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Research Article

Assessment of Local Scour at Bridges Abutment

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Abstract: Social and economical 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 the main concerns on enhancing the designing of abutment bridges to prevent or reduce embankement scour. In this study a detailed comparison of the researches on scour at abutment bridge are presented including all possible aspects and scour depth estimation formulae. The experimental data for prediction the abutment local scour depth were investigated. Statistical and graphical analysis allow to recommend the most accurate formula in prediction scour depth at the abutment bridges. Availability of additional data and further analysis would allow promoting the bridge abutment design and decreasing the bridges' construction and maintenance cost by increasing the accuracy of the footing depth design.

Keywords: Abutment bridge, graphical test, local scour, scour formula, statistical analyses

INTRODUCTION

Abutments are structures at the two ends of bridge which 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 advantages of the bridge structure without movement joints at the junction of the deck on the abutments, named joint-less or abutment bridges. This kind of bridge is feasible alternative for the conventional bridges. If abutment bridge is constructed on a waterway, abutments acquit the third function, to protect the embankment against scour. Lack of load capacity and bridge scour are the most common reasons of bridge collapse. Load capacity happen because of an ever-increasing demand for a larger volume of traffic and heavier trucks and scour occurs because of the erosive action of flowing water. Scouring excavates and carries away materials from streambeds and banks bridge foundations by the normal flowing water or flood. Although scour rate may be greatly affected by the presence of structures encroaching on the channel, the shear stress generated by the flowing water on the streambed is the basic erosive stress. Besides, the streambed materials provide the resisting stress against erosion. Scour reaches its equilibrium status when these two stresses get balanced.

Bridge failure leads to serious loss of 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. At the 1993 flood in the upper Mississippi basin caused 23 bridge failures for an appraised damage of 15$ million and abutment scour led to 14 of bridge failures (Richardson and Davis, 2001). Study on 503 bridge structure 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).

In this study selected equations for prediction scour depth at bridge abutments have been evaluated using the statistical comparison supported by laboratory data analysis and a comprehensive review of the up-to-date work on abutment local scour prediction.

METHODOLOGY

Bridge stability and scour: A truss bridge main structure and a jointless bridges are shown in Fig. 1. Jointless bridges (Fig. 1a), in comparison with joints and expansion bearings bridges (Fig. 1b), have many advantages such as being less expensive in terms of initial cost and long term maintenance.

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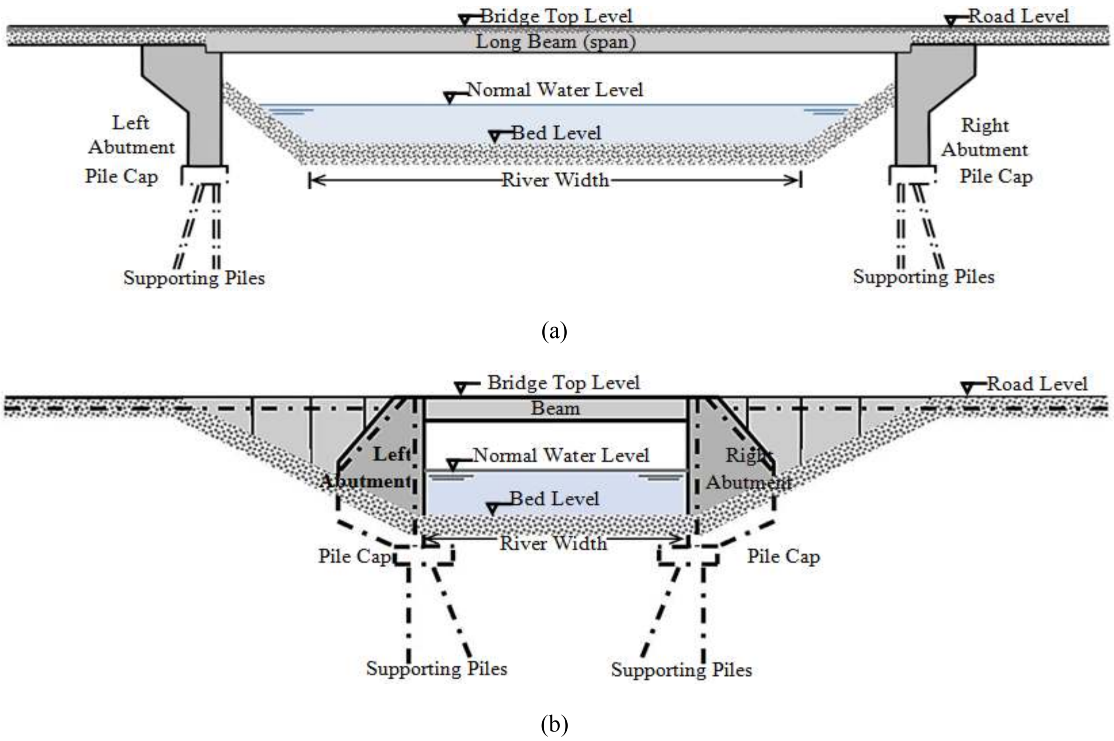

(a)

(b)

Fig. 1: (a) A simple beam bridge, (b) an abutment bridge main structures

Scour may happen at any time which excavates the bridge structure and lead the structures to be instable. Structural instability causes bridge failure. This predisposed to occur without any previous warning to bridge structure (Duc and Rodi, 2007). The main parameters which affect scour at bridge contain floodplain characteristics, bed materials, channel protection situation and stability, 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. Credible predictions of scour depths can assist the design engineers to monitor and correct the scour problem before any bridge failure or unsafely (Ettema *et al*., 2004). Abutment scour is found to be primarily a concern for bridges over smaller rivers and streams than for larger rivers. Inadequate design and monitoring attention has been given to abutment scour at the many small bridges.

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 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 continual erosion and deposition when there is general sediment transport during periods of flooding (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. 2.

Scour at bridge is often over-predicted that may result in construction of unnecessary countermeasures or excessively deep foundations, adding significant costs to bridge construction and maintenance. In a perfect laboratory experiments which often apply rectangular channels and uniform sediment effects of some important dimensionless parameters have not considered, which may reduce the accuracy of scour depth estimate in comparing with measured scour depth of field conditions (Hong, 2005).

LOCAL SCOUR AT ABUTMENT

An overview of local abutment scour prediction: Abutments are characterized considering of abutment form, structure and layout. These characteristics along with channel morphology and sediment characteristics, lead to the three regions of abutment scour as shown in Fig. 3.

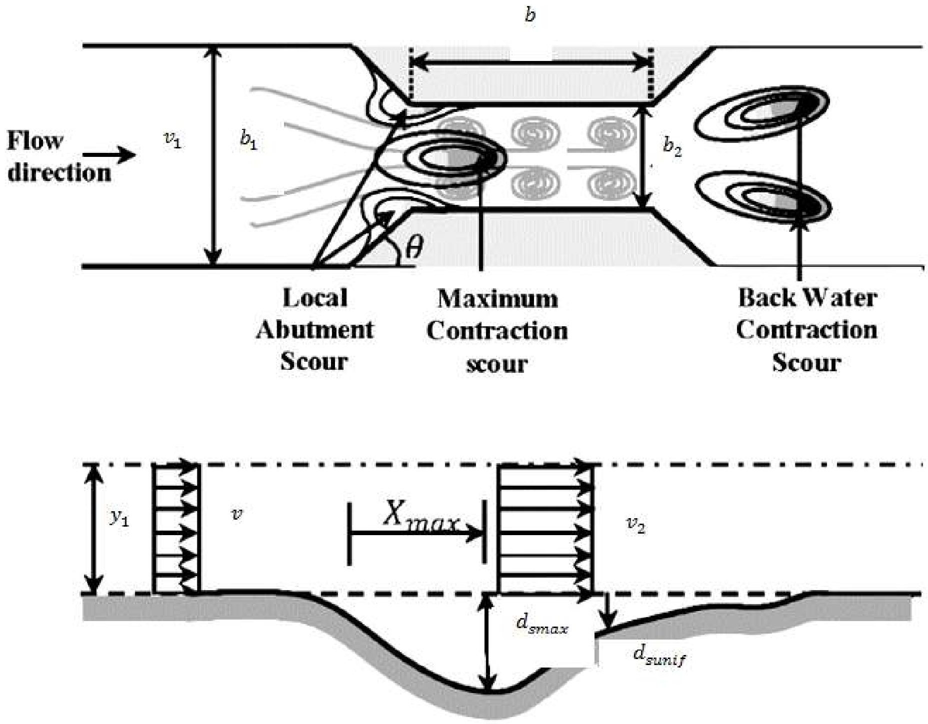

Fig. 2: Concepts in abutment bridge scour

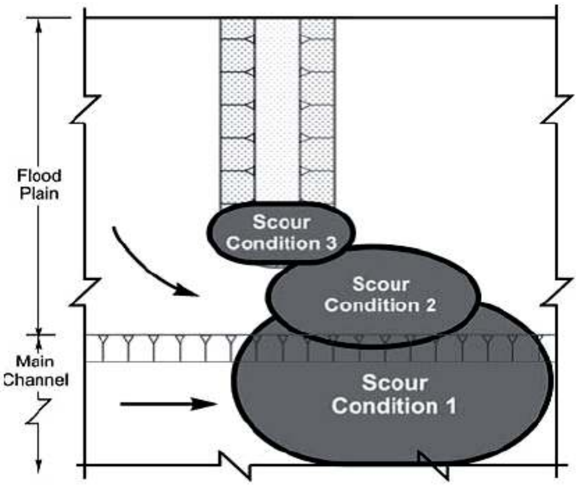

Fig. 3: Three regions of scour in abutment bridges (Yorozuya, 2005)

Abutment layout, flow field, along with the erodibility of sediment and soil at bridge site may cause the deepest scour to occur at any, or all of three locations near abutment. Scour condition 1 is located in the main channel near abutment; scour condition 2 occurs in a short distance downstream of the abutment; and scour condition 3 is located at the abutment itself. Maximum scour depth at these locations can be different and occurs at different rates, in conformity with soil and flow-field characteristics.

It was predicated that the obstruction ratio effect on the time development of abutment local scour depth may not be large; however, important effect can be observed (Ballio *et al*., 2009). The dimensional analyzing of abutment scour in compound channels for bank-line and setback abutments showed that the maximum scour depth was about 10 times the un-constricted floodplain depth, but this value may be reduced by large main channels with very rough floodplains, larger sediment sizes and less backwater or lower floodplain velocities (Sturm, 2006). It was detected that the maximum scour depths occurred around the upstream corner of the vertical-wall abutments (Yanmaz and Kose, 2007a). Increasing approach flow depth increases the scour depth (Dey and Barbhuiya, 2005). If the abutment length decreases and the width of the channel is constant, abutment scour depth approaches zero (Ettema *et al*., 2010). Increasing the relative abutment length, increases the distance between the abutment and the point of maximum abutment scour depth (Cardoso *et al*., 2010).

Equation A.1 for simple predicting local abutment scour in clear water condition was suggested (Liu *et al*., 1961). The relation between abutment geometry, scour-hole and turbulence elements and solid structures was investigated considering local and general characteristic values and contraction ratio between obstructed cross section and the width of the flume in long duration scour laboratory tests around bridge abutments in clear water flow. The results showed that there was a positive correlation between contraction ratio and the depth of the scour and the bridge pier model was not applicable directly to prediction of scour depth in the bridge abutment (Ballio and Orsi, 2001). Local scour depth development was analyzed in a several experiments at vertical-wall abutment with different lengths of abutment in clear-water flow and uniform sediments. Analyzing the records demonstrated that dimensionless time to equilibrium scour can be explained as a relation between flow intensity and the length of the abutment (Coleman *et al*., 2003). The data for clear water and uniform sediment in compound channel were analyzed to develop a scour prediction model based on the functional relationship that is shown in Eq. (A.11) by Kouchakzadeh (1996). (3D) flow field in scour hole under clear-water condition at a 45° wing-wall abutment was measured by conducting experiments in a laboratory flume. The profile of turbulence intensity and the average of time velocity elements, Reynolds stress and turbulent kinetic energy at different horizontal angle planes were captured. Plotting the contours of the vorticity showed that inside the scour hole the positive vorticity is compressed, although at the surface of the abutment wall the negative vorticity can be seen (Dey and Barbhuiya, 2010). The relation between abutment geometry, scour-hole and turbulence elements and solid structures was investigated in a laboratory experiments with three different geometrical phases. According to erosion processes these three phases are Flat Bed formation (FB), the Logarithmic Scour formation (LS) and the Equilibrium Scour formation (ES). Study of time-averaged coherent construction in these experiments show that in the last two phases (LS and ES) the development of the scour-hole increases the vortex complexity. The formulas based on the average of the shear stress at the wall border and critical Shield motion for sediment were not suitable for representation the local erosion characteristics (Bressan *et al*., 2011). The scouring process under clear-water scour condition was studied using heterogeneous and uniform sediments with different sizes of vertical abutment walls and 45° wing wall. The time variation of scour depth was computed by numerical solving of the different equations that are based on the conception of the sediment conservation. According to the results, several parameters that affect the dimensionless depth of the equilibrium scour are the ratio of the length of the abutment and sediment diameter, the ratio of the depth of the flow and the length of the abutment and the excess abutment Froude number (Fr). The Eq. (A.11)-(A.13) was obtained to compute the equilibrium scour depth in different abutment shapes by Dey and Raikar (2005). Based on the purposed Eq. (A.14) by Oliveto *et al*. (2002) 150 laboratory experiments were conducted to study the effects of slopping abutment, unsteady flow on scour development process. Results showed when the threshold Froude number is larger than 0.60 the proposed formula computed confident scour depth, meanwhile the formula were restricted to a larger amount of threshold Froude number, $F_T = 1.20$ (Oliveto and Hager, 2005). In order to investigate the time-dependent variation of scour hole shapes with size and location of maximum scour depth series of experiments were conducted with uniform sediment under clear water condition. Scour contours and variation of scour depth around vertical-wall abutment were measured temporally. It was observed if the length of the abutment decreases the horizontal distance between the sediment deposition location and maximum scour depth decreases. Also the maximum scour depths were took place at the upstream surface of the abutment. An empirical formula for time-dependent surface area and volume of the scour holes was extended as Eq. (A.15) Yanmaz and Kose (2007b). These well known equations on abutment scour prediction in clear water conditions are provided in Table 1.

Local abutment scour data and statistical test: The laboratory local abutment scour data under clear-water conditions used in this study was obtained from literature (Dey and Raikar, 2005) including 100 abutment local scour depths data. Statistical tests were conducted to evaluate the predicted scour depths at abutment location for the physical model using the Liu *et al*. (1961), Laursen (1963), Melville (1992, 1997), Kouchakzadeh (1996), Oliveto *et al*. (2002) and Yanmaz and Kose (2007a) methods. The predicted local abutment scour depths were obtained from the selected formulas of Table 1. Laboratories experimental data were used in computing the parameters of the statistical tests. The statistical tests include the coefficient of determination (R^2), correlation, Mean Absolute Error (MAE), Root Mean Square Error

Table 1: Equations for uniform local abutment scour under clear water conditions

Reference	Equation		Applicability
Liu *et al*. (1961)	$\frac{d_s}{y} = 12.5\ \mathrm{Fr}\ \beta$	(6)	Clear-water condition
Laursen (1963)	$\frac{L}{y} = 2.75\ \frac{d_s}{y}\left[\frac{\left(\frac{d_s}{11.5y}+1\right)^{7/6}}{\left(\frac{\tau_1}{\tau_c}\right)^{0.5}} - 1\right]$	(7)	Clear-water scour at an abutment encroaching in to the main channel
	$\frac{d_s}{L} = 1.89\left(\frac{y}{L}\right)^{0.5}$	(8)	At the threshold condition
Melville (1992)	$\frac{d_s}{L} = K_I\ K_y\ K_d\ K_\sigma\ K_s\ K_\theta\ K_G$	(9)	Clear-water condition
	$\frac{d_s}{y} = K_I\ K_L\ K_d\ K_\sigma\ K_s\ K_\theta\ K_G$	(10)	
	$d_s = 2K_S^*\ K_\theta^*\ \sqrt{Ly}$	(11)	$K_{yL} = 2(yL)^{0.5}$ for $1 \leq L/y \leq 25$
	$d_s = 2\ K_s L$	(12)	$K_{yL} = 2L$ for $L/y < 1$
	$d_s = 10\ K_\theta\ y$	(13)	$K_{yL} = 10y$ for $L/y > 25$
Melville (1997)	$d_s =\ K_{yL} K_L K_d K_s K_\theta K_G$	(14)	Clear-water condition
Kouchakzadeh (1996)	$\frac{d_s}{y_a} = 13.5\ \left(\frac{Q_w}{Q_a}\right)^{3.9}\ F_a{}^{1.17}\ F_c{}^{-0.25}$	(15)	Clear-water condition, uniform sediment in compound channel $\mathrm{F_c} = \frac{\mathrm{U_c}}{\sqrt{\mathrm{g\, y_a}}}$
Oliveto *et al*. (2002)	$d_s = 0.068\ \mathrm{N}\ \sigma_\mathrm{g}{}^{-1/2}\ F_d{}^{1.5} \log \mathrm{T}$	(16)	Clear-water condition N= 1.25 for vertical abutment $\sigma_\mathrm{g} = (\mathrm{d_{84}/d_{16}})^{1/2}$ $\mathrm{T = t/t_R}$ $\mathrm{t_R = d_{sR}/(\sigma_g{}^{1/3}(g'^{d_{50}})^{1/2})}$ $\mathrm{g' = [(\rho_s - \rho)/\rho]}$
Dey and Barbhuiya (2005)	$\hat{d}_s = 8.689\ F_d^{0.192} \hat{y}^{0.103} \tilde{l}^{-0.296}$	(17)	Clear-water condition for semicircular abutment
	$\hat{d}_s = 7.281\ F_d^{0.314} \hat{y}^{0.128} \tilde{l}^{-0.167}$	(18)	Clear-water condition for verticall-wall abutment
	$\hat{d}_s = 8.319\ F_d^{0.312} \hat{y}^{0.101} \tilde{l}^{-0.231}$	(19)	Clear-water condition for 45° wing-wall abutment $\hat{y} = y/L; \tilde{l} = L/d_{50}$
Yanmaz and Kose (2007b)	$d_s/L = 0.25\ F_d{}^{0.85}\ (L/y)^{0.15}(\log \mathrm{T_s})^{0.60}$	(20)	Clear-water condition, uniform sediment $\mathrm{T_s =\ t\, d_{50}(\Delta g\, d_{50})^{0.5}/L^2}$ $\Delta =\ (\rho_s - \rho)/\rho$

(RMSE) and the Theil's coefficient (U) that mathematically is described by Eq. (1) to (5). In order to evaluate the prediction accuracy of each equation, the scattered points of these figures can be compared with the line of perfect agreement:

$$\mathrm{R^2} = \left(\frac{\sum \mathrm{p_i o_i}}{(\sum \mathrm{p_i}^2 \sum \mathrm{o_i}^2)^{1/2}}\right)^2 \quad (1)$$

$$\mathrm{m} = \frac{\mathrm{p_n - p_1}}{\mathrm{o_n - o_1}} \quad (2)$$

$$\mathrm{MAE} = \textstyle\sum_{\mathrm{i=1}}^{\mathrm{n}} |\mathrm{e_i}|/\mathrm{n} \quad (3)$$

$$\mathrm{RMSE} = \sqrt{\textstyle\sum_{\mathrm{i}}^{\mathrm{n}} \mathrm{e_i}^{\mathrm{n}}/\mathrm{n}} \quad (4)$$

$$\mathrm{U} = \left[\frac{1}{\mathrm{n}}\sum(\mathrm{p_i - o_i})^2\right]^{1/2} \Big/ \left[\frac{1}{\mathrm{n}}\textstyle\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{p_i}^2\right]^{1/2} + \left[\frac{1}{2}\sum \mathrm{o_i}^2\right] \quad (5)$$

where, $\mathrm{y = y_i - \overline{y_i}}$, $\mathrm{f = f_i - \overline{f_i}}$, $\mathrm{y_i}$ are observed values, $\mathrm{\overline{y_i}}$ is the mean of $\mathrm{y_i}$, $\mathrm{y_i}$ is the predicted value, $\mathrm{\overline{f_i}}$ is the mean of $\mathrm{f_i}$, n is the number of samples and $\mathrm{e_i = |f_i - yi}$.

In statistical comparison, the closer the correlation coefficient is to either -1 or +1, the stronger the correlation is between the variables. We define the satisfactory, acceptable and comparatively preferable ranges for correlations as; ±10%, ±10-20% and ±21-40%, respectively. The minimum values of $\mathrm{R^2}$, MAE and RMSE represent reasonable predictions. The closer the Theil's coefficient (U) is to 0.00; the closer the predicted contraction scour depths are to the measured depths.

RESULTS

Figure 4 to 10 show scatter-grams for the predicted and measured abutment local scour depths obtained from the application of the selected formulas and laboratory experiments, respectively. It appears that the Melville (1992) and Laursen (1963) formulas give reasonable prediction, while the Yanmaz (2007b), Kouchakzadeh (1996), Liu *et al*. (1961) and Oliveto *et al*. (2002) formulas appear to over-predict. Furthermore, Melville (1997) formula appears to give under-predict the abutment local scour depth. Over-prediction and under prediction is expected for the fact

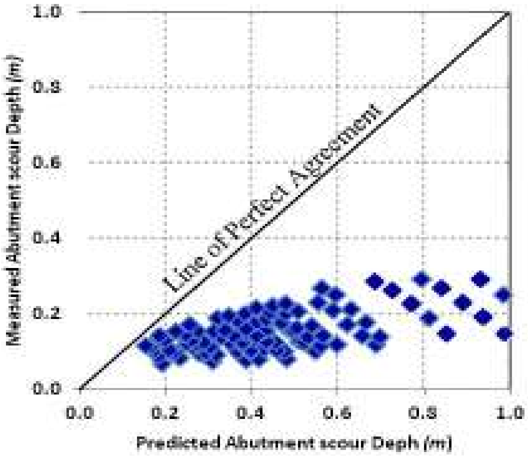

Fig. 4: Comparison between measured abutment local scour depths obtained from experiments and computed scour depths using Liu *et al*. (1961) formula

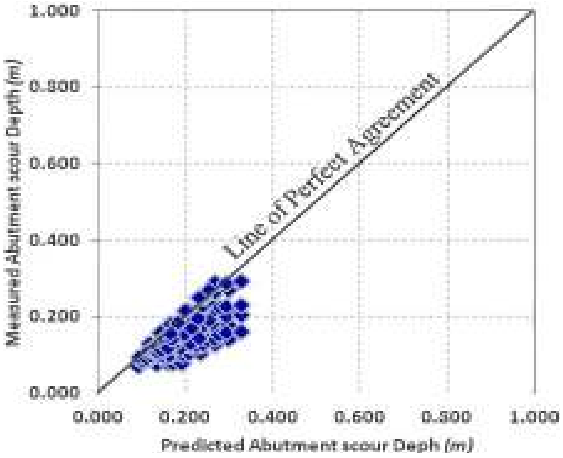

Fig. 5: Comparison between measured abutment local scour depths obtained from experiments and predicted scour depths using Laursen (1963) formula

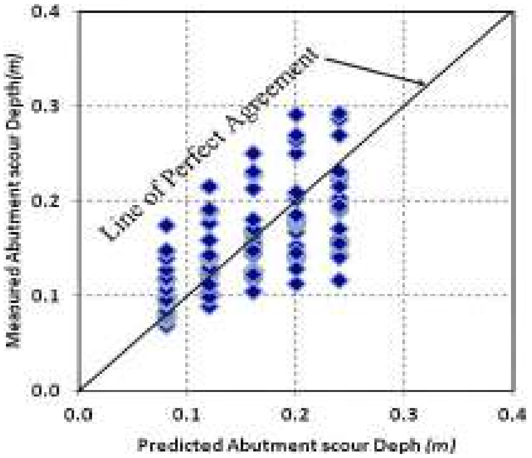

Fig. 6: Comparison between measured abutment local scour depths obtained from experiments and computed scour depths using Melville (1992) formula

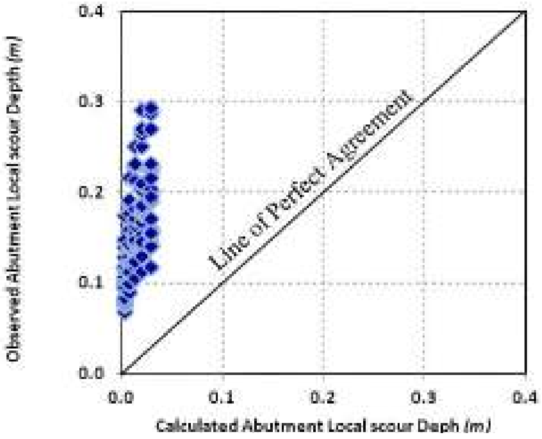

Fig. 7: Comparison between measured abutment local scour depths obtained from experiments and computed scour depths using Melville (1997) formula

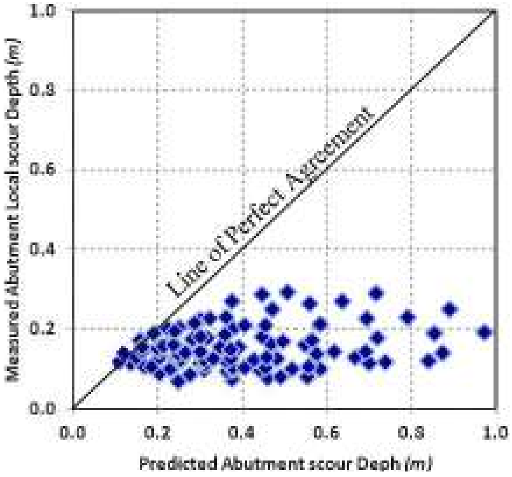

Fig. 8: Comparison between measured abutment local scour depths obtained from experiments and computed scour depths using Kouchakzadeh (1996) formula

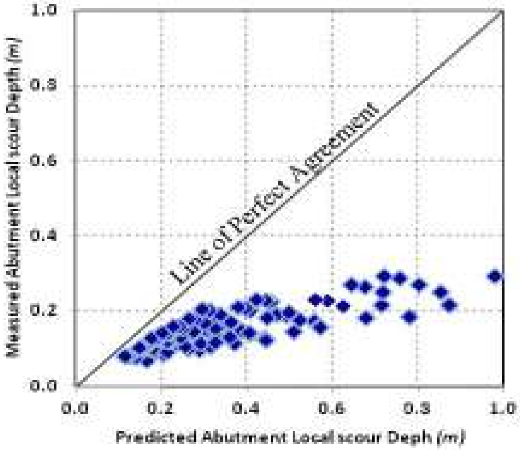

Fig. 9: Comparison between measured abutment local scour depths obtained from experiments and computed scour depths using Oliveto *et al*. (2002) formula

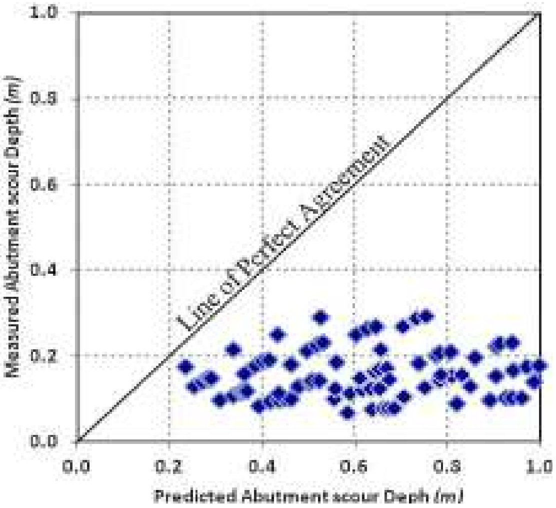

Fig. 10: Comparison between measured abutment local scour depths obtained from experiments and computed scour depths using Yanmaz and Kose (2007a) formula

that the corresponding formulae are obtained from experimental studies using laboratory flumes with simple rectangular cross section having flat immovable walls while most of the natural channels are non rectangular with unstable 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. This observation is supported by the statistical tests that were conducted on selected formulas as shown in Table 2.

Comparison of the correlations shows that no one is close to +1.00 or -1.00. In addition, all the methods correlations are out of the satisfactory correlation ranges. However, the Oliveto *et al*. (2002) correlation is the closer value to +1.00 than the others are. It means that Oliveto *et al*. (2002) formula predicts abutment scour depths comparatively similar to the measured depths, but still we need to consider the other statistical tests result for identifying the optimal method. Regression analysis (R^2) shows that the Laursen (1963) regression is the closest value to zero. Such proximitymeans that the Laursen (1963) scatter points are more similar to a line of the perfect agreement. Comparison the MAEs showed that the mean absolute error of the Melville (1992) and Laursen (1963) method are smaller than the others, respectively. In addition, the RMSE of the Laursen (1963) and Melville (1992, 1997) methods are the closest value to 0.00. Therefore, according to the outcomes of the MAE and RMSE tests, the Laursen (1963) and Melville (1992) methods are reasonable predictive methods. As the most important comparative parameter, the Theil's coefficient test shows that the U value of the Melville (1992) and Laursen (1963) are closer to zero than the others. Accordingly, Melville (1992) and Laursen (1963) methods give more reasonable predictions than the other methods.

No case of negative scour was documented in the application of the equations for any of the methods. Although negative scour could be explained as sediment accumulation, but could also be explained the predictions are outside the range of conditions for the equations. It indicated that the equations are not applicable for the given conditions. In these comparison, although no satisfactory correlation was found between measured and predicted abutment scour depths, Melville (1992) and Laursen (1963) methods predicted comparatively preferable scour depth predictions in the Table 2.

CONCLUSION

A comprehensive review of the investigations on abutment scour depths are introduced in this study. Different type and location of scour in bridge abutments and various approaches conducted for predicting local scour depth at abutment were presented. Experimental data of the laboratory abutment scour studies were collected and summarized. The experimental data for predicting the abutment scour as a function of variables characterizing the flow, abutments and sedimments collected from the literature. Statistical and graphical analysis showed that for predicting the local scour depth at abutments the Melville (1992) and Laursen (1963) formulas give relatively acceptable predictions, while the Liu *et al*. (1961), Kouchakzadeh (1996), Yanmaz and Kose (2007a) and Oliveto *et al*. (2002) formulas gave over-predictions and Melville (1997)

Table 2: Results of the statistical tests of the selected formulae

Scour equation	Correlation	R^2	Mean absolute error, MAE	Root mean square error, RMSE	Theil's coefficient, U
Liu *et al*. (1961)	0.58	0.35	0.34	0.19	0.67
Laursen (1963)	0.67	0.04	0.06	0.04	0.28
Melville (1992)	0.61	0.08	0.04	0.05	0.25
Melville (1997)	0.60	0.09	0.14	0.05	3.41
Kouchakzadeh (1996)	0.23	0.07	0.33	0.25	0.70
Oliveto *et al*. (2002)	0.86	0.39	0.23	0.15	0.59
Yanmaz and Kose (2007a)	-0.01	0.16	0.71	0.34	0.81

formula gave under-prediction for abutment scour depth. Although most of the empirical equations have been recommended to predict abutment scour depth for a certain data under certain field or laboratory condition, they may not be appropriate if the conditions are changed. In experimental laboratory studies, internal flow characteristices do not truly represent prototype abutment bridge scouring in river in view of large-scale distortion of models. Most of the recent investigations of scour predictions are based on the method assumptions, the simplified test conditions, the flume tests and the numerical simulation method. Whereas these methods have the limitations of the laboratory conditions in the absence of the appropriate abutment bridges models. The review showed a few verifications full scale case histories might constrain the application of the methods. Although many equations have been developed to predict abutment scour and a large database for flume measurements is now available in the published literature, based on the outcomes of the current analysis the problem of scour at bridge abutment has remained little understood. The main deficiency of prior studies is that they do not consider local scour development at abutments related with contraction bridge zone. Accordingly, accurate prediction of total scour depth in the abutment is crucial in designing. Underestimation can result in loss of life and structural collapse while overestimation can cause large financial losses on construction of a single bridge. Hence, multiple experiments may need more research on full scale abutment bridges. Additional data and analysis would allow to promote the abutment bridges' design and decreasing the bridges' cost.

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NOTATIONS

b = With of the water way (L)
d_s = Abutment scour depth (L)
d_{sR} = Instant abutment scour depth (L)
$\hat{d_s}$ = (d_s/L), $[M^0L^0T^0]$
d_{16} = 16 % of the particles by weight are finer (L)
d_{50} = Median particle diameter (50% of the particles by weight are finer) (L)
d_{84} = 84% of the particles by weight are finer (L)
$d_{uniform}$ = Scour depth at abutment downstream (L)
F_a = Froude number in the floodplain upstream of the end of the abutment, (dimensioless)
F_c = $U_c/(g' d_{50})^{0.5}$, densimetric critical Froude number, (dimensioless)
F_d = $v/(g' d_{50})^{0.5}$, densimetric particle Froude number, (dimensioless)
F_r = Froude number, (dimensioless)
g = Gravitaional acceleration force (LT^{-2})
g' = $[(\rho_s - \rho)/\rho]\,g$, reduced gravitational acceleration
K_d = Sediment size factor (dimensioless)
K_σ = Shear stress factor (dimensioless)
K_S = Foundation shape factor (dimensioless)
K_θ = Foundation alingment factor (dimensioless)
K_G = Approach channel geometry factor (dimensioless)
K_I = Flow intensity factor (dimensioless)
K_y = Flow depth factor (dimensioless)
K_{yL} = Depth size actor (dimensioless)
L = Total length of abutment and embankment (L)
MAE = Mean Absolute Error, it is dimensioless
n = Number of data (in statistical analysis)
N = Shape number, (dimensioless)
Q_a = Flow intercepted by the abutments and diverted towards the main channel (L^3T^{-1})
Q_w = Discharge moving in a specific width of the channel, *w*in a streamwise direction (L^3T^{-1})
R^2 = Coefficient of determination
RMSE = Root Mean Square Error
T = Dimensionless time
t = Time, (T)
t_R = Instant time for abutment scour, (T)
U = Theil's coefficient, (dimensionless)
U_c = Critical veloccity (LT^{-1})
v = Flow velocity (LT^{-1})
v_c = Critical velocity for sediments (LT^{-1})
x_{max} = Distance of the maximum scour depth to the upstream abutment toe (L)
y = Average approach flow depth (L)
y_a = Flow depth in the floodplain (L)
$\hat{y}$ = (y/L), $[M^0L^0T^0]$
β = Contraction degree, dimensionless
θ = Transition angle $(^o)$
ρ = Mass density of water (ML^{-3})
ρ_s = Mass density of sediments (ML^{-3})
ρ_w = Mass density of water (ML^{-3})
σ_g = Geometric standard deviation of the sediment, (dimensionless)
τ_1 = Initial bed shear stress (L^2L^2)
τ_c = Critical bed shear stress (L^2T^2)

SUBSCRIPTS

1 = Uncontracted (approach) section
2 = Bridge contracted section

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