SCOUR IN BRIDGE PIERS ON NON-COHESIVE FINE AND COARSE SOIL

S.K. Mazumder

Former AICTE Em. Prof. of Civil Engg., DCE (Now DTU)

E-mail:somendrak64@gmail.com

Abstract

Estimateion of scour in bridge piers is necessary for economic and safe design of bridges. Although a large numbers of mathematical models are available, scour estimation in Indian bridges is done by empirical equation like Lacey in both fine and coarse soil. Total scour depths in piers, founded on fine soil, are estimated in five bridges in India using different mathematical models and are compared with those found by IRC method based on Lacey's theory. IRC method is found to overestimate scour in all the cases and the error is found to vary between 5% to 275%. Local scour depths in bridge piers founded on coarse soil are observed at five bridge sites in Missisipi river basin in USA . Scour depths observed are compared with those predicted by different mathematical models and also by IRC method. Compared to IRC method, scour in piers founded on coarse soil , governed both by size and gradation of sediments, is found to be significantly less than that in fine uniform soil under all velocity of flow. It is observed that the scour depths predicted by mathematical models are quite conservative and closer to the observed ones.

Key words: Bridge pier, scour, fine and coarse soil, Lacey, IRC, mathematical models.

INTRODUCTION

Determination of scour around bridge piers is important in deciding the foundation level of the bridge piers. It is a universal practice to find total scour depth as sum of general scour, contraction scour and local scour, except in India where the total scour depth in piers is arbitrarily determined as 2R below HFL or R below mean bed level. R (hydraulic radius or hydraulic mean depth) is computed by Lacey's (1930) theory. The multiplying factor 2 is based on observed scour depths in 17 major railway bridges (CBIP,1989) given in a annual report (tech) by C.W.P.R.S.,Pune (1944). Moreover, all the piers are founded on very fine and uniformly graded soil (d_{50}-varying from 0.17 to 0.39 mm,). Yet, the same equation is adopted in India for computing scour in bridge pier founded on coarse and graded soils (e.g. bouldery soil having d_{50}>300mm) without any verification from field. Scour depth around pier is governed not only by Lacey's R but also many other parameters e.g. type of pier, pier width, shape of pier nose, flow conditions and sediment characteristics. Based on these parameters, several mathematical models [Kothyari et al,(1992),Melville and Coleman(2000), Breussers & Raudkivi(1991), Richardson(1995) etc.] have been developed in India and abroad for predicting maximum local scour depth to be measured below river bed level. Mazumder and Kumar (2006) computed total scour depths in some bridge piers founded on cohesionless fine bed materials (d_{50}<2mm, σ_g<1.3) and compared them with those found by IRC method based on Lacey's theory. It is found that in all the cases, IRC method overestimates the total scour depth compared with those found by mathematical models and the error ranged between 5% to 275%. (Annexure-I(a) & I(b). Holnbeck (2011) observed local scour depths in river Maine in USA and compared the observed scour values with predicted ones by using HEC-18 Model. It is noticed that except in one case, the predicted scour depths are highly conservative as compared with observed ones.(annexure-II).

Mazumder and Dhiman (IRC-2014) computed local scour depths around bridge piers founded on coarse bed materials (d_{50}>2mm,σ_g>1.3) by using both empirical methods and mathematical models at five bridge sites in Missouri river basin and one in a river in New Zealand. Observed maximum local scour depths under clear water conditions are compared with local scour depths predicted by empirical equations as well as different mathematical models under identical flow, sediment and pier characteristics. Local scour depths predicted by the mathematical models are much higher than the observed ones. However, they are closer to the observed values compared to those predicted by IRC method based on Lacey's(1930) and Blench's (1957) equations. In the case of a bridge site in New Zealand, the scour depth obtained by IRC method is more than two times the scour depth predicted by different mathematical models (annexures-III(a) &III(b)).Owing to different mathematical structure of empirical equations, different results may be obtained from the available equations (Gaudio et al.2010)

Based on these study on pier scour in fine and coarse bed material, it is suggested that the existing method of scour computations in India, based on Lacey's equation and adopted by IRC, RDSO and BIS in their relevant codes, should be replaced by mathematical models developed by eminent research workers from India and abroad over the years. Objective of writing this paer is to emphasise that the Indian codes need revision and introduce scientific mathematical models for scour computation in bridge piers, especially those founded in coarse soil.

TOTAL DEPTH OF SCOUR BELOW HIGH FLOOD LEVEL

IRC Method of Estimating Total Scour Depth

In India, the prevalent practice of computing total depth of scour (Y_{max}) below HFL is by using Lacey's (1930) regime theory. The methodology adopted in IRC-5 (1998) & IRC -78(2000) for finding Y_{max} is given below .

$$Y_{max} = K\,R \tag{1}$$

when there is no restriction of Lacey's regime waterway(L>W)

$$R = 0.473(Q/k_{sf})^{1/3} \quad (2)$$

when Lacey's regime waterway is restricted(L<W)

$$R = 1.34\,(d_{sb}^{2}/k_{sf})^{1/3} \quad (3)$$

where, R is Lacey's regime depth in m, L is effective clear waterway in m provided under the bridge, W is the Lacey's regime width in m given by the relation

$$W=4.8\,Q^{0.5} \quad (4)$$

$$k_{sf} = 1.76\,(d_{50})^{1/2} \quad (5)$$

where Q is the design flood in cumec , d_{sb} is discharge per unit width (d_{sb}=Q/L), and d_{50} is the median size of sediments in mm. K=2 for piers and spill through type abutments, K=1.27 for abutments with duly protected sloping riverside face, K varies from 1.50 to 2.75 for guide bunds depending upon scour location .It may be noted that equations(1) to (5)currently being followed in India for scour computation in bridge piers (as per IRC/RDSO codes) do not consider pier width which is one of the significant parameters governing scour.

Use of Mathematical Models for Estimating Total Scour Depth

Mathematical models, as discussed below, are used in all developed countries to determine Y_{max} as summation of

(i)General scour

(ii) Contraction scour and

(iii) Local scour

(i) General Scour

General scour occurs during the passage of floods (even without any bridge) due to several morphologic processes in a river e.g. degradation, meandering , braiding, confluence etc. Several eminent river engineers e.g.Lacey (1930), Lane (1955), Ning Chien (1957), Blench (1969), Chitale (1966), Diplas(1992), Kothyari et al(1992), Yalin(1992), Garde- RangaRaju (2000) ,Garde(2006) have immensely contributed for prediction of general scour. Their theories, popularly known as regime theories, can be used for prediction of stable channel dimensions, river plan forms (e.g. straight, meandering, braiding etc.) and also river bed forms (e.g. ripple, dune, anti-dune etc). Maximum scour depth found from the general scoured profile which develops during passage of high flood is shown by dotted line in Fig.1.

The firm line is the bed profile usually observed during low flow season. From the design flood, Lacey equation can be used to find R i.e. y_{mean} (in Fig.1) for the scoured profile (dotted). As shown in Fig.1, y-values in the scoured section can be determined by multiplying y-values (at corresponding points from measured low flow bed profile) with the ratio of y_{mean} for the design flood and y_{mean} for low flow.

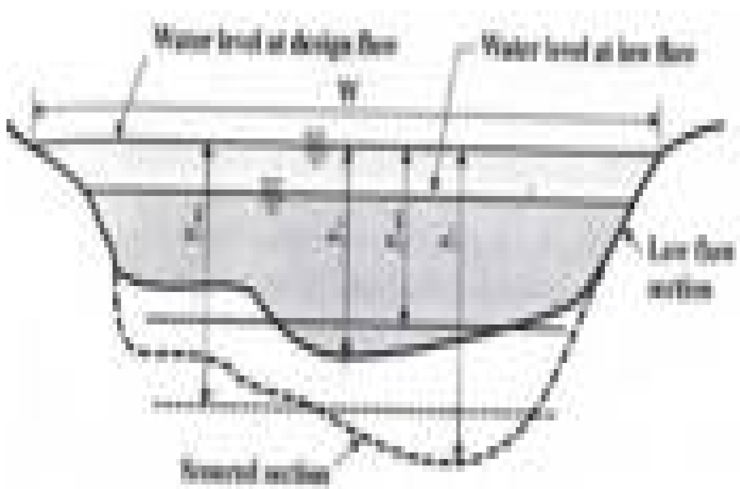


Fig.1Showing Bed Profile in a river during Lean Flow (Firm line) and Flood Flow(Dotted Line)
(y_{mean} and y_m stand for mean and maximum depths respectively)

(ii) Contraction Scour (by HEC-18 Model)

As illustrated in Fig.2, contraction scour occurs when the flood plain width of a river is contracted by approach embankment on one or both sides of a river to reduce the bridge cost. Clear water scour occurs when there is no bed movement (i.e. $\tau_0 < \tau_c$ or $V < V_c$) and live bed scour occurs when the bed is in motion (i.e.$\tau_o > \tau_c$ or $V > V_c$). Here, τ_o and τ_c stand for actual bed shear and critical bed shear stresses repectively, V and Vc are actual velocity and critical velocity respectively.

(a)For clear water condition when $\tau_0 < \tau_c$ or $V < V_c$

$$Y_2 = 1.48 \ Q_2 / (d_m^{1/3}.W_2)^{6/7} \qquad (6)$$

where,

$$d_m = 1.25 \ d_{50}$$

Q_2 is the flow under bridge and Q_{1m} is the flow in approach channel carrying bed load, Y_2 is the scoured depth under the bridge.

(b) For Live Bed Condition when ($\tau_o > \tau_c$ or $V > V_c$

$$Y_2/Y_1 = (Q_2/Q_{1m})^{6/7} \ (W_1/W_2)^{K1} \qquad (7)$$

W_1 & W_2 are normal and restricted waterways in approach channel and under the bridge respectively. K_1 varies from 0.59 (for sediments transported mostly as bed load) to 0.69 (for sediments transported mostly in Suspended form)

Scour depth due to contraction below river bed is $d_{sc} = (Y_2 - Y_1)$.

here, Y_2 is the flow depths at the constricted section of bridge and Y_1 is normal depth upstream of bridge.

Fig.2 Showing Contraction Scour due to Restriction of Flood Plain Width of River

(iii) Local Scour

Four popular mathematical Models used for estimating local scour in a bridge pier (Fig.3 and 4) are briefly discussed under (a) to (d) below.

(a)Melville and Coleman Model (2000)

Local scour under bridge piers can be estimated by using Melville and Coleman model given by equation (8) below

$$d_s = K_{yb} . K_1 . K_d . K_s . K_{al} . K_g . K_t \qquad (8)$$

where, $K_{yb} = 2.4$ b when $b/y < 0.7$, $K_{yb} = 4.5y$ when $b/y > 5$ and $K_{yb} = 2\sqrt{(yb)}$ when $0.7 < y/b < 5$, b is pier thickness and y is flow depth, K_1 is flow intensity factor, K_d is sediment size factor, K_s is pier shape factor, K_{al} is pier alignment factor, K_g is channel geometry factor, K_t is the time factor.

(b) IAHR Model (After Breussers & Raudkivi, 1991)

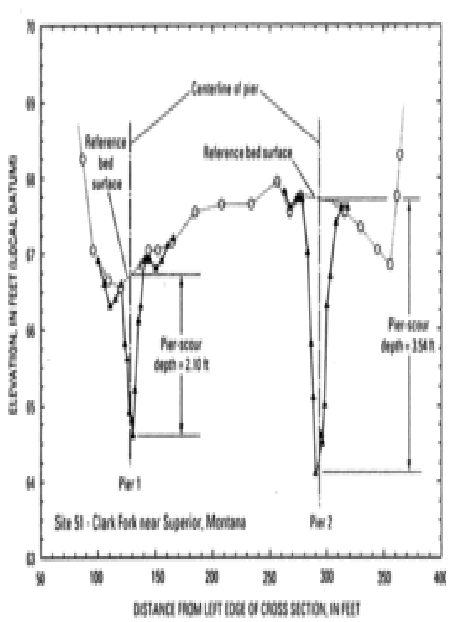
For clear water local scour (d_{se}) when $u^* < u^*_c$ or $V < V_c$

$$d_{se}/b = 2.3\, K_\sigma\, K_{(b/d50)}\, K_d\, K_s\, K_\alpha \quad (9)$$

For live bed scour when $u^* > u^*_c$ or $V > Vc$

$$d_{se}/b = X\, K_{(b/d50)}\, K_d\, K_s\, K_\alpha \quad (10)$$

d_{se} is the equilibrium scour depth, K_σ is sediment non-uniformity factor, $K_{(b/d50)}$ is sediment coarseness factor, K_s & K_α are pier shape and alignment factors respectively. Maximum value of X is 2.3 when $V > 4V_c$. When $V_c<V<4V_c$, value of X varies from 2 to 2.30 for uniform sediments ($\sigma_g \leq 1.3$) and "X"varies from 0.5 to 2.0 for non-uniform sediments ($\sigma_g > 1.3$)



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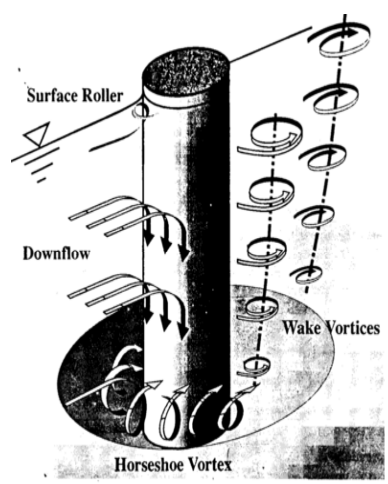

Fig.3 Showing Local Scour in Bridge Piers Fig.4 Development of Local Scour in a Pier

(c) HEC-18 Model (After Richardson and Davis, 1995)

$$d_s/y_1 = 2K_1.\ K_2\ .\ K_3\ .\ K_4\ .\ (b/y_1)^{0.65}\ .\ F_{r1}^{\ 0.43} \quad \textbf{(11)}$$

K_1 is correction factor for pier nose shape,K_2 is correction factor for flow obliquity ,K_3 is correction factor for bed condition i.e. plain bed, ripple and dune bed etc.,K_4 is the correction factor due to armoring of bed in non-uniform sediments, F_{r1} = approach flow Froude's number =, $V_1/(gy_1)^{0.5}$

(d) Kothyari – Garde – RangaRaju (K-G-R) Model (1992)

For clear water scour depth (d_{se}):

$$d_{se}/d_{50} = 0.66(b/d_{50})^{0.75} \{(D/d_{50})^{0.16}\} \{(V^2\text{-}V_c^2)\rho/(\Delta\gamma_s.d_{50})\} \alpha^{-0.30} \quad (12)$$

For live or mobile bed scour depth:

$$d_{se}/d_{50} = 0.88\,(b/d_{50})^{0.67}\,(D/d_{50})^{0.4}\,\alpha^{-0.30} \quad (13)$$

D is the flow depth, $\Delta\gamma_s = \gamma_s - \gamma_f$, where γ_s & γ_f are unit weights of sediment and water respectively, $\alpha = (B- b)/ B$, where B&b are the distance between consecutive piers and pier thickness, V & Vc are the actual mean velocity and critical velocity at threshold condition given by equation (14) below.

$$V_c^2\,\rho/\gamma_s.d_{50} = 1.2\,(b/d_{50})^{-0.11}\,(D/d_{50})^{0.16} \quad (14)$$

PREDICTION OF TOTAL SCOUR DEPTH IN COHESIONLESS FINE SOIL

Total scour depths under piers, founded on fine soil (d_{50}<2mm) in 5 major bridge piers in India, were estimated by different mathematical models as discussed above and compared with those obtained by IRC method under two different conditions, namely,

(a) when the river bed conforms to Lacey's scoured profile and
(b) when the low water bed profile remains unchanged during flood flow

Tables given in annexure I(a) and I(b) show the results obtained under conditions (a) and (b)respectively. It is seen that in all the cases IRC method overestimates total scour depth. Percentage error is defined as difference between total scour depths (by IRC method and by mathematical models) divided by total scour depth by mathematical models. The percentage errors given in parenthesis in annexure I(a) and I(b) are found to vary from 5% to 275%. As compared to IRC method, mathematical models give more consistent values.

Observed local scour depths (measured below bed) in piers founded on fine soil in Maine river basin in USA have been compared with the scour predicted by HEC-18 model in annexure-II(Holnbeck,2011). It may be seen that except in one case the predicted values are quite conservative and safe.

PREDICTION OF LOCAL SCOUR DEPTH IN COHESIONLESS COARSE SOIL

Local scour depths under bridge piers (Fig.3) founded on coarse soil (d_{50}>2mm), were observed in Missouri river basin in USA. Observed scour depths are compared with those predicted by different mathematical models (including empirical models by IRC and Blench) under identical flow conditions, pier geometry and sediment parameters. Results are given in Annexure-III(a) and III(b). It may be seen that the observed scour depths below river bed ($y_s^/$) given in column-2 of annexure-III(a) are considerably less than the values obtained by Lacey's R ($y_s^/$/R varying from 0.15 to 0.63). It may also be seen that the scour depths predicted by different mathematical models (under columns 5 to 8), although conservative, give scour depths lower than those predicted by Lacey's and Blench's models given in columns-3 and 4 respectively in annexure-III(a). Average values of local scour depths predicted by different mathematical models have been compared and summarized in Annexure-III(b) for clarity.

Fig.5 and Fig.6 (Holnbeck (2011) illustrate the effect of size and gradation of coarse sediments on local scour depth. It is seen from Fig.5 that the local scour depth in coarse soil is significantly less than that in fine soil for the same velocity of flow. Fig.6 illustrates the effect of gradation (σ_g) on local scour depth.

SUMMARY AND CONCLUSIONS

A large number of bridges in India are under construction due to massive roads and railway projects all over the country. In India, IRC method based on Lacey's regime theory is used in prediction of scour depths. If the predicted values are high, the cost of foundation will increase. On the other hand, bridge will be unsafe if scour is under-predicted. Regime equations for stable canal design were developed by eminent British engineers like Lacey, Blench, Inglis, Lindsley and others. Although not applicable in rivers, these equations are still being used in India for scour computations in bridge piers. There is hardly any observed scour data during flood flow in India. In the developed countries, however, mathematical models have been formulated and validated/proved from observed field data. In all the mathematical models developed in India and abroad, total scour depth below high flood level is computed by adding general scour, contraction scour and local scour computed separately. Some of these mathematical models have been described and used for prediction of pier scour in India and abroad. Results given in annexure I, II&III clearly indicate that IRC method over predicts scour. It is safe and economical to use mathematical models for prediction of scour depth. Scour depths computed by these mathematical models are quite conservative and scientific as they consider different parameters governing scour. Local scour depth in coarse soil is governed by size and gradation of sediments and is significantly less than that in fine uniform soil for the same velocity of flow.

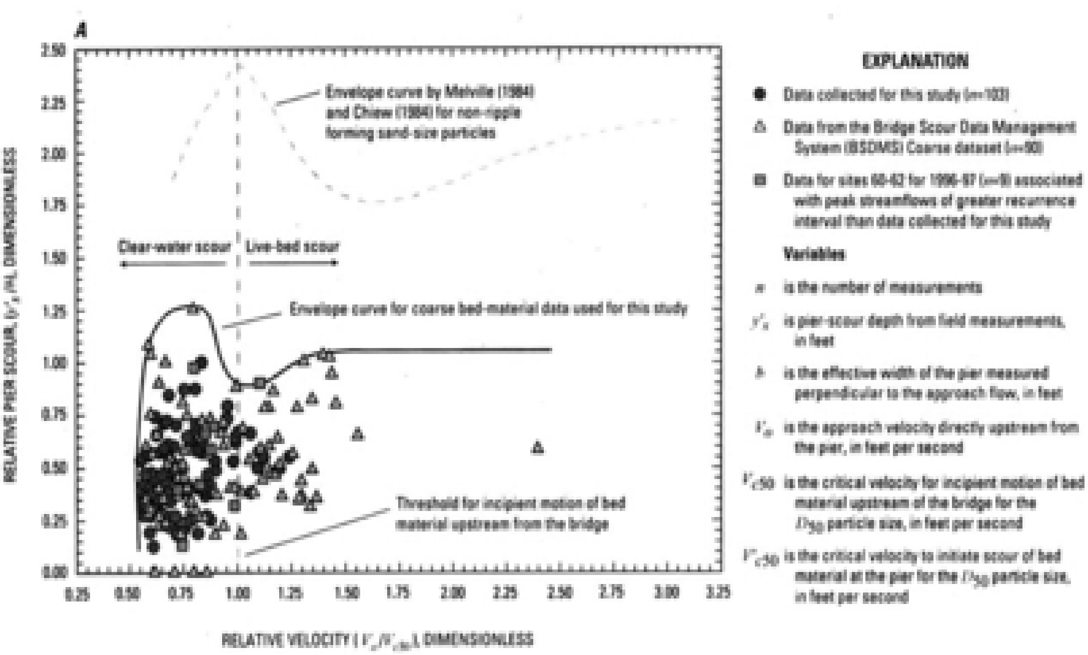

Fig.5 Comparison of Local Scour Depth in bridge piers with Velocity in Fine (dotted line) &Coarse (full line) soil.

Fig.6 Local Scour in Coarse Bed Materials showing-effect of size(d_{50}) and gradation (σ_g)

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Annexure-I-(a)

MAXIMUM SCOUR DEPTH (M) IN BRIDGE PIERS ON FINE SOIL COMPUTED BY DIFFERENT METHODS (ASSUMING LOW WATER BED PROFILE DEVELOPS TO LACEY'S REGIME PROFILE DURING FLOOD)											
Name of River Crossing (NH No.)	**General scoured depth below HFL (As per Regime theory)**	**Constriction scour depth below mean bed level**	**Total scour depth by Lacey (IRC method)**	**Local scour below bed and total scour below HFL (i.e., sum total of general scour, constriction scour and local scour)**							
				Melville & Coleman		**Richardson & Davis (HEC-18)**		**Breussers & Raudkivi (IAHR)**		**Kothyari, Garde & Ranga Raju**	
				Local	**Total**	**Local**	**Total**	**Local**	**Total**	**Local**	**Total**
Chambal (NH-3)	23.80	6.83	46.27	7.20	37.83 (22.3%)	6.23	36.86 (25.6%)	6.90	37.53 (23.4%)	13.18	43.81 (5.6%)
Saryu (NH-28)	10.20	1.10	26.04	2.88	14.18 (83.6%)	2.86	14.16 (84.0%)	2.40	13.7 (90.0%)	4.51	15.81 (64.6%)
Raidak-1 (NH-31C)	6.23	2.84	15.57	6.00	15.07 (3.2%)	4.26	13.33 (17.0%)	3.12	12.19 (28.8%)	6.12	15.19 (2.4%)
Raidak-II (NH-31C)	5.97	3.41	16.43	6.66	16.04 (2.4%)	4.75	14.13 (16.3%)	2.70	12.08 (36.0%)	6.29	15.67 (4.9%)
Sankosh (NH1.C)	5.86	0.15	13.70	6.96	12.97 (5.6%)	5.46	11.47 (19.4%)	3.50	9.51 (44.0%)	5.73	11.74 (16.7%)

Annexure-I-(b)

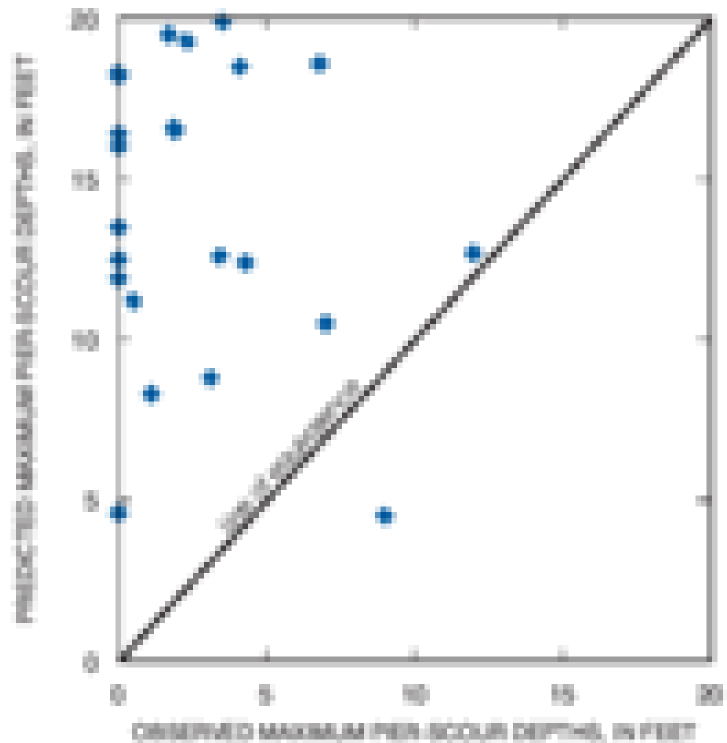
Name of River Crossing (NH No.)	MAXIMUM SCOUR DEPTH (M) IN BRIDGE PIERS ON FINE SOIL COMPUTED BY DIFFERENT METHODS (ASSUMING LOW WATER BED PROFILE REMAINS UNCHANGED DURING FLOOD)										
	General scoured depth below HFL (As per Regime theory)	Constriction scour depth below mean bed level	Total scour depth by Lacey (IRC method)	Local scour below bed and total scour below HFL (i.e., sum total of general scour, constriction scour and local scour)							
				Melville & Coleman		Richardson & Davis (HEC-18)		Breussers & Raudkivi (IAHR)		Kothyari, Garde & Ranga Raju	
				Local	Total	Local	Total	Local	Total	Local	Total
Chambal (NH-3)	17.92	6.83	46.27	7.20	31.95 (44.8%)	6.23	30.98 (49.5%)	6.90	31.65 (46.2%)	13.18	37.93 (22.0%)
Saryu (NH-28)	3.44	1.10	26.04	2.88	7.42 (250.9%)	2.86	7.40 (251.9%)	2.40	6.94 (275.2%)	4.51	9.05 (187.7%)
Raidak - 1 (NH-31C)	4.88	2.84	15.57	6.00	13.72 (13.4%)	4.26	11.98 (30.0%)	3.12	10.84 (43.6%)	6.12	13.84 (12.5%)
Raidak-II (NH-31C)	4.76	3.41	16.43	6.66	14.83 (10.8%)	4.75	12.93 (27.1%)	2.70	10.87 (51.1%)	6.29	14.46 (13.6%)
Sankosh (NH1-C)	4.69	0.15	13.71	6.96	11.80 (16.2%)	5.46	10.3 (33.1%)	3.50	8.34 (64.4%)	5.73	10.57 (29.3%)

Annexure-II

COMPARISON OF PREDICTED (BY HEC-18) & MEASURED SCOUR DEPTHS IN FINE BED MATERIALS (MAINE RIVER BRIDGES- USA)

Table 2. Predicted and observed maximum pier-scour depths in Maine River Basin during high flows

	Predicted (ft)	**Observed (ft)**
Kenduskeag River at Bangor	8.3	
Aroostook River at Ashland 1	8.8	3.1
Androscoggin River at Bethel 1	19.3	2.3
Penobscot River at Lincoln 1	11.9	0
Penobscot River at Lincoln 2	18.5	4.1
Penobscot River at Lincoln 6	16.6	1.9
Kennebec River at Gardiner 1	19.5	1.7
Kennebec River at Gardiner 2	18.6	6.8
Aroostook River at Ashland 2	16.5	1.9
Kennebec River at Gardiner 3	12.6	3.4
St. John River at Van Buren 1	12.0	4 41
St. John River at Van Buren 2	12.7	12.0
Austin Stream at Bingham 1	19.9	3.5
Austin Stream at Bingham 2	11.2	0.5
Penobscot River at Lincoln 3	18.3	0 18
River at Hiram	10.5	7.0



Annexure-III-(a)

COMPARISON OF LOCAL SCOUR DEPTHS IN PIERS ON COARSE SOIL (OBSERVED AND PREDICTED BY DIFFERENT METHODS)

NOTE: VALUES IN BRACKET INDICATE Y_S/R

Bridge Site	Observed Scour Depth (y_s' in m)	Predicated Scour Depth (y_s in m)					
		Lacey(R)	Blench	HEC-18	Melville & Coleman	IAHR	K-G-R
1	0.35 (0.15)	2.29 (1.00)	2.29 (1.00)	0.69 (0.30)	0.57 (0.25)	0.43 (0.19)	0.46 (0.20)
10	0.24 (0.25)	0.98 (1.00)	1.22 (1.24)	0.76 (0.77)	0.99 (1.01)	0.38 (0.39)	0.90 (0.92)
11	0.42 (0.42)	1.44 (1.00)	1.44 (1.00)	0.98 (0.68)	1.27 (0.88)	0.33 (0.23)	1.02 (0.71)
16	0.63 (0.12)	4.85 (1.00)	4.85 (1.00)	1.44 (0.29)	1.70 (0.35)	1.39 (0.28)	1.34 (0.27)
22	0.91 (0.25)	3.69 (1.00)	5.27 (1.43)	2.21 (0.60)	2.19 (0.59)	0.90 (0.21)	1.67 (0.45)
M & C	--	9.21 (1.00)	11.22 (1.22)	5.24 (0.57)	4.34 (0.47)	2.35 (0.25)	4.17 (0.45)

Annexure-III-(b)

COMPARISON OF LOCAL SCOUR DEPTHS IN PIERS ON COARSE SOIL BY DIFFERENT METHODS

Bridge Sites →	**1**	**10**	**11**	**16**	**22**	**M&C**
Observed Scour Depths (in m)	0.35	0.24	0.42	0.63	0.91	----
Average Scour ((in m)predicted by Different Math. Models	0.53	0.75	0.90	1.46	1.74	4.02
Lacey's Scour Depth (in m)	2.29	o.98	1.44	4.85	3.69	9.21
Average Scour predicted by different mathematical Models)/Observed Scour	1.51	3.12	2.14	2.31	1.91	----
Lacey's Scour/Observed Scour	6.54	4.08	3.42	7.69	4.05	-----
Lacey's Scour/ predicted Average Scour	4.32	1.30	2.37	3.32	2.12	2.29