LOCAL SCOUR IN BRIDGE PIERS ON COARSE BED MATERIAL - OBSERVED AND PREDICTED BY DIFFERENT METHODS

S.K.MAZUMDER

Individual Consultant

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

E-Mail: **somendrak64@gmail.com**

R.K.Dhiman, VSM,

Director,Border Roads Organisation

Email:d_himan12@yahoo.com

Abstract

IRC and other Indian codes recommend use of Lacey's regime formula for finding maximum depth of scour as 2R below high flood level or R below river bed level for fine bed materials (d_{50}<2mm), where R is Lacey's regime depth. Codes are silent about scour depth in piers on coarse bed materials (d_{50}>2mm) like gravels, cobbles, boulders etc. Scour in coarse bed material is generally less than that in fine bed materials due to armoring effect in well graded and non-uniform coarse sediments. Several mathematical models used for prediction of local scour depths have been discussed and limitations of empirical equation like Lacey are stated. Predicted local scour depths in six bridge piers founded on coarse bed materials have been obtained by both empirical and mathematical models and compared with scour depths observed by USGS in some of the streams in the Missisipi river basin in U.S.A. Scour depths predicted by mathematical models are conservative and closer to the observed ones in comparison with those obtained by Lacey's equations.. Based on an earlier study by the first author (Mazumder,2006) in fine bed materials and the present one, it is concluded that the local scour depths in both fine and coarse sediments should be estimated by use of mathematical models.

Key Words: bridge pier, coarse sediments, Lacey formula, local scour, mathematical model

1. INTRODUCTION

Determination of scour in bridge piers is an important consideration in the hydraulic analysis and design of highway bridges that cross streams, rivers, and other waterways. There are a large numbers of studies by a number of gifted workers on the subject who have developed a number of mathematical models for the prediction of scour around bridge piers. Scour depth should neither be under-predicted (for safety) nor over- predicted (for economy). It is established that local scour in coarse bed material is substantially less than that predicted by IRC method based on Lacey type theory (1930) which is applicable only for very fine alluvial bed material. Considerable economy can be achieved by computing local scour by using mathematical models developed recently. Most of the models developed over the years are, however, based on laboratory flume study since measurement of scour in field is a difficult task -especially during floods when scour is supposed to reach its maximum. Scour depth for piers in non-cohesive, non-uniform streambeds with a mixture of sand, gravel, cobbles, and boulders (coarse-bed streams) is generally less than that in finer-grained (fine sand and silt) streambeds under similar hydraulic conditions. The difference in scour depth is attributed to formation of an armor layer in coarse bed streams.

Numerous bridges, all over the world, have failed due to foundation failure of piers. One of the major causes of such foundation failure is due to scouring around pier during the passage of floods. In India, a large numbers of existing bridges rest on piers both in fine (<2mm) and coarse bed materials (>2mm). New bridges are going to be constructed in hilly and mountainous terrain where the river bed materials are coarse consisting of gravels (2-64mm),cobbles (64-256mm) and boulders (>256mm). All Indian codes (IRC:5-1998, IRC:SP:13-2004,IRC:78-2000, IS:6966-Pt.I-1989, MOR-1985) prescribe equations based on regime theory of Lacey (1930) for computation of scour in bridge piers for river bed consisting of fine materials only and are silent about scour in coarse bedded materials. Lacey's equation considers only two parameters, namely, discharge and mean size of bed materials (d_{50}). Actually, scour is governed by many other parameters, which have been duly considered in the recently developed mathematical models.

Mazumder and Kumar (2006) computed total scour depths in bridge piers (consisting of general scour, contraction scour and local scour) on fine bed materials using different mathematical models and compared them with those obtained by IRC method. It was noticed that in all the cases IRC method over-estimated the total scour depths to the extent varying from 5% to 275%.

It was, however, found that the local scour depths predicted by the different mathematical models did not differ significantly as compared to IRC method which over-predicted the scour depths in all the cases. It was not possible to confirm whether the mathematical models should be adopted for prediction of local scour in the absence of measured scour depths under identical flow and geometric conditions. However, it was revealed that IRC method predicted very high scour value in comparison with those predicted by the mathematical models developed by eminent researchers like .Mellvile and Coleman (2000), Richardson and Davis (1995), Breussers and Raudkivi (1991), Kothyari-Garde-RangaRaju (1992). All these models prescribe that the general scour, contraction scour and local scour depths should be computed separately and added up to get the total scour depth. Some of the models distinguish between clear water and live bed scour as discussed in following paragraphs. Dey (2005-06) also prescribed that total scour depth in bridge piers on boulder-bed rivers should be determined by adding up the general scour, contraction scour and local scour to be computed separately by use of mathematical models developed by him on the basis of laboratory flume study.

In this paper, authors have used some of the mathematical models and empirical formulae discussed under section-3 to predict local scour depths in bridge piers founded on coarse bed materials at different sites where observed local scour depths are available.

2. DEVELOPMENT OF LOCAL SCOUR AROUND BRIDGE PIERS

Local scour in bridge pier occurs due to obstruction by pier and pier foundation and the consequent changes in the flow field around the piers. Because of variation in velocity from top to bottom of a pier, the stagnation pressure head is the highest at top and lowest at the bottom of pier, thereby inducing a pressure gradient, since the potential head is highest at the top and lowest at the bottom of the pier. This causes a downward vertical flow impinging the bed. At the pier base, two horse-shoe vortices develop due to flow separation. It is primarily due to the horse shoe vortex formation, wake vortices and the downward flow impinging on the bed that cause local scour at the base of the pier as schematically shown in figure- 1.

It is observed that there is virtually no local scour around a pier till the approach velocity (V_0) is about 0.5 Vc_{50} where Vc_{50} is the critical velocity corresponding to mean sediment size d_{50} given by Shields (1936) equation

$V_{c50}/u_{*c} = 5.75 \log (5.53 y_0/d_{50})$ ….. (1)

here u_{*c} is given by the relation

$u_{*c} = [\theta_c g d_{50}(S-1)]^{0.5}$ …… (2)

$\theta_c = \tau_0/[\rho g d_{50}(S-1)]$ …… (3)

here u_{*c} is critical shear velocity $=\sqrt{(\tau_0/\rho)}$, τ_0 is bed shear stress, ρ is density of water, θ_c is non

dimensional value of Shields function (θ_c = 0.056 for coarse sediments of size d_{50} greater than 6mm (Garde,2006), ρ is density of fluid, y_0 is flow depth, S is specific gravity of coarse sediments (S=2.65).

Fig.2 illustrates the variation of measured non-dimensional local scour depths (y_s'/b) with non-dimensional approach velocity (V_0/V_{c50}) for fine bed material (dotted line) and coarse bed material (full line). It may be noted that these curves are the envelop covering maximum scour depths at different flow velocities measured at different bridge sites as noted under explanation. The curves show that in case of fine bed materials, the peak value of maximum local scour depths is about 2.4b and it occurs at threshold condition of bed motion (V_0/V_{c50} =1). In coarse bed materials, however, the peak value of scour depth is found to be about 1.3b and it occurs at clear water condition when V_0/V_{c50} = 0.75. Both the curves show that the scour first reduces after attaining the peak values and again increases with further rise in approach velocity and then stabilizes at an equilibrium value (y_{se}) less than the peak values with further increase in V_0 - both under live bed conditions. Whereas the reduction in peak is about 10% in fine soil, it is about 18% in coarse soil. The reduction in peak values of scour under live bed condition is due to the fact that once the river bed starts moving (for $V_0 > V_{c50}$) , the scour hole starts receiving sediments from upstream resulting in partial filling of the deepest scour hole formed near threshold condition. It may be also noted, that whereas the equilibrium value of scour y_{se}/b occurs at V_0/V_{c50} = 1.5, the same occurs at V_0/V_{c50} = 4 since the process of scour to attain equilibrium state is slow in fine soil compared to coarse one.

3. PARAMETERS GOVERNING LOCAL SCOUR IN BRIDGE PIERS

From non-dimensional analysis of the different parameters governing scour around a pier, it can be proved that the local scour depth below river bed (y_s) can be expressed as

$y_s/b = f\,[V_0/V_c,\ y_0/b,\ b/d_{50},\ \sigma_g,\ Sh, \alpha,\ G,\ t/t_e,\ V/\sqrt{(gb)}\,]$ `……. (4)

where, V_0 is mean approach flow velocity, V_c is the critical velocity at threshold condition of sediment motion corresponding to mean sediment size (d_{50}) - also known as incipient flow velocity, y_0 is approach flow depth, b is the effective thickness of pier, σ_g is the geometric non-uniformity coefficient of sediments expressed as $(d_{84}/d_{16})^{0.5}$, d_{16}, d_{50} and d_{84} represent sediment

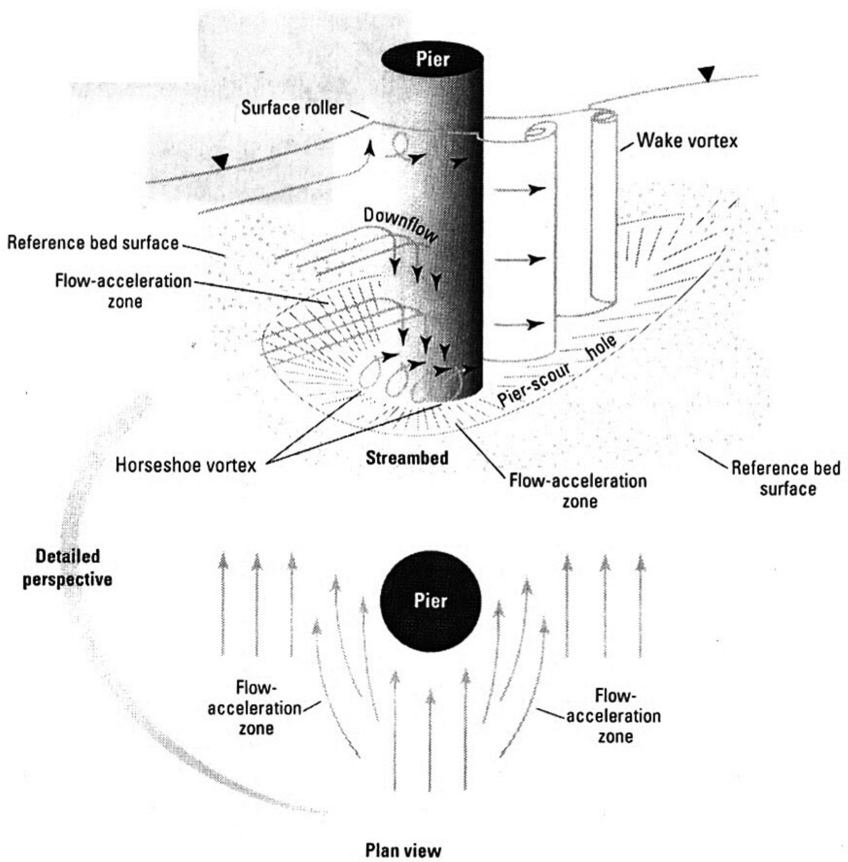

Fig.1 Flow field around a bridge pier and principal hydraulic features

(modified from Melville, 1995).

sizes corresponding to 16%,50% and 84% fineness, Sh is the effect due to pier nose shape, α gives the alignment of pier with respect to flow (also known as flow obliquity with respect to pier axis), G represents the non-uniformity of approach flow and shape of cross-section of the approach channel, t/t_e is a non- dimensional time parameter representing the actual time of scour (t) with respect to the equilibrium time (te) required to attain equilibrium scour depth (y_{se}), and the last parameter $(V/\sqrt{(gb)})$ gives Froudes number of approach flow based on pier size(b).

Thus the local scour around a pier is determined by a large number of parameters pertaining to flow intensity (V_0/V_c), shallowness of incoming flow (y_0/b) coarseness of sediments (b/d_{50}) and other parameters mentioned above.,

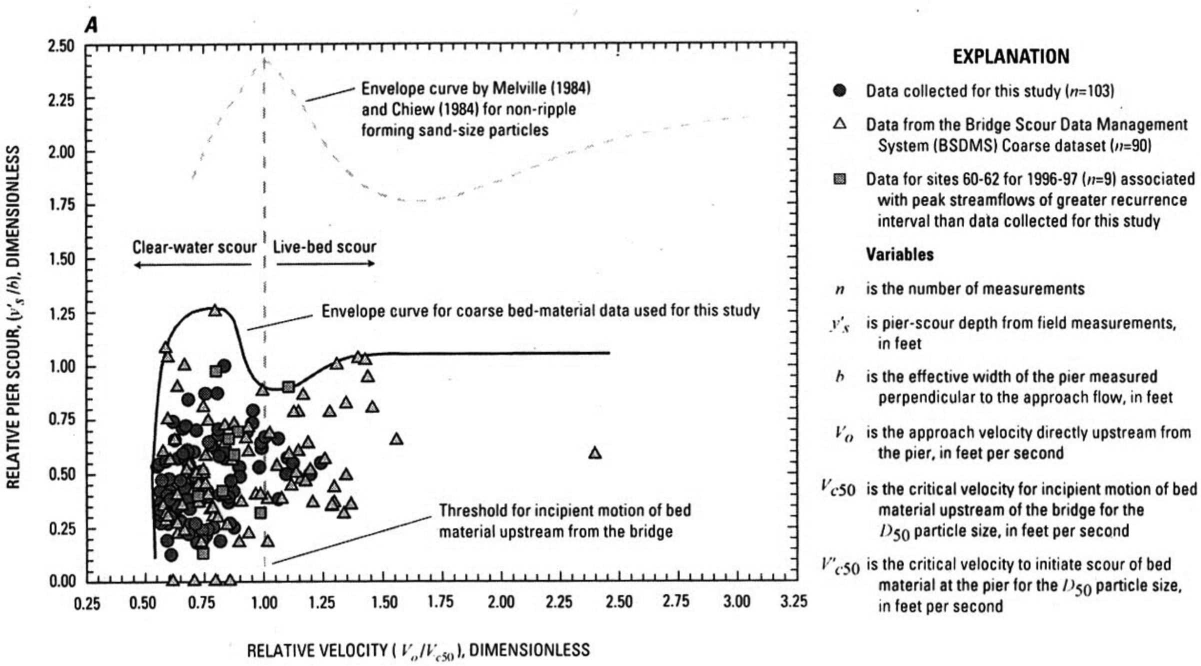

Fig.2 Comparison of Pier scour (y_s/b) in coarse (solid line) and fine (dotted) bed material with relative velocity (V_0/V_c) (Taken from Scientific Investigations Report 2011–5107,USGS)

3.1 Mathematical Models for Prediction of Scour in Bridge Piers Founded on Non-Cohesive Fine and Coarse Bed Materials

There is large number of research study on local scour around bridge piers all over the world and a large number of mathematical models have been evolved for estimating local scour around piers, principally on the basis of laboratory model study. Some of the most popular mathematical models which have been used to predict local scour depths in a few bridges (Table-1) are briefly discussed in the following paragraphs.

3.1.1 HEC-18 Model (Richardson and Davis)

Richardson and Davis (1995) recommend use of the following mathematical equation for both clear water and live bed scour depth, y_s (measured below bed) , in terms of approach flow depth, y_0 as

$$y_s/y_0 = 2K_1.\ K_2\ .\ K_3\ .\ K_4.\ (b/y_0)^{0.65}\ .\ Fr^{\ 0.43} \qquad ..... \qquad (5)$$

where,K_1 is correction factor for pier nose shape, K_2 is correction factor for flow obliquity(α)., K_3 is correction factor for bed forms i.e. ripple and dune bed etc., K_4 is the correction factor due to armoring of bed in non-uniform sediments, F_r is the Froudes number of approaching flow upstream of pier given by the relation

$$F_r = V/\ \sqrt{(gy_0)} \qquad \cdots\cdots \qquad (6)$$

Values of K_1, K_2, K_3, K_4 are given in HEC-18 (Richardson and Davis – 1990) as well as in the book “Hydraulic Design Hand book” by Mays, (1999) in Chapter 15. Local scour depths for the few bridges computed by HEC-18 model are given in Table -2.

3.1.2 Melville and Coleman Model

Melville and Coleman (2000) computed local scour depth (y_s) below river bed for both clear water and live bed by the following equation

$$y_s = K_{yb}.\ K_1\ K_d\ .\ K_s\ .\ K_{al}\ .\ K_g\ .\ K_t \qquad \ldots\ldots. \quad (7)$$

All other parameters except K_{yb} are non-dimensional and K_{yb} is having the same dimension as that of y_s i.e. scour depth. K_{yb} is depth-size or shallowness factor and is given by the relation

$K_{yb} = 2.4\ b$ when $b/y_0 < 0.7$,

$K_{yb} = 4.5y_0$ when $b/y_0 > 5$ and

$K_{yb} = 2\ \sqrt{(y_0b)}$ when $0.7 < b/y_0 <5$

K_1 is flow intensity factor including sediment gradation and armoring effect, 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. For evaluation of the different K-values, the various mathematical equations and the design curves are given in the book "Bridge Scour" by Melville and Coleman (2000). The local scour depths computed by Melville and Coleman method for few bridges are given inTable-2.

3.1.3 IAHR Model (Breussers & Raudkivi)

Breussers and Raudkivi (1991) have given different equations for live bed scour and clear water scour up to threshold condition.

For clear water condition, local scour depth (y_s) is given by

$$y_{s//}b = 2.3\ K_\sigma\ K(b/d_{50})\ K_d\ Ks\ K_\alpha \quad \text{when } V_0 < V_c \qquad \ldots\ldots \quad (8)$$

and for live bed condition, local scour depth is given by

$$y_s/b = X.\ K(b/d_{50}).\ K_d.\ K_s.\ K_\alpha \quad \text{when } V_0 > V_c \qquad \ldots\ldots..\ (9)$$

Here y_s is the equilibrium scour depth measured below river bed, K_σ is a coefficient for gradation of non-uniform sediment (σ_g), $K(b/d_{50})$ is a coefficient owing to size of sediments with respect to pier size 'b', K_d is a factor due to depth of flow or flow shallowness (y_0/b), K_s is shape factor for pier nose, K_α is the pier alignment factor due to skewness of flow(α). Maximum value of X is 2.3 when V > 4Vc. When $V_c<V_0<4V_c$, 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 ($\sigma_g > 1.3$). Values of the different coefficients are available from design curves given in the book "Scouring" by Breussers and Raudikivi (1991). Local scour depth computed by IAHR method for few bridges are given in Table -2.

3.1.4 Kothyari – Garde - Rangaraju (K-G-R) Model

Based on the analysis of extensive laboratory data collected for both uniform, non-uniform and stratified sediments, steady and unsteady flows, the following mathematical equations have been proposed by Kothyari, Garde and Ranga Raju (1992) for estimation of local scour under clear water and live bed conditions when the flow is parallel to pier axis without any flow obliquity.

For clear water scour depth (y_s) measured below bed :

$$y_s/d_{50} = 0.66(b/d_{50})^{0.75} \{(y_0/d_{50})^{0.16}\} \{(V_c^2-V_0^{\ 2}) /g(S-1)d_{50}\} \ r^{-0.30} \qquad \ldots\ldots \quad (10)$$

For live or mobile bed scour :

$$y_s/d_{50} = 0.88\ (b/d_{50})^{0.67} (y_0/d_{50})^{0.4}\ r^{-0.3} \qquad \ldots\ldots. \quad (11)$$

where r = (B-b)/ B, B is the centre to centre spacing of piers, b is the pier thickness, V is the actual mean velocity of flow under the bridge, V_c is the mean critical velocity of flow for the given bed material(d_{50}) at threshold condition . Local scour depth found from equations 10 and 11 for few bridges are given in table-2.

4. EMPIRICAL METHODS OF SCOUR PREDICTION AND THEIR LIMITATIONS

Based on regime concept and field data collected in India, Kennedy (1895), Lacey (1930), Inglis(1949), Lane(1955), Blench (1957), Chitale (1966) developed several empirical equations for the purpose of design of stable chnannel/canal with fine/very fine incoherent alluvial bed materials. These equations for regime depth (R) and regime width (W) are based on two parameters only i.e. discharge (Q) and mean size of sediments (d_{50}). Multiplying the regime depth (R) with factors (K), the regime concept has been further extended to predict maximum scour depth below HFL/FSL in river/canal for design of hydraulic structures in India and some neighboring countries. Different K-values as found from field observations in very fine soil (CBIP-1989) commonly used for design purpose are given in table-1.

Table- 1: K-Values Adopted for Finding Maximum Scour Depth (KR) Below HFL/FSL

Type of Channel/Structures	K- Values
Greatly Constricted Section	1.00

Straight Channel	1.27
Moderate Bend	1.50
Severe Bend	1.75
Right Angled Bend	2.00
Alongside Cliffs & Walls	2.25
At nose of bridge pier	2.00
At u/s head of guide bundh	2.75
At the shank of guide bundh	1.5

4.1 Lacey's Metod Adopted by IRC

Based on his observations in stable canals with fine bed and bank materials in Punjab, Lacey proposed a number of equations for stable canal design. Lacey's equations for regime width (W) and regime depth(R) in meter are:

$$W = 4.8\,(Q)^{0.5} \quad \ldots\ldots. \quad (12)$$

$$R = 0.475\,(Q/f)^{1/3} \quad \ldots\ldots. \quad (13)$$

where Q is regime flow in m^3/s and f is silt factor given by the relation

$$f = 1.76\,(d_{50})^{1/2} \quad \ldots\ldots \quad (14)$$

Based on observed maximum depths of scour in 17 railway bridge piers founded on very fine alluvium (d_{50}-varying from 0.17 mm to 0.37mm) in major north Indian rivers (CWPRS,1944), Railway Board , Govt. of India, recommended 2R as maximum scour depth below HFL for design purpose, using Lacey's regime depth R given by equation 13.

In case a channel flows in regime width (W), using equations (12) and (13) the regime depth (R) can also be expressed as

$$R = 1.35\,(q^2/f)^{1/3} \quad \ldots\ldots\ldots(15)$$

where q = (Q/W) i.e. discharge intensity in m^2/s, IRC has recommended Lacey's equations for R as given by equation (15) for computing scour depth. IRC Prescribes 2R as maximum scour depth at pier nose measured from HFL or in other words R as maximum local scour depth measured below river bed. Lacey's scour depth below river bed in some of the bridges in coarse bed material is given in table-2.

4.2 Blench's Method

Similar to Lacey's expressions, Blench (1969) proposed the following empirical equations for prediction of regime depth (R in meter) for stable channels in fine and coarse bed material as

$$R = 1.20(q^{2/3}/d_{50}^{1/6}) \quad \text{for } 0.06\text{mm} < d_{50} < 2\text{mm and} \qquad \ldots\ldots \quad (16)$$

$$R = 1.23\ (q^{2/3}/d_{50}^{1/12}) \quad \text{for } d_{50} > 2\text{mm} \qquad \ldots\ldots \quad (17)$$

Blench's scour depths (R) below river bed in some bridges in coarse materials computed by equation. (17) are given in table-2.

4.3 Dhiman's Formula

Based on observed scour data collected by Border Roads Organization (General Reserve Engineers Force) ,Govt. of India, in some exiting bridges on boulder- bed rivers without any constriction, Dhiman (2004) proposed the following empirical formula for estimating maximum scour depth:

$$D_{max} = KV_{max} \qquad \ldots. \quad (18)$$

where D_{max} is maximum scour depth below lowest bed level and V_{max} is maximum velocity; K=1.2 for circular pier and 1,3 for rectangular pier

4.4 Limitations of Empirical Methods

Some of the limitations of empirical methods adopted by IRC/IS/RDSO codes for finding local scour depth in bridge piers are stated below.

- They do not distinguish between general, contraction and local scour.
- Total scour around piers are measured below HFL in Lacey/Blench equations
- Local scour depth around a pier is taken arbitrarily equal to 2R below HFL or otherwise R below bed surface in both Lacey's and Blench's. equations. This is irrational since local scour and regime depths are separate things governed by separate parameters.

- Lacey's R-value is applicable for steady uniform and continuous flow in canals with uniform fine incoherent alluvial soils in both bed and bank- unlike rivers flowing in fine and coarse bed with non-uniform sediments with varying flows
- Many of the important parameters governing local scour e.g. velocity of incoming flow with respect to critical velocity at initiation of sediment motion, flow shallowness, flow obliquity, pier size, pier nose geometry, incoming debris, size, non-uniformity and size of sediments, bed forms etc. are not considered. In Lacey, Blench and Dhiman formulae. Maximum scour depth is expressed in terms of only two parameters
- Actual time of scouring(t) with respect to equilibrium time (t_e) to attain equilibrium scour depth is not considered
- Scouring processes under live bed and clear water conditions are totally ignored .It is well established universally that the local scour reaches its maximum value at threshold/critical/incipient condition of bed motion when $Q= Q_c$ or $V=V_c$. Scour reduces thereafter when $Q> Q_c$ or $V>V_c$. It attains an equilibrium state and remains constant at after V>4Vc (for clear water condition) and $V>1.5V_c$ (for live bed condition) as shown in Fig.2. In all empirical methods , however, scour is independent of the critical conditions and it goes on increasing with increasing values of Q or V which is far from truth.

5. LOCAL SCOUR IN PIERS FOUNDED ON COARSE BED MATERIAL IN MISSOURI BASIN

As explained in section-2 and illustrated in Fig.2, local scour depth for piers in stream bed with non-cohesive, non-uniform coarse materials - a mixture of sand, gravel, cobbles, and boulders- is less than the scour depth in fine-grained (mostly fine sand and silt) streambeds under similar hydraulic conditions. The difference in scour depth is attributed to formation of an armor layer. Armoring of bed takes place in coarse and non-uniform bed material when the bigger particles in the scour hole are found to shelter the fine ones reducing scour depths.

USGS in its Scientific Investigations Report 2011–5107(Holnbeck,2011) measured local maximum scour depths in coarse bed streams at 103 bridge sites in Montana, USA with the objective of evaluation of K_4-values (representing size and gradation effect of sediments on local scour) in HEC-18 model. Fig.3 illustrates a typical cross-section of a river showing the reference bed level and local scour depth. Fig.4 shows the plot of observed scour depths (y_s'/b) against σ_g [$=\sqrt{(d_{84}/d_{16})}$] where y_s' is the observed scour depth. Envelop curves covering the maximum observed scour depths were plotted for different sizes (d_{50}) of sediments indicating the peak values (under clear water condition).It is apparent that the peak scour reduces with both size (coarseness) and gradation (σ_g) of non-uniform sediments.

5.1 Flow parameters, Pier Geometry, Sediment Sizes.

Particulars of flow and geometric data of piers and sediments at five bridge sites are given in table-1. There was no contraction and flow obliquity in all these bridges and all of them were founded on coarse bed material of different sizes (d_{50}) varying from 17.1mm to 102 mm, non-uniformity (σ_g) varying from 1.95 to 4.14) as given in the table. While bridge sites 1,10,11,16 and 22 were in the Missouri river basin, the particulars given under M&C refer to an example worked out by Mellvile and Coleman (2000) for a bridge pier in a river in New Zealand

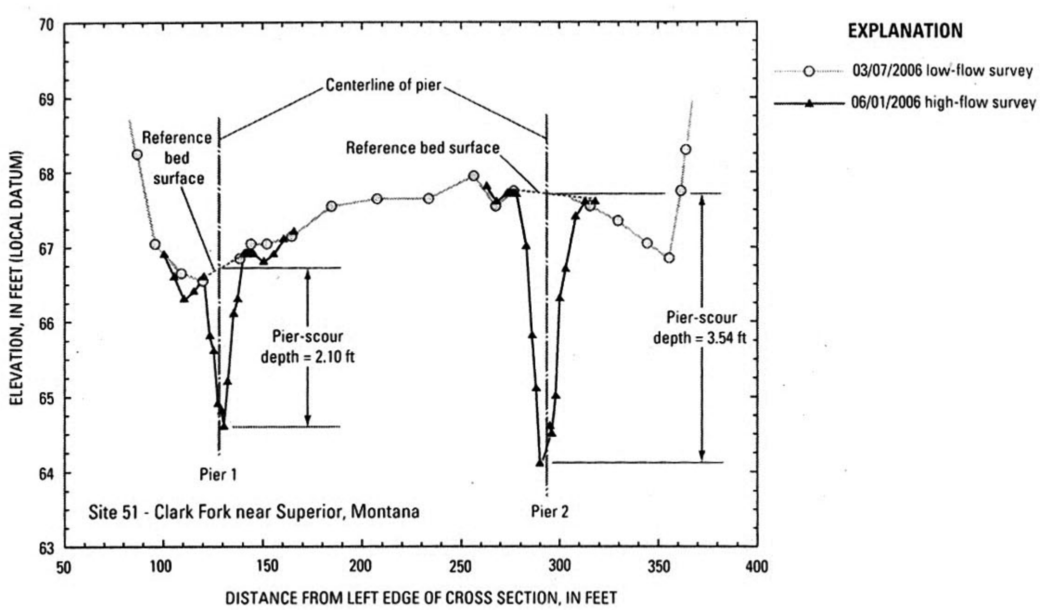

Fig.3 Surveyed cross section showing pier-scour holes and reference bed surface used to determine local scour depth in piers

(taken from Scientific Investigations Report 2011–5107, USGS)

Table-2 gives the observed maximum local scour depths at first five bridge sites in Missouri basin. No observed scour depth was, however, available for the last bridge site. Maximum local scour depths predicted by different methods in table-2 correspond to clear water conditions except the last bridge where the predicted local scour is under live bed conditions. All the local scour depths given in table -2 are below river bed level. The values indicated in bracket under scour depths give K-values i.e. the ratio of scour depths and Lacey's scour depth (R) below bed.

5.2 Observed and Predicted Scour Depths in Bridge Piers

Scour depths by empirical methods (e.g. Lacey and Blench) far exceed the observed values of scour in all cases. Columns 3 to 8 in table-2 give the predicted scour depths, including

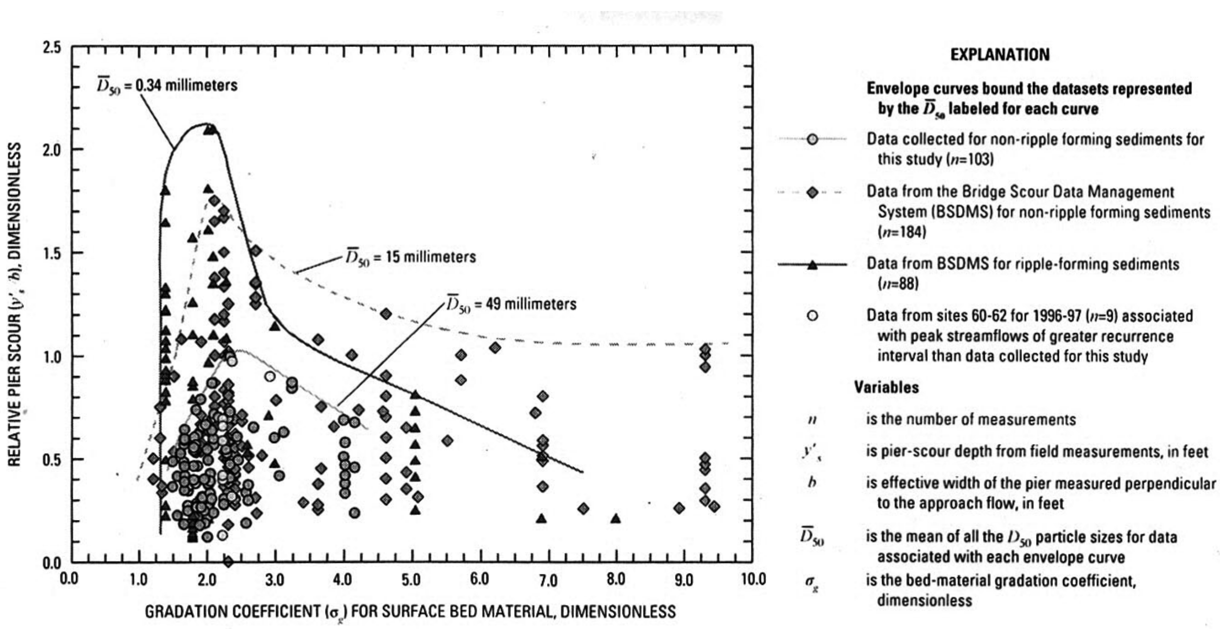

Fig.4 Relation between relative pier scour and gradation coefficient for pier-scour showing the effect of size and gradation.(taken from Scientific Investigations Report 2011–5107, USGS)

TABLE – 1

FLOW AND GEOMETRIC DATA OF BRIDGE PIERS IN MISSOURI RIVER BASIN, USA

Bridge Site	Flow Depth (y_0 in m)	Flow Velocity (V_0 in m/s)	Pier Geometry			Sieve size of Bed Material in mm				
			Width (b in m)	Nose Shape	Obliquity of flow (α)	d_{16}	d_{50}	d_{84}	d_{95}	$\sigma_g = \sqrt{(d_{84}/d_{16})}$

1	2.29	2.29	0.61	Sharp	0^o	40.5	102	176	269	2.09
10	0.98	1.72	0.854	sharp	0^o	29.9	79.8	149	253	2.23
11	1.44	1.22	0.915	Round	0^o	2.58	17.1	44.1	82.9	4.14
16	4.85	1.91	1.0	Sharp	0^o	5.91	22.3	57	89.6	3.11
22	2.92	4.5	1.83	Sharp	0^o	7.36	22.7	44	59.3	2.44
M&C	9.21	4.34	1.81	Round	0^o	7	20	44.1	100	2.5

the empirical methods of Lacey and Blench. K- values are given in brackets below the observed and predicted scour depths. Lacey's and Blench scour depths are found to be higher than the predicted depths of scour by mathematical models in all the cases except at bridge site-10 where only Melville and Coleman method gives almost same value of scour depth as Lacey's one. Except this case, all the predicted scour depths are found to be closer to the observed scour depths.

TABLE – 2

COMPARISON OF LOCAL SCOUR DEPTHS

(OBSERVED AND PREDICTED BY DIFFERENT METHODS)

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)

Note: 1.The values given in bracket are ratio of scour depth and Lacey's scour depth (R) below river bed.

2.M & C stand for Melville & Coleman – No measured scour depth is available

3.K-G-R stand for Kothyari – Garde – Ranga Raju method.

5.3 Comparison of Average Predicted Scour Depths by Mathematical models and Lacey's Values with Observed Scour in Piers at Different Bridge Sites

First and second rows of Table-3 summarize the observed scour depths and average of scour depths predicted by different mathematical models at the different bridge sites (obtained from table-2). Ratios of the average scour depths (by mathematical models) and observed scour depths and Lacey's scour depths and observed scour depths are given in third and fourth rows of the table respectively. The last row gives the ratio between Lacey's scour depth and the average scour depth obtained by mathematical models.

It is apparent from table-3 that the average scour depths computed by different mathematical models are more (because all the parameters are taken from upper boundary of measured values) than the observed scour depths but much less than Lacey's scour depths as adopted in IRC codes due to several reasons already mentioned under section 4.3. It is advisable, therefore, to compute local scour depths in bridge piers on coarse material using mathematical models all of which give conservative values compared to observed scour depths and are much economic compared to Lacey's scour depths adopted in IRC guidelines on bridge scour.

Table-3 Comparison of Scour Depths 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) (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/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/Average Scour	4.32	1.30	2.37	3.32	2.12	2.29

6. SUMMARY AND CONCLUSIONS

Determination of scour around bridge piers is important in deciding the foundation level of the 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 bed level where R is computed by Lacey's theory. Local scour depth around pier is not governed by R but many other parameters related to pier size and geometry, flow conditions and sediment characteristics. Based on these parameters, several mathematical models have been developed in India and abroad for predicting maximum local scour depth to be measured below river bed level. In an earlier paper, Mazumder and Kumar(2006) computed total scour depths in some bridge piers founded on fine cohesion less bed materials and compared them with those found by IRC method based on Lacey's theory. It was found that in all the cases, IRC method overestimated the total scour depth when compared with those found by the several mathematical models and the error ranged between 5% to 275%. In this paper, authors computed local scour depths around bridge piers founded on coarse bed materials 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 in the Missouri basin are compared with local scour depths predicted by empirical equations as well as different mathematical models under identical flow, sediment and pier characteristics. Scour depths predicted by mathematical models, although higher than the observed ones, are closer to the observed values in comparison to scour depths obtained by Lacey's and Blench's equations. In the case of bridge site (M&C) in New Zealand also, the scour depth obtained by Lacey's method is more than two times the scour depth predicted by different mathematical models.

Based on the previous study on scour in fine bed materials and the present one in coarse bed material, it is concluded that the IRC method of scour computations based on Lacey's equation should be replaced by mathematical models developed by eminent research workers from India and abroad over the years.

REFERENCES

Blench,T.(1957) "Regime Behavior of Canals and Rivers" Butterworth Scientific Publications, London.

Blench,T.(1969),"Mobile Bed Fluviology, University of Alberta Press, Edmonton,Canada

Breussers, HNC and Randviki, A.J. (1991) "Scouring" , Chapter-5 "Scour at Bridge Piers" A.A. Balkema Pub., IAHR Hydraulic Structures Design Manual

CBIP(1989), "River Bhaviour, Management and Training, Vol.I",Central Board of Irrigation and Power, Malcha Marg, New Delhi.(p

Chew, Y.M.(1984), "Local Scour at Bridge Piers",Report No.355, School of Engg., The Univ. of Auckland, Newzealand.

Chitale,S.V (1966)."Design of Stable Channels," Q-20,R-17, Proc. 6th Congress of ICID, New Delhi

CWPRS(1944),"Annual Report(Tech)",Central Water & Power Research Station, , Pune.

Dey, S. (2005-06), Principal Investigator of the Research Project "Determination of Scour Depth(for General Bed, Within Channel Contraction and at Bridge Piers) in Boulder- Bed Rivers Under High Stream Velocities (B-33)"- Sponsored by The Min. of Shipping, Road Transport and

Highways, Govt. of India, Highway Research Record No.33, (2005-06), IRC Highway Research Board, Indian Roads Congress.

Dhiman,R.K.(2004,), "Scour in Bouldery Bed-Proposed Formula" paper no 508 Pub. in Journal of The Indian Rods Congress

Holnbeck,2011, " Investigation of Pier Scour in Coarse-Bed Streams in Montana, 2001 through 2007"- Scientific Investigations Report 2011–5107, by U.S. Department of the Interior , U.S. Geological Survey ,U.S.A.

Garde, R.J.(2006) "River Morphology", New Age International(P) Ltd. Ansari Road, Daryaganj, New Delhi

Inglis,C.C.(1949),"The behavior and control of Rivers and Canals", research Pub. No.13, Central Water and Power Research Station, Khadakwasla, Pune.

IRC:5(1998), "Standard Specifications and Code of Practice for Road Bridges-Section-I", Indian Roads Congress, Jamnagar House, Shajahan Road, New Delhi-110 011

IRC:78(2000), "Standard Specifications and Code of Practice for Road Bridges, Section-VII" Indian Roads Congress, Jamnagar House, Shajahan Road, New Delhi-110 011

IRC:SP:13(2004),"Guidelines for the Design of Small Bridges and Culverts"Indian Roads Congress, Jamnagar House, Shajahan Road, New Delhi-110 011

IS:6966:(1989), "Guidelines for Hydraulic Design of Barrages and Weirs, Part-I", Bureau of Indian Standards, Manak Bhawan, Bahadur Shah Zafar Road, New Delhi-110 002

Kennedy, R.G.(1895), "Prevention of Silting in Irrigation Canals", Proc., Inst. Of Civil Engineers, London, Vol.119

Kothyari, U.C., Garde, R.J. and Ranga Raju, K.G. (1992a) "Temporal Variation of Scour Around Circular Bridge Piers", JHE, A.S.C.E., 118(8), PP 1091-1106.

Lacey, G.(1929) "Stable Channels in Alluvium" Paper 4736, Proc. of Institution of Civil Engineers, Vol. 229, William Clowes & Sons Ltd., London, U.K. P. 259-292.

Lane,E.W.(1955) “stable Channels in Alluvium” Trans. A.S.C.E, Vol.120

Mazumder, S.K. and Kumar,Y.K.(2006) “Estimation of Scour in Bridge Piers on Alluvial Non-Cohesive Soil by different methods”, IRC Highway Research Bulletin. Oct.,2006 , presented in the 67 th IRC Congress at Panchkula, Haryana, during 17-21 Nov.2006.

Melville, B.W.(1984)”Live Bed Scour at Bridge Sites”, J. of Hyd. Engg. ASCE,110(9), p.1234-1247

Melville, B.W. and Coleman, S.E.(2000) “Bridge Scour”, Water Resources Publications, LLC, Vol.I and II

MOR(1985),”Code of Practice for the Design of the Design of Substructures and Foundation of Bridges-Revised”, Ministry Of Railways, Govt. of India, Railway Board, New Delhi

Richardson, E.V. and Davis, S.R. (1995), “Evaluating Scour at Bridges”, Report No. FHWAIP-90-017, Hydraulic Engineering Circular No. 18 (HEC-18), Third Edition, Office ofTechnology Applications, HTA-22, Federal Highway Administration, U.S. Department of Transportation, Washington D.C., U.S.A.

Richardson and Mays (1999)“Hydraulic Design Handbook” Mc Graw-Hill Company,Chapter-15

Shields,A.(1936)”Anwendung derth Ahnlichkeitsmmechanik undTurbulenzforschung auf dieGeschiebebe wegung Mitteilungen der Pruesspsichen Versuchsanstaltfur Wasserbau und Schiffbau, Berlin, No.26