

BEHAVIOR AND TRAINING OF RIVER NEAR BRIDGES & BARRAGES - SOME CASE STUDY

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SYNOPSIS

Large numbers of bridges and barrages are being constructed across innumerable rivers in India and abroad to serve different purposes for the benefit of people. It is important to understand the river behavior before and after the construction of bridges and barrages for their proper planning, design, construction, operation and maintenance. Costly protective measures are often needed to train the river against uncontrolled scouring, silting, meandering, anabranching and many other problems for the safety of the structures as well as the approach and marginal/afflux embankments. Breaching of embankments, outflanking of the structures, river avulsion etc. cause disruption of traffic, unprecedented damages and unimaginable sufferings of the people and often defeat the very purpose of the structures. In this paper, author has discussed with figures and photographs about the morphological changes that were found to occur upstream and downstream of some bridges and a barrage and the protective measures adopted to train the rivers in the Himalayan region of India.

INTRODUCTION

Proper understanding of river behavior in the vicinity of hydraulic structures (Mazumder, 2004) like bridges and barrages is extremely important for their planning, design, construction, operation and maintenance apart from the safety of the structures. Except in their mountainous reaches, most of the rivers in the Himalayan region have wide flood plains and the normal waterway is often restricted (Mazumder et al,2002) due to economic considerations. Such restriction often changes the river regime and stability. Flow field which used to prevail prior to the construction of the structures also gets changed. There is afflux subjecting the channel to backwater effect upstream. Hydraulic and energy gradients are decreased in the backwater reach. As a result, stream power, proportional to the product of discharge and energy slope ($Q.S_e$), decreases and the sediment carrying capacity of the stream is considerably reduced. This causes deposition of sediments upstream of the structures leading to aggradations and flow instability. Immediately downstream of the structures, there is degradation due to release of water with less sediment load. Often there is flow distortion and localized erosion (Mazumder ,1993) due to residual kinetic energy of flow and high turbulence level of the released water . In barrages, there is diversion of flow from the main channel and as such there is reduction of flow (Q) in the main channel and sediment carrying capacity of river is reduced since stream power ($Q.S_e$) is reduced . Uncontrolled aggradations and degradation (MOWR,2004) often lead to serious problems of river training near these structures.

Depending upon the extent of constriction and location of the structure in the flood plain , the approaching river may often be unstable and asymmetric. Such unstable river may shift its course and wander anywhere within the flood plain resulting in meandering and widening of the river, localized erosion of bed and banks and a bowl like delta formation in the vicinity of these structures (Fig.1) sometimes leading to their outflanking (photograph-1). Costly river training measures are often found necessary to protect afflux/approach embankments and arrest wild meandering and possible shift of the existing river course (flow avulsion) and outflanking of the structures. Often the river is found to breach the protection embankments resulting in flood damages and unprecedented sufferings of the people living nearby (Photographs-2 and 3).

If the river is in a meandering state, the process of aggradations and degradation occur simultaneously. Islands (locally called chars/shoals) are formed upstream due to sediment

deposition and the main flow shifts away from the shoals inducing curvature to the stream and formation of secondary current. The outer side of the curved flow undergoes constant erosion and the eroded materials are deposited on the inner bank side resulting in further growth of the chars/shoals. This process of erosion of outer bank and deposition on inner bank result in further

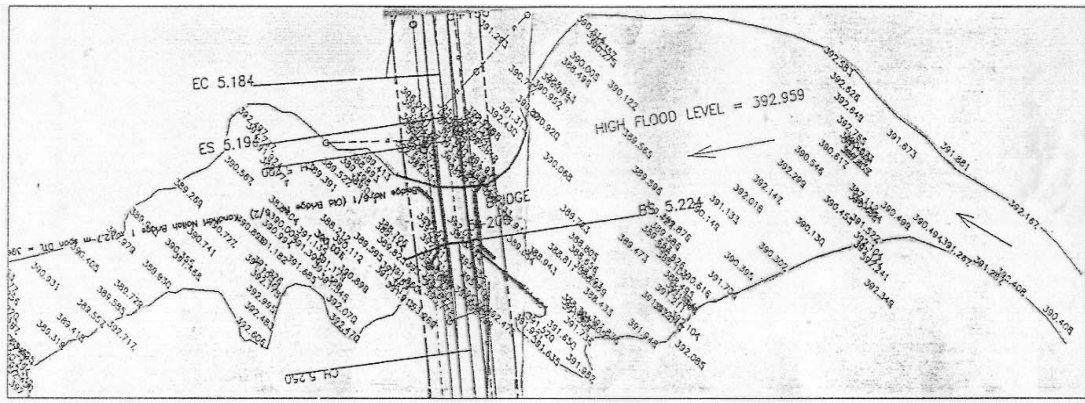


Fig. 1 Formation of a Bowl upstream and downstream of a Bridge (in a State Highway in M.P.) due to excessive restriction of waterway .The Bridge is likely to be outflanked



Photograph-1: Outflanking of a vented causeway on the stream 'Danab Khola' in Nepal

increase in curvature, stronger secondary current and greater erosion of the outer bank causing migration of the meander on the outer side (Fig.2) till a state of stability occurs.

One of the primary objective of writing this paper is to discuss about the above mentioned river behavior with particular reference to two bridges on rivers Mahananda and Bagmati and a barrage on river Ganga (Farakka Barrage). Normal waterway has been restricted and approach embankments have been constructed in all these structures built in wide alluvial flood plains as observed in most of the rivers in the Himalayan region.



Photograph-2: Disastrous Flood in Malda District in West Bengal after Breach of Left Marginal Embankment Upstream of Farakka Barrage in the year 1998



Photograph-3: Devastation brought about by river Kosi due to change of its course on August 18 th, 2008 due to Breach in left Embankment about 12 km upstream of Kosi Barrage

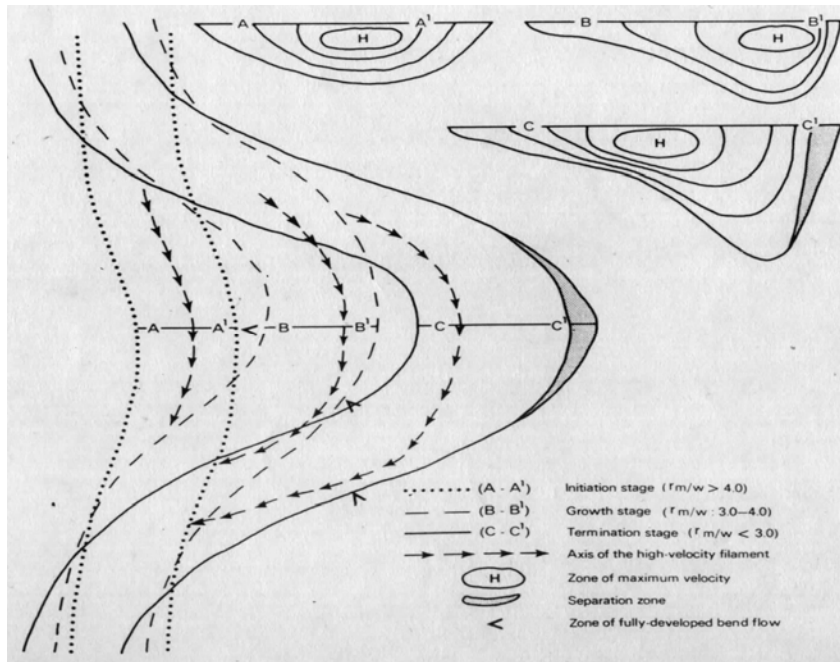


Fig. 2 Lateral Migration of Meander and Development of Stream Cross -Section in a Typical Meandering Bend with Time

MORPHOLOGY, STABILITY AND PLAN FORMS OF RIVERS

Understanding the behavior of a river is complicated due to interrelated geomorphologic, hydrologic, hydraulic and sediment parameters. A geologist and a geo-morphologist is concerned about evolution and changes in river over a long period of time. A river engineer concerned with design of bridges and barrages and river training/improvement works usually studies the past history of the river and its morphological changes over a much shorter period, generally about 100 years or so, depending on the length of life of the structures. The interrelation between channel plan forms, hydraulic and sediment parameters and relative stability of a river is illustrated in Fig. 3 (Schum-1980, Leopold and Wolman-1957). It may be seen that the different plan forms of a river e.g.

straight, meandering, anabranching, braided etc. depend on the geometry, sediment load, bed slope and discharge of the river. Quantitative prediction of stream response to climatological or watershed changes is based on the fundamental relation given by equation -1(Lane- 1955).

$$Q S_e \propto Q_s d_{50} \dots \dots \dots (1)$$

where Q is the discharge, S_e is energy slope, Q_s is sediment transport rate and d₅₀ is mean sediment size. Garde (2006) used Area- velocity- flow relation, Manning's equation and sediment transport equation and modified the above equation as

$$Q^{6/7} S_e^{7/5} \propto Q_s d_{50}^{3/4} \dots \dots (2)$$

Increase in sediment load due to erosion, mining operation, land slide, etc. in the catchment areas results in rise in Q_s. Since Q and d₅₀ remain the same, it invariably leads to aggradations and increase in energy slope (S_e), till the stream power (Q S_e) is sufficient to carry the increased sediment load 'Q_s' and the relation given by eq. 1 & 2 are satisfied.

Farakka barrage was constructed on river Ganga with the primary objective of flow diversion to river Bhagirathi/Hoogly (a tidal river) so that its flow (Q) and hence sediment carrying capacity (Q_s) are increased. Hoogly river - the lifeline of Kolkata port, the cities/towns and the industrial hub on both banks of Hoogly river - was silting up very fast resulting in deterioration of its navigability and increase in salinity, especially during lean flow period. With higher upland discharge (Q) in Bhagirathi/Hoogly (due to flow diversion from Ganga through the feeder canal), Q_s increased and hence navigability of Hoogly river improved and salinity decreased after the construction of Farakka barrage.

Quantitative relationships between channel plan forms, bed slope (S_o) and mean annual flow (Q) are illustrated in Fig.4 (Lane -1957).

A non-cohesive stream bed composed of silts and sands is predicted to meander when

$$S_o Q^{0.25} > 0.00070 \dots \dots \dots (3)$$

and braided when

$$S_o Q^{.25} > 0.0041 \dots \dots \dots (4)$$

The challenge to the river engineer is to understand the hydrologic, hydraulic and morphologic balances prevailing in the river system and their catchments and to design projects within the frame work of these balances. Such an approach generally proves to be more efficient than continually trying to maintain the system against the natural tendencies of the river.

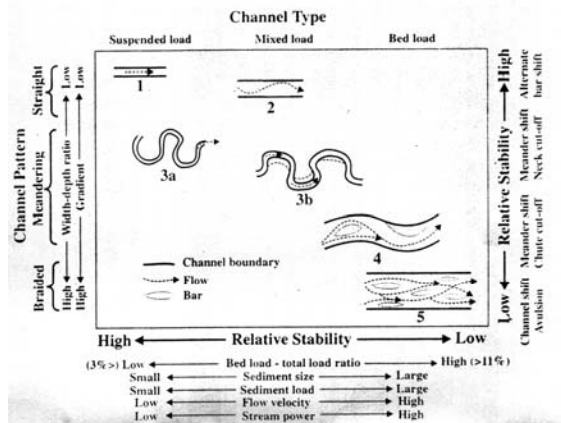


Fig. 3 Interrelation between channel type, hydraulic and sediment parameters and relative stability of streams

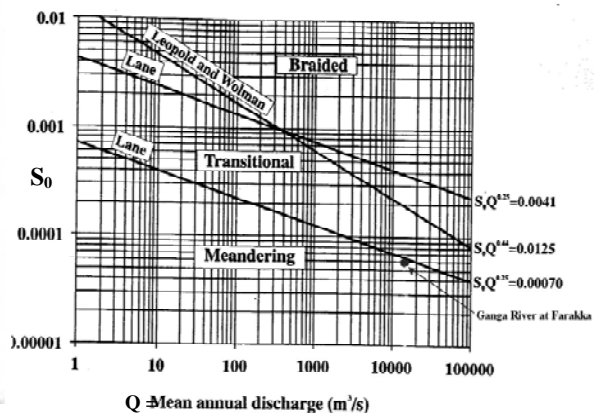


Fig. 4 Interrelation between stream forms, bed slope and mean annual discharge

RIVER REGIME AND MEANDERING

Aggradations and degradation in the vicinity of hydraulic structures like bridges and barrages are principally due to the loss in balance between sediment supply and transport rates. Rivers attain a stable regime over thousands of years through adjustment of its slope and cross-section according to the volume of water and sediment carried over time. Commendable work on river regime have been done by Lacey (1930), Blench (1957), Chang (1988), CBIP(1989), Diplas (1990), Englund (1973), Yalin (1999), Garde (2006), Garde and Ranga Raju (2000) for prediction of stable river geometry based on sediment size in bed and banks and the dominant flow carried by the river.

The major cause of change in stream characteristics can be attributed to human activities. Regardless of degree of channel stability, human activities may produce dramatic changes in the river behavior and fluvial morphology locally and throughout the river. Man made hydraulic structures like bridges and barrages and river training works like embankments, groynes, revetments etc. often result in great departure from the equilibrium/regime state that existed prior to the construction of these structures.

A typical straight stream is rarely stable. As shown in Fig. 3, 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 (about 10-15 km). Development of lateral instability associated with deposition and erosion on alternate river banks give rise to thalweg pattern. Uncontrolled deposition and erosion ultimately give rise to meander formation as illustrated in fig. 2. A lot of research work on meandering river have been carried out by river engineers like Rozovsky (1957), Zimmerman and Kennedy (1978), Engueland (1973), Oddgard (1986), Yalin (1999), Chitale (1981). Wang (1992) developed a mathematical model of the meandering process to prove that the typical cross slope developed in a meander with lower bed elevation on the outer side of bend and higher elevation on the inner bank side (arising out of secondary current) essentially provides stability to the meandering stream.

Meanders are dynamic and found to move both laterally (at faster rate) and longitudinally (at slower rate). Lateral migration of meanders in Yellow river in China measured by Chien (1961) was found to vary from 20 to 100 meter per day due to extremely high sediment load. He also observed that high lateral shifting of meander occurs downstream of constriction/control section along the river course. Lateral migration rate of river Ganga upstream of Farakka barrage is reported to be 300-400 m per year as per Keskar Committee (1996) report.

Hickin and Nanson (1984) described the lateral migration rate (M) of a meander by the functional relation

$$M = f(\Omega, b, G, h, \tau_b) \quad \dots(5)$$

where Ω is stream power ($\tau.v$), b is a parameter expressing plan form geometry of the stream, h is the height of outer bank (degree of incision), τ_b is the erosional resistance offered by the outer concave bank undergoing erosion. Plotting measured migration rate against relative curvature (r/w , where r is the radius of curvature and w is the stream width) , Hickin concluded that the migration rate is maximum when meander stabilizes at an approximate value of $r/w = 2.5$ and obtained the relation

$$M_{2.5} \text{ (m/year)} = \rho g QS / \tau_{b,h} \quad \dots\dots\dots(6)$$

Where $M_{2.5}$ is the maximum rate of migration corresponding to $r/w = 2.5$. However, this relation is applicable for natural meanders without any interference from man made hydraulic structures like bridges and barrages

HYDRAULICS OF FLOW IN THE VICINITY BRIDGES AND BARRAGES

Hydraulic structures like bridges and barrages often cause constriction of waterway either vertically or laterally or both. In bridges for example, the constriction is only lateral whereas in the case of

dams and barrages it is mostly vertical and sometimes both lateral and vertical. Depending on the degree of such restriction of waterway, the flow may be free or submerged. In free flow past a bridge and barrage, the flow gets choked with the structure acting as a control point. In choked flow, afflux is very high due to the minimum specific energy requirement and there is hydraulic jump on the downstream side. Weirs and barrages have low solid obstructions i.e. low crest elevation. Now-a-days, barrages are generally made of low crest height with high head gates for the purpose of creating increased head and storage and for flushing out sediments deposited in the reservoir. The flow over the weir/barrage during flood may be free or submerged/drowned depending on crest height and modular limit (Mazumder, 1981) of the structure. Depending on whether the flow is choked or not, hydraulic jump may or may not form. In case of choked flow, there is always a difference in energy level (ΔE) across the structure. If the actual loss of energy ($\Delta E'$) within the jump is equal to the drop in energy level (ΔE), there is no residual kinetic energy of flow downstream of the structure (Mazumder, 1985) and the flow is normal and uniform downstream of the structure. If the energy dissipation is inadequate/incomplete within the jump, there is residual kinetic energy of flow which causes turbulence and non uniformity in the flow distribution since a given flow with a given depth and a mean velocity can contain the excess residual kinetic energy only through non-uniformity and distortion of flow - resulting in production of high level of turbulence (Mazumder, 1993a). Mazumder and Sen (1991) found that in many of the low height barrages in India, the pre-jump Froude's number of flow lies between 2 to 4. It is well established that the hydraulic jump in this region of inflow Froude's number is either undular or oscillating in nature and the jump efficiency (as energy dissipater) is very poor. As a result, the flow downstream has high non-uniformity and is often found to swing either on left or right bank side due to flow instability (Mazumder 1993b). It becomes highly turbulent causing erosion of bed and banks on the side where the turbulent wall jet type flow adheres to. Deposition of sediment occurs on the opposite bank side creating cross slope and meander formation.

In north and north-east India, most of the rivers are found to be moving in a wide flood plain formed principally due to meandering/braiding channel formation. When a bridge or a barrage is constructed on such a wide flood plain (khadir), usually the waterway for the bridges (Mazumder-2009a) and barrages are kept limited up to Lacey's regime waterway. The khadir width is restricted (Mazumder, 2008) by providing approach embankments and guide bundhs as shown in fig-5. Such restriction may or may not be symmetrical. As a result, there is considerable afflux (Mazumder, 2003) and back water upstream of the structure resulting in sedimentation and lateral instability of flow upstream. The main flow is often found to hug on to one of the banks causing erosion and the eroded materials are deposited on the opposite bank resulting in meandering flow.

On the one hand the outer bank of a meandering bend is subjected to high concentration of flow and drag, on the other hand, the critical shear stress for incipient motion of bed and bank materials is extremely low on the outer bank side principally due to the formation of secondary current (Mazumder-2010). This results in caving in of the outer bank material even with negligible drag, especially where the outer bank is made of fine alluvial soil of extremely poor shear strength.

Uncontrolled and progressive erosion of outer bank causes migration of meander as shown in Fig.2. This may ultimately lead to, breaching, outflanking of hydraulic structures and flow avulsion when the river shifts its course and join other low lying rivers as observed in case of Kosi river upstream of Kosi barrage (Mazumder-1985, 2009b, Chitale-2009) in August, 2008 as predicted earlier by Chitale (2000). Similar tendency is also observed in river Ganga upstream of Farakka barrage discussed afterwards under case study. The approach flow is often found to separate at the head of guide bund resulting in a skew flow both upstream and downstream of the bridge and barrage, resulting in high flow concentration and scouring. As a result, the very purpose of providing guide bund is defeated sometimes. Non-uniformity (obliquity) of approach flow causes not only deep scour due to high flow concentration, it creates large cross - slope along the bridge/barrage axis resulting in

stronger secondary current and greater scour. High degree of non-uniformity of flow approaching and departing the barrage is reported in case of both Kosi and Farakka barrages .

TRAINING OF RIVER NEAR BRIDGES AND BARRAGES

When damages are caused by a river prior to construction of any structure, people blame God. But the same people curse the project authorities and ask for compensation when even less damage occur after the construction of structures like bridges and barrages on a river. Thus, river improvement and river training works should be an integral part of hydraulic structures like bridges and barrages for the safety of the structures and the people living near the river banks.

River training measures like, afflux/flood embankments, guide bunds, groynes, pitching, launching apron etc. are often found necessary to protect the structure and to ensure that the river continues to flow along the desired course without causing any damage to the bridges and barrages. Adequate protection of the approach and flood/afflux embankments and their annual maintenance is vitally needed to prevent breaching, outflanking and possible flow avulsion. Gate operation schedule in a barrage is to be decided based on the nature of sediment deposition in the vicinity of barrage. Procedure for planning, design, construction, operation and maintenance of the different river training works are available in IRC , BIS and RDSO Codes/guidelines. Choice of appropriate river training measure is site specific and require both knowledge and experience about river behavior before and after the construction of bridges and barrages. Some of them are discussed briefly under case study.

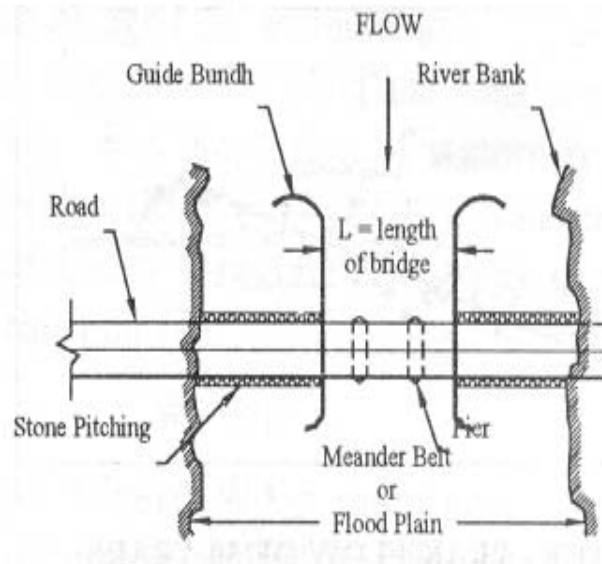


Fig. 5 Restriction of Waterway in Bridges in Flood plain with Guidebundhs and Approach Embankment

CASE STUDY OF RIVER BEHAVIOR & TRAINING

(a) Bridge on NH-31 Crossing River Mahananda

Fig.6 and photographs 4 and 5 illustrate the river bank erosion upstream of Mahananda river bridge on NH-31 The length of the bridge is 636 m with 12 equal spans of 53 m each. It has a catchment area of about 8000 sq km up to the bridge site. Design discharge is about 5000 cumec with 50 year return period and the corresponding HFL is 36.74 m. Due to restriction of its large flood plain extending up to 3 km or more. a big central island has been formed upstream of the bridge due to deposition of sediments resulting in anabranching (bifurcation) of the river and erosion on the outer banks of the branches as shown in Fig.6. Costly river training measures consisting of permeable spurs and cut-offs were recommended to protect the villages and agricultural lands on either side of the banks and to prevent outflanking of the bridge

(b) Bagmati River Bridge on NH-57

Bagmati Bridge on NH-57 across river Bagmati is 100.8 m long with 4 equal spans 25.2 m each. The river is severely threatening both the national highway and the bridge. Originating from Nepal, Bagmati river has a catchment area of about 1200 sq km up to the bridge site. Design discharge is about 1000 cumec with a return period of 50 year and the corresponding HFL is 50.81 m. Like other rivers in north Bihar, river Bagmati carries huge amount of sediments along with water. Due to

deposition of these sediments and development of sharp meandering bends as shown in photograph 6 and Fig.7 , the conveying capacity of the river has reduced considerably over the years.

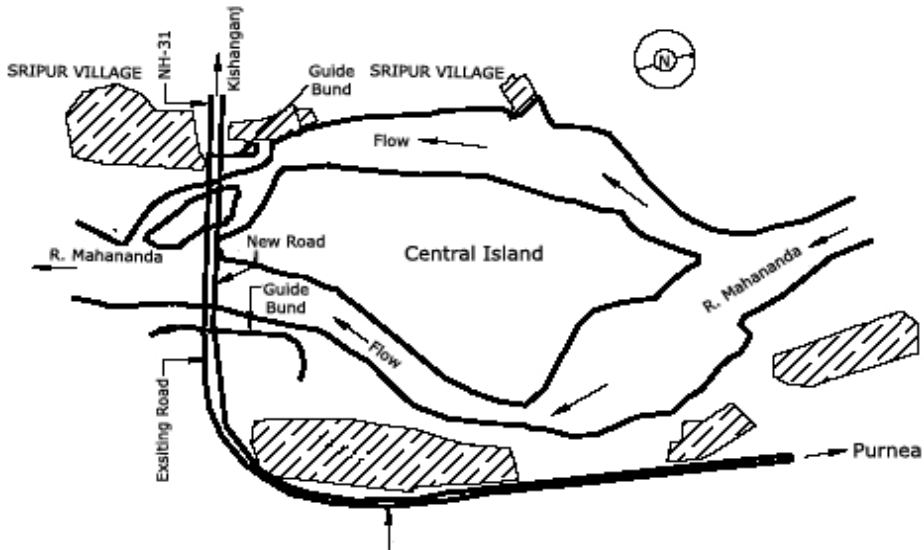


Fig.6 Plan showing Anabranching of River Mahananda u/s of Bridge on NH-31



Photograph-4: Erosion on Right Bank U/S of Mahananda Bridge



Photograph-5: Embayment of Right Bank of River Mahananda U/S of Bridge

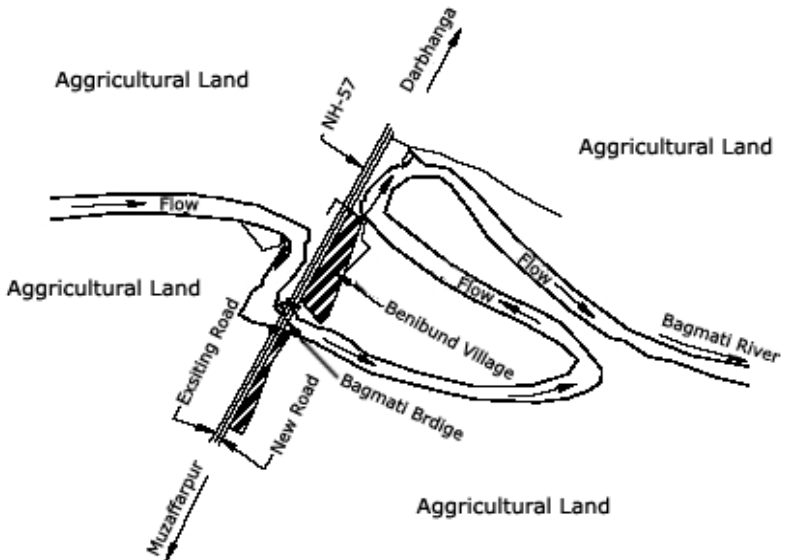


Fig.7 Plan view of River Bagmati showing Sharp Bends u/s and d/s of Bridge on NH-57



Photograph-6: Erosion on Left Bank of Bagmati River Damaging the Habitats on Outer Bank of 90° Bend U/S of Bagmati Bridge

Due to high restriction of flood plain, the river spills its low height banks and spreads over a large width both upstream and downstream of the bridge during monsoon. The river is on the verge of forming natural cut-offs both upstream and downstream of the bridge. Training measures (Mazumder,2008) consisting of artificial cut-offs , spurs and guide bunds have been recommended to straighten the river and make it flow axially under the bridge for the safety of the bridge and the approach embankment

(c)Farakka Barrage on River Ganga

Commissioned in 1975, 2,244m long Farakka barrage across river Ganga is a project of national importance. Main purpose of the project is to forcibly divert 1135 cumec fresh upland flow of river Ganga to its tributary Bhagirathi/Hoogly as illustrated in Fig.8(a). River Hoogly is the lifeline of Kolkata (including Kolkata port) and a large industrial complex developed on both sides of Hoogly over the years. During lean flow season, the river was getting dried up due to silting of its offtake point near Jangipur. A 38.3 km long feeder canal has been constructed for forcible diversion of flow from Ganga to Hoogly. The barrage is designed for a flood discharge of 76,455 cumec with design afflux of 0.5 m. Further details of the barrage are available elsewhere (Mazumder- 2004, Naresh Kumar, et al-2010).

With a longitudinal bed slope of 1 in 20,000 and a mean annual flow of 12,200 cumec, the river is in a meandering state near Farakka as indicated in Fig. 4. On an average, river Ganga carries 800 million tons of sediments (Sanyal 1980) every year up to the barrage and it is estimated that approximately 13 lakh ha.m of sediments have already been deposited upstream of the barrage. Several shoals have been formed upstream of the barrage resulting in lateral flow instability, meandering and strong flow curvature resembling a braiding delta like pattern. On several occasions, the marginal embankments were breached causing unprecedented flood damages (Mazumder, 2000). The river has moved about 7 km inside Malda district as shown in Fig.8(b) wiping out thickly populated villages near the left marginal embankment. 450 people died and property worth about rupees 1000 crore was damaged in 1995 and 1998 floods alone. 27 nos. of spurs were constructed to protect the marginal embankment upstream. But the river has swallowed most of these spurs due to deep erosion near the left bank marginal embankment. At the offtake of river Pagla near Panchanandpur village, as many as 10 nos of retired embankment (Fig.9) were constructed to prevent further migration. Any avulsion of the mighty river Ganga upstream of the barrage may cause change in its course and it may capture rivers like Pagla, Kalindri and

Mahananda. The barrage will be ineffective and it will cause colossal damage to Malda district including the National highway (NH-34), Railway line and afflux bund protecting Malda town as shown in Fig.8(a).

Downstream of Farakka barrage, river Ganga has scoured the right bank in Murshidabad district of West Bengal. A typical meander is developing with Malda on the outer side of the upstream meander(left bank) and Murshidabad on the outer side of the downstream meander with Farakka Barrage at the centre acting as a nodal /fixed point. The river is threatening the existence of several towns located on right bank and loss of very fertile land. If the erosion continues further, the river may merge with Feeder canal defeating the very purpose of the barrage. Railway line and NH-34 will be washed out. 96 nos of submersible type boulder spurs were constructed to arrest erosion from Farakka to Jalangi, a distance of about 100 km. Several spurs and revetments have been washed out. A master plan of riverbank protection both upstream and downstream of the barrage has been drawn at a cost of about rs. 927 crores (at 1995 prices) as per the recommendations of Pritam Singh and Keskar Committee appointed by the Ministry of Water Resources. Govt. of India.

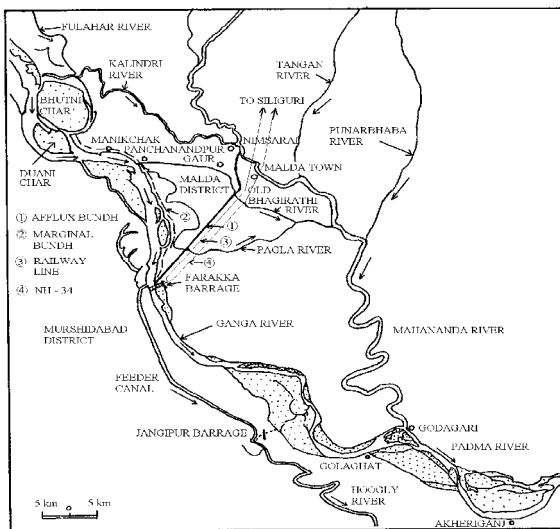


Fig.8 (a) River Ganga and its Tributaries near Farakka Barrage

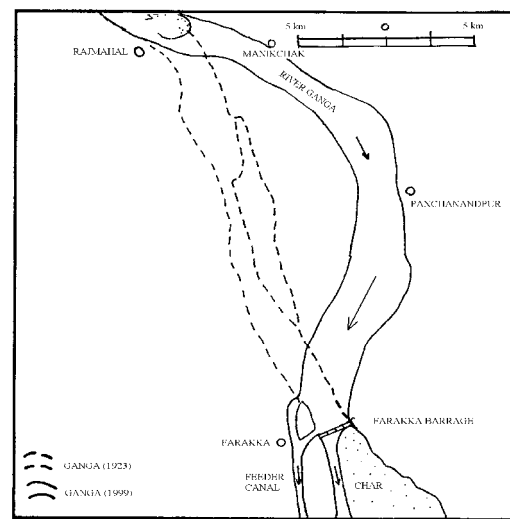


Fig.8(b) Change in Course of River Ganga Over the years 1923 to 1999



Fig. 9 Construction of Retired Embankments to Prevent Migration of Meander Towards Left Bank Upstream of Farakka Barrage Near Panchanandpur

CONCLUSION

Understanding river behavior is important for proper planning, design, construction, operation and maintenance of bridges and barrages. Morphological study of river before and after the construction of these structures is essentially needed for the safety of the structure, the approach and afflux embankments and for planning and design of appropriate river training measures. Due to high restriction of wide flood plains of the Himalayan rivers carrying large volume sediments during flood seasons, some of the hydraulic structures are creating unforeseen problems arising out of flow instability, meander formation, deep scour and formation of shoals. Uncontrolled erosion and deposition process in the vicinity of bridges and barrages often create serious problems of river training and threaten the people living nearby. Case studies of bridges on NH-31 across river Mahananda and Bagmati bridge on NH-57 across river Bagmati have been discussed with figures and photographs. Similar case study of Farakka barrage across river Ganga has been made and the need of proper training measures has been stressed for the safety of the barrage and protection of life and properties both upstream and downstream of the barrage.

ACKNOWLEDGEMENT

Author wishes to thank Aqgreen Engineering Management, ICT and SWI authorities for extending all facilities needed for writing the paper.

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