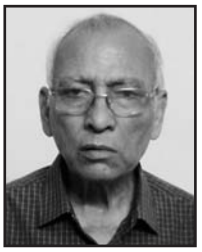
WATERWAY FOR A BRIDGE IN MEANDERING AND BRAIDING FLOOD PLAIN OF A RIVER-SOME CASE STUDIES



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ABSTRACT

Sometimes a bridge engineer is compelled to construct bridges on the wide flood plain of meandering/braided rivers where the flood plain width far exceeds Lacey's regime width. Underestimation of waterway and scour may result in failure of a bridge, loss of properties and outflanking of bridge. 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/braiding belt under the bridge resulting in non-uniformity of flow distribution which may result in high scour under some of the bridge spans and silting in some others. After briefly discussing the fundamentals of meandering and braiding processes, authors have made an attempt to develop some important hydraulic criteria as well as cost criteria for fixing the waterway of bridges constructed in meandering/braiding flood plains. Waterway for three important bridges on rivers Ganga, Yamuna and Brahmaputra have been illustrated under case study.

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 4/6-lanes. For safe design of a bridge, hydrologic and hydraulic aspects of planning and design is important in deciding the bridge location, its waterway, afflux, scour, hydraulic forces, river training measures etc. Computation of waterway under the bridge has to be made very scientifically for its safety as well as economy. Underestimation of waterway and scour may result in failure of a bridge, loss of properties and outflanking of bridge. 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/braiding belt under the bridge resulting in non-uniformity of flow distribution which may result in high scour under some of the bridge spans and silting in some others.

IRC:5-2015 recommends waterway equal to Lacey's regime width given by equation (1).

$$L = KQ^{0.5} \qquad (1)$$

Where, Q is the design flood discharge in m^3/s for a return period of 100 years. K is a constant- value of which may vary from 4.8 to 6.3 depending on flow in the river and its morphology. There are other considerations for deciding waterway e.g. road connectivity, past history of river in the near and far field, confluence with other streams etc. In an earlier paper, Mazumder (2009, 2017) discussed how the waterway differed from Lacey's waterway in different terrains through which river travels.

Actual waterway provided for the bridge in the meandering and braiding flood plain of a river may be substantially different from Lacey's waterway. In meandering/braiding rivers, width of river is found to vary along its course mainly due to bank conditions. Usually, a bridge engineer looks for such locations where width of the river is the minimum and river is found not to shift from the location over a long period termed usually as Fixed Point (Fig.1). But such ideal sites are gradually diminishing with time. Sometimes, local circumstances compel a bridge engineer to construct the bridge in the wide flood plain- width of which may be many times more (CBIP,1989) than Lacey's regime waterway given by Eq.(1).

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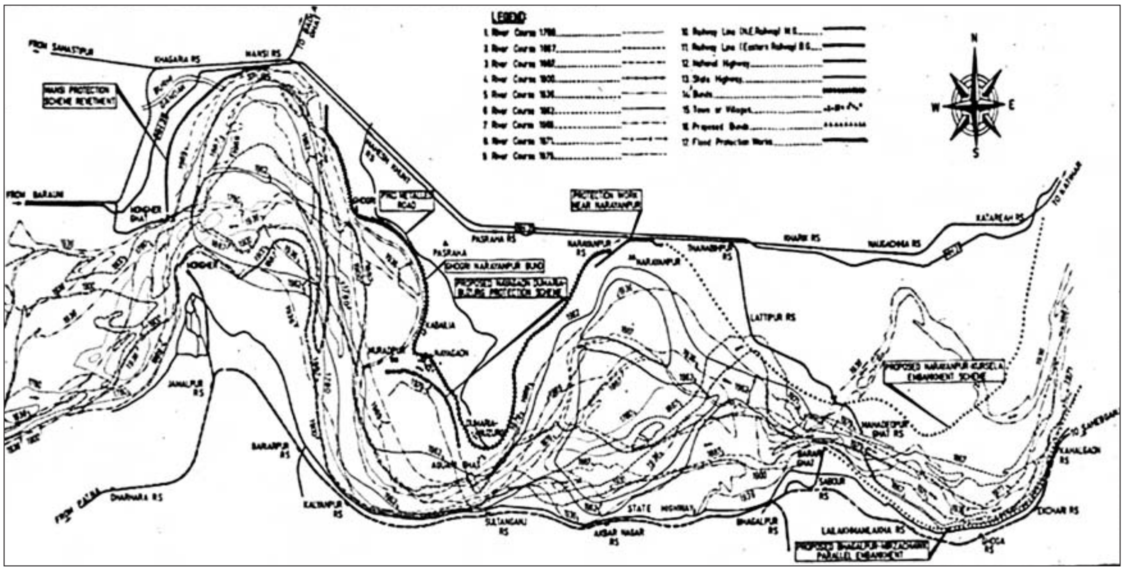

Fig.1 Illustrating Fixed Point in River Ganga Offering Ideal Sites for Bridges

Objective of the paper is to examine how the bridge waterway is decided in a meandering/braided flood plain of the river. Some of the major bridges constructed recently in rivers like Ganga, Yamuna and Brahmaputra where bridges are constructed in their meandering/ braided flood plains have been illustrated under case study at the end of the paper. In some of the cases, Lacey's waterway has been provided but in some others, waterway provided is found to be much more than Lacey's waterway.

2. MEANDERING AND BRAIDING PROCESSES

Interrelation between stream form and bed slope is schematically illustrated in Fig. 2(a) and 2(b). Quantitative relationships between channel bed slope (S_o) and mean flows (Q) were developed by Lane (1957), Leopold &Wolman (1964), Garde & Ranga Raju (2000). A non-cohesive stream bed composed of silt and sand is predicted to meander when

$$S_oQ^{0.25} > 0.00070 \qquad (2)$$

and braided when

$$S_o\,Q^{0.25} > 0.0041 \qquad (3)$$

A typical straight river is rarely stable. As shown in Fig. 2 (a), streams with very small sediment load, low gradient and low velocity, low variability in flow and low aspect ratio (width to depth ratio) may be stable for some distances. Development of lateral instability associated with erosion and deposition give rise to meandering processes as illustrated in fig. 3 (a). A lot of research work on meandering bends in a river have been carried out by eminent river scientists like Oddgard (1986), Rozovsky (1957), Zimmerman and Kennedy (1978), Engueland (1973), Wang (1992), Yalin (1999), Chitale (1970), Garde and Raju (2000), Schum (1980).

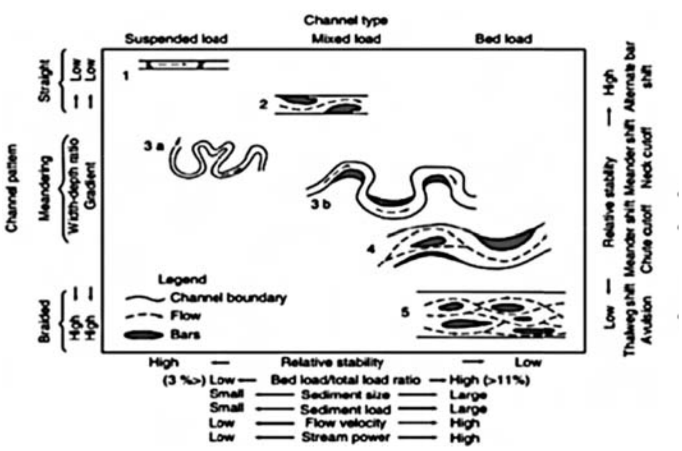

Fig. 2(a) : Different Plan Forms of a Stream like, Straight,Meandering and Braided (after Shen et al. 1981)

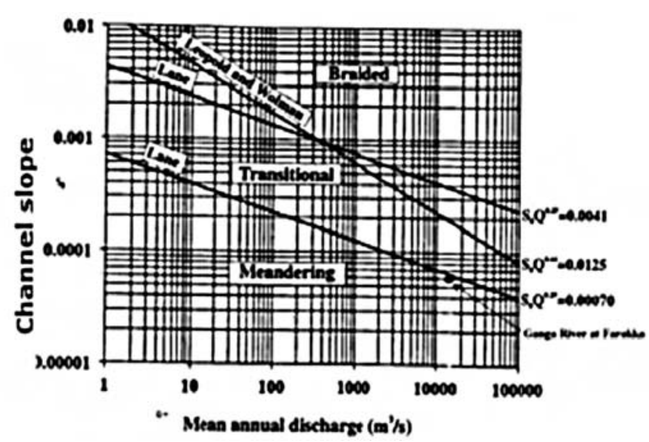

Fig. 2(b) : Lane's Criteria for Finding River Regimes (Lane,1957)

Centrifugal effect of flow curvature in a river bend results in the development of secondary current which when superimposed with axial flow causes spiral motion in a bend. Wang (1992) developed a mathematical model of the meandering processes to prove that the typical cross-slope as observed in a meander with lower bed elevation on the outer side of the bend (due to erosion of outer bank) and higher elevation of bed on the inner bank side (due to deposition of the eroded materials on the inner bank) provides stability to the stream. Hickin and Nanson (1984) described the lateral migration rate (M) of a meandering stream by the functional relation:

$$\mathbf{M = f(\Omega, b, G, h, \tau_b)} \qquad (4)$$

Where,

Ω is stream power (τ.v), τ is mean shear stress, v is mean velocity, b is the channel width, G is a parameter expressing plan form geometry of the stream, h is the height of outer bank, M is migration rate (m/year),τ_b is the erosional resistance offered by the outer concave bank undergoing erosion. Hickin and Nanson (1984) plotted M-values in a meandering river (Fig.3b) and concluded that the migration rate is maximum when meander stabilizes at an approximate value of r/w =2.5 and got the relation

$$\mathbf{M_{2.5}\ (m/year) = \rho g\ QS / \tau_b h} \qquad (5)$$

Migration of meander, as illustrated in fig. 3(a) occurs on the outer bank side subjected to higher stream flow concentration and consequent erosion of outer bank. Lateral migration of meander due to uncontrolled erosion of outer bank, as illustrated in fig. 3(a), results in the development of meandering belt.

Ashmore (1991) and Lane (1957) studied plan forms of several braided streams and concluded that there are two primary causes of braiding, namely (i) overloading i.e. stream is supplied with more sediment than that it can carry and hence part of the sediments get deposited and

(ii) Steep slope causing a wide shallow stream in which bars and islands may readily form. Garde (2006) described different causes of braiding of rivers like Brahmaputra and Kosi in India. Braiding process helps a stream to dissipate its internal energy through dividing and impinging around bars formed by deposition of sediments in the main channel itself.

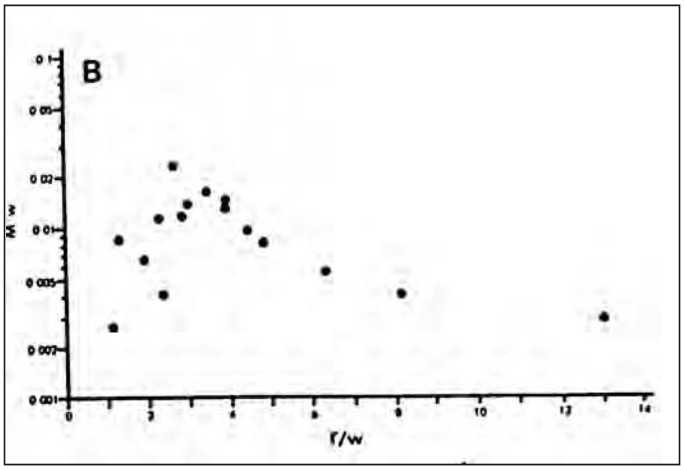

Fig.3(a) Meandering Process in a River with Gradual Development of its Cross-Section

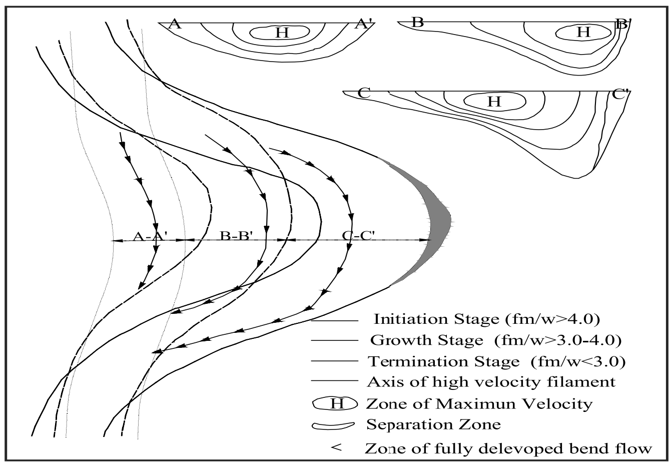

Fig. 3(b) Variation of Migration Rate, M (m/yr) with Relative Curvature (r/w) in a Meander

2.1 Meandering/Braiding Belt

It is the flood plain width in which river is found to mender/braide by lateral migration or by shifting its course. In Fig.2(a) meander belt or meander width are indicated by firm line-4 encompassing the outer side of consecutive meanders. Firm line-5 in Fig.2(a) covering the braiding channel is the braided width. It is the width in which river is found to play in the flood plain due to meandering and braiding process. Depending upon the type of banks, the mender/braiding width of a river is found to generally vary from 4 to 6 times (or even more) the regime waterway of a river given by Eq.(1).

3. WATERWAY FOR A BRIDGE IN MEANDERING/BRAIDING BELT

When a bridge is to be constructed in meandering/braided belt of a river, waterway for the bridge has to be very carefully fixed so that the bridge is safe. Too much contraction of the meandering/braiding flood plain of the river may cause unforeseen problems like high afflux and damages upstream, river instability, outflanking and wash out of the bridge, high maintenance cost, high cost of river training etc. Too long a waterway, on the other hand, will not only escalate cost and time of construction, it may lead to some hydraulic problems like non-uniform flow distribution under the bridge resulting in high scour in some spans and silting in some others. These are discussed briefly in the following paragraphs.

3.1 Hydraulics of Channel Contraction

In a mild sloping channel where the flow is at sub-critical stage, the normal waterway in the channel can be contracted to an extent so that the flow under the bridge is not choked. If B_1 is the normal waterway and B_0 is the contracted waterway under the bridge, contraction ratio (B_0/B_1) can be derived from the fundamental relation given by equation (6).

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

where F_1 and F_0 are the Froude's number of flow at the normal and the contracted sections respectively. **Fig.4** shows the functional relation between B_0/B_1 and F_0 for different values of F_1 for approaching normal flow. Flow is choked (also called critical flow) when $F_0=1$. It may be seen from Fig.4 that higher the F_1-value, less is the opportunity of contracting. It also shows that there is hardly any advantage/economy if contraction is made such that F_0 exceeds approximately 0.70. Also, flow surface becomes wavy when $F_0 > 0.70$, with highest degree of wave amplitude at critical flow at $F_0 = 1$.

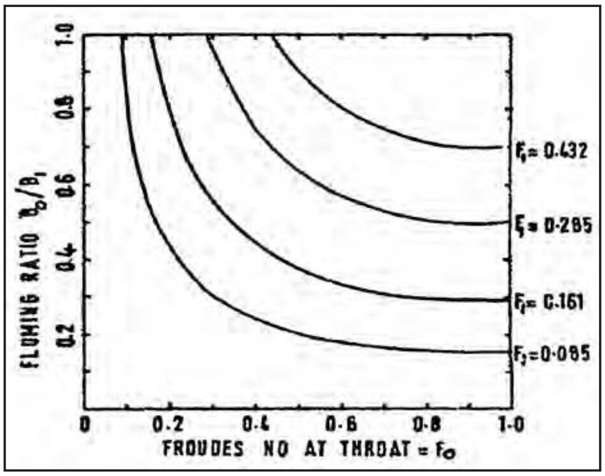

Fig.4 Variation of B_0/B_1 with F_0 for Different F_1-Values

Excessive contraction of sub-critical flow causes high loss in head due to higher velocity of flow at the contracted section resulting in higher afflux. Any contraction beyond a critical limit (at $F_0=1$) will result in the formation of hydraulic jump downstream and there will be excessive afflux upstream.To be on safe side, it will be wise not to contract a channel for F_0-value higher than 0.50.

3.2 Computation of Afflux and Its Harmful Effect

As stated under 3.1, contraction of normal flood plain width of a river will always result in afflux upstream. In case of a straight channel with uniform flow and firm bank without any flood plain, Molesworth formula prescribed by IRC:5-2015 may be adopted to compute afflux given by Eq.(7) below.

$$h_1 * = [V^2 /17.88 + 0.015] [(A/A_0)^2 - 1] \qquad (7)$$

where,

$h1^*$ is the afflux in m, V is the mean velocity of flow in the river prior to bridge construction in m/s, A_1 and A_0 are the areas (in m^2) of flow section at design HFL in the approach section and under the bridge respectively. Molesworth equation (7) is not applicable for rivers with wide flood plains and non-uniform approach flow for which Bradley (1970) suggested equation (8) for finding an approximate value of afflux.

$$h_1^* = 3(1- M) V_n^2/2 g \qquad (8)$$

where,

$M = A_0/A_1$ and V_n is the mean velocity of flow under the bridge at design HFL. Eq.8 shows that with increase in contraction, M will decrease and V_n will increase thereby increasing afflux. As already stated, too high afflux will result in submergence of flood plain of the river causing damage to life and properties upstream. Excessive afflux may cause overtopping and washing out of the bridge. Due to loss of freeboard, debris will accumulate near the piers and abutments leading to increase in scour near piers and and abutments and consequent failure of the bridge. IRC:5-2015 recommends that permissible maximum afflux due to bridge should not exceed 15 cm. As per FHWA (2012), afflux should be limited to a maximum value of 30cm where submergence of flood plain will not result in any substantial damage upstream.

3.2.1 River instability upstream due to high afflux

Too high afflux may cause river instability both upstream and downstream of a bridge. Afflux (h_1^*) results in decrease of hydraulic gradient (S_w=dy/dx) as shown in Fig.5. In the absence of bridge, the bed slope (S_0) is the same as water surface slope(S_w) and energy slope(S_f) i.e. $S_0=S_w=S_f$ as the flow is normal. With afflux, both S_w and S_f reduces (Fig.5) resulting in reduction of stream power (Ω) which can be expressed as

$$\Omega=\gamma Q S_f \qquad (9)$$

Higher the afflux (h_1^*), lower is the hydraulic gradient(S_w) and energy slope (S_f) and lower will be stream power (Ω) resulting in loss of sediment carrying capacity of river. Sediments start depositing upstream resulting in reduction in bed slope (S_0). As propounded by Bharat Singh (1964), Kennedy (1969), Lacey (1930) and other research workers, regime width of a channel increases with decrease in bed slope. Maximum increase in stream width occurs near the bridge where the magnitude of afflux is the highest. **Fig.6** illustrates widening of a river upstream of a bridge on NH-6 in MP with wide flood plain. The waterway provided was less resulting in high afflux and consequent widening of the river upstream of the bridge which is likely to be outflanked. Development of eddies in the flood plain of the river upstream of bridge results in flow instability and shifting of its main channel either left or right of the bridge which is likely to be outflanked on either side.

If the waterway is inadequate, similar instability may occur downstream of the bridge also. The difference between the high kinetic energy (K.E.) of flow ($V_0^2/2g$) at the contracted section and the normal K.E. of flow ($\alpha_2 V_2^2/2g$) in tail channel i.e.($V_0^2/2g$- $\alpha_2 V_2^2/2g$) does not get converted to potential energy unless the jet flow coming out from the contracted section is provided with a very long expanding transition with a total angle of expansion not exceeding about 10^0 to 12^0 (Mazumder,1992). The only way a stream, with a given flow, given tail water depth (Y_2) and a given mean velocity of flow(V_2) in the tail channel, can contain the excess K.E. ($V_0^2/2g$- $\alpha_2 V_2^2/2g$) is through distortion of flow resulting in flow non-uniformity and jet type flow downstream (Fig.7). K.E. coefficient or Corrioli's coefficient (α_2) given by Eq.(9) will be very high in jet type flow compared to that in normal flow where α_2~1.0.Corrioli's coefficient is defined by equation (10).

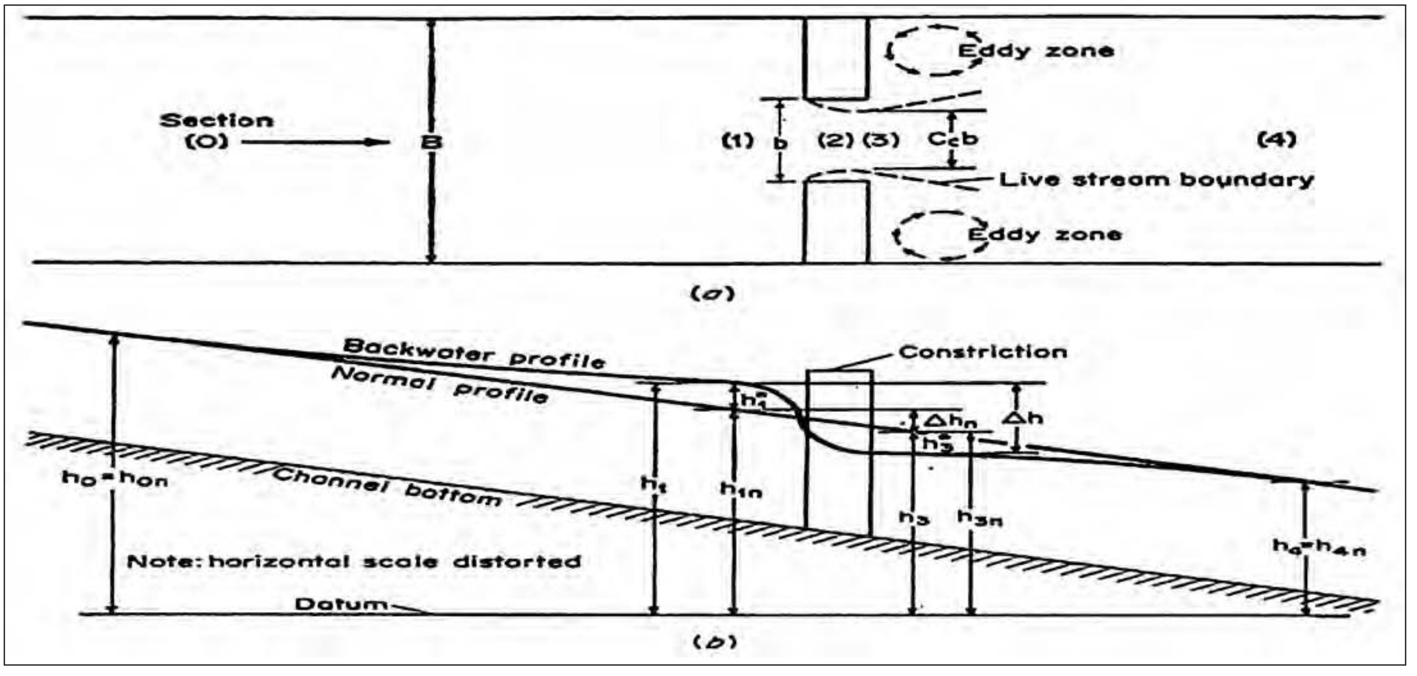

Fig.5 Plan (a) and Sectional View (b) of a Chanel Constriction, Showing Afflux (h_1^*) and Backwater Profile (Note the flattening of Hydraulic Gradient near the structure)

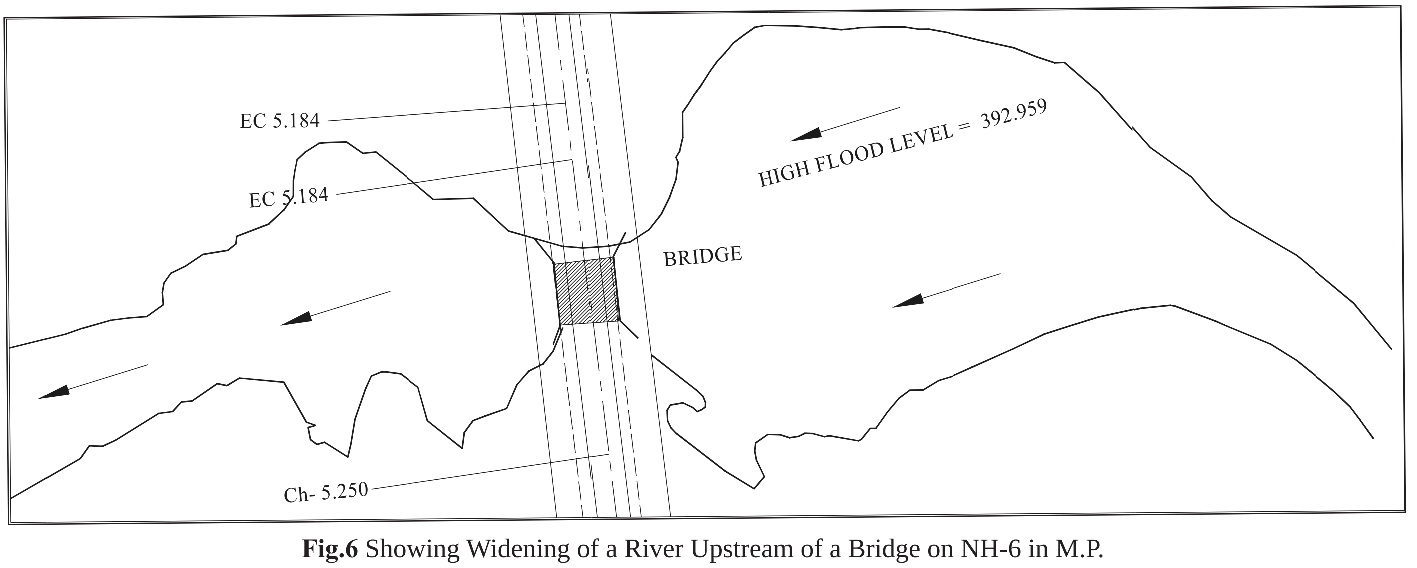

Fig.6 Showing Widening of a River Upstream of a Bridge on NH-6 in M.P.

$\alpha_2 = 1/A_2V_2^3\sum u^3dA$ (10)

where, A_2 is sectional area of flow, V_2=Mean Velocity of flow=Q/A_2, and u is the local velocity normal to an elementary area dA. When $u=V_2$ i.e. for uniform flow, α_2=1;but α_2 will be very high when flow is distorted and $u>>V_2$. The flow downstream of the contracted section turns to jet type flow which gradually diffuses to normal one far downstream where α_2~1.0. The excess K.E.of flow ($V_0^2/2g$- $V_2^2/2g$) is dissipated through turbulence production in the reach between contracted and normal section downstream. Due to formation of eddies on either side of the contracted section (Fig.5), the central jet flow becomes unstable- wandering either to left or right within the stream causing erosion of banks (Fig.6). Such unstable stream may result in wild meandering as shown in Fig.8 which shows sharp bends upstream and downstream of the bridge on NH-57 on river Bagmati. The bridge was constructed on a wide meandering flood plain with inadequate waterway.

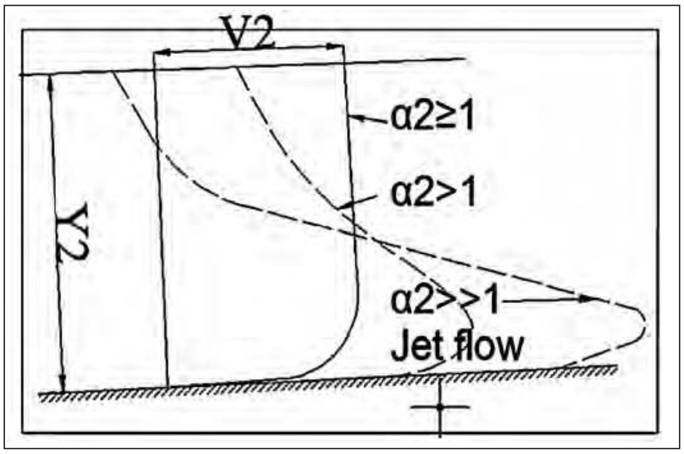

Fig.7 Showing Jet Flow with Same Velocity V2 as in Case of Normal Flow

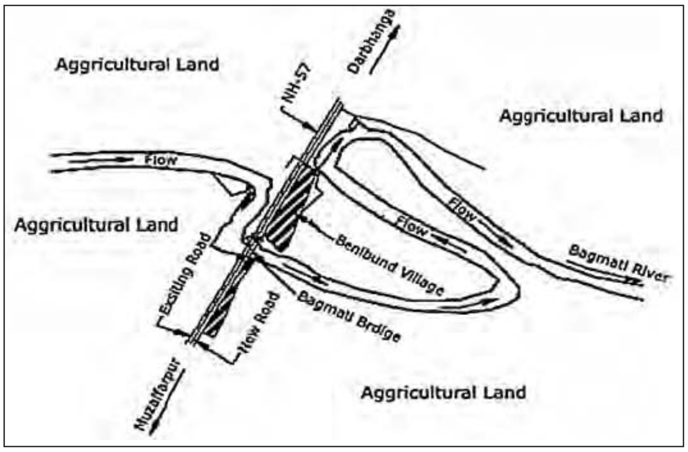

Fig.8 Sharp Bend u/s and d/s of a Bridge on NH-57

(**Note:** K.E. of Jet Flow is Much Higher (α_2>>1) than Normal Flow (α2~1.0)

3.2.2 Experimental investigations on flow stability

Experimental investigations were carried out (Mazumder and kumar, 2001) to determine flow regimes, hydraulic efficiency and flow stability in sub-critical straight expansion. It was noticed that flow stability downstream of expansion is governed by both the parameters expansion ratio (B_2/B_0) and rate of expansion $1/2(B_2$-$B_0)/L$. Here B_2 is the normal width of channel downstream of bridge and B_0 is the contracted width of channel at bridge site, L is the length of expansion. Since there is an abrupt expansion of flow downstreamof all bridges, L=0 and hence expansion ratio (B_2/B_0) alone governs stability. Experiments were performed with three different values of Froude's number (F_0) at the contracted section, namely, F_0= 0.3,0.5 and0.7 with different expansion ratio (B_2/B_0). It was observed that in sub-critical stage, flow stability downstream was primarily governed by expansion ratio. Higher the expansion ratio, higher was the instability. The flow was symmetric with symmetric eddies on either side up to a critical value of expansion ratio (B_2/B_0) of about 1.5. When B_2/B_0 exceeds 1.5 or so, the side eddies become asymmetric and central jet flow became unstable.

4. COST ANALYSIS

Apart from the hydraulic considerations discussed under sections 3.2, 3.2.1 and 3.2.2, overall cost of the bridge, approach embankments and training works should be considered while deciding waterway/length of a bridge in a meandering/braiding flood plain of a river. Cost of bridge structure will reduce if contraction is more; but the cost of approach embankment, training measures will be more. Afflux will increase with increase in design flood discharge of higher return periods. A composite hydraulic design curve was plotted by Bradley (1970) for a particular river in USA with meandering flood plain as shown in Fig.9. The designer can read from the figure the length of bridge required to pass various flows with a given backwater. To illustrate use of the resulting chart; suppose it is decided to design the bridge for a 50-year recurrence interval. If 1.5 feet (45.7 cm) of backwater can be tolerated, the bridge can be 780 feet(238m) long at a cost of $520,000. While if the backwater must be limited to 0.6 foot (18.3cm) the bridge lengthrequired would be 1,350 feet(412m) at a cost of $870,000 i.e. $350,000 more. To stay within a certain limiting rise of water surface can mean a relatively large increase in the cost of a bridge. A hydraulic design figure of this type is very useful for conveying information to others who are responsible for making decisions

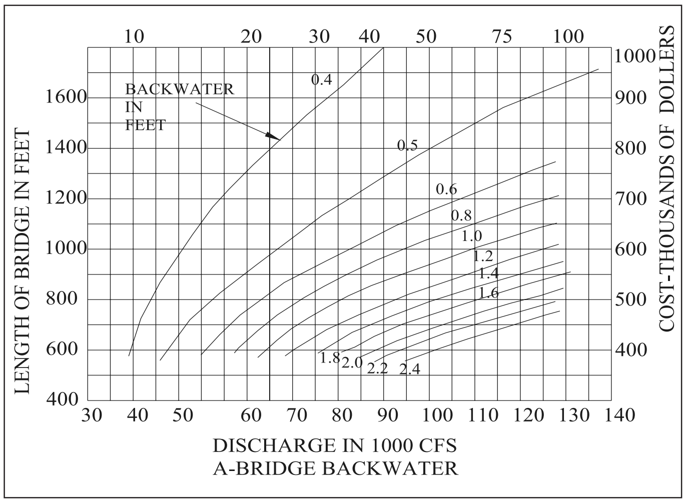

Fig.9 Length and Cost of BridgesAgainst Design Flood for Different Values of Afflux (Bradley,1978)

5. CASE STUDIES

Waterways provided for some important bridges built recently in the meandering/braiding flood plains of some major rivers are briefly mentioned below.

5.1 Bridge on Meandering Flood Plain of River Ganga

Due to non availability of land, a new bridge (in red color) is to be constructed at a site where the meandering flood plain width of Ganga is about 4.5 km. As shown in Fig.10, the river course is found to shift about 4.5 km from left to right during the period 2007 to 2016. Considering the change of its course, and the impact of the proposed bridge on the existing bridges about 2 km downstream, it was decided to provide a waterway of 3.7km (in red color) with approach embankments (in blue color) on either side. Lacey's waterway corresponding to a design flood discharge of 18,000 cumec is about 550 m.Final decision regarding waterway will be taken after physical model study.

5.2 Bridge on Meandering Flood Plain of River Yamuna

The bridge is constructed on the meandering flood plain of river Yamuna about 15.25 km downstream of Okhla barrage. Design flood discharge of 100 year return period is 10,000 cumec, Bed slope- 1 in 5,300 and design HFL is 199.50m, Lacey's waterway is 484m and total Length of the bridge provided is 530 m with elliptical guide bundhs on either side. as shown in Fig.11. Guide bundh lengths are 350 m on left side and 300 m on right side. Approach embankments of lengths 1960m on left side and 590 m on right hand side are constructed in the flood plain of the river, as shown in Fig.11. Width of the meander belt at the site is about 3 km. Mean flow velocity under the bridge-3.57m/sec.with an aflux of 0.30 m. Maximum water level u/s as observed in Physical model study are found as 200.2 m on right abutment side and 200.1mon left abutment side upstream. Normal HFL at the bridge site at the design flood is 199.5 m.

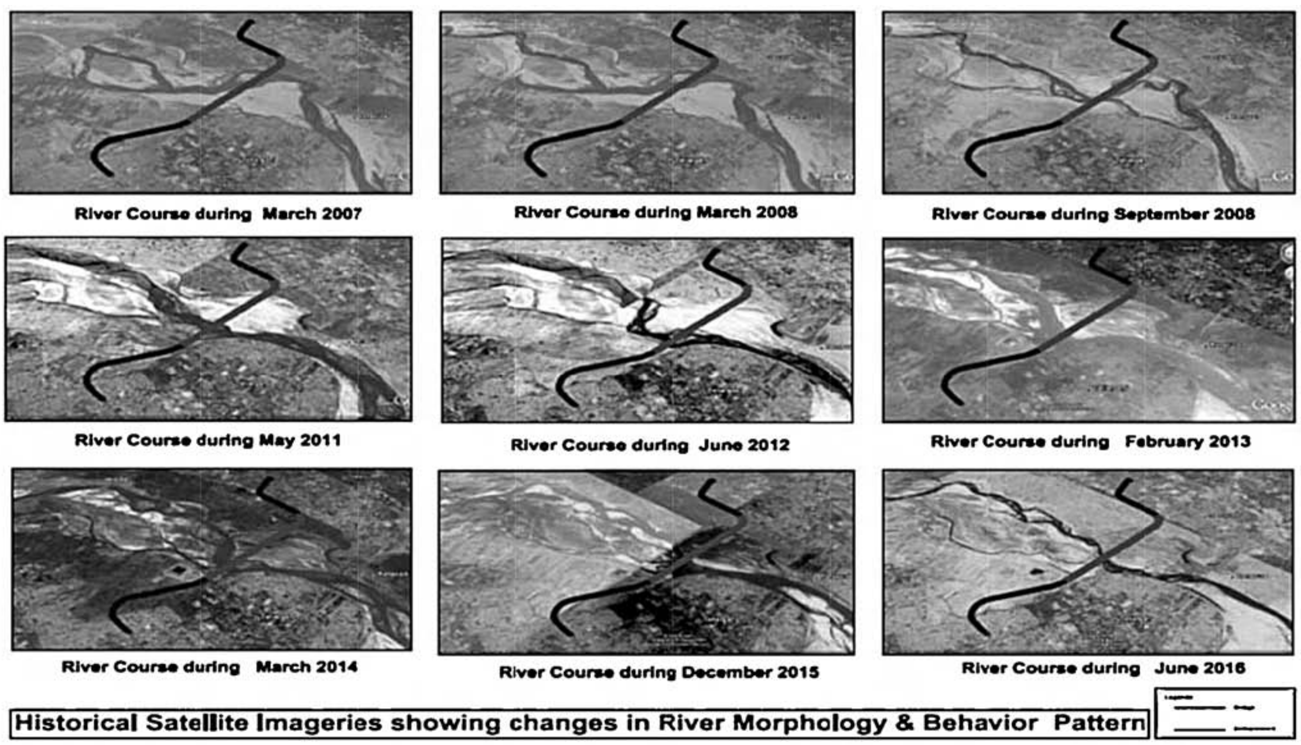

Fig.10 Shifting of the Main River Course of River Ganga During 2007-2015

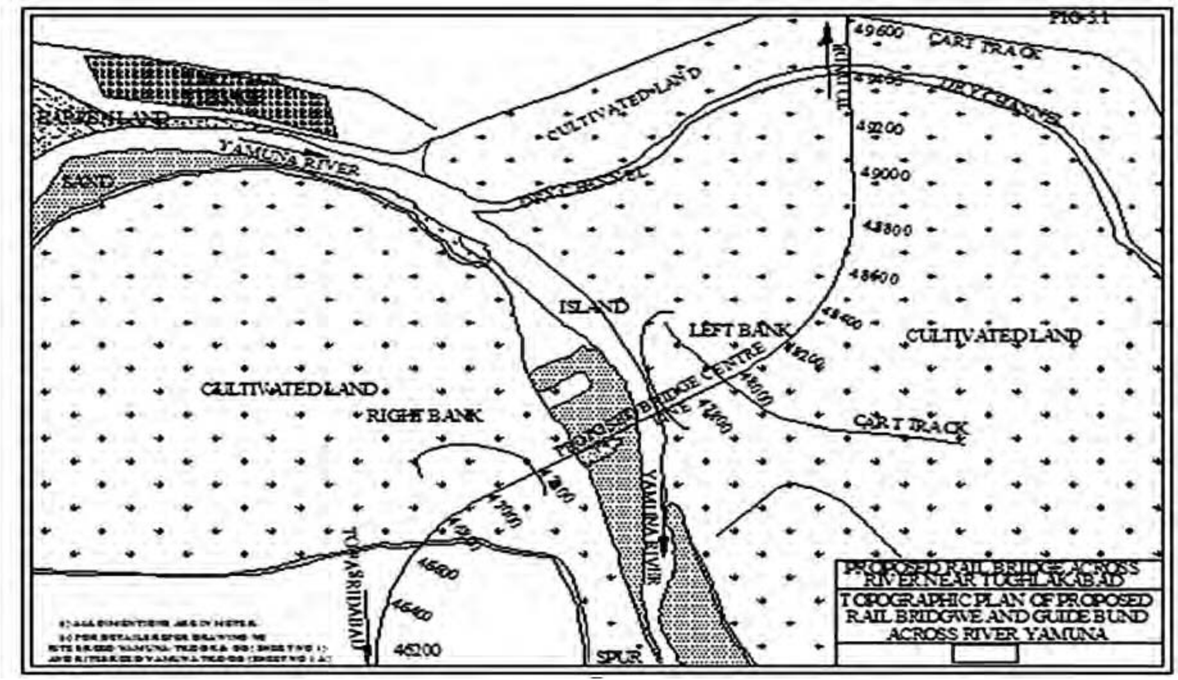

Fig.11 Bridge on Meandering flood Plain of River Yamuna

5.3 Bogibeel Bridge on River Brahmaputra

Length of the bridge is about 4.9 km in the braided flood plain of river Brahmaputra with a flood plain width of about8.4 km. Design discharge is not known. The bridge was constructed by M/s Gammon India Pvt. Ltd.Two guide bunds were provided on either side of the bridge as shown in Fig.12(taken from Google earth).

Fig.12: 4.9km long Bridge on Braided Flood Plain of River Brahmaptra

6. SUMMARY AND CONCLUSIONS

Locating a bridge in the meandering/braided flood plain of a river becomes inevitable sometimes due to non-availability of ideal sites for one reason or the other. Waterway for the bridge in meandering/braided flood plain has to be very carefully decided since any underestimation of waterway may lead to serious problems like excessive afflux and flooding upstream of the bridge apart from likelihood of outflanking and wash out of the bridge, high cost of river training etc. Overestimation of waterway, on the other hand, will not only increase the cost of bridge, it permits the river to play under the bridge leading to objectionable silting in some spans and excessive scouring in some others.In this paper, authors have discussed about some important criteria for fixing the waterway e.g. flow choking, afflux, flow stability both upstream and downstream of the bridge and of course the cost of the bridge. They have illustrated two important bridges constructed recently on the meandering flood plain of rivers Ganga and Yamuna.The third bridge is located on the braided flood plain of river Brahmaputra. Except the bridge on Yamuna river where the waterway is kept same as Lacey's waterway, the other two bridges have waterway far exceeding the Lacey's waterway. Except the bridge on river Ganga where guide bundh is yet to be finalized after model study report, the other two bridges are provided with long guide bundhs on either side of the bridges.

7. ACKNOWLEDGEMENT

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