MORPHOLOGIC, HYDROLOGIC & HYDRAULIC ASPECTS FOR DESIGN OF BRIDGES

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Summary

Morphologic, hydrologic and hydraulic consideration in planning, design and maintenance of bridges are as important as structural and foundation design of bridges. Author has discussed the above aspects of bridge design with illustrative figures and references so that the problems encountered post bridge construction may be avoided. Some of the morphologic, hydrologic and hydraulic considerations are discussed under sections 2, 3 and 4 of the paper respectively. Important references have been listed in section-5.

Keywords: Plan and bed forms; meandering; braiding; design flood; waterway; afflux; river behaviour; scour; river training.

1. Introduction

A large numbers of bridges are being constructed all over India for better and faster communication. Inadequacy in morphologic, hydrologic and hydraulic aspects of bridge design may not cause immediate failure, but it may cause serious long term problems afterwards e.g. meandering and erosion of river bed and banks, outflanking of abutments and flow avulsion, failure of piers and abutments, excessive afflux resulting in overtopping of bridge and approach embankments, submergence of land and damage to properties in the adjoining areas etc. Costly maintenance, protection works and river training measures will be needed throughout the life span of the bridge. There is always a risk of failure of the bridge due to inadequacy of waterway owing to under estimation of design flood and design HFL. It is almost an universal practice to design waterway under a bridge for a peak flood of 100 years return period **[1]** under normal conditions. If the exiting waterway is inadequate, it results in high afflux , loss of freeboard, overtopping of the road, aggradations (upstream) and degradation (downstream) and possible outflanking of the bridge **[2].** Costly river training measures and annual maintenance will be needed for the safety of the bridge and the adjoining approach road. Computation of waterway and scour depth has to be made very scientifically for the bridge safety as well as economy **[3].** Underestimation of waterway may result in outflanking of a bridge and other unforeseen problems. 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 flood plain under the bridge causing non-uniformity of flow distribution which may result in high scour under some of the spans and silting in some others. Fixing waterway for a bridge under different terrains requires an intimate knowledge of morphology, hydrology, hydraulics, river mechanics and the alluvial stream processes **[4]**. Any arbitrary decision regarding waterway under a bridge without considering its past history and behaviour of the river in the near and far field may create unforeseen problems in future during the life span of the bridge**[5]**.

2. Morphological Considerations

As mentioned earlier, knowledge of river morphology helps a bridge designer for deciding proper location of the bridge, waterway required, length of guide bund, scour estimation, protective and river training works etc. River morphology **[6]** is a subject which deals with both short term and long term changes in river behaviour principally by the flow of water and sediments carried by the river mostly during flood flows as well as human activities. Some of the important morphological considerations in bridge design are briefly discussed underneath.

2.1 Plan Form and Different River Regimes

Schum **[7]** studied different plan forms of a river and termed them as autogenic and allogenic changes. Autogenic changes lead to change in river regime and involve braiding, meandering, cut-offs, channel migration, flow avulsion etc. Allogeneic changes occur due to system change caused by climate variation, fluctuations of flood discharges, sediment load and human activity in the river and its flood plains. Relative stability of a river and different channel patterns governed by flow and sediment parameters have been studied by Lane **[8]** .

2.2 River Meandering and Braiding Processes

Development of lateral instability associated with erosion and deposition give rise to meandering processes as illustrated in **Fig. 1(a)** . Braiding occurs with high bed slope (S) , high flow velocity (V), high sediment load and high stream power (**ã**QS), Where ã is unit weight of water, Q is flow rate and S is energy slope. Wang **[9]** developed a mathematical model of the meandering process to prove that the typical cross – slope observed in a meander **(Fig.1a)** with lower bed elevation on the outer side of the bend (due to erosion) and higher bed elevation on the inner bank side (due to deposition) arises out of secondary current which is essentially needed for the river stability. Chitale **[10]**, Garde and Raju **[4]** made significant contribution on river meandering. Uncontrolled erosion and deposition ultimately give rise to typical meandering pattern and change in cross-section as illustrated in **Fig.1(a)**. Hickin and Nanson **[11]** investgated the lateral migration rate (M) of a meandering bend. It was concluded that migration rate is maximum when r/w = 2.5, where r is radius of curvature of the bend and w is the mean width of channel as shown in **Fig. 1(b).** Mazumder **[12]** proved that the lateral migration rate predicted by Hickin &Nanson is not applicable in rivers in the vicinity of hydraulic structures like bridges and barrages and it far exceeds the rate predicted by Hickin and Nanson. Knowledge of meandering and braiding help in deciding proper location and span of a bridge, guide bunds and protection works.

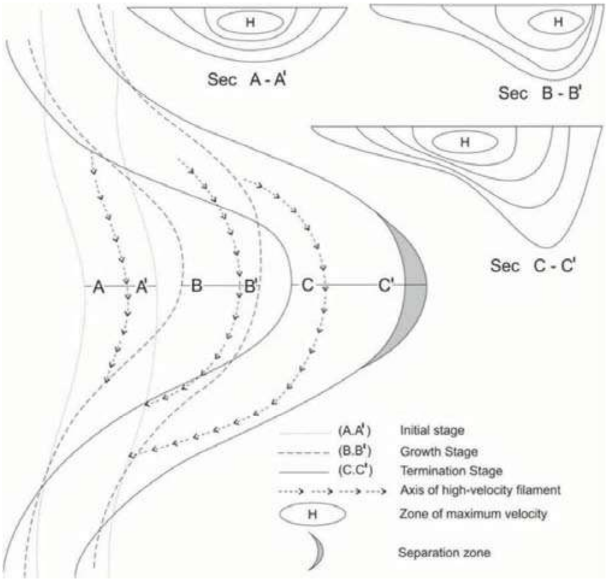

Fig.1(a): Meandering Process

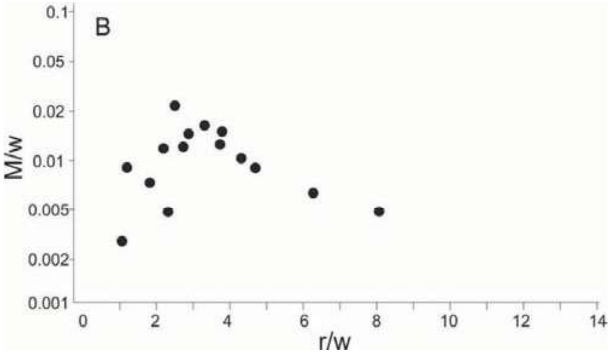

Fig. 1(b) Variation in the Meandering Rate With Curvature of Bend (r/w)

(r is radius of curvature of the bend and w is mean width of river)

2.3 Bed Forms of River

Different bed forms which successively occur with rise in flow velocity are shown in **Fig. 2**. It may be mentioned that bed forms occur only after the bed becomes live i.e. when bed shear stress(τ_0) exceeds the critical shear stress (τ_c) at threshold condition of sediment motion.

Flow is classified as clear water flow when $\tau_0 < \tau_c$ and live bed flow when $\tau_0 > \tau_c$. Knowledge of bed form is useful in scour estimation in piers and abutments as well as in estimation of bed load and suspended load transport in rivers and for determination of bed roughness

3. Hydrological Considerations

Hydrologic study **[13,14]** and hydrologic data collection are essentially needed for finding design

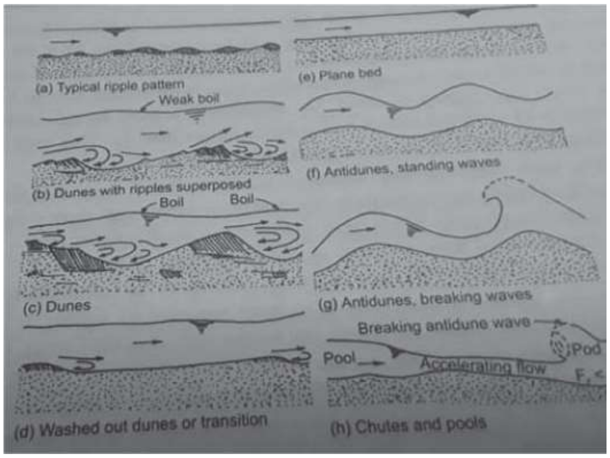

Fig.2: Different Types of Bed Forms in River

discharge and design HFL for determining waterway, afflux, deck elevation, scouring in piers and abutments, river training and other protective works for a bridge- all of which will be covered under hydraulic design.

3.1 Topographic and Hydrologic Information

Topographic information like roads, buildings, rivers etc. are available in topo -sheets prepared by survey of India, Dehradun. Satellite imageries obtained from remote sensing institute, Hyderabad, are very useful, especially in a hilly terrain, to delineate several surface features, e.g. soil types, forests, water bodies, river behaviour in the near and far field of the bridge. The imageries can be used in deciding suitable location and length of a bridge. As illustrated in **Fig. 3**, 3.4 km length of a bridge on river Ganga near Prayagraj (earlier Allahabad) was decided considering the shift of main river course during 2007-2016. Topographic/ remote sensing maps are used for determining watershed line and catchment area of the proposed bridge etc. essentially needed for computation of flood discharge, terrain slope, land use, river behaviour, time of concentration etc.

3.2 Rainfall –Run off

All indirect methods of flood computations e.g. Rational method (for small catchments), US Soil Conservation Service method (for small and medium catchments), Synthetic Unit Hydrograph (SUH) method (for medium and large catchments) are dependent on rainfall estimation of 100 years return period in the given catchment. These methods have been described with examples in the revised IRC:SP-42 **(15)** with author as convenor. Flood estimation reports prepared jointly by CWC, DRDO, IMD & MORTH, and published by hydrology division of CWC **[16],** for 23 sub-zones of India (determined by similar hydro-meteorologic characteristics of basins) are excellent documents where the methodology of flood computations by SUH method are discussed in detail with illustrative examples.

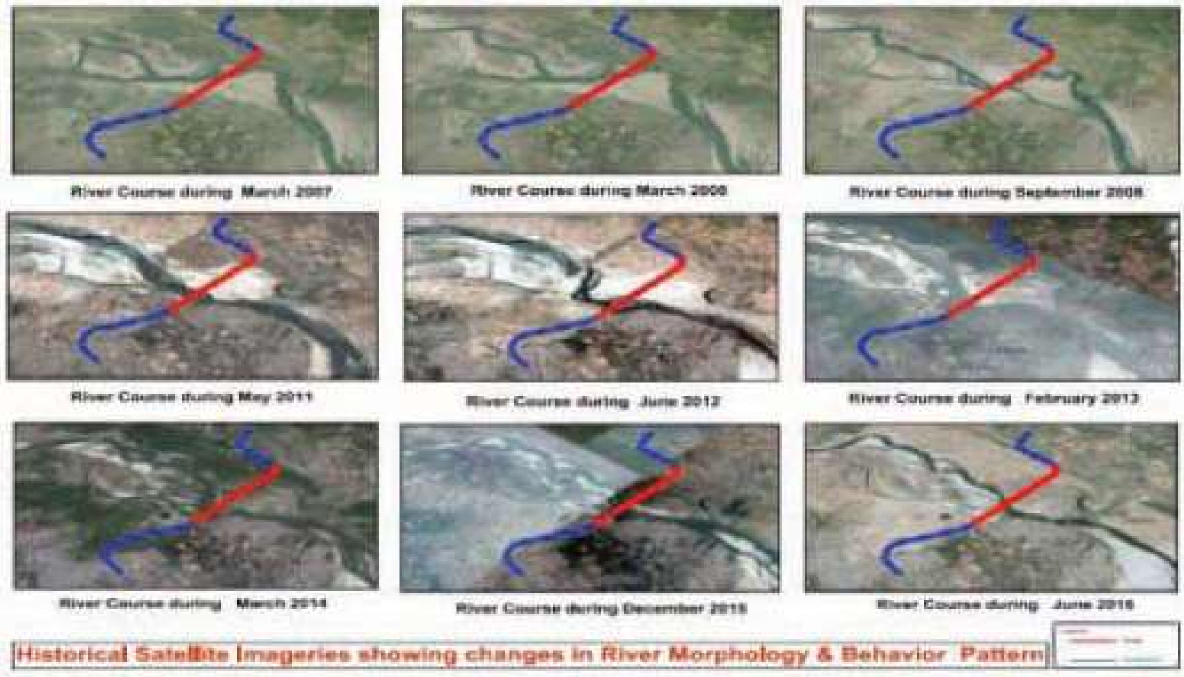

Fig. 3: Showing 3.70 km Long Bridge (Red colour) on River Ganga

3.3 Direct Determination of Peak Flood by Probabilistic Methods

For very large catchments of Indian rivers like Ganga, Brahmaputra, Mahanadi, Narmada etc. , peak flood for a given return period should be determined by using measured annual peaks for at least 10-15 consecutive years. Several probabilistic methods e.g. Gumbel's method, Log-Pearson method etc. are available in standard text books of hydrology (**13,14**). There are mathematical models e.g. HEC-RAS **(1 7)** etc. which can be used for extra-ordinarily large catchments consisting of several sub-catchments.

3.4 Manning's Equation/Area-Velocity Method

Manning's equation can be used for peak flood estimation provided the peak HFL of given return period is available. Further details of Manning's method with illustrative examples are available in IRC:SP:42 **[15].** It may be pointed out that direct measurement of peak discharge during floods by area-velocity method using instruments like current meters, ADCP, PVM **[18]** etc. are not only costly but time consuming and risky too. They also need trained manpower for measurement and servicing of equipment.

3.5 Using Hydraulic Structures

Existing Hydraulic structures like dams and barrages can be used for direct determination of peak flood by simply gauging water level upstream in case flow is free. In submerged flow, however, water levels both upstream and downstream are needed for flood estimation. Existing small bridges and culverts can be conveniently used for stream gauging . Detailed procedure with examples are worked out in IRC:SP:13 **[19].**General equation for flood discharge (Q in cumec) can be expressed as

$$Q= C_d . L_{eff} . H_e^{3/2} \qquad \text{... (1)}$$

where L_{eff} is the effective waterway i.e. clear waterway minus end contractions due to piers and abutments in m; H_e is the energy head above crest in m and C_d is the co-efficient of discharge in $m^{1/2}$/sec. C_d-values for free and submerged flow are available in standard text books **[20,21].** Mazumder **[22]** developed an innovative proportional flow meter for stream gauging such that flow remains always free within a given range of flood discharge.

3.6 Determination of Design HFL

As mentioned earlier, determination of design High Flood Level (HFL) corresponding to design peak flood is extremely useful for fixing bridge deck elevation, submergence of area, guide bund length and height, scour, river training works etc. Simplest way is to enquire from local people or pick up water marks from trees or from existing bridges. However, such information about HFL do not have any value unless it is collected for 10-15 years consecutively for carrying out statistical analysis of design HFL of given return period. Knowing the design flood discharge, design HFL can also be found by preparing stage-discharge curve (from river gauging stations) or by using Manning's equation explained under section 3.4. Softwares like HEC-RAS**[17]** can be used for finding design HFL for important rivers provided necessary input data are available from the site. It may be pointed out that HFL so obtained are normal HFL without the presence of the bridge i.e. the normal HFL downstream of bridge. Design HFL upstream of bridge can be obtained by adding afflux with the normal HFL. Afflux reduces gradually to zero at a distance far upstream of the bridge as illustrated in **Fig. 4(b)**. Procedure for computing back water curves for finding afflux at any point within the backwater reach are explained in detail in standard text books **(20,23).**

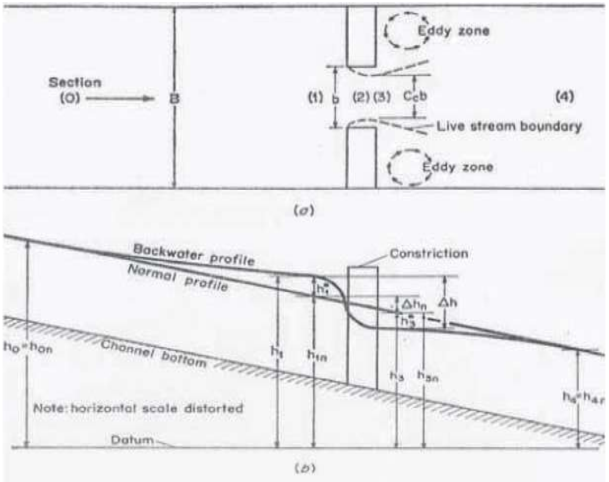

Fig.4: Backwater Profile behind a Constricted Bridge Showing Maximum

Afflux (h1), normal and Backwater Profile (a) plan view (b) L-section*

3.6.1 Aggradation of River Bed and Rise in HFL due to Land Slides & GLOF

In the mountainous terrain of Himalayas, there is risk of landslides due to glacial lake outburst floods (GLOF) or similar reasons, as experienced in Kedarnath valley **[24]** in 2013 and Chamoli valley in 2021. Such phenomena are always accompanied with sudden release of huge volumes of water , sediments and debris resulting in aggradation of river bed and consequent abrupt rise in HFL upstream of barrages causing severe damage/washout of Roads and Road bridges.

4. Hydraulic Considerations

Hydraulic design of bridges involves

(a) Determination of waterway required for safe passage of peak flood

(b) Determination of Afflux for finding areas likely to be flooded and protected

(c) Determination of maximum scour depth in piers and abutments to find foundation level

(d) Design of Guide bund, if required, to reduce bridge cost

(e) Design of protective and river training measures in the vicinity of bridges

4.1 Waterway

When a new bridge is to be constructed, a designer has all the freedom to provide waterway as required for safe passage of design flood without creating harmful afflux. As per IRC-5 [**25]**, waterway (W) should be equal to Lacey's regime waterway **[26]** given by the equation:

$$P = W = 4.8\, Q_d^{\,1/2} \qquad \ldots(2)$$

Where, P= Lacey's Regime Waterway in m, Q_d = design flood discharge in m^3 /sec, P = Wetted perimeter in m, W = Linear waterway in m (for wide river W is almost equal to P). 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.

4.1.1 Waterway under Different Terrain Conditions

(a) In a hilly or mountainous terrain

River flows in gorges with steep bed slope and the flow is usually in supercritical state when depth (y) is small and velocity of flow (V) is very high. In supercritical flow, Froude's number of flow, defined as,

$$F_r = V/\,(gy)^{1/2} \qquad \ldots (3)$$

is more than one. Lacey's waterway in such situation will be very high compared to linear waterway at HFL. Thus the minimum waterway under the bridge will be determined by the linear waterway at HFL and not by Lacey's regime waterway. In fact, Lacey's regime condition is not valid in such a terrain at all. Waterway under the bridge in supercritical flow should not be less than the linear waterway at HFL. Any restriction of normal waterway under a bridge in supercritical flow will result in the formation of shock waves **[27]** upstream of the bridge 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 creating serious morphological problems. In other word, the clear span under the bridge should be equal to or more than the linear waterway**[28]** at HFL so that the river continues to flow in its normal state under the bridge without affecting the natural movement of water and sediments, as it used to carry before the construction of the bridge.

(b) In a sub-hilly/ Trough Terrain

In a sub-hilly/trough region, slope of river bed and stream power (ãQS_e) reduces drastically resulting in deposition of the sediments brought from the mountainous stretch. In this stretch, the river is unstable and changes its course periodically resulting in a fan shaped delta type formation. It is better to avoid construction of any hydraulic structure including bridges in such region and shift it either upstream or downstream since there is always a risk of outflanking of the bridge due to the shifting river course. If it is not possible, the past history of river behaviour in the area must be studied carefully to select appropriate location of the bridge so that the cost of the bridge is less but at the same time bridge safety is ensured. In such stretches, Lacey's waterway is only a guideline but the actual waterway to be provided may be much more depending on width of the fan shaped braided area which may be several times more than Lacey's waterway **[28]**.

(c) In a Meandering Flood Plain

As the river descends further downstream to the flood plains, longitudinal bed slope reduces further. 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 **[29,30]** of any natural stream like a river, the river flow is hardly axial. During high flow or flow at bankful stage, the river erodes its outer bank and the eroded materials get deposited on the inner bank opposite to the eroded one. It is due to this process of simultaneous erosion and deposition on alternate banks, rivers flows in meandering bends. In the meandering stretch, the river develops a wide flood plain known as meander belt over the years. The river is often found to change the meander pattern subjecting both the banks to either erosion or deposition. In a meandering belt, it is customary to provide waterway equal to Lacey's regime waterway (P) with guide bund and approach embankments in the flood plain in case of major bridges as illustrated in **Fig.5.** In case of medium and minor bridges, however, it is customary to provide waterway**[28]** under the bridge less than normal / Lacey's waterway by contraction of normal / Lacey's waterway with a view to reduce cost.

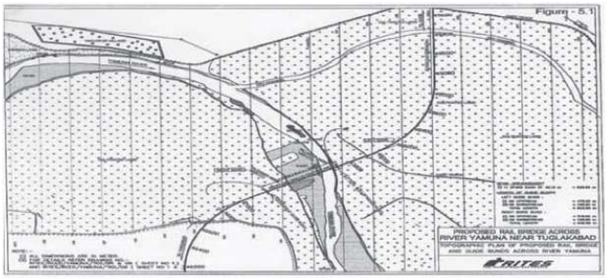

Fig.5: Showing 530m long Bridge with Guide bunds on Meandering Flood Plain of River Yamuna at Shantivan

IRC-5 [1] code permits a maximum amount of restriction of up to 1/3 rd of normal / Lacey's waterway (i.e. a fluming ratio of about 0.67) with a rider that the afflux due to such restriction should not be more than 15 to 20 cm. In many of the existing bridges, however, restriction is found to be more than 33% of normal / Lacey's waterway resulting in excessive afflux and problems of river training discussed by the author in his papers **[29].** Mazumder **[31]** developed an unique method for finding waterway in a bridge on a river with wide flood plains using permissible maximum Froude's number and permissible maximum afflux to avoid instability of river.

(d) In the Braided Flood plain

Braided flood plains of a river is characterised by steep flood plains and high sediment load when the river subdivides and unite again with multiple channel formation e.g. in Brahmaputra river as shown in **Fig.6**. Because of uncertainty and periodic shift of main channel within its flood plain, long span bridges from existing bank to bank are often provided with or without guide banks.

Fig.6: Bogibeel Bridge (4.9km long) on Braided Flood Plain of River Brahmaputra

(e) In the deltaic stretches

Longitudinal bed slope of the river becomes extremely small varying from 1 in 10,.000 to 1 in 20,000 or even less. In such a flat terrain, the stream power reduces to such an extent that even the fine sediments like fine silts and clays start depositing in the channel beds and banks. With reduction in conveying capacity (due to siltation), river divides and sub-divides and starts flowing in multiple channels forming deltas (like Sunderban, Mahanadi etc). The large volume of water carried by the rivers from its catchment can not be conveyed with very little conveying capacity at their bankful stage. As a result, flow from one channel often shifts to another channel and as such prediction of design flood in any particular channel becomes difficult. 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 defined course. Usually, Lacey's waterway corresponding to design flood will be adequate. It will, however, be necessary to compute maximum possible afflux due to restriction of flood plain width. In case waterway is less resulting in higher afflux, there is likelihood of outflanking of the bridge.

4.2 Afflux

Afflux occurs whenever the normal cross-section of a river is restricted for economy. As indicated in **Fig.4**, maximum afflux occurs just upstream of the bridge. Molesworth's equation given below is recommended by IRC **[1]** for computation of afflux. However, such equation is not applicable when the bridge is to be constructed in wide flood plains. Bradley **[3]** developed the following equation for computing afflux in rivers wih wide flood plains.

Molesworth Equation:

$$h_1^* = [\,V^2/17.88+0.015] \times [(A/A_1)^2-1] \qquad ...(4)$$

Bradley Equation :

$$h_1^* = 3\,(1-M)\,(Vn_2^2/2g) \qquad ...(5)$$

where, h_1^* is afflux in m, V is the mean velocity of flow in m/sec in the river prior to bridge construction, A and A_1 are the areas of flow section at normal HFL in the approach river section and under the bridge respectively, $M = Q_b/Q$, where Q_b is that portion of the total discharge Q (in m^3/sec) in the approach channel within a width equal to the projected length of the bridge and $V_{n2} = Q/A_{n2}$ and A_{n2} is the gross area of waterway in m^2 under the bridge opening below normal stream depth corresponding to design flood discharge. Afflux is governed by several other parameters e.g. skewness of flow, state of incoming flow i.e.sub-critical or super-critical, scour under the bridge, dual bridges etc. Methodology and details of computations for afflux are available in reference **[3]**

In sub-critical flow, Mazumder **[31]** developed a relation to determine the limit of contraction given by the equation

$$B_o/B_1 = (F_1/F_o)[\,(2+F_o^{\,2})/(/2+F_1^{\,2})]^{3/2} \qquad ...(6)$$

where, B_0 and B_1 are the mean widths and F_0 and F_1 are the Froude's number of flow in the channel at the control section under the bridge and of original normal section of the channel upstream of bridge respectively. **Fig.7** illustrates the functional relationship between B_0/B_1, F_1 and F_0.

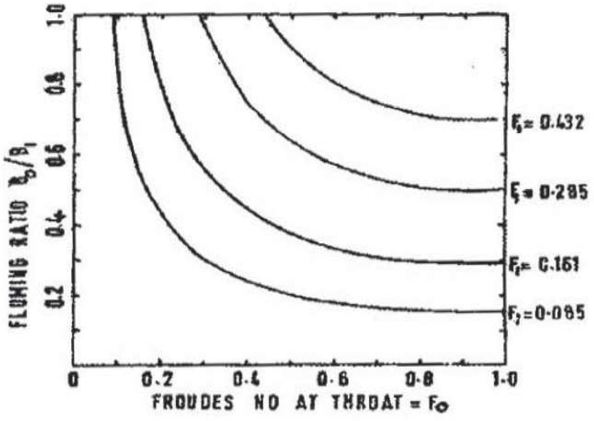

Fig.7: Showing the Relationship between B_0/B_1 with F_0 for Different F_1-Values

Fig.7 shows that the opportunity of fluming (B_0/B_1) of a channel depends upon the value of incoming Froude's no. F_1 and there is hardly any economy when F_0 is greater than 0.7. Higher fluming is also accompanied with greater afflux accompanied with formation of hydraulic jump and flow instability**[30].** When there is very high afflux due to excessive fluming of flood plains, flow downstream of a bridge becomes unstable and likely to shift its main course either left or right attacking left or right bank of the channel which needs costly protective works.

4.3 Scour

IRC-5 **[1]**,IRC:SP-13**[19]** and IRC-78 [**32**] prescribe use of Lacey's regime theory for determination of maximum scour depths in piers and abutments in terms of two parameters only , namely, discharge (Q) and mean sediment size (d_{50}). It is established universally that scour is governed not only by Q and d_{50} but also by several other parameters e.g. size and shape of piers and abutments, non-uniformity of sediments, skewness of flow, live or clear water flow condition etc. Lacey's theory gives infinite scour when the flow (Q) is infinity which is far from truth since the theory does not consider threshold condition of sediment motion when scour ceases to occur because river bed starts moving i.e. under live bed condition as illustrated in **Fig.8**. Mathematical models should be adopted to scientifically estimate scour **[33,34,35]** as explained by the author in several papers [**36,37**].

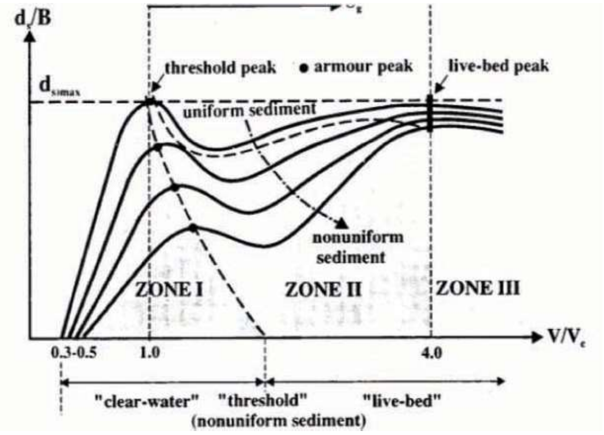

Fig.8: Maximum Scour Depth (d_s/b) in Pier Against Flow Velocity (V/V_c) Under Clear Water and Live Bed Conditions.

4.4 Guide Bund

Apart from safety of the bridge, guide bunds help in reducing the bridge cost on the main channel with wide flood plains. Without guide bunds, the oblique flow may cause excessive scour leading to the failure of abutments and adjoining piers as well as approach embankments. Properly planned and guarded with railings, benches, flowers etc. , they offer an excellent recreational area for public who are attracted by the bridge to view river and flowing water. With proper hydraulic design of Guide bund which is a flow transition structure **[31]**, it can reduce afflux considerably. Length of parallel guide bunds as prescribed in unrevised IRC-89 **[38]** suffer from a fundamental error due to the fact that longer the bridge (i.e.less the fluming), greater is the guide bund length. Lagasse's **[39]** elliptical curves shown in **Fig.9** is scientific, economic and rational for finding guide bund length.

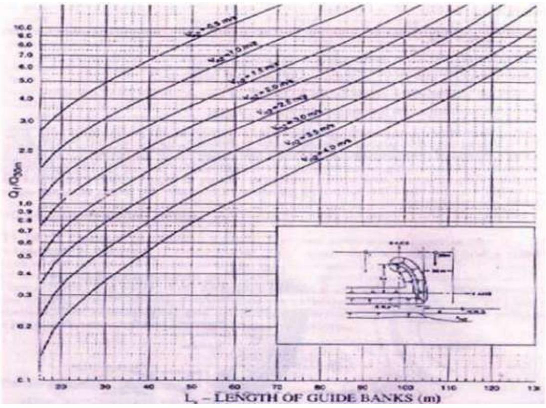

Fig.9: Design Curves for Elliptical Guide Bunds (After Lagasse et al. 1995)

4.5 Protection Measures

River and river flow are dynamic in nature. When a hydraulic structure like bridge or barrage is constructed on a river, the normal morphological processes are altered, especially when flood plains are contracted. **Fig.10** illustrates a typical such case where river Mahananda (with wide flood plains) is anabranched just upstream of a bridge on NH-34. Both the banks were severely eroded and a central island was formed. People living nearby started raising crops on the island with temporary dwellings built on it. Sometimes, ring bunds are even constructed around such islands to protect the properties and crops which is illegal. For the safety of the bridge, approach embankments and the local villages on river banks, costly river training measures **[40]** e.g. spurs, artificial cut-offs, stone pitching with launching apron etc. had to be constructed. Further details of hydraulic design of such river training measures are available in the revised IRC-89**[38]** where author was a consulting member.

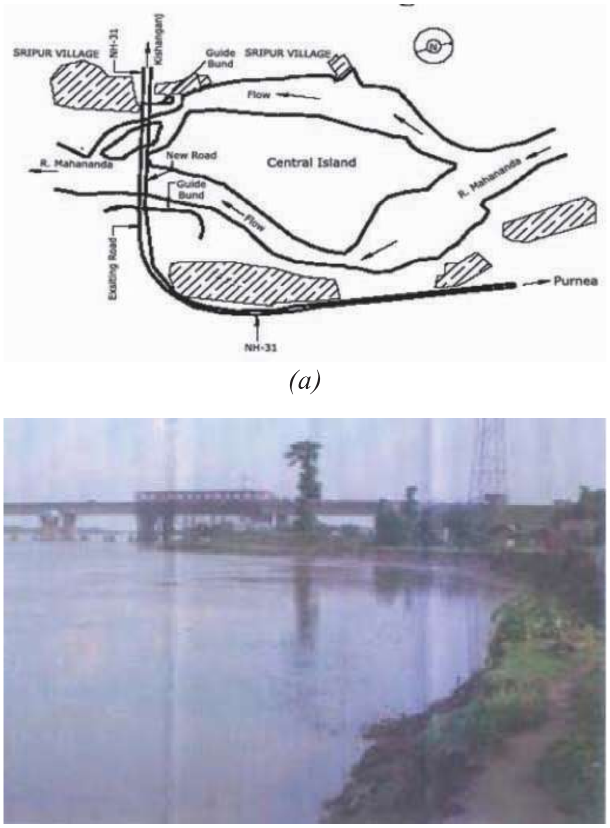

Fig.10 River Bank Erosion due to Anabranching of River Mahananda Upstream of Bridge on NH-34

(a) Anabranching of the River (b) Photograph of Eroding Right Bank

5. Conclusion

Morphologic, hydrologic and hydraulic design are as important as structural and foundation design of a bridge. Any negligence may cause severe problems afterwards resulting in lack of safety, recurring maintenance and river training measures which are very costly. Existing IRC codes , especially those related to waterway, afflux, design HFL, maximum scour depth, guide bunds and other river training measures (particularly in hilly terrain) need updating by incorporating latest scientific research. Use of remote sensing, GIS application, digital elevation mapping, mathematical modelling in deciding location of bridge, waterway, scouring etc. should be encouraged.

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