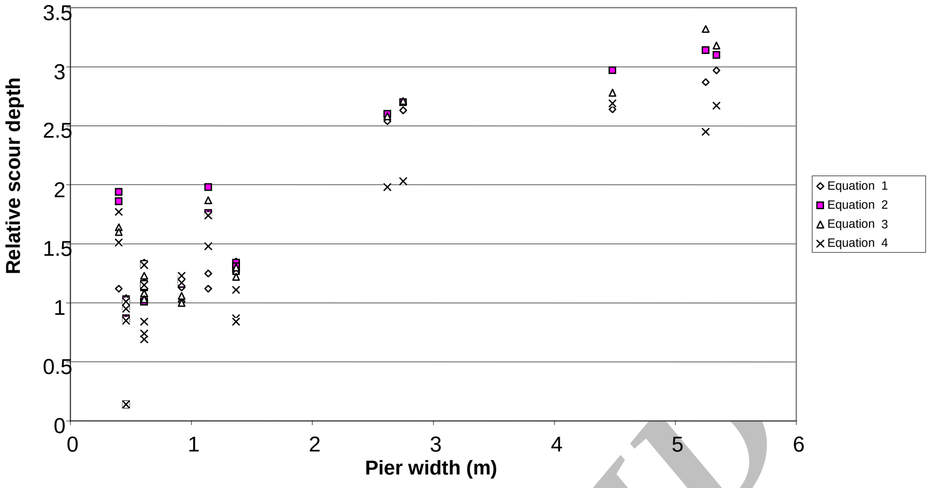

Fig. 5. Relative scour depth versus pier width for four equations

Further work is needed to determine the cause of the difference between laboratory and field-based data methods, and to investigate other dimensionless explanatory variables that may provide a better explanation of the difference between observed and computed scour depth.

5. VERIFICATION

Verification involved application and comparison of the model to different known real-life cases. The results of this comparison determine the validity and quality of the calibration. Verification was performed with some field data in Fars province [17]. The characteristics of these rivers are shown in Table 4. Unfortunately three bridges collapsed during the 1986 December flood, and investigations continued on the six remaining bridges.

Table 4. Stream data for model verification

Bridge name	Stream name	Province	Stream size	Bed material
Shirbaba	Ardakan	Fars	Unknown	Unknown
Shesh Pir	Shesh Pir	Fars	Medium	Gravel
Ghotb Abad	Shoor(Jahrom)	Fars	Medium	Gravel
Baghesafa	Khoshk River	Fars	Medium	Gravel
Hor		Fars	Medium	Gravel
Aberepiade		Fars	Medium	Gravel
Bereihan	Ghara Aghaj	Fars	Medium	Gravel
Choghade		Fars	Wide	Gravel
Kerade		Fars	Medium	Gravel

The important data that affects scour depth are presented in Table 5. Input files were created from the above data. Daily hydrograph flood was applied for scour computation. Computed scour depth and measured scour depth from four equations that were used in BRI-STARS program (i.e., CSU, Froehlich, Laursen and Jain and Fisher equations) can be seen in Fig. 6. These results were modified by regression equations, which can be seen in Fig. 7. Computed scour depth and modified output by regression equation versus measured scour depth can be seen in Fig. 8. The results were compared with Root Mean Square Error (RMS), as in Eq. (8)

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

The results can be seen in Table 6, implying that the CSU equation, after modification by the regression equation, has less RMS. Also, for other equations after modification, the RMS decreases as an evidence of calibration validity.

Table 5. Effective bridge and stream parameters on scour depth

Bridge name	Pier ID	B (m)	θ	L (m)	Pier type	Pier shape	D_{50} (mm)	Flow depth (m)	Q_{peak}(m^3/s)
Shesh Pir	1	2.5	20	19	Single	Round	72	0.7	8.14
	2	2.5	20	19	Single	Round	72	0.7	
Abere Piade	1	0.75	15	1.65	Single	Square	16.5	1.3	189
	2	0.75	15	1.65	Single	Square	16.5	3.07	
	3	0.75	15	1.65	Single	Square	16.5	1.94	
	4	0.75	15	1.65	Single	Square	16.5	2.06	
	5	0.75	15	1.65	Single	Square	16.5	1.08	
Hor	1	0.42	0	12.5	Single	Round	4.4	1.3	192
	2	0.42	0	12.5	Single	Round	4.4	1.42	
	3	0.42	0	12.5	Single	Round	4.4	1.44	
	4	0.42	0	12.5	Single	Round	4.4	1.4	
	5	0.42	0	12.5	Single	Round	4.4	1.3	
Bghesafa	1	0.42	0	12.5	Single	Round	47.5	1.27	190
	2	0.42	0	12.5	Single	Round	47.5	1.51	
	3	0.42	0	12.5	Single	Round	47.5	1.57	
	4	0.42	0	12.5	Single	Round	47.5	1.45	
	5	0.42	0	12.5	Single	Round	47.5	1.2	
Bereihan	1	1	30	6	Single	Round	2.63	3.73	620
Choghade	1	1.2	0	8	Single	Round	36	3.14	1848
	2	2.6	0	8	Single	Round	36	3.75	
	3	1.2	0	8	Single	Round	36	4.15	
	4	4	0	8	Single	Round	36	3.33	
	5	1.2	0	8	Single	Round	36	3.3	
	6	4	0	8	Single	Round	36	2.76	
	7	1.2	0	8	Single	Round	36	3.12	

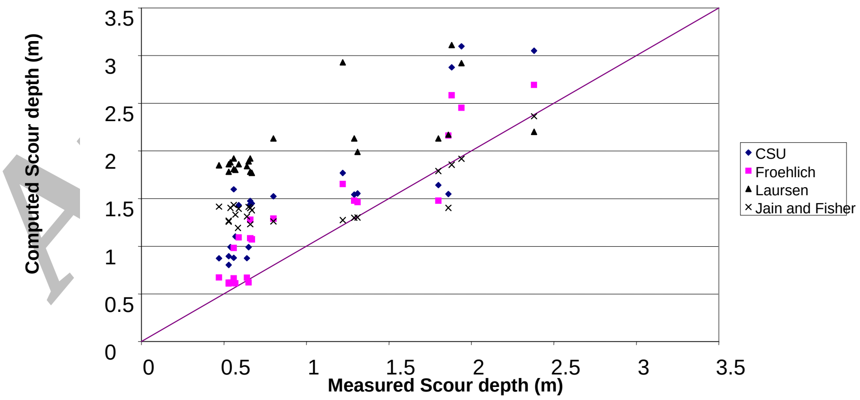

Fig. 6. Computed and measured scour depth based on field data

Table 6. 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

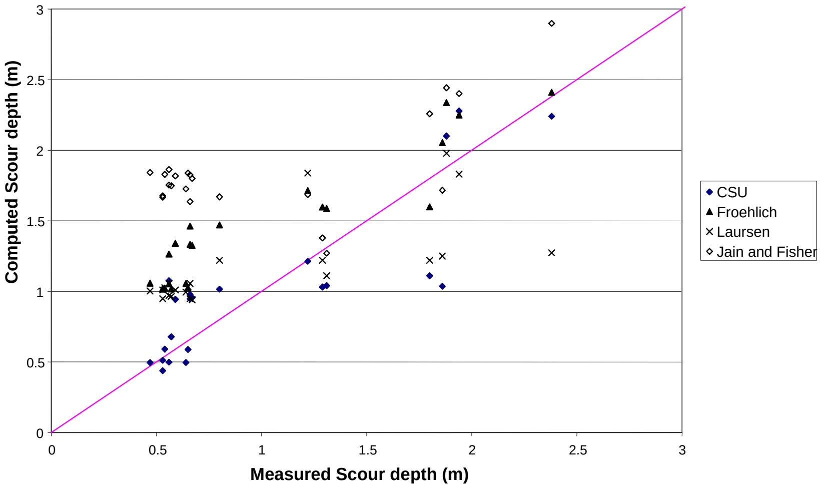

Fig. 7. Modified output by regression equation versus measured depth

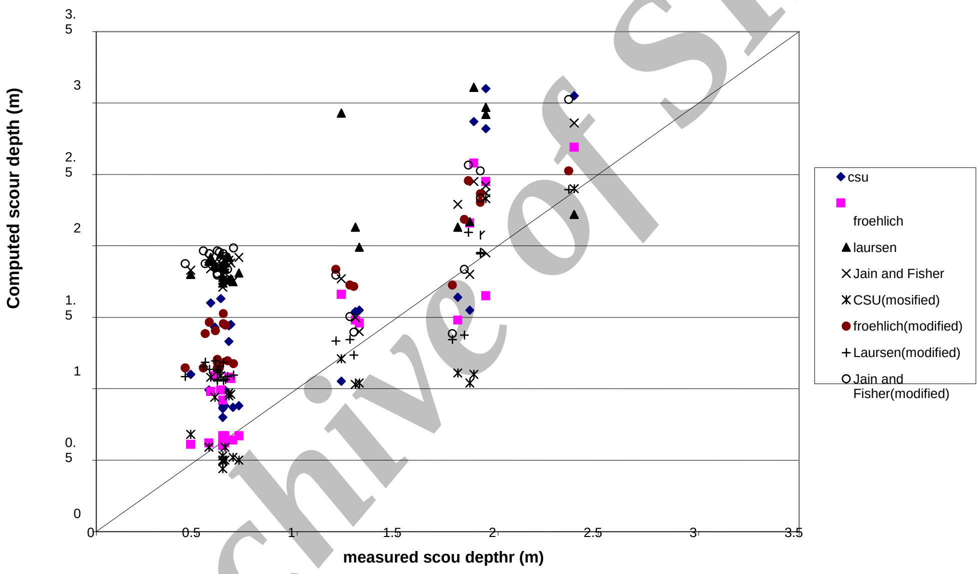

Fig. 8. Computed scour depth and modified output by regression equation versus measured scour depth

6. PREDICTION

The four bridges that were investigated are the Ghadir Bridge on the Zayanderood River, Chamesohrabkhani on the Kor River, and the Khan Bridge on the Kor River (see Table 7). Ghadir Bridge is the longest bridge on the Zayanderood River. The Scour depth of this bridge was computed for a 100 year flood. The January, 2002 flood (the biggest observed flood during the last decade) was applied to estimate scour depth for other bridges. Unfortunately, during the flood there was no measured data. Table 8 shows the results for scour depth computation. Input files were created and fed into BRI-STARS.

Table 7. Bridge and stream data in Iran

Bridge name	State	Stream name	Stream size	slope	Bed material
Ghadir	Isfahan	Zayanderood	Wide	0.0003	Clay
Khan	Fars	Kor	Medium	0.0002	Sand
Chamesohrabkhani	Fars	Kor	Medium	0.0001	Sand

Table 8. Effective bridge parameters on scour depth

Bridge name	Pier ID	Pier station	B (m)	θ	L (m)	Pier type	Pier shape	Protection
Ghadir	1	56.4	1.6	35	-	Group	Cylinder	None
	2	86.8	1.6	35	-	Group	Cylinder	None
	3	117.4	1.6	35	-	Group	Cylinder	None
	4	147.8	1.6	35	-	Group	Cylinder	None
	5	178.4	1.6	35	-	Group	Cylinder	None
Khan	1	11.66	1.6	0	-	Group	Cylinder	None
	2	32.18	1.6	0	-	Group	Cylinder	None
Chamesohrabkhani	1	149.12	1.04	0	4.4	Single	Square	None

Table 9 shows computed scour depths and Table 10 shows the results after modification by regression equations. These results were obtained without debris effect. These bridges are located in an area that is covered by small trees, which have a shallow depth. Therefore during floods these trees are felt and accumulate in front of piers acting like voluminous piers, and show that scour depth will be greater than computed scour depth.

In the Khan Bridge, the pile foundation is near the bed. During a flood the surface bed material are eroded and the piles become exposed. Because of this, the depth of scour may be greater than the computed scour.

Table 9. 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
Chamesohrabkhani	1	1.71	2.27	2.03	2.21

Table 10. 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
Chamesohrabkhani	1	1.65	1.53	1.61	1.69

7. CONCLUSION

- Results show that for wide piers, computed scour depth is more than a measured one; the reason lies in the fact that many equations have been established based on small pier width in laboratory flumes.
- In gravel bed streams, computed scour depth is greater than measured scour depth. The reason is due to the formation of an armor layer in the bottom of the channel. When this layer is eroded, the computed scour depth gets near the measured one.

- In clay bed streams, the computed scour depth is less than the scour depth for sandy bed streams; the reason is due to cohesion for clay beds whose effects have not been included in computation equations.
- Results show that the BRI-STARS computer program can be used for scour depth estimations in various streams after proper calibrations.
- The calibration results show that sandy bed material produce the best response. The reason is because the equation of scour in the BRI-STARS computer program was obtained for sandy materials.
- The results show that the CSU equation computes scour depth more accurately than other equations.
- Due to large debris accumulation in front of bridge piers, the BRI-STARS computer program is not able to predict scour depth. It is recommended that for these cases, BPP (Bridge Pier Prediction) be used [18].

REFERENCES

1. Richardson, J. E., Panchang, V. G. & Kent, E. (1998). Three dimensional numerical simulation of flow around bridge sub-structure. *ASCE proceedings of stream stability and scour at highway bridges,* edit by Richardson E. V. and Lagasse F.
2. Coleman, S. E. (2005). Clearwater local scour at complex piers. *Journal of Hydraulic Engineering*, *131*(4), 330-334.
3. Bozkus, Z. & Yildiz, O. (2004). Effects of inclination of bridge piers on scouring depth. *Journal of Hydraulic Engineering*, *130*(8), 827-832.
4. Mia, Md. F. (2003). Design method of time-dependent local scour at circular bridge pier. *Journal of Hydraulic Engineering*, *129*(6), 420-427.
5. Sheppard, D. M., Odeh, M. & Glasser, T. (2004). Large scale clear-water local pier scour experiments. *Journal of Hydraulic Engineering*, *130*(10), 957-963.
6. Johnson, P. A. & Niezgoda, S. L. (2004). Risk-based method for selecting bridge scour countermeasures. *Journal of Hydraulic Engineering*, *130*(2), 121-128.
7. Chang, H. H., Jennings, M. E. & Olona, S. (1998). Computer simulation of river changes at bridge crossing on point bar. *ASCE proceedings of stream stability and scour at highway bridges*, edit by Richardson E. V. and Lagasse F.
8. Yucel, O. (1998). BRSC a spreadsheet program for bridge scour sensitivity analysis. *ASCE proceedings of stream stability and scour at highway bridges*, edit by Richardson E. V. and Lagasse F.
9. Muller, D. S. (1998). Bridge scour analysis using the water surface profile (WSPRO) model. *ASCE proceedings of stream stability and scour at highway bridges*, edit by Richardson E. V. and Lagasse F.
10. Chang, H. H., Harris, C., Lindsay, B. Nakao, S. S. & Kia, R. (1998). Simulation of general scour at US-5 bridge crossing of the Trinity River, Texas. *ASCE proceedings of stream stability and scour at highway bridges*, edit by Richardson E. V. and Lagasse F.
11. Ports, M. A., Turner, T. G. & Froehlich, D. C. (1998). Practical application of two dimensional hydraulic analysis for the Baltimor Street Bridge rehabilitation project. *ASCE proceedings of stream stability and scour at highway bridges*, edit by Richardson E. V. and Lagasse F.
12. Walton, R. & Bradley, J. B. (1998). HEC-2 modification for bridge scour analyses. *ASCE proceedings of stream stability and scour at highway bridges*, edit by Richardson E. V. and Lagasse F.
13. Peng, J., Kawahara, Y. & Tamai, N. (1998). Numerical analysis of three-dimensional turbulent flows around bridge submerged groins. *ASCE proceedings of stream stability and scour at highway bridges*, edit by Richardson E. V. and Lagasse F.

14. Molinas, A. (2000). *User's manual for BRI-STARS*. Federal Highway Administration, USA.
15. Jain, S. C. (1981). Maximum clear-water scour around circular piers. *Journal of Hydraulic Engineering ASCE 107*, 611-626
16. Ettema, R., Melville, B. W. & Raudkivi, B. (1991-98). Pier width and local scour depth. *ASCE Comp. of Conf. Scour Paper Reton.V.A.*
17. Ghorbani, B. (1989). *Investigation of existing computational methods to determine scour depth around hydraulic structures and selection of suitable method in Fars Rivers*. MS Thesis presented to irrigation department, Shiraz University.
18. Wallterstein, N. P. & Thorne, C. R. (1998). Computer model for prediction of scour at bridge pier by large debries. *ASCE proceedings of stream stability and scour at highway bridges*, edit by Richardson E. V. and Lagasse F.