Research Article
Comparative Analysis between Observed and Predicted Contraction Scour at Bridges Abutments

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Abstract: Social and economic damages are the most important damages of the bridge failure. Stability problems of such structures against failure and the depth of the abutments are directly related to the amount of the adjusted scour. Economy, reliability and stability have been main concerns regarding designing abutment bridges enhanced preventing scouring. In this study a detailed comparison of the up-to-date works on scour at the bridge abutment are presented including all possible aspects and contraction scour depth estimation formulas. The experimental data was obtained from the literature and three statistical tests were carried out to determine which of the formulae would give minimum prediction errors. Statistical and graphical comparison between the predicted and measured depth of scour showed the better relatively acceptable prediction scour formulas depth at abutments.

Keywords: Abutment, bridge stability, contraction scour, scour formula, statistical test

INTRODUCTION

Abutments are structures at the two ends of bridge that acquit double objectives of transferring the loads from the superstructure to the foundation bed and giving sidelong support to the approach embankment. Economy, dependability and strength are the main reasons of attention to increase international concerning in a bridge structure without movement joints at the junction of the deck on the abutments, named jointless or abutment bridges. If this kind of bridge is constructed on a waterway, abutments acquit a third function, to protect the embankment against scour of the stream. Lack of load capacity and bridge scour are the most common reasons of bridge collapse. Load capacity is happened because of an ever-increasing demand for larger volumes of traffic and heavier trucks and scour occurs because of the erosive action of flowing water, which excavates and carries away materials from streambeds and banks bridge foundations by the normal flowing water or flood. Although it may be greatly affected by the presence of structures encroaching on the channel, scour is a natural phenomenon caused by the flow of water over an erodible boundary, where the shear stress generated by the flowing water on the streambed is the basic erosive stress and the streambed materials provide the resisting stress against erosion. Scour reaches its equilibrium status when these two stresses get balanced. Study on 503 bridge structures failures in the United States from 1989 to 2000 showed that, the major reason for damage or failure of bridges are those related to scouring at bridge piers and abutments (Wardhana and Hadipriono, 2003).

Bridge failure or its' structural damage through the scour leads to serious loss for public safety and economy. Designing the bridge foundation safely needs an accurate estimation of scour depth, underestimation may lead to bridge failure while over estimation will lead to excessive construction cost. In this study comprehensive review of the up-to-date work on abutment contraction scour prediction have been evaluated supported by laboratory data analysis and statistical test.

BRIDGES INSTABILITY AS A RESULT OF SCOUR

Excavating and carrying away material from the bed and banks of streams is named general scour (Richardson and Davis, 2001). The long-term or short-term scour can be recognized by the time taken for general scour development (Melville and Coleman, 2000). The structures increase the local flow velocities and turbulence level and depending on their spaces, can give rise to vortices that exert increased erosive forces

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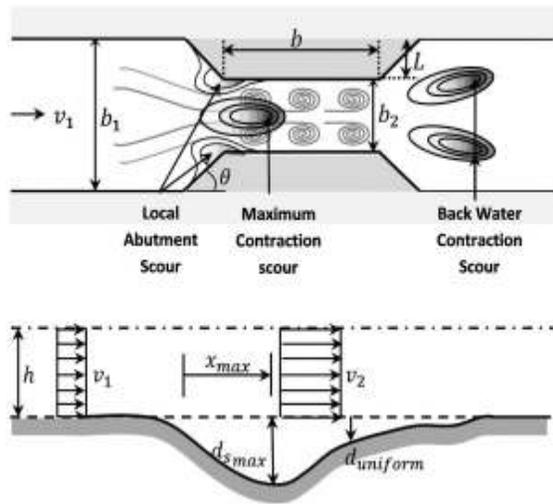
Fig. 1: Concepts in local and contraction scour at bridge abutment

on the adjacent bed and remove the sediment material in the surroundings of the bridge piers or abutments. This kind scour is called local scour (May *et al*., 2002). The total depth of scour, which includes general and localized scour, is called total scour. Localized scour can occur as either clear-water scour or live-bed scour. Clear water scour occurs in relatively low flows when the bed material upstream of the scour area is at rest. At the bridge area, bed material is removed and transported away but there is no deposit of material from upstream simultaneously (Maddison, 2012). Live bed scour occurs by the continuous erosion and deposition when there is general sediment transport during periods of flooding. Contraction scour occurs because of the constriction of a waterway and/or a natural means or human adjustment of the floodplain (Melville and Coleman, 2000). The overall effect of this phenomenon is the lowering of the channel bed (Alabi, 2006). An overview of the scour distribution around bridge abutments is showed graphically in Fig. 1. Short or long abutment are defined as having small or large ratio between abutment length and the depth of flow (L/y, respectively (Melville, 1992). Depending on the ratio of the length of contraction b to the approaching channel width b_1, channel contractions are designated as long or short (Dey and Barbhuiyab, 2005). When L/b>1, a contraction becomes long (Komura, 1966), whereas it had been considered L/b>2, (Webby, 1984). However, recent experimental study confirmed that L/b≥1, is satisfactory to be considered as a long contraction (Raikar, 2004).

According to the result of the perfect laboratory experiments which often applying rectangular channels and uniform sediment, it was conducted that the accuracy of scour depth estimate is less than the measured scour depth of the field or laboratory conditions (Hong, 2005).
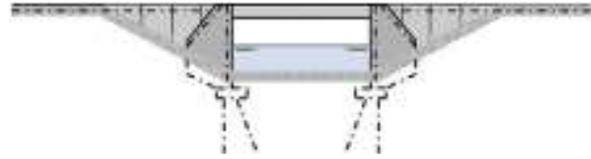
Fig. 2: Truss bridge

Fig. 3: Abutment (joint less) bridge

Truss bridge main structures are shown in Fig. 2. Furthermore, Fig. 3 shows jointless (abutment) bridges. In comparison with truss bridges, abutment bridges have many advantages such as being less expensive in terms of initial cost and long-term maintenance. As scour excavates the bridge structure and structural instability, causes bridge failure. Scour may happen at any time, this event predisposed to occur without any previous warning to bridge structure (Duc and Rodi, 2008). The main parameters which affect scour at bridge contain; floodplain characteristics, bed materials, channel protection situation, bridge geometry and flow hydraulics during the scouring time (Deng and Cai, 2010). The engineering design of such a hydraulic structure requires consideration of these factors. In fact, balancing safety and cost is the main problem. Credible predictions of scour depths can assist the design engineers to monitor and correct the scour problem before any bridge failure or collapse. Abutment scour is found to be primarily a concern for bridges over smaller rivers and streams than for larger rivers, because inadequate design and monitoring attention has been given to abutment contraction scour at the many small bridges (Ettema *et al*., 2004).

CONTRACTION SCOUR AT BRIDGE ABUTMENT

An overview of contraction scour prediction: Recent research on bridge scour has focused on local scour, such as scour around bridge piers or near abutments; by comparison, contraction scour has received much less attention. When a channel is constricted, the approach flow accelerates and causes increase in the bed shear stress and related turbulence. When the bed shear stress exceeds the critical shear stress of the bed material, contraction scour expands. Natural channels, bridges and highways contractions are the most frequently confronted of contraction scour reasons. Referring to the profile of the contraction scour two scour depth can be separated; the scour that occurs contiguously at the
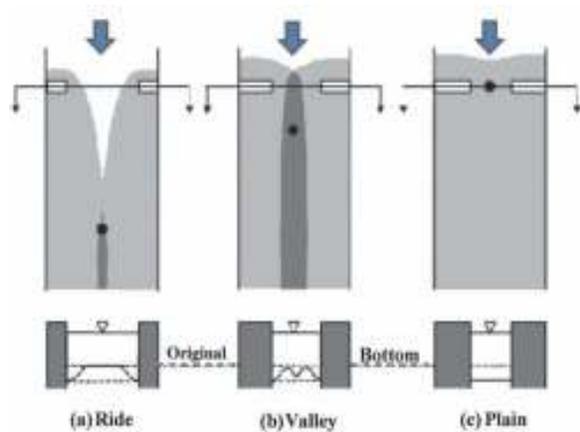
Fig. 4: Location of maximum contraction scours (Briaud *et al*., 2004)

downstream of the constricted area is named maximumcontraction scour and another scour hole that occurs at a greater distance from downstream as shown in Fig. 3 (Duc and Rodi, 2008). The contraction scour parameters have been computed using analytical models by several researchers. Straub (1934) did the primary study on the equilibrium scour depth applying one-dimensional model and theory in long contraction. Subsequently a series of analytical experiments were conducted on this issue (Laursen, 1960; Komura, 1966; Gill, 1981; Lim and Cheng, 1998; Melville and Coleman, 2000; Richardson and Davis, 2001; Briaud *et al*., 2004). The most common factors that affect the magnitude of the bridge contraction scour are indicated in Fig. 2. The flow velocity and water depth affect the magnitude of the shear stress and the shear stress decay rate with scour depth respectively. Contraction ratio (B_2/B_1) directly defines the severity of the contraction, which determines the value of the contracted velocity V_2 with respect to the approaching velocity V_1. Contraction Length (L) and transition angle (θ) will affect the flow pattern in the contracted channel and the distribution of the scour depth (Li, 2002). Dependability of the location of to the contraction geometry is observed in the contraction scour profiles in Fig. 3. When the contraction ratio B_2/B_1 is small and the transition angle θ is sharp contraction scour location could be much closed to the abutment scour. Figure 4 shows three distributions at bridge site between the contraction scour and the abutment local scour. These three kinds are sequentially resulted when the contraction geometry changes from less contraction, smooth transition angles (a) to severe contraction and sharp transition angles (c).

The major concern of previous researchers was to predict the uniform contraction scour in a long contraction channel with a uniform rectangular cross-section in sands. This extensively studied situation is

the simplest contraction case, where a uniform flow can be assumed at the section far from the contraction opening and the associated unidirectional flow parameters can be easily calculated by open channel theories. Live-bed and clear-water contraction scours were studied differently but both use the uniform flow in constricted and unconstricted channels (Li, 2002). A simplified model of streambed armoringwas used to enlarge the clear-water contraction-scour equation to contain the condition of armoring. The equilibrium clear-water contraction-scour depth was predicted by equating bed shear stress to the critical shear stress through a long constriction where uniform flow is supposed to exist by Froehlich (1995). The parameters which affect scour depth in a system have been represented in the range of dimensionless framework (Coleman *et al*., 2003; Fael *et al*., 2006; Oliveto *et al*., 2002). In another study it was shown that when the constricted section of the channel caused by the obstacle existence is significant, the depth of the scour is larger than the scour depth due tothe same abutment in a wider channel (Melville and Coleman, 2000). It has been showed that increasing the flow velocity at the constricted section causes contraction scour rather than to the vortex that develop at the obstruction section in three-dimensional system. Thus related with its definition, contraction scour is anticipated to take place nearly over the constricted section, uniformly. Contraction ratio can be define as the ratio between the width of the contracted section and abutment length, if the contraction ratio is smaller than 40% it has no considerable effect on abutment scour depth (Breusers and Raudkivi, 1991). Although in some prior studies contraction ratio is detected as a one of the principal parameters impressing the scour procedure (Garde *et al*., 1962; Gill, 1972), butin many other scour depth studiesthe contraction ratio is ignored (Coleman *et al*., 2003; Kothyari and Ranga Raju, 2001; Melville, 1997; Oliveto *et al*., 2002). Referring to the abutment scour in a floodplain area, some researchershave expressed that instead of the contracted area the flow contraction in terms of the percentage of blocked dischargemust be accounted (Kouchakzadeh and Townscend, 1997; Sturm and Janjua, 1994).

The Manning and Du Boys transport equation in constricted section were applied to investigation on equilibrium scour depth in long contraction. Straub (1934) achieved the Eq. (16). To predict thescour depth square root part must be greater than zero. Afterward based on total sediment transport relations, in clear water condition Eq. (17) was suggested by Laursen (1960). Based on the dimensional analysis and experimental data the effect of standard deviation on the equilibrium scour depth in clear water condition was studied by Komura (1966) and the Eq. (18) was

Table 1: Equations for uniform contraction scour under clear water conditions

Reference	Equation		Applicability
Straub (1934) Straub (1934)	$\dfrac{d_2}{d_1} = \left(\dfrac{B_1}{B_2}\right)^{6/7}\left[\dfrac{\tau_c}{2\tau_1} + \sqrt{\left(\dfrac{\tau_c}{2\tau_1}\right)^2 + \left(1 - \dfrac{\tau_c}{\tau_1}\right)\dfrac{B_1}{B_2}}\right]^{-3/7}$	(1)	Long contraction the subscripts 1, 2 and c indicate unconstricted, constricted sections and initial sediment motion, respectively
Laursen (1960) Laursen (1960)	$\dfrac{d_2}{d_1} = \left(\dfrac{Q_2}{Q_1}\right)^{6/7}\left(\dfrac{B_1}{B_2}\right)^{\alpha}\left(\dfrac{n_2}{n_1}\right)^{\alpha_1}$	(2)	Clear-water condition
Komura (1966) Komura (1966)	$\dfrac{d_2}{d_1} = 1.6\,Fr_1^{0.2}\left(\dfrac{B_1}{B_2}\right)^{0.67}\sigma_g^{-0.5}$	(3)	Clear-water condition $\sigma_g = (d_{84}/d_{16})^{0.5}$
Gill (1981)	$\dfrac{d_2}{d_1} = \left(\dfrac{B_1}{B_2}\right)^{6/7}\left(\dfrac{\tau_c}{\tau_1}\right)^{-3/7}$	(4)	Clear-water condition
Froehlich (1995) Froehlich (1995) Laursen (1960)	$d_s = \left[\dfrac{Q}{\dfrac{1}{K_n}\sqrt{\theta_{c50}(S_s - 1)D_{50}^{1/3}\left(\dfrac{D_a}{D_{50}}\right)^{(1-m)/2}\sigma_g^{-K_{50/6}}\,W}}\right]^{6/7} - y_a$	(5)	Clear-water condition
Lim and Cheng (1998) Lim and Cheng (1998)	$\dfrac{d_2}{d_1} = \left(\dfrac{B_1}{B_2}\right)^{0.75}$	(6)	Clear-water condition
Chang and Davis (1998) Chang and Davis (1998)	$d = \left(q/(6.35D_{50}^{0.333})\right)^{0.86},\ D_{50} > 0.03\ m$ $d = \left(q/(4.16D_{50}^{0.25})\right)^{(y)},\ 0.03 > D_{50} > 0.0003m$ $d = 1.49\,q^{0.67},\ 0.0003m \geq D_{50}$	(7) (8) (9)	$y = \dfrac{1}{1 + \dfrac{0.125}{D_{50}^{0.18}}}$
Richardson and Davis (2001) Richardson and Davis (2001)	$y_2 = \left[\dfrac{K_u Q^2}{D_m^{2/3}W^2}\right]^{3/7}$	(10)	Clear-water condition $y_s = y_2 - y_0$ $D_m = 1.25D_{50}$ $K_u = 0.025$ in SI and 0.0077 in english

obtained. The sediment transportation rate was considered in a series of clear water flow experiments and an Eq. (19) slightly different from the Straub (1934) was presented by Gill (1981). By the assumption that for the contraction scour in clear-water condition reaches to its maximum depth when the average flow velocity under the bridge becomes equal to the critical velocity for the bed material, the total flow depth (d) under the bridge can be predicted by one of the Eq. (22) to (24). Lim and Cheng (1998) obtained a simple equation for predicting equilibrium scour depth from discharge of the sediment measured in a long contraction related with the continuity flow and sediment transport valid for clear water and live-bed conditions. Richardson and Davis (2001) recommended an Eq. (25) based on the development of the Laursen's equation (Laursen, 1963) in clear-water condition to predict the average equilibrium contraction scour depth. In the laboratory, experiments of clear-water condition the scour-hole geometry were measured with different durations. The flow depth, angle of approach and sediment size for all the experiments were equal. It was observed that the maximum scour depths were occurred at the downstream of constricted section. In the lower-velocity series scour processes continue even after 48 hours and the maximum scour depth grows at a logarithmic rate (Hahn and Lyn, 2010). Some well-known equations on contraction scour, in clear water condition, are provided in Table 1.

Laboratory contraction scour data at abutments and statistical test: The laboratory contraction scour data under clear-water conditions used in this study were obtained from literature (Li, 2002). The shape of abutments have been used in these experiments were rectangular with the 90° transition angle (θ) and defferent Length (L) and width (b). Statistical tests were conducted to evaluate the predicted contraction scour depths for the physical model using the Straub, Laursen, Komura, Gill, Chang, Lim and Richardson methods in Fig. 5 to 12. The predicted contraction scour depths at abutments that were obtained from the application of the selected formulas of Table 1 and laboratories experimental data were all used in computing the parameters of the statistical tests. The statistical tests include the Standard Deviation, Regression, Correlation, Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and the Theil's coefficient (U), that mathematically are described by Eq. (1) to (3). In order to evaluate the prediction accuracy of each equation, the scattered points of observed and computed contraction scour depths have be compared with the line of perfect agreement.

RESULTS

Figure 5 to 12 show scattergrams for the predicted and measured contraction scour depths obtained from the application of the selected formulas and laboratory
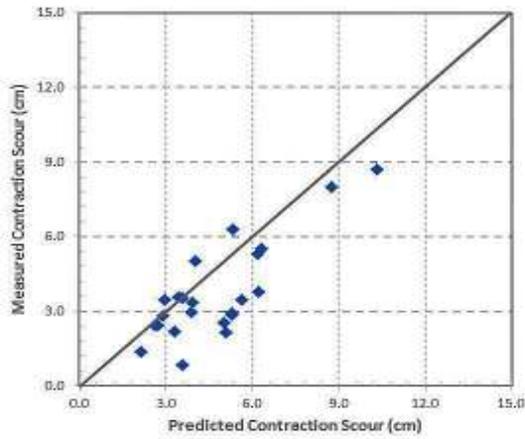
Fig. 5: Comparison between measured contraction scour depths obtained from experiments and computed scour depths using Li (2002) formula
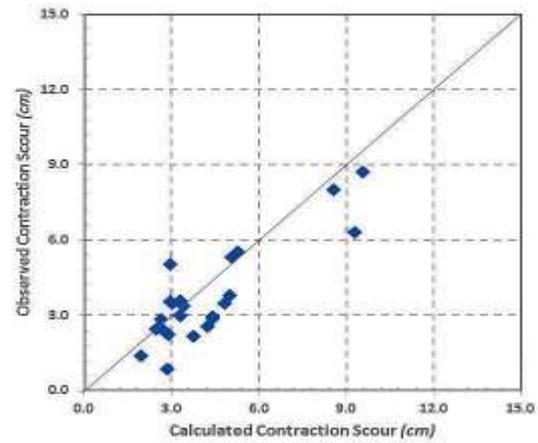
Fig. 8: Comparison between measured contractions scour depths obtained from experiments and computed scour depths using Lim and Cheng (1998) formula
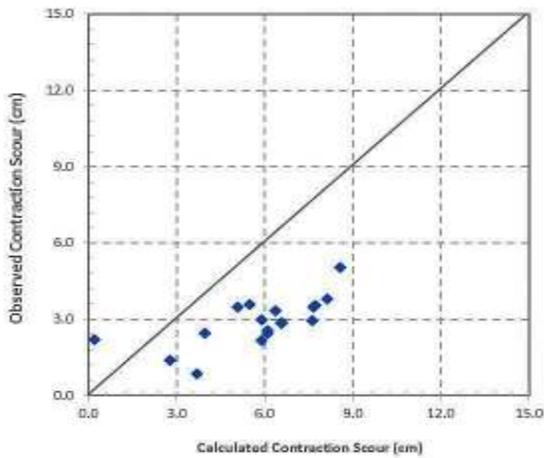
Fig. 6: Comparison between measured contractions scours depths obtained from experiments and computed scour depths using Richardson and Davis (2001) formula
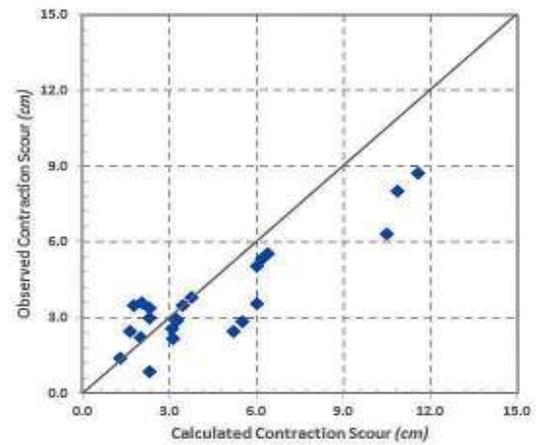
Fig. 9: Comparison between measured contraction scour depths obtained from experiments and computed scour depths using Gill (1981) formula
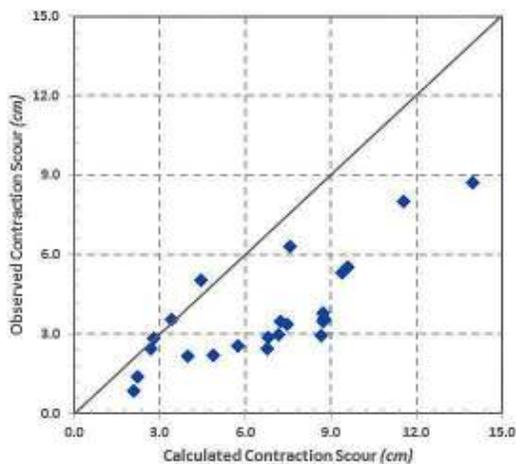
Fig. 7: Comparison between measured contraction scour depths obtained from experiments and computed scour depths using Chang and Davis (1998) formula
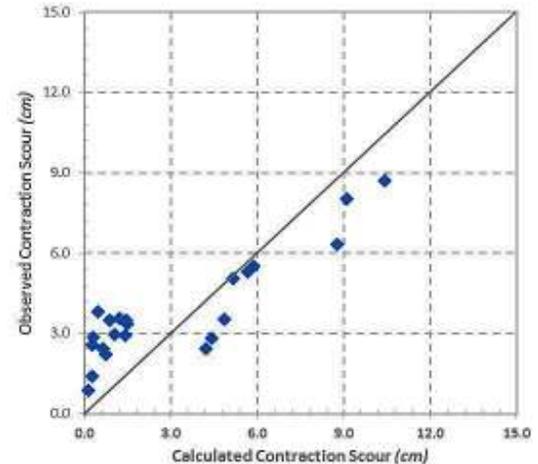
Fig. 10: Comparison between measured contraction scour depths obtained from experiments and computed scour depths using Komura (1966) formula
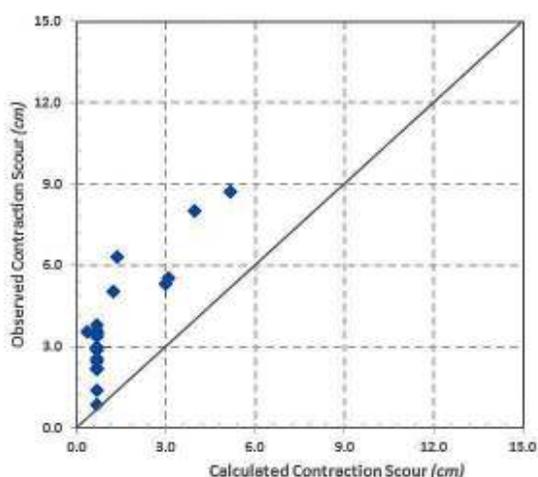
Fig. 11: Comparison between measured contraction scour depths obtained from experiments and computed scour depths using Laursen (1963) formula
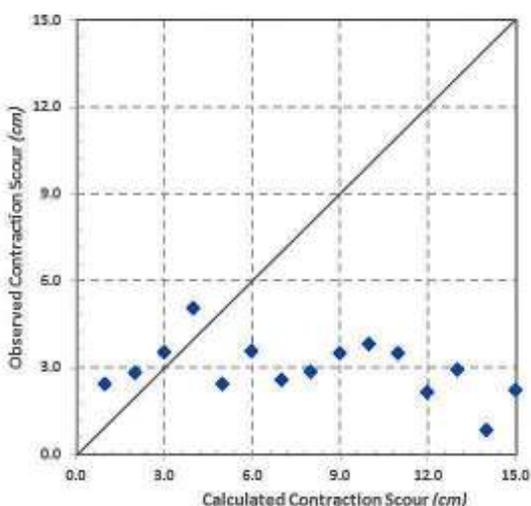
Fig. 12: Comparison between measured contraction scour depths obtained from experiments and computed scour depths using Straub (1934) formula

experiments, respectively. It appears that the Lim and Cheng (1998) and Li (2002) give reasonable prediction, while the Straub (1934), Chang and Davis (1998) and Richardson and Davis (2001) formulas appear to over-predict and Laursen (1963) formula appears to under-predict the abutment contraction scour depth. This is perhaps to be expected for the fact that the formulas are obtained from experimental studies using laboratory flumes with rectangular cross section and have flat immovable walls, while most of the natural channels are nonrectangular with instable and rough bed and banks. Moreover, flow distribution through the natural channel is non-uniform. Under-predictions were less common than over-predictions, but occurred in some of the methods. The satisfactory, acceptable and comparatively preferable rang for correlations are defined as; $\pm5\%$, ±5-20% and ±20-30%, respectively. In this comparison, no satisfactory correlation was found between observed and predicted abutment contraction scour from the two prediction methods, Gill (1981) and Komura (1966). These observationsare supported by the statistical tests conducted on selected formulas as shown in Table 2.

CONCLUSION

A comprehensive review of the up-to-date investigations on contraction scour depth at bridge abutments are is introduced in this study. Various approaches conducted for predicting scour depth are presented. Laboratory studies designed for investigation of contraction scour at bridge abutmentsare summarized. The experimental data collectedfrom the literaturefor predicting the contraction scour as a function of variables characterizing the flow, abutments and sediments. Statistical and graphical comparison between the predicted and observed depth of contraction scour showed that the Lim and Cheng (1998) and Li (2002) give reasonable prediction, while

Table 2: Maximum, average, minimum, regression and the correlation of predicted contraction scour depth compared to observed contraction scour depth

	S.D.		Mean absolute error, MAE		Root mean square error, RMSE computed data	Regression computed data	Correlation computed data	Theil's coefficient, U computed data
Scour equation	Lab. data	Computed data	Lab. data	Computed data				
Li (2002)	1.906	0.815	1.443	1.527	0.019	0.801	0.815	0.082
Gill (1981)		2.951		2.401	0.030	0.478	0.727	0.113
Straub (1934)		3.505		2.359	0.035	0.782	0.929	0.128
Lim and Cheng (1998)		2.085		1.544	0.021	1.507	0.897	0.076
Komura (1966)		3.151		2.748	0.032	0.491	0.742	0.109
Laursen (1963)		1.285		0.923	0.013	1.813	0.740	0.077
Chang and Davis (1998)		3.023		2.456	0.030	0.324	0.763	0.176
Richardson and Davis (2001)		2.030		1.509	0.020	0.320	0.277	0.103

S.D.: Standard deviation

the Straub (1934), Chang and Davis (1998) and Richardson and Davis (2001) formulas appear to over-predict and Laursen (1963) formula appears to under-predict thecontraction scour depth. Although these methods have the limitations of the laboratory conditions in the absence of the appropriate abutment bridges models. The review shows little verification full scale case histories might constrain the application of the method and the conclusions. In addition, numerous studies have been done on contraction scour depth around bridge abutment, but most of the experiments have been conducted on a single abutment. Even though some research has been conducted with a contraction structure in the river, only a very few studies show results for contraction scour around a scaled model having the same shape as actual field bridge abutments. Furthermore, these researches have been applied using unproven scaling and have been made to accurately predict scour depths at simple contraction structures.

It was observed that the most of the formula give an over predictioncontraction scour depth at bridge abutments, especially when compared with the recorded scour at the abutment site. Thisstatement was supported by the statistical tests, i.e., when the Theil's coefficient, U, Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) of each of the selected formulaswere compared.According to the literature review and statistical analyzes, if the channel and bridge geometry condition change, then most empirical equations for predictingabutment contractionscour depth may not be appropriate. In laboratory model studies, internal flow characteristics do not truly represent prototype bridge abutment scouring in the river in view of large-scale distortion of models. Most of the recent methods on scour prediction have the limitations of the laboratory conditions based on the method assumptions, the simplified test geometry conditions, the flume tests and the numerical simulation method. Although the review showed many equations have been developed to predict contraction scour at bridge abutments and a large database for flume measurements is now available but the problem of contraction scour at bridge abutment has remained little understood. The main deficiency of prior studies is that they do not consider contraction scour development at abutments related with contraction bridge zone. Hence, multiple experiments may need more research on full-scale abutment bridge case histories. Additional data and analysis would allow promoting the abutment bridges' design and decreasing the bridges' cost. Accurate prediction of total scour depth in an abutment bridge is crucial in bridges' stability designing. Underestimation can result in loss of life and structural collapse while overestimation can cause large financial losses on construction of a single bridge.

APPENDICES

Equations for uniform local abutment scour under clear water conditions: Mean Absolute Error (MAE) is a quantity used to measure how close predictions are to the eventual outcomes. The mean absolute error is given by:

$$MAE = \sum_{i=1}^{n} |e_i|/n \tag{A1}$$

Root Mean Square Error (RMSE) is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed. RMSE is a good measure of accuracy and defined as the square root of the mean square error:

$$RMSE = \sqrt{\frac{\sum_i^n e_i^2}{n}} \tag{A2}$$

Theil's coefficient (U) is a measure of nominal association and is define by following equation:

$$U = \frac{\left[\frac{1}{n}\sum\{(d_s)_c - (d_s)_o\}^2\right]^{\frac{1}{2}}}{\left[\frac{1}{n}\sum_{i=1}^{n}(d_s)_c^2\right]^{\frac{1}{2}} + \left[\frac{1}{n}\sum(d_s)_o^2\right]} \tag{A3}$$

where, e_i isthe error in the predicted abutment contraction scour depth for i^{th} event of the record from the application of the formulas, n is number of records, U is theil's coefficient (U $\cong$ 0 for model of perfect prediction and U $\geq$ 1 for unsuccessful model), $(d_s)_o$ is scour depth obtained from experiments or laboratory observation and $(d_s)_c$ is the corresponding predicted scour obtained from the application of the selected scour formulas. The smaller values of MAE, RMSE and U obtained from Eq. (1) to (15) indicate an effective prediction.

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