Validation of Bridge Pier and Abutment Scour Equations

Yehia Kamal[1], Yasser E. Mostafa[2] and Doaa M. Atta[3]

ABSTRACT

Scour around bridges has been one of the most important research fields in the last few decades. Many equations for scour prediction have been reported in the literature. The validation of these equations became necessary. In this paper, 30 equations that estimate scour around bridge piers and abutments are validated against a wide base of experimental and filed data. For design purposes, the study recommends the best equations to be used in scour prediction at bridge piers and abutments. The limitations of each equation are presented. The best equations for scour prediction at bridge piers and abutments are identified. Also, the study indicates that some equations should not be used in scour prediction as they significantly overestimate the scour depth.

Keywords: Scour, prediction, bridge, pier, abutment

[1] Professor, Dept. of Irrigation & Hydraulics, Ain Shams Uni.
[2] Associate Prof., Dept. of Irrigation & Hydraulics, Ain Shams Uni., E-mail: ymostafa04@yahoo.ca
[3] Postgraduate Student, Dept. of Irrigation & Hydraulics, Ain Shams Uni.

1. INTRODUCTION

Structures built in rivers and estuaries are prone to scour around their foundations. If depth of scour becomes significant, the stability of foundations may be endangered, with a consequent risk of the structure suffering damage or failure. There have been several cases of bridge failures in which some cases caused loss of life and most cases resulted in transport disruption and economic loss. The factors influencing the development of scour are complex and vary according to structure type.

Scour is a natural phenomenon caused by the flow of water in rivers and streams. It is the consequence of the erosive action of flowing water, which removes and erodes material from the bed and banks of streams and also from the vicinity of bridge piers and abutments.

An accurate prediction of scour depth at piers and abutments is essential for the safe design of the bridge foundation that under estimation may lead to bridge failure and over estimation lead to over construction cost. Numerous formulae for estimating maximum scour depth have been developed depending on limited data collected from physical models with condition different from that existed in the prototype. In this study, 30 equations reported in the literature for scour prediction at bridge piers and abutments are validated against experimental laboratory and field tests. The aim of this study is to screen the equations and define the best equations that can be used for design purposes and the limitations of these equations, if any.

2. PIER SCOUR EQUATIONS

2.1 Summary of Main Scour Equations

A large number of equations are collected from the literature. The main scour equations are validated against a wide data base of experimental and field tests. The selected formulae used for validation process had been developed by Colorado State University (CSU), Melville and Sutherland (1988), Jain and Fisher (1980), Jain (1981), Laursen and Toch, Laursen-Callender, Laursen I, Blench-Inglis I, Blench-Inglis II, Inglis-Poona I, Inglis-Poona II, Inglis (1949), Hancu (1971), Richardson et al, (1990), Shen et al, (1969), Coleman (1971), Mississippi, Chitale (1988), Chitale (1962), Breusers (1969), Breusers (1977), Hec-18, Veiga (1970) , Laursen (1962) and Laursen (1958), Neil (1973).

Table 1 presents the main equations, reported in the literature, for predicting scour around bridge piers.

Table 1: The main equations used to predict scour around bridge piers.

Reference	**Equation**	**Notes**
Laursen I (Neill, 1964)	$d_s = 1.5b^{0.7} y^{0.3}$	For live-bed scour
Laursen-Callender (Melville, 1975)	$d_s = 1.11b^{0.5} y^{0.5}$	
Shen at al. (1969)	$d_s / b = 2.34(Y/b)^{0.381} Fr^{0.619} y^{-.06}$	
Coleman (1971)	$d_s / b = 0.54(Y/b)^{0.19} Fr^{1.19} y^{0.41}$	
Neil (1973)	$d_s / b = K_s$	K_S = 1.5 for rounded nosed and circular piers, K_S = 2 for rectangular piers
Breusers et al. (1977)	$d_s / b = 3.3(D_{50}/b)^{0.2} (Y/b)^{0.13}$	
Breusers et al. (1965)	$d_s = 1.4b$	
Jain & Fischer (1980)	$d_s / b = 1.86(Y/b)^{0.5}$	
Jain (1981)	$d_s / b = 1.84(Y/b)^{0.3} Fr_c^{0.25}$ $d_s / b = 1.84(Y/b)^{0.3}$	
Melville and Sutherland (1988)	$d_s / b = K_I K_y K_d K_s K_\theta$ For an aligned pier $d_{s)\max} = 2.4 K_y K_d b$ $K_{yb} = 2.4b \rightarrow b/y < 0.7$ $K_{yb} = 2(yb)^{0.5} \rightarrow 0.7 < b/y < 5$ $K_{yb} = 4.5y \rightarrow b/y > 5$	K_I = Flow intensity factor K_d = Sediment size factor K_s = Foundation Shape factor K_θ= foundation Alignment Factor
Colorado State University (CSU) (Hoffmans & Verheij, 1997)	$d_s = 2K_s y_\circ Fr^{0.43} \left(\frac{b}{y_\circ}\right)^{0.65}$	
Richardson and Davis (1995)	$d_s / b = 2K_3 K_4 K_s K_\theta (Y/b)^{0.35} Fr^{0.43}$	

Mississippi (Wilson, 1995)	$d_s = 0.9b^{0.6}Y^{0.4}$	
Blench-Inglis I (Blench, 1962)	$d_s = \left[1.53b^{0.5}Y^{0.5}V^{0.5}D_{50}{}^{-0.125}\right] - Y$	
Blench-Inglis II (Blench, 1962)	$d_s = \left[1.8b^{0.5}Y^{0.75}\right] - Y$	
HEC-18 (NHI, 2001)	$d_s = 2K_1K_2K_3K_4y_{\circ}Fr^{0.43}(b/Y_o)^{0.65}$	
Chitale (1988)	$d_s = 2.5b$	
Chitale (1962)	$d_s = Y\left[-5.49Fr^2 + 6.65Fr - 0.51\right]$	
Laursen (1962)	$d_s/b = 1.8(Y/b)^{0.75}$	For live-bed scour
Veiga (1970)	$d_s/b = 1.35(Y/b)^{0.3}$	For live-bed scour
Inglis-Poona I (Inglis, 1949)	$d_s = \left(1.7b^{0.22}V^{0.52}Y^{0.52}\right) - Y$	
Inglis-Poona II (Inglis, 1949)	$d_s = \left(1.73b^{0.22}V^{0.78}\right) - Y$	
Inglis (1949)	$d_s = 4.2(Y/b)^{0.78}Fr^{0.52}b$	
Laursen & Toch	$d_s = 1.35(b)^{0.3}Y^{0.7}$	The formula described by Johnson (1995).

2.2 Validation of Pier Scour Equations

In this paper, the scour equations listed in Table 1 were validated using measured scour depth from experimental and field data. A large number of experimental data, reported in the literature, was used in the validation process. The main used experimental data is provided by Mohamed et.al (2005) and Yanmaz et.al. (1991). Also, field data collected by Federal Highway Administration (2005) [(29)] from U.S. Route 12 and Swift Country Route 22 over the Pomme de Terre River in Minnesota was used in the equations validation.

The following parameters were considered in the validation process:

1- Pier shape (circular, square, sharp nose).

2- Pier width (b)

3- Angle of flow attack or angle of pier skew (θ)

4- Grain size of bed material of which 50% is finer (D_{50})

5- Froude Number (F_r)

The estimated scour depth using each equation listed in Table 1 was compared to the actual measured scour depth under the same circumstances. The validation process resulted in a large number of charts. Figures 1 to 8 present some examples of scour depth predicted by the equations and actual measured depth using laboratory and filed data.

It appears from the available field data that Blench-Inglis I and Inglis-Poona II equations provide reasonable estimate of scour at circular or sharp nose pier which have a large width. Inglis-Poona I (9) and Mississippi (30) equations provide reasonable estimate of scour at circular and sharp nose pier which have a small width.

The equation of Colorado State University (CSU) provides reasonable estimate in case of square piers with small width. Richardson et al. (1990) and Breusers (1969) equations provide reasonable estimate in case of square piers with relatively large width.

From the available laboratory data, it appears that Inglis_Poona I (9) and Neil (1973) equations provide reasonable estimate for circular and square piers with relatively large pier width and high Froude number but for low Froude numbers Richardson et al., 1990 and Laursen I equations provide reasonable estimate. For sharp nose pier, Mississippi (30) equation seems to provide the best estimate for scour depth.

Mohamed et.al (2005) conducted a study for validation of scour equations around bridge piers. They validated only four equations namely: the CSU equation, Melville and Sutherlan, Jain and Fisher, and Lausen and Toch equations. Mohamed et.al (2005) showed that the Laursen and Toch and the CSU equations appear to give a reasonable estimate of the local scour depth, while the Melville and Sutherland and the Jain and Fisher formulae appear to over-predict the scour depth. Compared with the other equations, it appears that the Melville and Sutherland equation tends to significantly over estimates the scour depth, especially when compared with measured scour depth in the field.

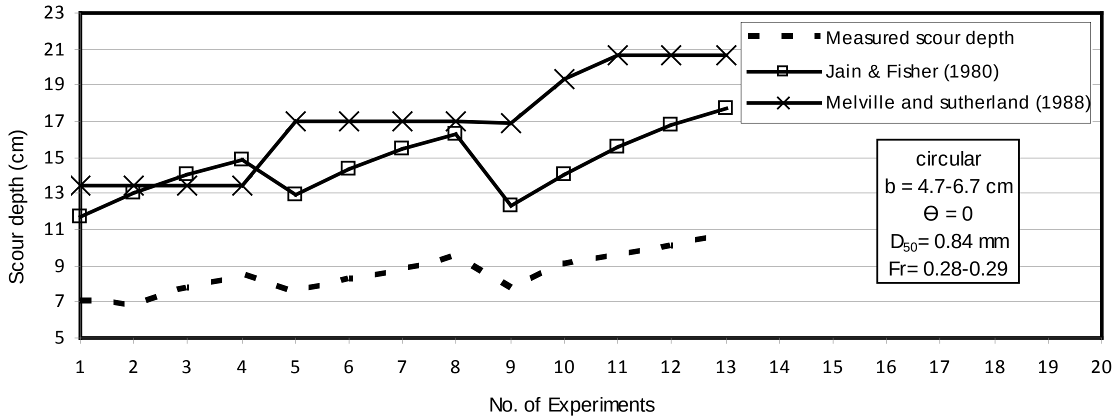

Fig. 1: Comparison between measured laboratory scour depth and predicted scour depth using equations of Melville & Sutherland (1988) and Jain & Fisher (1980).

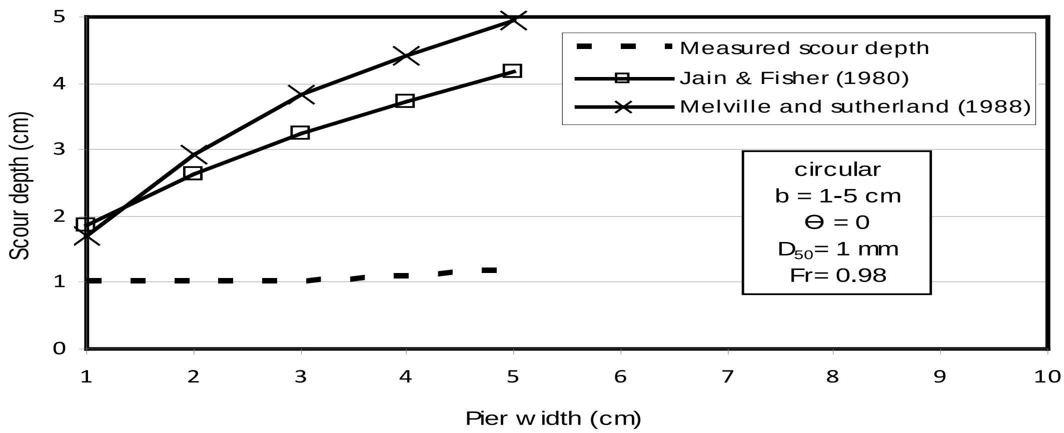

Fig. 2: Comparison between measured laboratory scour depth and predicted scour depth using equations of Melville &Sutherland (1988) and Jain &Fisher (1980).

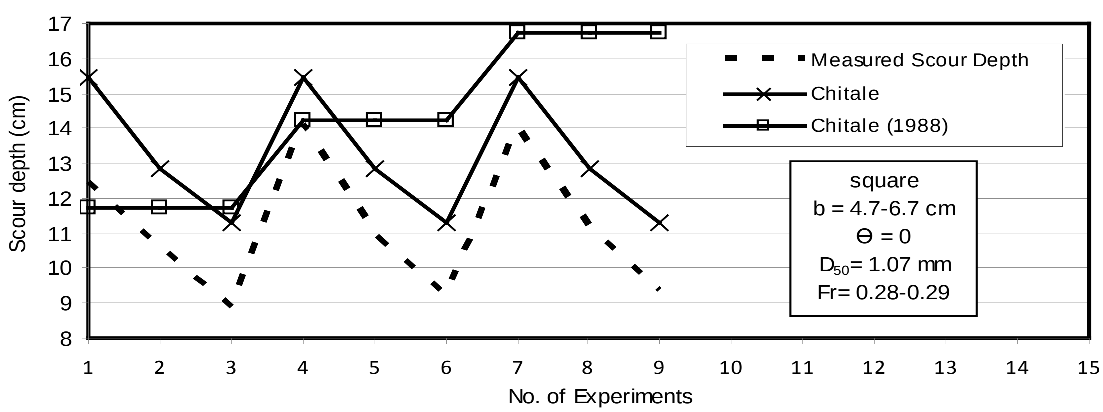

Fig. 3: Comparison between measured laboratory scour depth and predicted scour depth using equations of Chitale (1988) & Chitale.

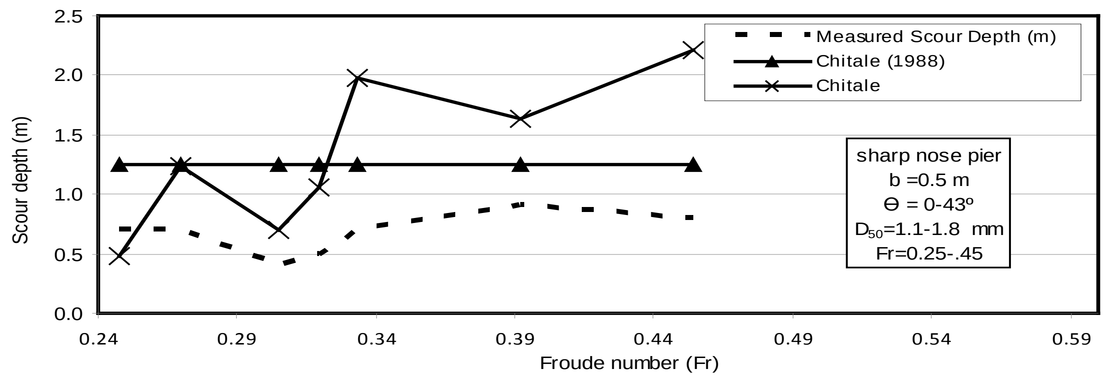

Fig. 4: Comparison between measured field scour depth and predicted scour depth using equations of Chitale (1988) and Chitale

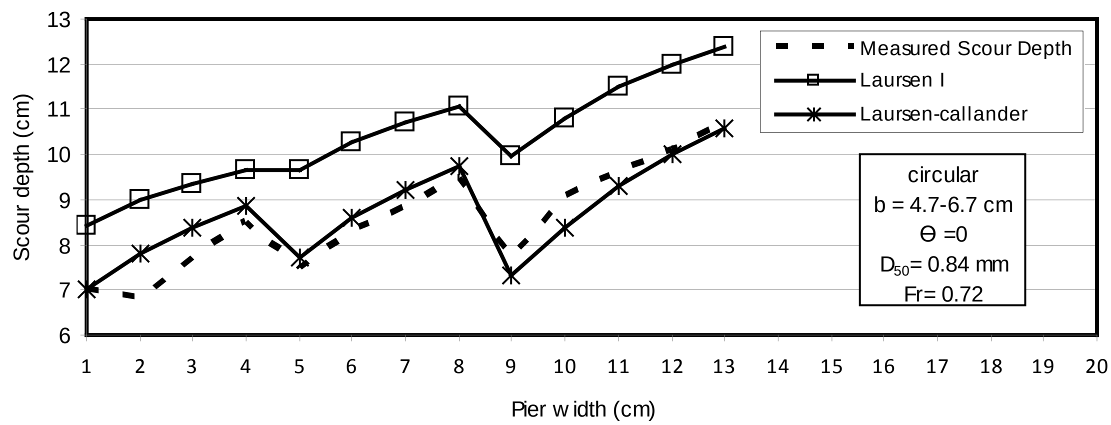

Fig. 5: Comparison between measured laboratory scour depth and predicted scour depth using equations of Laursen I & Laursen-Callander

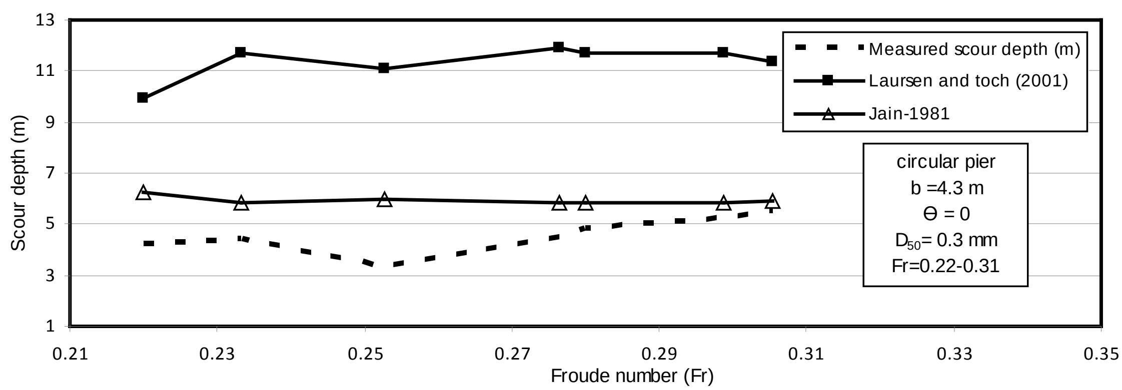

Fig. 6: Comparison between measured field scour depth and predicted scour depth using equations of Jain (1981), and Laursen and Toch.

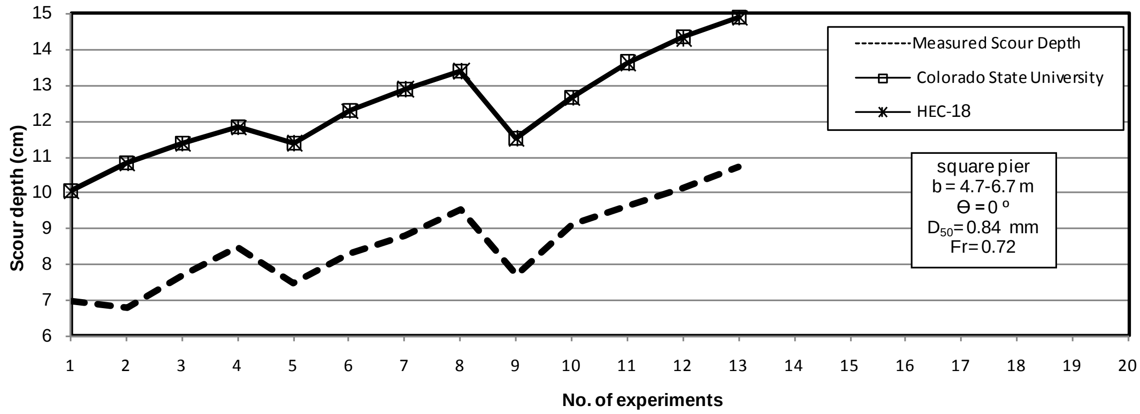

Fig. 7: Comparison between measured laboratory scour depth and predicted scour depth using equation of Colorado State University (1993) and HEC-18.

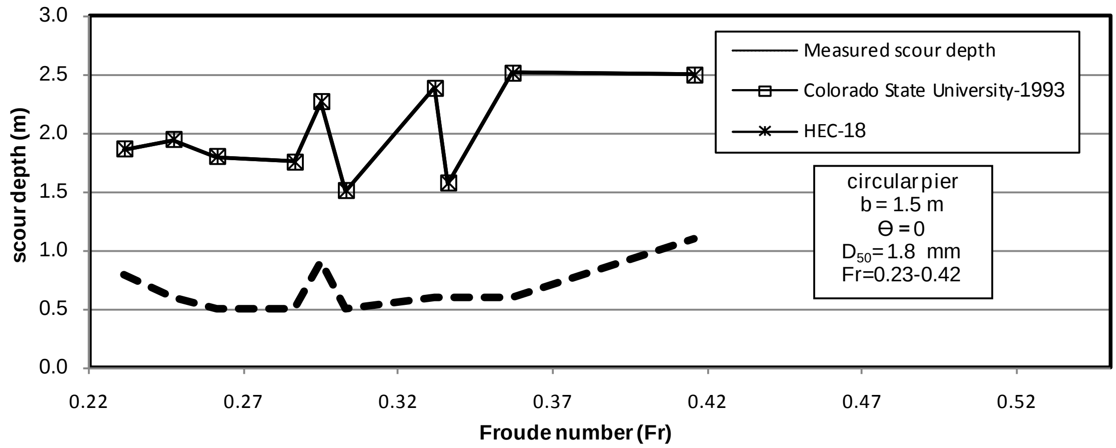

Fig. 8: Comparison between measured field scour depth and predicted scour depth using equation of Colorado State University (1993) and HEC-18.

Table 2: Summary of scour equation evaluation

Equation	Evaluation
Laursen I	• Overestimates the scour depth by a range of 24% to 187% compared to measured scour depth in the field.
Laursen-Callender	• Estimated scour depth ranges between 24% to 1317% of measured field scour depth but in case of large pier width (b=4.3 m) it under estimate scour depth by about -14% • Compared to laboratory data, the estimated scour depth varies between about 2% to 75% of the measured scour depth.
Shen at al. (1969)	• Compared to field data, the equation may underestimate the scour depth by about 65% or overestimate the scour depth by about 170%. • Compared to laboratory data, the estimated scour depth varies between about -33% (underestimation) to 40% (overestimation) of the measured scour depth. The equation may overestimates the scour depth by about 310% at circular pier and high Froude number (Fr = 0.98).
Coleman (1971)	• The equation may underestimate the scour depth by about 87% and may overestimate the scour depth by about 32% compared to measured field scour depth. • The equation underestimates the scour depth by about 20% to 80% compared to measured laboratory scour depth • The equation provides good estimate (about 17% of measured laboratory scour depth) in case of high Froude number (Fr = 0.98).
Neil (1973)	• Overestimates the scour depth by a range of 19% to 258% compared to measured field scour depth. • Overestimates the scour depth by a range of 2% to 314% compared to measured laboratory scour depth
Breusers et al. (1977)	• The estimated scour depth ranges between about -10% and 110% of the measured field scour depth. • The estimated scour depth ranges between about -13% to 4% of the measured laboratory scour depth. • Overestimates the scour depth by about 290% in case of high Froude number (Fr = 0.98).
Breusers et al. (1965)	• Estimated scour depth ranges between -14% to 8% of field measurements but it overestimates the scour depth up to 234% in

	case of high values of D_{50}. • Estimated scour depth ranges between about -27% to 285% of laboratory measurements.
Jain & Fischer (1980)	• Overestimates scour depth by a range of 108% to 2275% of field measurements • Overestimates scour depth by a range of 50% to 192% of laboratory measurements.
Jain (1981)	• Overestimates scour depth by a range of 18% to 1600% of field measurements. • Overestimates scour depth by a range of 24% to 260% of laboratory measurements.
Melville and Sutherland (1988)	• Overestimates scour depth by a range of 62% to 1463% of field measurements. • Overestimates scour depth by a range of 37% to 231% of laboratory measurements.
Colorado State University (CSU) HEC-18	• In case of the factor K4 = 1 at D_{50}< 2mm the CSU equation gives same result of the HEC-18 equation. • In general the two equations overestimate the scour depth by about 14% to 212% compared to measured field scour depth. • For laboratory data, the equations provide estimate ranges between about -17% to 45%. • Compared to measured laboratory scour depth, the equations overestimates the scour depth by about 266% in case of high Froude number (Fr = 0.98).
Richardson and Davis (1995)	• Overestimates the scour depth by about 12% to 243% compared to measured field scour depth • Compared to measured laboratory scour depth, the equation overestimates the scour depth up to about 56%. The difference may be up to 303% in case of high Froude number (Fr = 0.98).
Mississippi	• The estimated scour depth varies between about -10% to 55% of measured field scour depth. • The equation overestimates scour depth up to 55% of measured laboratory scour depth.
Blench-Inglis I	• Compared to measured scour field depth, the equation may underestimate the scour depth up to about 33% and may overestimate the scour depth up to about 100%. (i.e., estimated scour depth ranges between -33% to 100% of measured field scour

	depth) • Estimated scour depth ranges between about -15% to 23% of measured laboratory scour depth.
Blench-Inglis II	• Overestimates the scour depth by a range of 175% to 500% for field data • Overestimates the scour depth by a range of 382% to 1178% for laboratory data.
Chitale (1988)	• Overestimates the scour depth by a range of about 92% to 18209% for field data • Overestimates the scour depth by a range of about 30% to 590% for laboratory data
Chitale (1962)	• Overestimates scour depth by a range of 30% to 1440% for field data • Estimated scour depth ranges between about -29% to 18% of measured laboratory scour depth. But it overestimated the scour depth up to 81% in case of high Froude number (Fr = 0.72).
Laursen (1962)	• Overestimates scour depth by a range of 161% to 336% compared to field measurements.
Veiga (1970)	• Overestimates scour depth by a range of about 18% to 236% compared to field measurements.
Inglis-Poona I	• Estimated scour depth ranges between about -166% to 70% of field measurements. • Estimated scour depth ranges between about -22% to -47% of laboratory measurements. • Overestimates scour depth by only 8% of laboratory measurements in case of high Froude number (Fr = 0.98).
Inglis-Poona II	• Estimated scour depth ranges between about -34% and 93% of field measurements. • Overestimates scour depth by about 350% to 990% of measured laboratory scour depth.
Inglis (1949)	• Overestimates scour depth by about 250% to 580% for of field measurements • Overestimates scour depth by about 126% to 287% of laboratory measurements.
Laursen & Toch	• Overestimates scour depth by about 88% to 2247% of field measurements and overestimates scour depth by about 20% to 70%

	of laboratory measurements.

3. SCOUR AT BRIDGE ABUTMENTS

Scour occurs at bridge abutments when the abutment and embankment obstruct the flow. Several causes of abutment failures during post-flood field inspections of bridge sites have been documented. Some main phenomena that may occur include the following:

- Overtopping of abutments or approach embankments.
- Lateral channel migration or stream widening processes.
- Contraction scour.
- Local scour at one or both abutments.

The main equations for predicting scour at bridge abutments had been developed by Richardson et al., HEC-18, Melville, Laursen and Lim. Table 3 presents the main equations for sour prediction at bridge abutments.

Table 3: Abutment scour equations

Reference	**Equation**
Melville (1992)	$d_s lL = K_i K_y K_d K_s K_\theta K_G$
Froehlich (1989a)	$d_s lL = 2.27 K_s K_\theta (Y_a / L)^{0.57} Fr^{0.61}$
Richardson and Davis (1995)	$d_s lL = 7.27 K_s K_\theta (Y / L)^{0.57} Fr^{0.33}$
HEC-18 (Richardson, 1990).	$d_s = 4 Fr^{0.33} Y$
Lim (1997)	$d_s = 1.8 (L/Y)^{0.5} Y$
Laursen (1963)	$d_s = 1.89 (L/Y)^{0.5} Y$

Figures 9 to 13 present some examples of comparisons between measured laboratory data collected by Federal Highway Administration, 2004 [28] and scour prediction using the equations listed in Table 3. Table 4 summarized the evaluation of these equations.

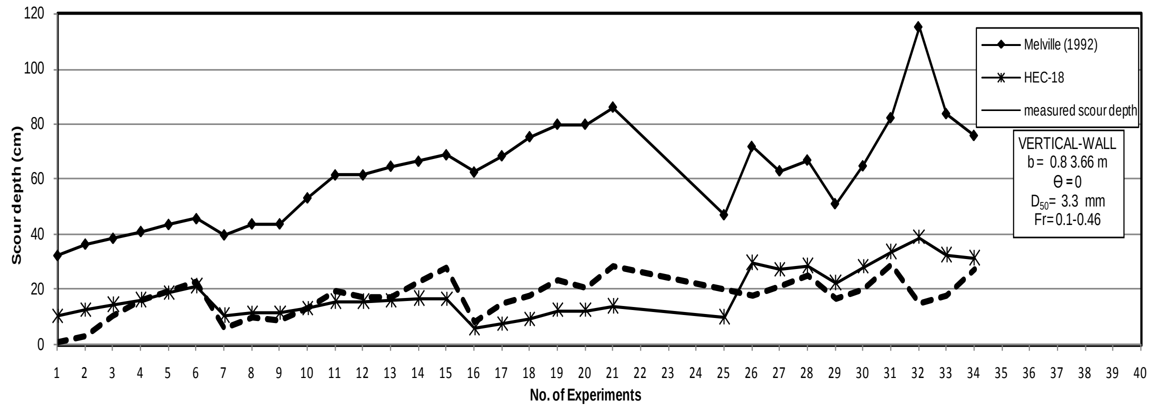

Fig. 9: Comparison between measured laboratory scour depth and predicted scour depth using equations of Melville (1992) and HEC-18 for case of vertical wall abutment

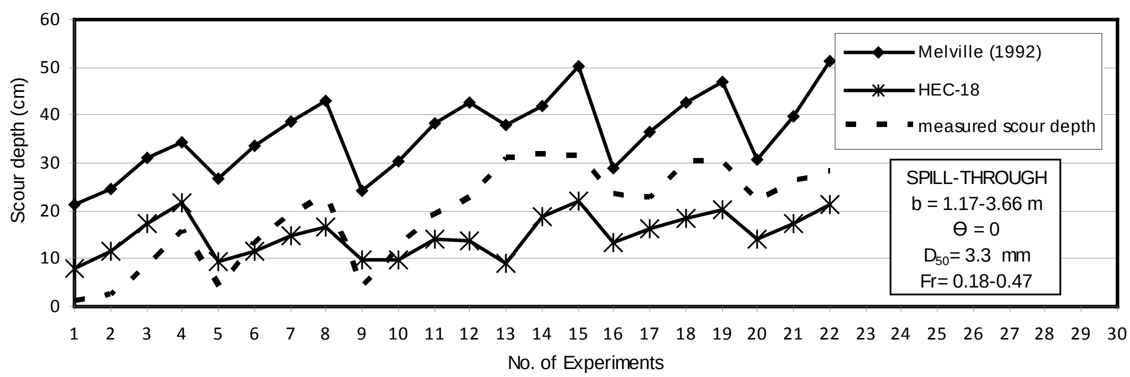

Fig. 10: Comparison between measured laboratory scour depth and predicted scour depth using equations of Melville (1992) and HEC-18 for case of Spill-Through abutment.

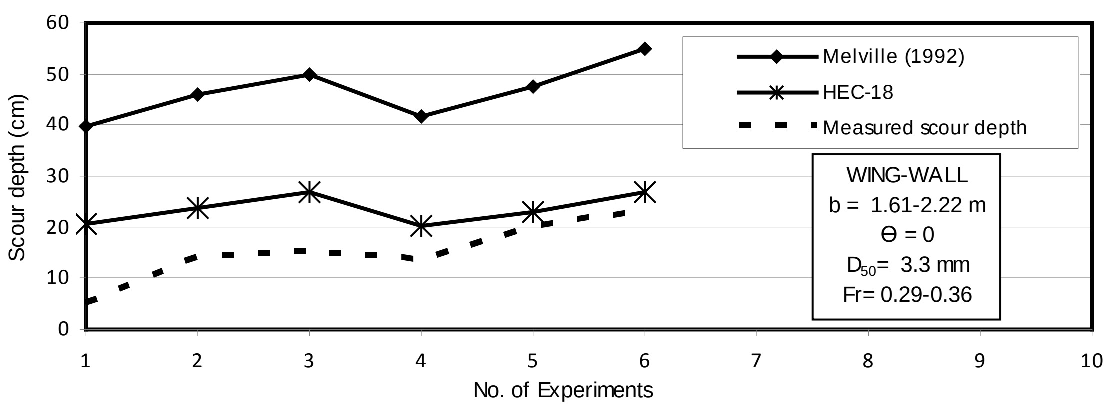

Fig. 11: Comparison between measured laboratory scour depth and predicted scour depth using equations of Melville (1992) and HEC-18 for case of wing wall abutment.

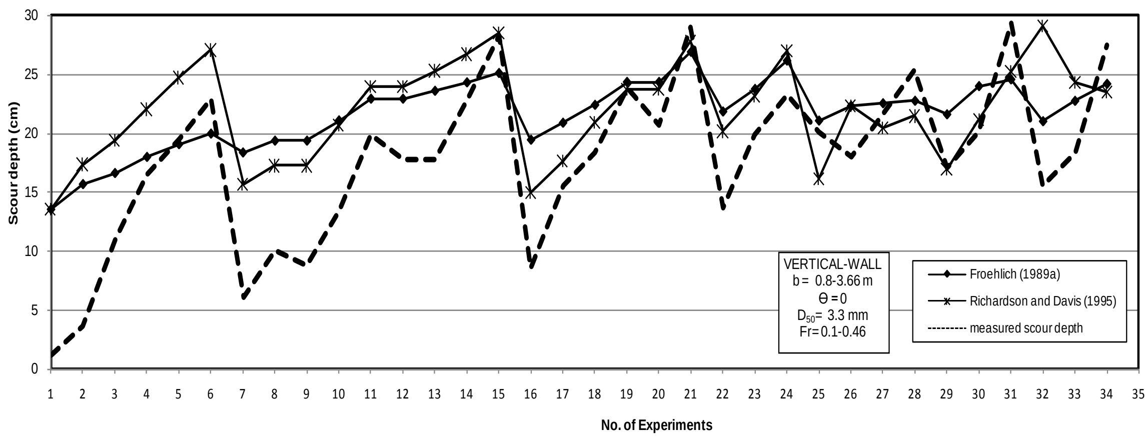

Fig. 12: Comparison between measured laboratory scour depth and predicted scour depth using equations of Froehlich (1989a) and Richardson and Davis (1995) for case of vertical wall abutment.

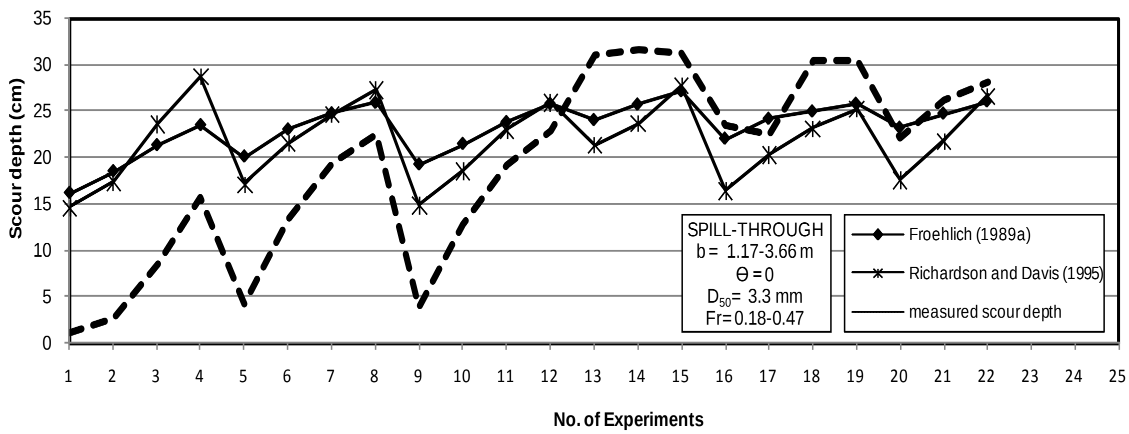

Fig. 13: Comparison between measured laboratory scour depth and predicted scour depth using equations of Froehlich (1989) and Richardson and Davis (1995) for case of spill-through abutment

Table 4: Summary of assessment of bridge abutment scour equations

Reference	Equation
Melville (1992)	Overestimates the scour depth by a range of 93% to 363%.
Froehlich (1989)	Estimated scour depth ranges between about -22% to 113% of measured scour depth.
Richardson and Davis (1995)	Estimated scour depth ranges between about -10% to 132% of measured scour depth.
HEC-18	Estimated scour depth ranges between about 4% to 91% of measured scour depth.
Lim (1997)	Overestimates the scour depth by a range of 120% to 360%.
Laursen (1963)	Overestimates the scour depth by a range of 135% to 410%.

Table 4 indicates that HEC-18 equation provides the best estimate scour depth for bridge abutment.

4. CONCLUSIONS

4.1 Bridge Pier Equations

In this paper, 24 equations for scour prediction around bridge piers were validated against experimental laboratory and field measurements. Table 2 provides a detailed assessment of all these equations.

From the available data, the following can be concluded:

1- Blench-Inglis I and Inglis-Poona II equations provide reasonable scour depth estimate at circular or sharp nose piers with relatively large pier width.

2- Inglis-Poona I and Mississippi equations provide reasonable scour depth estimate at circular and sharp nose piers with small pier width.

3- Colorado State University (CSU) equation provides reasonable scour depth estimate at square piers with small width.

4- Richardson et al., 1990 and Breusers-1969 equations provide reasonable scour depth estimate at square piers which have a large width.

5- Inglis_Poona I and Neil (1973) equations provide reasonable scour depth estimate at circular and square piers with large pier width in case of high Froude numbers.

6- Richardson et al., 1990 and Laursen I equations provide reasonable scour depth estimate in case of low Froude numbers.

7- Mississippi equation seems to be the best equation for scour prediction around sharp nose piers.

8- Some equations significantly overestimate the scour depth especially compared to field measurements.

4.2 Bridge Abutment Equations

Table 4 summarizes the evaluation of 6 main equations reported in the literature for scour prediction around bridge abutments. From the available data, it appears that HEC-18 equation provides the best estimate of scour depth at bridge abutment.

5. LIST OF SYMBOLS

b is the pier width.

D_{50} is the grain size of bed material for which 50 percent is finer; the median grain size.

F_r is the flow Froude number defined as $V/\sqrt{gy}$

g is the acceleration of gravity.

K_d is a coefficient for sediment size by Melville and Sutherland (1988).

K_I is a coefficient for flow intensity defined by Melville and Sutherland.

K_s is a coefficient for pier shape defined by Melville and Sutherland.

K_u is 1.0 for SI units and 1.81 for customary English units in the critical velocity equation.

K_y is a coefficient for flow depth defined by Melville and Sutherland.

K_1 is a coefficient based on the shape of the pier nose, defined as 1.1 for square-nose piers, 1.0 for circular- or round-nosed piers, 0.9 of sharp-nosed piers, and 1.0 for a group of cylinders.

K_2 is a coefficient for pier skew defined as (cos α + (L/b)sin α)0.65.

K_3 is a coefficient for channel bed condition, defined as 1.1 except when medium to large dunes are present, and then it can range from 1.2 to 1.3.

K_4 is a coefficient for bed material size and gradation.

L is the length of the abutment.

Q is the discharge in the stream.

S is the slope of channel in the vicinity of the bridge.

V is the approach velocity for pier scour.

V_c is the critical (incipient-transport) velocity for the D50 size particle.

Y is the approach depth of flow for pier scour.

d_s is the depth of scour.

θ is the skew of the pier to approach flow.

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