SOME HYDROLOGIC AND HYDRAULIC ASPECTS OF PLANNING AND DESIGN OF ROAD BRIDGES

Former AICTE Em. Professor
Delhi College of Engineering/
Delhi Technology University
Somendrak64@gmail.com

Born in 1938, Prof. S.K. Mazumder, a Ph.D. in Civil Engg.(IIT,KGP) has 57 years of teaching, research & consultancy experience in hydraulic and water resources engineering. Further details of Prof.Mazumder is available in his website: www.profskmazumder.com

Summary

Indepth knowledge in hydraulics and hydrology is needed in planning and design of a bridge and its foundation. Several data e.g. topography, stream flow, rainfall , soil and sub-soil have to be collected and analysed . It is essential to conduct morphologic study e.g. plan form, bed form, meandering processes, river behavior etc. for selection of site and safety of bridge. Computational procedure for design flood, HFL, waterway requirement in different valley settings, afflux etc. have been explained. Existing method of computing scour under bridge piers and abutments has been examined. Limitations of IRC method of scour computation based on Lacey's theory and need for employing mathematical models for scour computation have been outlined.

Key Words: River morphology, design flood, waterway, afflux, scour depth

1.INTRODUCTION

Large numbers of bridges are being constructed all over India by the railways and roads authorities for better and faster communication and connectivity to the different parts of the country. Some of the roads and road bridges are new; but a large numbers of existing bridges are being widened from 2- lanes to 4-lanes. For safe design of a bridge, knowledge of structural and foundation engineering is essential. Hydrologic and hydraulic aspects of planning and design of a bridge is equally important in deciding its location, waterway, afflux, scour, hydraulic forces, river training measures etc. [1]. Computation of waterway under the bridge has to be made very scientifically for safety as well as economy. Underestimation of waterway and scour may result in failure of a bridge, loss of properties and outflanking of bridge. Due to inadequate waterway provided under Bagmati bridge on NH-57 there is severe meandering of river Bagmati upstream and downstream resulting in damage to the road , the village and the agricultural lands as shown in Fig.1. Overestimation of waterway, on the other hand, will not only increase the cost of the bridge, it will also provide an opportunity to the river to play in its meandering belt under the bridge causing non-uniformity of flow distribution which may result in high scour under some of the bridge spans and silting in some others.

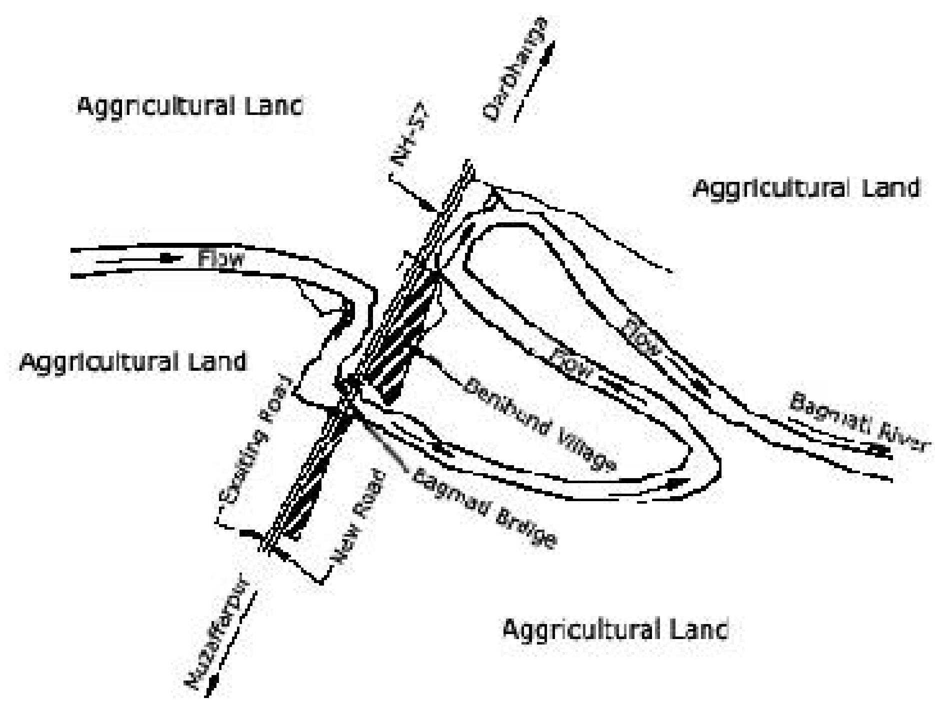

Fig.1 Meandering of River Bagmati U/S & D/S of Bagmati Bridge on NH-57

Most of the rivers, especially those in the north and north-east of India [2] pass through a varieties of terrains e.g. hilly and mountainous, sub-hilly and trough, braided and meandering zones with wide flood plains, deltaic and tidal reaches etc. Fixing waterway for a bridge under different terrains requires an intimate knowledge of river morphology, river-mechanics and alluvial stream processes [3], hydrology [4], hydraulics [5] etc. Any arbitrary decision regarding waterway under a bridge without considering its past history and behavior of the river in the near and far field may create unforeseen problems in future during the life span of the bridge. [6,7]. Costly river training measures may be necessary to prevent outflanking and damage to bridge and adjoining structures.

Primary objective of writing this paper is to focus on some of the important hydrologic and hydraulic aspects of planning and design of a bridge and its foundation.

2.0 INVESTIGATIONS/DATA COLLECTION

A number of routine investigations are to be carried out for the safe design of a bridge. These are briefly described below.

2.1 Topographic Data

Topographic sheets are used for determining the catchment area , terrain slope, river course and its tortuisity, land use, soil and cover conditions etc. When they are not readily available due to classified nature of certain catchments (restricted areas), satellite imageries obtained from Google Earth can be used. Use of digital terrain maps by GPS/GIS are very useful to obtain topographic information and in visualizing terrain condition and the river behavior.

2.2 Hydrologic Data:

Hydrologic investigations e.g. rainfall, stream flow, flood history, dominant flow, stream forms and their tributaries, sediment characteristics, debris flow etc. are vitally needed for determining location, waterway, scouring etc. and to avoid future problems of failure and excessive maintenance cost

2.2.1 Peak Flood and High Flood Level (HFL) Data

Peak flood discharge and corresponding flood levels are necessary for finding design flood, design HFL, waterway and the deck level of a bridge. In the case of major bridges on large rivers where gauging (stage-discharge) data are readily available, design peak flood for a return period of 100 years is computed by Gumbel, Log Pearson type-III method or similar other methods of frequency analysis. At least 15 to 20 consecutive years of annual peaks and the corresponding high flood levels are required.

2.2.2 Rainfall data

Where flood data is not readily available, rainfall data in the catchment is of vital importance to determine the design flood. Depending upon the return period of peak flood, maximum probable rainfall of 100 year return period is found from frequency analysis of rainfall data. Since continuous recording type rain gauges are now installed in many parts of our country, it is desirable to use such rainfall records of different storm durations for estimation of design peak flood

2.3 Stream Data

Stream survey data e.g. contour plan, L-section, cross-sections, HFL etc. are vitally required for fixing the location of the bridge and waterway required for the bridge.[8]. IRC Pocket book for bridge engineers gives the details of river survey data to be collected at a bridge site

2.4 Morphologic Data

Morphologic investigations should be carried out in regard to the history of river behavior in the vicinity of the bridge site, change in flow pattern in the past etc. Morphologic behavior of a river is governed by the flow of water and sediments in the river**.** Many a river engineers [9,10,11,12] have developed procedures for determining stability and regime characteristics of rivers as briefly discussed below.

2.4.1 River Planform

Based on flow of water (Q) and sediment (Q_s). bed slope (S_0) and stream power ($Q.S_0$), Schum [11] developed criteria to decide plan-form of streams depending on water and sediment flow as illustrated in Fig.2(a)

2.4.2 River Regime and Meandering

Lane [13] and Garde [12] developed similar criteria for finding stream stability and meandering process by developing following laws

- $QS_e \ \alpha \ Q_s d_{50}$ … by Lane (1)
- $Q^{6/7} \ Se^{7/5} \ \alpha \ Q_S \, d_{50}^{\ 3/4}$….by Garde (2)

Knowing mean annual flow in a river and bed slope, different regimes of a river can be predicted as illustrated in Fig.2(b).

2.4.3 Meandering Process

River meanders migrate both laterally (faster rate) and longitudinally (slower rate). Understanding the migration process (fig.3) and the effect of bridge on the change on meander pattern is necessary for deciding waterway and designing river training measures[14]. Many a times, fixing waterway without proper morphological study and meandering process has resulted in wash out of the bridge, excessive cost of maintenance and other problems related to safety of the bridge and the approach embankments.

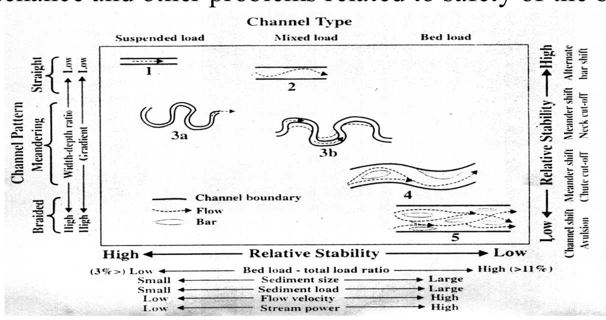

Fig.2(a)Different Plan Forms of a Stream like,Straight, Mendering &Braided (Masse)

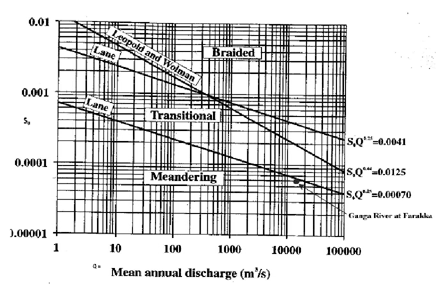

Fig.2(b)Lane's Criteria for Finding river Regimes(Lane)

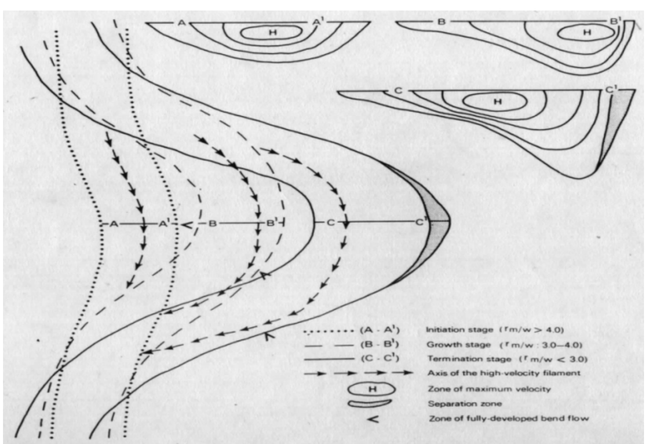

Fig.3 Illustrating Lateral Migration of River

3.0 COMPUTATION OF DESIGN FLOOD

IRC:5[8] **&** IRC:SP-13[15] recommend peak flood of 100 year return period for safe design of bridges and appurtenant works like guide bunds, approach embankments etc. Additional discharge varying from 10% to 30% (depending on catchment area) is to be added with peak design flood for design of pier and abutment foundations [16]. For freeboard under a major bridge, AASTHO [17] recommends a peak flood of 500 year return period and corresponding HFL for safety of the bridge. Computations of peak flood and corresponding HFL are briefly discussed underneath.

3.1 For Gauged Catchments

Most reliable method of peak flood estimation is to collect past annual flood series for 15 to 20 consecutive years depending upon the return period of design flood. Frequency analysis is performed by tabulating the recorded peak floods and the high flood levels according to their magnitudes with the highest value on top and lowest at the bottom. There are several methods of computing design flood of any given frequency/return period e.g. Gumbel method, Log normal method, Log Pearson type-III etc. All of them are essentially probabilistic methods of best curve fitting of extreme value distributions. Details of these methods are given in standard hydrology text books[4,18]

3.2 For Ungauged Catchments

Peak flood/HFL data are not available in many catchments, especially for streams in remote and inaccessible areas. However, rainfall data collected by Indian Meteorological Department (IMD) are usually available for years. Depending on the size of catchment areas, a number of reliable methods of flood estimation based on observed rainfall data are briefly discussed underneath.

3.2.1 Rational Method

The rational method is appropriate for estimating peak discharges for small catchments up to about 25 sq. km. Rational Method presupposes an uniform critical rainfall intensity continuing indefinitely and uniformly all over the catchment. The runoff at the outlet of a catchment will increase until the time of concentration T_C, when the whole catchment is contributing flows to the outlet. The peak runoff is given by the following expression:

$$Q = 0.028\ P\ f\ A\ I \tag{3}$$

where, Q = Maximum runoff in cumec, A= Catchment area in hectares, I = Design Rainfall intensity in cm/hr for the selected frequency and duration equal to the time of concentration, P= Coefficient of run-off for the given catchment, f= Spread factor for converting point rainfall into areal mean rainfall. Further details of computation of peak flood by Rational method may be found in IRC: SP:42[19],IRC:SP:13 [15]

3.2.2 SCS Method (Run-off Curve Number Method)

SCS (Soil Conservation Services) method or Runoff Curve Number(CN) method of estimating direct runoff from storm rainfall is developed by U.S Soil Conservation Services. Relation between rainfall, runoff, initial abstraction and potential maximum retention can be expressed as;

$$Q_r = (P-I_a)^2 / [(P-I_a) + S] \tag{4}$$

where, Q_r = storm runoff depth in mm, P = storm rainfall in mm, Ia = initial abstraction in mm = 0.2S
S = potential maximum retention in mm = (25,400/CN) – 254
Further details of computation of peak flood by SCS method by use of SCS curve numbers are available in IRC: SP:42[19]

3.2.3 Unit Hydrograph Method

Unit hydrograph can be prepared synthetically by using physiographic data like area of catchments, length of stream, longitudinal bed slope, soil and cover conditions etc. Daily rainfall corresponding to design flood return period is found from iso-hyetal curves for the catchment. Hourly distribution of rainfall and rainfall excess-values corresponding to design storm are found. By using the unit hydrograph and rainfall excesses, flood hydrograph is prepared and the peak flood is determined. Details of computing peak flood by using synthetic unit hydrograph method are available in Flood Estimation Reports [20] prepared jointly by CWC, RDSO, IMD & MORTH, Govt. of India.

3.2.4 Use of Hydraulic Structures

Peak floods can be estimated by recording HFL upstream and downstream of existing hydraulic structures in the river e.g. dams and barrages, bridges, culverts and other cross-drainage structures. General equation for measuring flow past such hydraulic structures may be written as

$$Q = C_d\ L_{eff} H^{3/2} \tag{5}$$

where, Q is flow rate in cumec, L_{eff} is the effective waterway in m, H is the head above crest in m and C_d is the coefficient of discharge in $m^{1/2}/s$. C_d-value varies from structure to structure depending upon whether the flow is free or submerged, geometry of the structure etc. C_d-values for dam/ spillways under free and submerged conditions may be obtained from USBR [21], IRC: SP:13[15],Mazumder and Joshi[22].

3.2.5 Using Manning's Equation

When stream cross-section is available, Manning's equation can be used to determine stream flow

$$Q = (1/n)x\ (AR^{2/3}.S^{1/2}) \qquad (6)$$

where, n is Manning's roughness coefficient, R is hydraulic mean depth in m given by R= A/P and S is the energy slope, A is area of cross-section normal to flow in m^2,P is wetted perimeter in m and Q is flow rate in m^3/s. Manning's n-values can be obtained from standard textbook of hydraulics by Chow[5]. Assuming different stages (water levels), Q-values corresponding to the different stages can be found from Manning's equation for the given stream section. Stage-discharge curve can be obtained by plotting discharges against corresponding stages/water levels. Design peak flood can be obtained from the stage – discharge curve corresponding to measured HFL or vice versa.

4.ESTIMATION OF DESIGN HFL

Design HFL corresponding to design peak flood can be found from stage-discharge curve where flow records are available. Stage – discharge curve can also be prepared by Manning's equation discussed under section 3.2.5. These are normal HFL assuming that the low water bed level (usually surveyed during lean flow period) remains unaltered during flood. Actually, there is always some change in bed level due to scouring of bed during passage of high floods. River bed usually undergoes retrogression (especially downstream of hydraulic structures like dams and barrages) resulting in lowering of HFL. Aggradations occur in rivers where heavy sediment load comes from landslides. Photograph no.1 illustrate heavy sediment deposition due to landslides in Vishnuprayag_HEP Barrage on Alaknanda River, Uttarakhand in June-2013. River bed level rose around 17m due to landslides and flooding debris. Obviously such aggradations will cause rise in normal HFL HFL can be estimated by using software e,g. HEC-RAS or MIKE-11and Mike-21 etc. HFL upstream of structures can be found by adding afflux with normal HFL downstream [23] .

Photo.1 Aggradations of Alaknanda River Bed at Vishnuprayag HEP Barrage due to Landslides June, 2013 (Photos show bed levels before and After Flood). [Courtsey: S.D.Sharma, GMR Group of CO. New Delhi]

5.0 ESTIMATION OF WATERWAY

When a new bridge is to be constructed, a designer has all the freedom to provide waterway as required. As per IRC-5[8], waterway (W) should be equal to Lacey's regime waterway (P) given by equation:

$$P = W = 4.8\, Q^{1/2} \tag{7}$$

where, Q = design flood discharge in m3 /sec, P = Wetted perimeter in meter. W = Linear waterway in metre The code also stipulates that the waterway so found should also be compared with linear waterway at HFL corresponding to design flood discharge and the minimum of the two should be adopted as the clear waterway under the bridge. The methodology for determining waterway under different situations is discussed briefly underneath.

5.1 In a Hilly Terrain

In a hilly or mountainous terrain where the river flows in gorges with steep bed slope, the flow is usually in supercritical state when depth (y) is small and velocity of flow (V) is very high. Lacey's waterway in such terrain is very high compared to linear waterway at HFL. Thus the minimum waterway under the bridge will be determined by the linear waterway at HFL. Any restriction of normal waterway under a bridge in supercritical flow will result in the formation of hydraulic jump upstream which is not desirable. Moreover, restriction of normal waterway will affect free movement of gravels and boulders which move along the river bed during flood season.

5.2 In a sub-hilly/Trough Terrain

In a sub-hilly/trough region, slope of river bed and stream power per unit width per unit weight (QS_o) reduce drastically resulting in deposition of the sediments brought from the mountainous stretch. In this stretch, the river is found to be unstable and changing its course periodically. As a result, a fan shaped delta type formation occurs. It is better to avoid construction of any bridge since there is always a risk of outflanking of the bridge due to its shifting course **[7].** In such stretches, Lacey's waterway is only a guideline but the actual waterway to be provided may be more depending on width of the fan shaped braided area. which may be several times more than Lacey's waterway. Too much restriction of flood plain should be avoided to ensure free flow of water and sediments. Physical and mathematical model study should be carried out to fix up waterway, alignment, location of the bridge, protective works etc.

5.3 In a Meandering Flood Plain

In this region, the river bed and bank consists of fine alluvial soil which can be as easily eroded as deposited. Due to an inherent instability [24]**,** the river erodes its outer bank and the eroded materials get deposited on the inner bank opposite to the eroded one. Guide Bund and Approach embankments with Pitching are to be provided where the wide flood plain is restricted**.** Excessive restrictions of meandering flood plain of a river create high afflux and many unforeseen problems [25]**.** Elliptical type guide bunds as per design proposed by Lagasse, et al[26]. should be provided for the safety of the bridge.

5.4 In a Deltaic Region

In the deltaic stretch, longitudinal bed slope and stream power are so low that even fine silts and clays deposit in the channel beds and banks. River divides and starts flowing in multiple channels forming deltas. Many of the rivers in their deltaic stretch are also subject to backflow during high tides. Thus, determination of waterway in deltaic channels is a very difficult task due to unsteady varying flow over time, unless river is trained with flood embankments to follow a steady course. Submergence of area in between the embankments occurs due to storage of incoming flood water during tidal lockage period. When an all weather road is be constructed in such tidal stretch, waterway under the bridge across the river should be sufficient enough in order to avoid undue afflux above normal high flood level It is prudent to carry physical and mathematical model study for a final decision.

6. COMPUTATION OF AFFLUX

Afflux is the rise in water level upstream before and after the construction of a bridge. IRC:5-2015[8] stipulates a maximum afflux of 15 cm. High afflux due to excessive constriction of normal waterway should be avoided as it may result in hydraulic jump and consequent scour downstream, increase in

overall cost of construction and many other unforeseen problems viz. outflanking, silting, damage to properties, river instability , costly protective measures . etc.
Afflux computed by Molesworth equation (8) prescribed in IRC:5-2015 [8] is applicable only in straight rivers without any flood plain

$$h_l * =[V^2 /17.88 +.015] [(A/A_1)^2 -1] \quad (8)$$

where, h_l * is the afflux, V is the mean velocity of flow in the river prior to bridge construction i.e. corresponding to normal HFL, A and A_1 are the areas of flow section at normal HFL in the approach river section and under the bridge respectively. Molesworth equation (8) is not applicable for rivers with wide flood plains and non-uniform approach flow. In such a situation**,** Bradley [27] suggested equation (10) for determination of afflux.

$$h_l * = 3(1- M) V_n^2/2 g \quad (10)$$

where, $M=A/A_1$, V_n is the mean velocity of flow under the bridge with water level same as under normal flow condition.

7. BRIDGE SCOUR

Determination of scour around bridge piers is important in deciding the foundation level of the piers and abutments. 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 scoured bed level as given in IRC-5 [8] and IRC-78[16]. Hydraulic radius or mean scoured depth ($R=d_{sm}$) in a river is computed by Lacey's theory [28]. The multiplying factor 2 is based on observed scour depths in 17 major railway bridges [29] given in a annual report (Tech.) by C.W.P.R.S., Pune [30] . All the piers investigated are founded on very fine and uniformly graded soil (d_{50}-varying from 0.17 to 0.39 mm,). Yet, the same factor 2 is adopted for computing scour in piers founded even on coarse and graded soils (e.g. gravely and bouldery soil) having $2mm<d_{50}<300mm$ and $\sigma_g>1.3$) without any verification from field. σ_g is the geometric standard deviation given by the expression

$$\sigma_g = (d_{84}/d_{16})^{0.5} \quad (11)$$

Scour around pier below river bed is governed by many parameters viz. type of pier, pier thickness, shape of pier nose, flow obliquity, flow conditions and sediment characteristics-not considered in IRC formula. Based on these parameters, several mathematical models proposed by Kothyari,et al.[31]**,** Melville and Coleman [6], Breussers & Raudkivi [32],Richardson and Davis [33] etc. have been developed in India and abroad for predicting maximum local scour depth to be measured below river bed level.

Mazumder and Kumar [34] computed total scour depths in six bridge piers founded on cohesion less uniform fine bed materials ($d_{50}<2mm$, $\sigma_g<1.3$) and compared them with those found by IRC method based on Lacey's theory.IRC method was found to overestimate scour in all the cases and the error was found to vary from 5% to 275%. Holnbeck [35] observed local scour depths in fine soil in river Maine in USA and compared the observed scour values with predicted ones by using HEC-18 Model. It is noticed that the predicted scour depths are highly conservative as compared with observed ones. Mazumder & Dhiman [36] made exhaustive study on local scour in bridge piers in Missisipi river on coarse graded soil $d_{50}>2mm$, $\sigma_g>1.3$ and compared them with the observed ones and those obtained by IRC method. It is found that in all the cases, IRC method overestimates the local scour depth. Fig.4 illustrates the effect of size and gradation of bed materials on local scour depth in bridge piers.

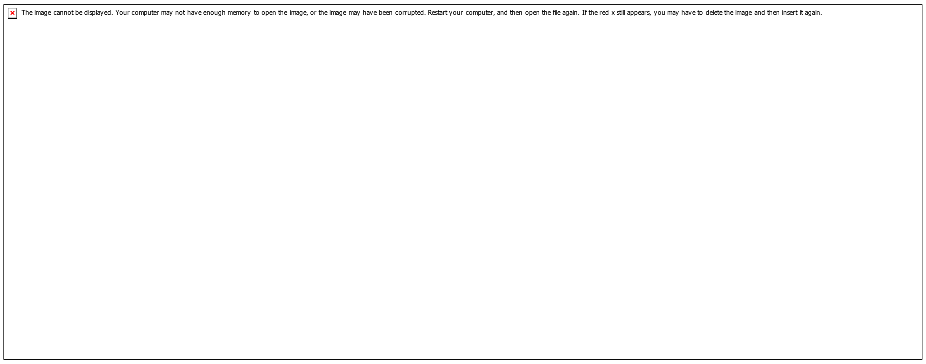

Fig.4 Showing variation of Local Scour Depth in Bridge
Piers with Size and Gradation of River Bed Materials

8.0 OTHER FACTORS

Apart from the various hydraulic and hydrologic considerations discussed under sections 1 to 7 above, other factors such as hydrostatic force, buoyant force, drag and lift forces, wave forces, effect of debris on these forces should be taken into account in the safe design of bridge structures. These are available in the publication by US Department of transportation, Federal Highway Administration [37].

REFERENCES

1.Mazumder,S.K.,"Morphology and Training of Rivers Near Bridges" Indian Highways,Vol.44,No.7, July,2016, pp.25-35.

2. Mazumder, S.K.,"Determination of Waterway Under a Bridge in Himalayan Region - Some Case Studies" Paper presented at 70th IRC congress held at Patna on 11-14 Nov., 2009 and Published in the Journal of IRC, Vol.70-2, July-sept., 2009.

3. Garde, R.J. and RangaRaju, K.G., "Mechanics of Sediment Transport and Alluvial Stream Problems" New Age Int. Pub. Pvt. Ltd. , New Delhi, 3rd Ed., 2000 ,

4. Raghunath, H.M., "Hydrology" pub. by Wiley Eastern Ltd. Delhi, Bangalore, Mumbai, Kolkata, Madras, Hyderabad 1985

5.Chow, Ven Te , "Open Channel Hydraulics", McGraw-Hill Book Co. Open Channel Hydraulics, McGraw-Hill Book Co.,1970

6. Melville, B.W. and Coleman, S.E., "Bridge Scour", Water Resources Publications, LLC, Vol.I and II,2000

7. Mazumder, S.K., "River Behaviour Upstream and downstream of Hydraulic Structures", Proc. Int. Conf. On "Hydraulic Engineering Research and Practice (ICON-HERP-2004) in honour of Prof. K.G.Rangaraju, org. by Deptt. Of C.E., IIT, Roorkee, Oct 26-28, 2004

8. IRC:5 "Standard Specifications and Code of Practice for Road Bridges-Section-I", Indian Roads Congress, Jamnagar House, Shajahan Road, New Delhi-110 011, 2015

9. Lacey, G., "Stable Channels in Alluvium" Paper 4736, Proc. of Institution of Civil Engineers, Vol. 229, William Clowes & Sons Ltd., London, U.K. ,1930,P. 259-292.

10. Lane, E. W. ,"A Study of the slope of channels formed by Natural Stream flowing in "Erodible material" U.S. Army Core of Engineers, Missouri River Division, Omaha, Sediment series 9, 1957.

11. Schumm, S.A. ,"Plan form of Alluvial Rivers" Proc of the International Workshop on Alluvial River Problems held at Univ. of Roorkee, March 18-20, 1981

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

13. Lane,E.W. "stable Channels in Alluvium" Trans. A.S.C.E, Vol.120, 1955

14. Chitale, S.V. , " Shape and Mobility of River Meanders" Proc. XIX Congross of IAHR, Vol. 2, pp 281-286, New Delhi,1981

15. IRC:SP:13, “Guidelines for the Design of Small Bridges and Culverts”, Published by Indian Roads Congress, New Delhi IRC:SP:42 “Guidelines for Road Drainage” pub.by Indian Roads Congress, R.K.Puram, New Delhi, 2013
16. IRC:78, “Standard Specifications and Code of Practice for Road Bridges, Section-VII” Indian Roads Congress, Jamnagar House, Shajahan Road, New Delhi-110 011, 2000
17. AASHTO “Hand Book of Highway Engineering” Section 14 on ‘Drainage’ by C.F. Izzard,1994.
18. Subramanya,K. , “Engineering Hydrology” pub. Mc.Graw hill Book Co.New York,2013
19. IRC:SP:42, “Guidelines for Road Drainage” pub.by Indian Roads Congress, R.K.Puram, New Delhi, 2014
20. “Flood Estimation Reports” prepared jointly by CWC, IMD, RDSO &MORTH, Govt. of India, and published by Hydrology Division of Central Water Commission, Sewa Bhawan, R.K.Puram, New Delhi
21. USBR ‘Design of Small Dams’, (Int. Edition) Chapter-F ‘Hydraulics of Spillways-Culvert Hydraulics’pp326-333, pub. by Oxford & IBH pub. Co Ltd. New Delhi and Kolkata.1968
22. Mazumder,S.K.&L.M.Joshi “Studies on Critical Submergence of Flowmeters” J. of Irrigation and Power,CBIP, Vol.32,No.2,April,1981.
23. Mazumder, S.K. & Dhiman, Rajni “Computation of Afflux in Bridges with Particular reference to a National highway, Proc.,HYDRO-2003, CWPRS,Pune, Dec.26-27, 2003
24. Mazumder, S.K., “Stability of River Downstream of Hydraulic Structres” Proc. of VIII APDIAHR Congress, Vol II org by CW&PRS Pune, Oct. 20-23, pp 273-282, 1993.
25. Mazumder, S.K., “River Behaviour near Bridges with Restricted Waterway and Afflux- Some Case Study” Paper pub. in Indian Highways. Vo.37, No10, Oct 2009.
26.Lagasse,P.F.,schall,P.F., Johnson,F., Richardson,E.V.and Chang.F.,”Stream Stability at Highway Structure, Department of Transportation, federal Highway administration, Hydraulic Engineering Circular No.20,Washington, D.C.,1995
27. Bradley, Joseph, N. “Hydraulics of Bridge Waterways” Federal Highway Admn, Hydraulic design Series No. 1,1970
28. Lacey, G. “Stable Channel in Alluvium” J. of Instn. of Civil Engineers, U.K., Paper no. 4736,Vol. 229, PP. 259-292,1930
29. CBIP “River Bhaviour, Management and Training, Vol.I”,Central Board of Irrigation and Power, Malcha Marg, New Delhi, 1989
30.CWPRS,”Annual Report(Tech)”,Central Water & Power Research Station, , Pune.
31. Kothyari, U.C., Garde, R.J. and Ranga Raju, K.G. “Temporal Variation of Scour Around Circular Bridge Piers”, JHE, A.S.C.E., 118(8), PP 1091-1106 , 1992
32. Breussers, HNC and Randviki, A.J. “Scouring” , Chapter-5 “Scour at Bridge Piers” A.A. Balkema Pub., IAHR Hydraulic Structures Design Manual, 1991
33. Richardson, E.V. and Davis, S.R. (1995), “Evaluating Scour at Bridges”, Report No. FHWAIP-90-017,
34.Mazumder, S.K. and Kumar,Y.K, “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.
35. Holnbeck “ 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., 2011
36, Mazumder,S.K.& R.K.Dhiman , “Local Scour in Bridge Piers on Coarse bed material-Observed and predicted by Different methods”, J.of The Indian Roads Congress,Vol.74-4,April-June, pp.126-135,2016
37. U.S. Department of Transportation, Federal Highway Administration, “Hydraulic Design of Safe Bridges,” Publication Number FHWA-HIF-12-018, April 2012.