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A CRITICAL REVIEW OF ABUTMENT SCOUR DEPTH PREDICTORS

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ABSTRACT

Realistic estimation of scour depth around bridge abutments in alluvial rivers is important for safe and economic design of their foundations.. Under-estimation may lead to costly bridge failure and possibly the loss of lives, while over-estimation can result in huge money wasted on the construction of a bridge. Over the years, numerous predictors have been developed to predict the maximum local scour depth at bridge abutments and almost all of these predictors are based on laboratory data. These predictors produce wide range of scour estimates for the same hudraulic conditions. This paper presents a comprehensive review of the up-to-date work on scour at bridge abutments. Different existing abutment scour depth predictors are critically reviewed and presented. Finally, all the abutment scour depth predictors are critically examined with their limitation of applicability.

Keywords: Abutment, Bridge, Critical, Local Scour, Predictors.

I. INTRODUCTION

When an obstruction such as a bridge abutment or spur dike or pier, is placed on the a bed of a flowing stream, it leads to a three-dimensional modification of the flow due to the development of a vortex flow in the vicinity of the obstruction. In the case of abutment, the flow separates at the upstream face of the abutment as it travels by its side, creating a vortex trail that moves downstream and leading to scouring of the sediment bed in the vicinity of the abutment locally. This local scour exposes the abutment foundation that leads to the failure of the bridge. Local scour at foundations has long been a concern of engineers (Cardoso and Bettes, 1999). In the safety evaluation of bridges, local scour of bridge foundation material near pier/abutment is, therefore, an important issue (Huber, 1991; Dey and Barbhuiya, 2004). Various approaches to the scour depth prediction at abutments are generally classified into three categories: (i) regime approach relating the scour depth to the increased discharge intensity; (ii) empirical approach using dimensional analysis of the main parameters causing scour; and (iii) analytical or semi-empirical approach (Ahmad, 1953; Laursen, 1960; Garde, Subramanya and Nambudripad 1961; Gill, 1972; Melville, 1992; Melville, 1997; Lim, 1997; Lim and Cheng, 1998; Kothyari and Ranga Raju, 2001; Dey and Barbhuiya, 2004). All the experimental and theoretical investigations provide a better understanding of the problem. However, it remains unexplored in many aspects. Also, from the available literature, it is revealed that the exact scour mechanism and effects of different parameters on scour depth are yet to be fully understood or explored (Barbhuya and Dey, 2004).

There are wide divergences in the scour depths estimated through the available empirical and semi-empirical methods. The scour around bridge piers has been studied in greater detail than that around abutments. Considerable similarity is between the flow patterns and scour processes at a bridge pier and at a bridge abutment (Melville, 1997). The horse-shoe vortex and associated down-flow which are considered to be the prime agents causing scour at a bridge pier were found to be the main cause of scour at abutments as well. Abutment scour depth predictors presented in this paper are based on laboratory and field data. These models lack in applicability to the range of conditions for which the data were collected. In this paper an effort is made to examine all the existing abutment scour depth predictors with their limitations.

II. SELECTED ABUTMENT SCOUR DEPTH PREDICTORS FOR PRESENT STUDY

Laursen (1960)

$$\frac{L}{Y_1} = 2.75\frac{d_s}{Y_1}\left[\left(\frac{d_s}{11.5Y_1}+1\right)^{1.7}-1\right] \tag{1}$$

Laursen (1963)

$$\frac{L}{Y_1} = 2.75\frac{d_s}{Y_1}\left[\frac{\left(\frac{d_s}{11.5Y_1}+1\right)^{7/6}}{\left(\frac{\tau_1}{\tau_c}\right)^{0.5}}-1\right] \tag{2}$$

Garde et. al. (1961)

$$\frac{d_s}{Y_1} = \Gamma\left(\frac{1}{\alpha}\right)F_1{}^{\delta} \tag{3}$$

Liu et al (1961)

For live-bed condition

$$\frac{d_s}{Y_1} = 1.1\left(\frac{L}{Y_1}\right)^{0.4}F_1{}^{1/3} \tag{4}$$

For spill-through abutments: $F_1 = {V_1}/{(gY_1)^{0.5}}$,V_1= approach flow velocity

$$\frac{d_s}{Y_1} = 2.15\left(\frac{L}{Y_1}\right)^{0.4}F_1{}^{1/3} \tag{5}$$

Gill (1972)

Using his experimental Gill derived the following equation

$$\frac{Y_2}{Y_1} = 8.375\left(\frac{d}{Y_1}\right)^{0.25}\beta^{6/7}\left[\beta^{1/m}\left(1-\frac{\tau_c}{\tau_1}\right)+\frac{\tau_c}{\tau_1}\right]^{-3/7} \tag{6}$$

$Y_2 =$ flow depth at bridge $\approx Y_1 + d_s$ equation given at the threshold condition

Froehlich (1989)

$$\frac{d_s}{Y_f} = 2.27K_sK_\theta\left(\frac{L}{Y_f}\right)^{0.43}F^{0.61} \tag{7}$$

For live-bed scour;

$$F = {V_e}/{(gY_f)^{0.5}} ,V_e = {Q_e}/{A_e}, \tag{8}$$

Y_f = average depth of flow in the floodplain;

Q_e = flow obstructed by the embankment, A_e = flow area corresponding to Q_e

Melville (1992,1997)

$$d_s = K_{yL} K_I K_d K_s K_\theta K_G \tag{9}$$

Where, K_s = shape factor of the abutment as it affects scour by the flow field, K_θ =embankment skewness factor as it affects scour

$$K_{YL} = 2L \quad L/Y_1 < 1$$

$$K_{YL} = 2(Y_1 L)^{0.5} \quad 1 < L/Y_1 < 25$$

$$K_{YL} = 10Y_1 \quad L/Y_1 > 25$$

The classification scheme is based on L/Y_1 which is useful in comparing abutment scour formulas:

$0 < L/Y_1 < 1$ Short abutments similar to pier

$1 < L/Y_1 < 25$ Intermediate length a of abutments

$25 < L/Y_1$ Long abutments

Sturm and Janjua (1994)

$$\frac{d_s}{Y_F} = 7.7\left[\frac{F_1}{MF_c} - 0.35\right] \tag{10}$$

Kouchakzadeh and Townsend (1997)

$$\frac{d_{se}}{Y_{F0}} = 13.5\left(\frac{Q_w}{Q_a}\right)^{3.9} F_{F0}{}^{1.17} F_c{}^{-0.25} \tag{11}$$

Lim (1997,1998b)

For live bed scour

$$\frac{d_s}{Y_1} = K_s(0.9X - 2) \tag{12}$$

For clear-water scour

$$X = 0.9\left[\theta_c{}^{-0.375} F_d{}^{0.75}\left(\frac{d_{50}}{Y_1}\right)^{0.25}\left(0.9\left\{\frac{L}{Y_1}\right\}^{0.5} + 1\right)\right] - 2 \tag{13}$$

θ_c = Shields entrainment function

F_d = densimetric Froude number

Chang and Davis (1998, 1999)

For live-bed scour

$$d_s = K_s K_\theta\left[Y_1 K_f K_p\left(K_v \frac{q_2}{q_1}\right)^{K_2} - Y_{0adj}\right] FS \tag{14}$$

For clear-water scour

$$d_s = K_s K_\theta\left[\left(K_f K_p K_v{}^{0.857}\frac{q_2}{V_c}\right) - Y_{0adj}\right] FS \tag{15}$$

Cardoso and Bettess (1999)

$$\frac{d_s}{d_{se}} = 1 - \exp[-1.025(t/T)^{0.35}] \tag{16}$$

Rahman and Muramoto (1999

For sloped wall abutment

$$\frac{d_s}{y} = \sqrt{a_3(b/y)} \tag{17}$$

$$a_3 = \{\beta/\tan \varnothing(1-\beta) + 1/2 \tan \theta\}^{-1}$$

For vertical wall abutments

$$\frac{d_s}{y} = \sqrt{\{\tan \varnothing(1-\beta)/\beta\}(b/y)} \tag{18}$$

Melville and Coleman (2000)

$$d_s = K_{yL}K_I K_d K_s K_\gamma K_G K_t \tag{19}$$

Richardson and Davis (2001)

$$\frac{d_s}{y} = 7.27 K_s K_\theta F_r^{\ 0.33} \tag{20}$$

Chaurasia and Lal (2002)

$$\frac{d_{se}}{y} = 2.657\theta_c^{\ -0.16} F_d^{\ 0.765} \left(\frac{L_a}{y}\right)^{0.245} \left(\frac{d_{50}}{y}\right)^{0.265} - 1 \tag{21}$$

Coleman *et al* (2003)

$$\frac{d_s}{d_{se}} = \exp\left[-0.07\left(\frac{V_c}{V}\right)\left|\ln\left(\frac{t}{t_e}\right)\right|^{1.5}\right] \tag{22}$$

Dey and Barbhuiya (2004B)

$$\frac{d_s}{l} = 5.16 K_s \left(\frac{y}{l}\right)^{0.18} \left(\frac{V_c}{\sqrt{\Delta g l}}\right)^{0.26} \tag{23}$$

Dey and Barbhuiya (2005)

For Clear-water condition for semicircular abutment

$$\hat{d}_s = 8.689\ F_d^{\ 0.192}\ \widehat{y}^{\,0.103}\ \hat{l}^{-0.296} \tag{24}$$

For Clear-water condition for vertical-wall abutment

$$\hat{d}_s = 7.281\ F_d^{\ 0.314} \hat{y}^{0.128}\ \hat{l}^{-0.167} \tag{25}$$

For Clear-water condition for 45˚ wing-wall abutment

$$\hat{d}_s = 8.319\ F_d^{\ 0.312}\ \widehat{y}^{\,0.101}\ \hat{l}^{-0.231} \tag{26}$$

Where ,$\hat{d}_s = d_s/L$, $\widehat{y} = y/L$, $\hat{l} = L/d_{50}$

Yanmaz and Kose (2007b)

$$\frac{d_s}{L} = 0.25\ F_d^{\ 0.85} \left(L/y\right)^{0.15} (\log T_s)^{0.60} \tag{27}$$

Where , $T_s = td_{50}(\Delta g d_{50})^{0.5}/L^2$, $\Delta = (\rho_s - \rho)/\rho$

Briaud et al. (2009)

$$\frac{d_s}{Y_1} = 6.5K_sK_1K_\theta K_p(1.57F_2 - F_c)^{0.7} \tag{28}$$

Y_1 = flow depth upstream from the toe of the abutment; F_2 =Froude number at the toe of the abutment = $V_2/(gY_1)^{0.5}$; F_c =critical Froude number at the toe of the abutment = $V_c/(gY_1)^{0.5}$

K_p=pressure flow coefficient in Maryland formula

For sloped wall abutment

$$\frac{d_s}{y} = \sqrt{a_3(b/y)} \tag{29}$$

$a_3 = \{\beta/\tan\emptyset(1-\beta) + 1/2\tan\theta\}^{-1}$

For vertical wall abutments

$$\frac{d_s}{y} = \sqrt{\{\tan\emptyset(1-\beta)/\beta\}(b/y)} \tag{30}$$

Ettema et al **(2010)**

Propose the relationships for two conditions A&B based on geotechnical approach for estimating scour depth

Condition A (Scour in main channel):

$$\frac{Y_{max}}{Y_c} = f\left(\frac{q_2}{q_1}\right) \quad \text{(erodible embankment)} \tag{31}$$

Where, Y_{max}=maximum flow depth at the bridge after scour, Y_c= flow depth of live-bed contraction scour in main channel, $q_2,\ q_1$ = discharge per unit width in contracted and approach sections of main channel.

Condition B (Scour in floodplain) :

$$\frac{Y_{max}}{Y_{fc}} = f\left(\frac{q_{f2}}{q_{f1}}\right) \tag{32}$$

III. CRITICAL ANALYSIS OF SELECTED ABUTMENT SCOUR DEPTH PREDICTORS

Formulae of Laursen (1960, 1963) treat abutments as a “half pier” for small value of or as a wide pier in shallow flow for larger values of abutment length. Formula of Garde et. al. (1961) is applicable for clear-water scour condition and only for d_{50}=0.20 mm, 0.45 mm, 1.00 mm and 2.25 mm having average. Geometric contraction ratio m = (B-2L)/B and valid for m, 0.5 < m < 0.9 and Froude number F_1, 0.1<F_1<0.4. Valid for vertical wall abutment formula of Liu et al (1961), under live-bed scour condition, *is* applicable to bed material of d_{50}= 0.56 mm ,Froude number F_1 0.3<F_1 < 1.2 and 1 < L/Y_1< 10 and under clear-water scour condition formual 5 of Liu et al (1961)is a applicable to bed material of d_{50}= 0.56mm, 0.65mm ,Froude number F_1 0.1< F_1 < 0.6 and 0.5 < m< 0.9 Formula of Gill (1972) is applicable for bed material of d_{50}=0.9mm, 1.5mm , 20<Y_1/d<90, and 0.6<m<0.9 Formule of Froehlich (1989) are reported to overestimate Equation had a tendency to overestimate the scour depth. Formula of Melville (1992,1997) is applicable to short, solid-wall abutments and depends on abutment length. It is applicable to bed material of d_{50}= 0.9mm, 1<L/Y_1<60, and 0.7< V_1/V_c<6.4, V_c=critical velocity for initiation of sediment motion Formula of Sturm and Janjua (1994) does not include sufficient parameters for characterizing the larger-scale turbulence features generated by the abutment or within the interacting flows passing in the main channel and the floodplain. Formula of Kouchakzadeh and Townsend (1997) does not capture the parameters needed to account for the effects on scour of the larger-scale features of flow turbulence. Formulae of Lim (1997,1998b is valid for vertical-wall type abutment. Formula of Chang and Davis (1998, 1999) are valid for K_f is limited to 1.0 to 3.2 1 <q_{f2}/q_f ≤ Formula of Cardoso and Bettess (1999) is valid for vertical-wall abutments**.** Formulae of Rahman and Muramoto (1999)is valid for 0.1≤ b/B ≤ 0.3, 0.15 ≤ F_r ≤ 0.9. It is not available to explain the experimental features of long abutment (b/h > 25). Formulae of Melville and Coleman **(2000)** is valid for bed material of d_{50}= 0.9mm, 1<L/Y_1<60, and 0.7< V_1/V_c<6.4. Formula of Richardson and Davis (2001) valid for L/Y_1>25 and it is applicable to live bed scour. Formula of of Chaurasia and Lal (2002) is applicable for clear water flow condition and d_{50}= 0.56mm – 1.40mm. Formula of Coleman *et al* (2003) *is valid for* d_{50}= 0.8-1.02 mm and V/V_c= 0.46-0.99. Formula of Dey and Barbhuiya (2004b) valid for clear water scour and short abutment. Formula of Dey and Barbhuiya (2005) valid for short abutment under clear water scour conditionand applies to non uniform bed material. Formula of Yanmaz and Kose (2007b) valid for to clear water conditions with uniform bed materials. Formula of Briaud et al (2009) are valid 0.1≤ b/B ≤ 0.3 and 0.15 ≤ F_r ≤ 0.9. Formulae of Ettema et al (2010) are based on geotechnical approach for estimating scour depth is not reliant upon the need to estimate a critical value of erosion resistance for the boundary around an abutment.

IV. CONCLUSIONS

Local scour at piers and abutment is one of the main causes of bridge failure. 21 abutment scour depth predictors are reviewed and presented. Abutment scour depth predictors considered in this paper are mostly empirical based on the measurement of scour depth in the laboratory. As such, they are limited in applicability to the range of conditions for which the data were collected. The abutment scour depth predictors considered herein are data specific. These predictors are not applicable to all conditions of sediment, abutment and flow. It is suggested that the predictors can be grouped region wise for which they are developed.

V. NOTATIONS

B = Channel width.

d_{se}= Equilibrium scour depth at the abutment.

F_d = densimetric Froude number.

FS=calibration/safety factor.

F_{f0}=approach Froude number on floodplain.

K_f=spiral flow adjustment factor.

K_p=pressure flow factor.

K_v=velocity adjustment factor.

K_{yL}= Depth size factor.

K_I=Flow intensity factor.

K_d=Sediment size factor.

K_G=Approach channel geometry factor.

K_s= shape factor of the abutment.

K_θ=embankment skewness factor as it affects scour.

L= length of the abutment.

L_a=Projecting length of abutment, perpendicular to the flow.

l= transverse length or protrusion length of abutment.

q_2, q_1 = discharge per unit width in contracted and approach sections of main channel.

Q_w=flow component related to specific width of channel at end of abutment.

Q_a=flow component intercepted by abutment

T= time scale.

Y_{0adj}=flow depth at bridge before scour.

y= Approach flow depth,

y= Approach flow depth, $\emptyset$= angle of repose of the bed sediment

Y_1= upstream approach flow depth in main channel

Y_{max}=maximum flow depth at the bridge after scour,

Y_c= flow depth of live-bed contraction scour in main channel,

ρ_s=Mass density of sediments

τ_1 = grain roughness component of bed shear stress

τ_c = critical shear stress

β = contraction ratio

θ_c = Shields entrainment function

$\varnothing$= angle of repose of the bed sediment ,

θ= side slope of the structure ,

REFERENCES

[1] . Laursen, E.M., “Scour at Bridge Crossings.” Journal of the Hydraulics Division, ASCE, Vol. 86, No. HY2 (1960) pp. 39-54.

[2] . Laursen, E.M., “An Analysis of Relief Bridge Scour.” Journal of the Hydraulics Division, ASCE, Vol. 92, No. HY3 (1963) pp. 93-118.

[3] . Garde, R.J.; Subramanya, K., and Nambudripad, K.D., “Study of Scour Around Spur Dikes.” Journal of the Hydraulics Division, ASCE, Vol. 87, No. HY6 (1961) pp. 23-37.

[4] . Liu, H.K.; Chang, F.M.; and Skinner, M.M., Effect of Bridge Construction on Scour and Backwater, Report CER 60 HKL 22, Department of Civil Engineering, Colorado State University, Fort Collins, CO (1961).

[5] . Gill, M.A., “Erosion of Sand Beds Around Spur Dikes.” Journal of the Hydraulics Division, ASCE, Vol. 98, No. HY9 (1972) pp. 1587-1602.

[6] . Froehlich, D.C., “Local Scour at Bridge Abutments,” Proc. ASCE National Hydraulic Conference, Colorado Springs, Colorado, (1989) pp. 13-18.

[7]. Melville, B.W., “Local Scour at Bridge Abutments.” Journal of Hydraulic Engineering, ASCE, Vol. 118, No. 4 (1992) pp. 615-631.

[8]. Melville, B.W., “Pier and Abutment Scour: Integrated Approach.” Journal of Hydraulic Engineering, ASCE, Vol. 123, No. 2 (1997) pp. 125-136.

[9] Kouchakzadeh, S., and Townsend, R. D., Maximum Scour Depth at Bridge, Abutments Terminating in the Floodplain Zone. Canadian. J. of Civ. Engr., Vol. 24, (1997). 996-1006.

[10]. Sturm, T.W., and Janjua, N.S., “Clear-Water Scour around Abutments in Floodplains.” Journal of Hydraulic Engineering, ASCE, Vol. 120, No. 8 (1994) pp. 956-972.

[11]. Lim, S.Y., “Equilibrium Clear-Water Scour Around an Abutment.” Journal of Hydraulic Engineering, ASCE, Vol. 123, No. 3 (1997) pp. 237-243.

[12]. Lim, S.Y., and Cheng, N.-S., “Prediction of Live-Bed Scour at Bridge Abutments.” Journal of Hydraulic Engineering, ASCE, Vol. 124, No. 6 (1998b), pp. 635-638.

[13]. Chang, F., and Davis, S., “Maryland Procedure for Estimating Scour at Bridge Abutments, Part 2–Clear Water Scour.” Proc. of Water Resources Engineering, ’98, ASCE, Memphis, TN, (1998) pp. 169-173.

[14]. Chang, F. and Davis, S., “Maryland SHA Procedure for Estimating Scour at Bridge Waterways, Part 1 – Live Bed Scour.” In Stream Stability and Scour at Highway Bridges, (Eds.) Richardson, E. and Lagasse, P., ASCE, Reston VA, (1999) pp. 401-4011.

[15]. Cardoso, A.H., and Bettess, R., “Effects of Time and Channel Geometry on Scour at Bridge Abutments.” Journal of Hydraulic Engineering, ASCE, Vol. 125, No. 4 (1999) pp. 388-99.

[16]. Rahman, M. M and Muramoto, Y, (1999). "Prediction of Maximum Scour Depth Around Spur-dike like structures, Annual J. of Hydraulic Engineering, JSCE, 43Melville, B.W., and Coleman, S.E. (2000). Bridge Scour, Water Resources Publications, Colorado, U.S.A., 550p.

[17]. Richardson, E.V., and Davis, S.R., "Evaluating Scour at Bridges." Hydraulic Engineering Circular No. 18, 4th Ed., Federal Highway Administration, Arlington, VA. (2001).

[18]. Chaurasia, E. S. R., and Lal, P. B. B., (2002). Local Scour Around Bridge Abutments. Int. J. of Sed. Reseach, Vol. 17, No. 1, 48-74.

[19]. Coleman, S. Lachlan, C. and Melville, B. "Clearwater Scour Development at Bridge Abutments," Journal of Hydraulic Research, IAHR, Vol. 41, no. 5 (2003) pp. 521-531.

[20]. Dey S, Barbhuiya A K Clear-water scour at abutments in thinly armored beds. J. Hydraul. Eng., Am. Soc. Civ. Eng. 130: 622–634.

[21] Dey, S. and A.K. Barbhuiya, 2005. Time variation of scour at abutments. J. Hydraul. Eng., 131(1): 11-23

[22]. Yanmaz, A.M. and O. Kose, 2007b. Time-wise variation of scouring at bridge abutments. Sadhana, 32(3): 199-213.

[23]. Briaud, J.-L., Chen, H.-C., Chang, K.-A., Oh, S.J., and Chen, X., "Abutment Scour in Cohesive Material." NCHRP Report 24-15(2), Transportation Research Board, National Research Council, Washington, DC (2009).

[24]. Ettema, R., Nakato, T. and Muste, M., "Estimation of Scour Depth at Bridge Abutments." Final Report, NCHRP 24-20, Transportation Research Board, Washington, DC, (2010).