RIVER BEHAVIOUR UPSTREAM AND DOWNSTREAM OF HYDRAULIC STRUCTURES

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ABSTRACT

Understanding river behaviour upstream and downstream of hydraulic structures help in their proper planning, design and maintenance. Morphology of the river and its aggradation/degradation process have been discussed with reference to flow of water and sediments in the river. Uncontrolled erosion and deposition process create lateral instability of flow and meandering of the river. Migration of meander laterally due to secondary current and cross-slope developed in a typical meandering bend have been explained and the parameters affecting the migration have been described. Hydraulic analysis is made of the river behaviour upstream and downstream of hydraulic structures like bridges and barrages as a result of sediment deposition upstream and inadequate energy dissipation due to skewed hydraulic jump downstram. Problems being encountered in Kosi and Farakka barrages both upstream and downstream have been narrated and the future problems of river training have been discussed with figures and photographs. River behaviour upstream and downstream of some bridges where the normal waterway is highly restricted have been outlined.

INTRODUCTION

Numerous hydraulic structures e.g. Bridges, Barrages, Dams, cross- Drainages, Groyens etc are constructed on rivers. Proper understanding of river behaviour in the vicinity of the hydraulic structures is extremely important in their planning, design and maintenance apart from the safety of the structures. They obstruct the normal waterway. Flow field which used to prevail prior to their construction is changed. There is afflux subjecting the channel to backwater effect upstream. Hydraulic and the energy gradients are decreased. The sediment carrying capacity of the stream is reduced causing deposition of sediments upstream. On the downstream side of the structures, there is degradation due to release of water with less sediment load and residual kinetic energy flow with higher turbulence. Uncontrolled aggradation and degradation often lead to serious problems of river training.

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 location and wander anywhere within the flood plain resulting in erosion of bed and banks and delta like formation in the vicinity of the structures. Costly training works are required to prevent the possible shift in the existing river course and outflanking of the structures. Often the river breaches the protection embankments, resulting in flood damages and unprecedented sufferings of the people living nearby.

If the river is in a meandering state, the process of aggradation and degradation occur simultaneously. Islands (locally called chars) get formed upstream due to sediment deposition and the main flow shifts away from the chars 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 side resulting in further growth of the chars. This process of erosion of outer bank and deposition on inner bank may result in further increase in curvature, stronger secondary current and greater erosion of the outer bank causing migration of the meander on the outer side till a state of stability occurs.

One of the primary objective of writing this paper is to discuss about the above mentioned river behaviour with particular reference to two barrages (Farakka and Kosi) and a few bridges normal waterway of which is restricted and approach embankments are constructed in wide alluvial flood plains as observed in most of the rivers in north and north east India.

RIVER MORPHOLOGY/AGGRADATION/DEGRADATION

Understanding the behaviour of any given stream is complicated due to interrelated geomorphologic, hydraulic and hydrologic parameters. The interrelation between channel planform, hydraulic and sediment parameters and relative stability of a river is illustrated in Fig. 1 (Schum, 1981). It may be seen that the different plan forms of a river e.g. straight, meandering and braided depend on the geometry, sediment load, slope and discharge of the river. Interrelation between stream form, bed slope and mean discharge is also illustrated in Fig. 2 (Lane 1957). A decrease in discharge combined with increase in sediment load will result in decrease in flow depth and increase in flow width (mostly observed upstream of hydraulic structures). Quantitative prediction of stream response to climatological or watershed changes is based on the fundamental relation given by equation- 1 below.

$$QS_e \; \alpha \; Q_s d_{50} \; \ldots. \qquad \ldots\ldots\ldots(1)$$

Where Q is the discharge, S_e is energy slope, Q_s is sediment transport rate and d_{50} is median sediment size. This relation was originally proposed by Lane (1955). Garde (2004) used Area- velocity- flow relation, Manning's equation and Sediment Transport equation to prove the exact relation

$$Q^{6/7} \, S_e^{\;7/5} \;\; \alpha \; Q_S \;\; d_{50}^{\;3/4} \qquad \ldots..\;(2)$$

Increase in sediment load due to erosion in catchment, mining, land slide, etc. results in rise in Q_s. Since Q and d_{50} remain the same, it invariably leads to aggradation and increase in energy slope (S_e), till the stream power (QS_e) is sufficient to carry the increased Q_s and the relation given by eq. 1 is satisfied.

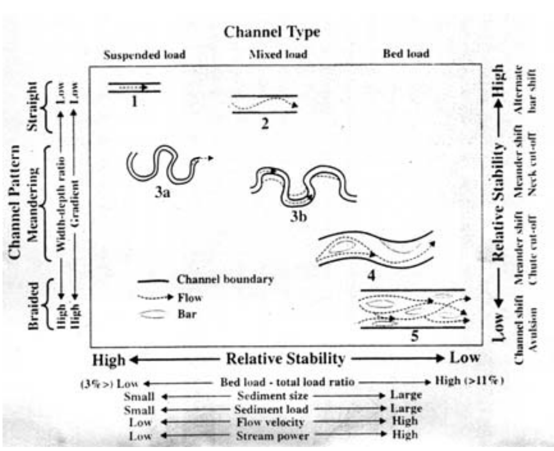

Fig. 1 Interrelation between channel type, hydraulic and sediment parameters and relative stability of streams

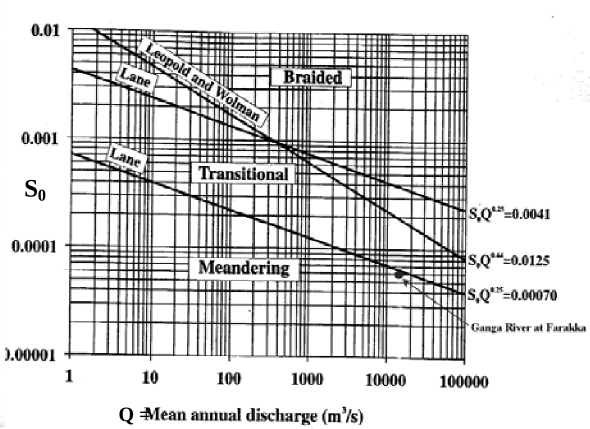

Fig. 2 Interrelation between stream form, bed slope and mean discharge

When waterway is restricted, there is afflux and back water upstream of the structure resulting in reduction in energy slope (S_e). Q and d_{50} remaining same, the stream power ($Q.S_e$) is reduced and the sediment carrying capacity of the stream is reduced. As a result, there is deposition of sediments resulting in aggrdadation upstream of the hydraulic structure till such time the original slope is restored and the balance given by equation (1) is restored.
In all diversion structures, comparatively clear water is withdrawn from upstream (for irrigation, hydropower, water supply etc.) resulting in decrease in Q downstream. As a result stream power ($Q.\ S_e$) gets reduced and hence the sediment carrying capacity (Q_s) is reduced, d_{50} remaining the same. Obviously, sediments will be deposited downstream of such diversion points and there will be aggrdadation and rise in slope till such time equation (1) is satisfied and the original stream power is restored.

Downstream of the hydraulic structures, there is erosion of stream bed and degradation occurs due to release of comparatively clear water (due to sediment deposition upstream) as well as higher turbulence level. Choking of flow results in hydraulic jump formation downstream (Mazumder 1993). If energy dissipation is insufficient, residual kinetic energy of flow causes non- uniformity and distortion of flow since the only way a stream (with given depth and discharge) can carry excess kinetic energy downstream is through flow non-uniformity. Corriolis coefficient (α) is increased and hence the kinetic energy of flow $\alpha\, v^2/2g$. It has been established (Mazumder 1993) that even 1% residual K.E. is sufficient to raise value of α to about 2 and 2% residual K.E. of flow creates enough flow distortion to raise α value to about 4. It is also established that clear water causes more erosion compared to silt laden water due to decrease in drag (silts provide damping of turbulence). It is well known (Mazumder, 1995) that higher turbulence level causes greater erosion, other parameters remaining the same.

REGIME CHANNEL AND HUMAN INTERFERENCE

Aggradation/degradation in the vicinity of hydraulic structures is 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 section according to the volume of water and sediment carried over time. Commendable work have been done by Lacey (1929) Blench (1957) Diplas (1990), Yalin (1999), Garde and Ranga Raju (2000) and many others 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 stream characteristics locally and throughout the entire waterway. Stream improvement works by man made river structures (for use of river water) often result in great departure from the equilibrium than that existing prior to these works. The challenge to the engineer is to understand the hydrologic, hydraulic and geomorphologic balances within a given waterway and the catchment and to design project within the frame work of these balances. Such an approach will generally prove to be more efficient than continually trying to maintain the system against the natural tendencies.

RIVER STABILITY AND MEANDERING

Interrelation between stream form and bed slope is schematically illustrated in Fig. 1 and 2. Quantitative relationships between channel bed slope (S_o) and mean flow (Q) are presented by Lame (1957). A non cohesive stream bed composed of silts and sands is predicted to meander when

$$S_o\, Q^{0.25} > 0.00070 \;\ldots\ldots\ldots \qquad (3)$$

and braided when

$$S_o\, Q^{.25} > 0.0041 \;\ldots\ldots.\ \ldots.. \qquad (4)$$

A typical straight stream is rarely stable. As shown in Fig. 1, 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 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. 3. A lot of research work on bends in a meandering river have been carried out by eminent river scientist like Rozovsky (1957), Zimmerman and Kennedy (1978), Engueland (1973), Oddgard (1986), Wang (1994), Yalin (1999), Chitale (1981), Garde and Raju (2000). 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 (due to erosion) and higher elevation on the inner bank side (due to deposition) arising out of secondary current provides stability to the meandering stream.

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

$$M = f\,(\Omega, b, G, h, \tau_b) \qquad \ldots.(5)$$

Where Ω is stream power (τ.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 (m/year) against relative curvature (r/w, where r is the radius of curvature and w is the stream width) as shown in fig. 4. Hickin concluded that the migration rate is maximum when meander stabilizes at an approximate value of r/w =2.5 and got the relation

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

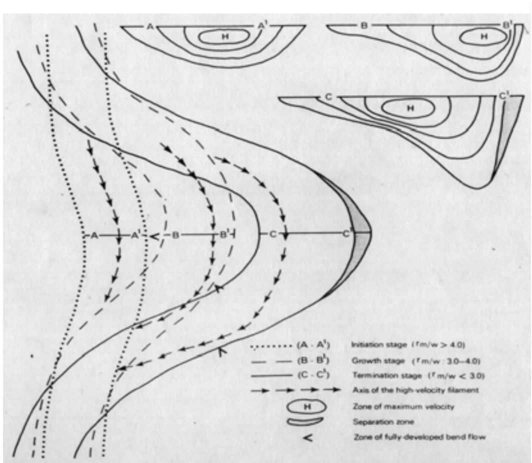

Fig. 3 Lateral Migration of a Meander and Stream cross Section in a bend

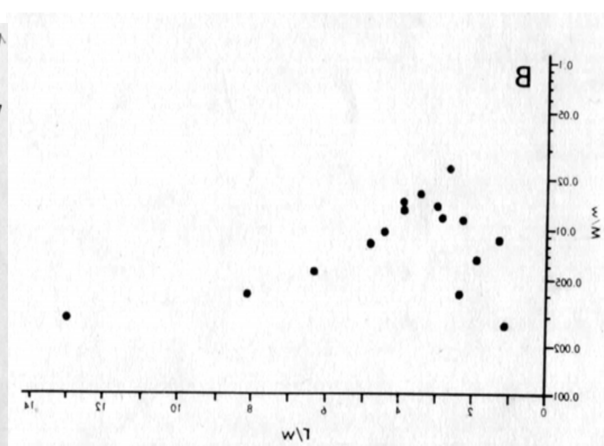

Fig. 4 Variation of Migration Rate (M) with Relative curvature (r/w) in a Meander

Where $M_{2.5}$ is the maximum rate of migration corresponding to r/w = 2.5. Migration of meander as illustrated in fig. 3 occurs on the outer bank side subjected to higher stream flow concentration. Uncontrolled meandering may lead to outflanking of hydraulic structures and flow avulsion when the river shifts its course and may join other low lying rivers (tendencies as observed in both the case of Farakka and Kosi barrages discussed afterwards).

ANALYSIS OF FLOW BEHAVIOUR IN THE VICINITY OF HYDRAULIC STRUCTURE

Hydraulic structures often causes restriction of waterway either vertically or laterally or both. In bridges for example, the restriction 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, the flow gets choked and the afflux is high (to satisfy the minimum specific energy requirement) and there is hydraulic jump on the downstream side. In submerged weirs/barrages of low solid obstructions (nowadays, the barrages are generally made of low crest height with high head gates for the purpose of storage), the flow may be 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. But the fact remains that there is difference in energy level (ΔE) across the structure. In case the actual energy loss ($\Delta \acute{E}$) within the jump (free or submerged) 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 free from any turbulence downstream and it remains more or less uniform. If the energy dissipation is inadequate, 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 mean velocity can contain the excess residual kinetic energy only through non-uniformity and production of turbulence. Author has found (Mazumder and Sen 1991) that in many of the low height barrages in India, the prejump Froudes number of flow lies between 2 to 4. It is known that the hydraulic jump in this region of Froudes number is either undular or oscillating in nature and the jump efficiency is very poor. As a result the flow downstream has high non-uniformity and is often found to swing to either on left or right bank side due to instability (Mazumder 1993). 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 other bank side creating cross slope and meander formation.

In north and north- east India, most of the streams are found to be moving in a wide flood plain formed principally due to meandering/braided channel formation (depending on slope and magnitude of water and sediment transport). When a bridge or barrage is constructed on such wide flood plain (khadir), usually the waterway of these structures are kept limited up to Lacey's regime waterway. The khadir width is restricted by providing approach and embankments and guide bundhs as shown in fig-5. Such constriction may or may not be symmetrical. As a result, there is considerable afflux (Mazumder, 2003) and back water upstream of structure resulting in sedimentation and lateral instability of flow. The main flow is often found to move along one of the banks and deposition is found to occur on the opposite bank resulting in meandering upstream. Uncontrolled erosion on the outer bank side and deposition on the inner bank side of such meandering approach flow lead to migration of meander especially where the banks are made of fine alluvial soil of extremely poor shear strength $\tau_{b.}$ Often the approach flow separates at the head of guide bund and move towards the head works of diversion canal. High degree of non-uniformity of approach flow is reported in both Kosi and Farakka barrage, discussed afterwards. 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 resulting in stronger secondary current and greater scour. Development of such strong cross -slope along the structure also results in imperfect energy dissipation downstream of the structure. Skewed hydraulic jump gets formed along with roll waves along the structure. It is well known that the energy dissipation in a skewed jump is far from satisfactory and a considerable amount of kinetic energy of flow remains undissipated downstream of the structure. The residual kinetic energy of flow is responsible for formation of wall jet like phenomenon (observed downstream of both Farakka and Kosi Barrage) which is largely responsible for large scale erosion of the bank along which the main jet like flow moves downstream.

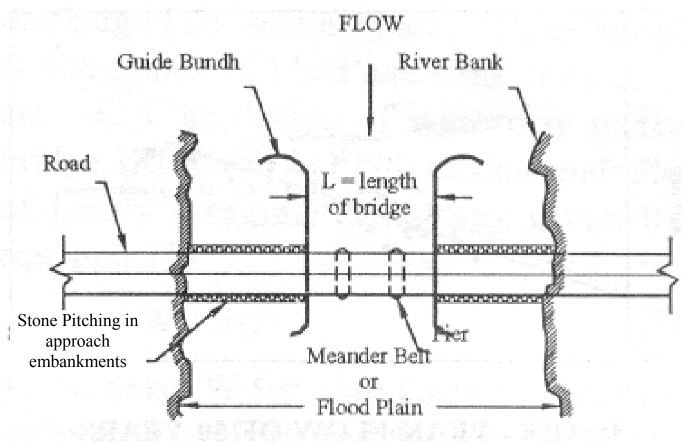

Fig. 5 Restriction of Waterway in Bridges in Flood plain with Guidebundhs and Approach Embankment

RIVER BEHAVIOUR NEAR BARRAGES

To illustrate the above mentioned river behaviour, author wishes to discuss the problems being faced in two major barrages in India, namely Farakka and Kosi barrages.

Farakka Barrage on River Ganga

Built in 1971 at a cost of about Rs. 400 crores (at ’71 prices), Farakka barrage is constructed across river Ganga near Malda town in West Bengal. Its main purpose is to forcibly divert 1135 cumec flow of main Ganga to its tributary, (Hoogly river) which was getting dried up due to silting of its offtake near Jangipur. A 38 km long feeder canal has been constructed for diversion of the flow. The barrage is designed for a flood discharge of 70,930 cumec (25 lakh cusec) with design afflux of 0.5 m. Further details of the barrage are available elsewhere (Mazumer 2004). With a longitudinal bed slope of 1 in 21000 and a mean annual flow of 12200 cumec, the river is in a meandering state as indicated in Fig. 2. On an average ganga carries 800 million tons of sediments (Sanyal 1980) every year up to the barrange and it is estimated that approximately 13 lakh ha.m of sediments have already been deposited upstream of the barrage causing formation of several islands, meandering, cross slope, and strong flow curvature, lateral flow instability, upstream of the barrage. As shown in Fig-6, the river has developed a sharp meander upstream of the barrage subjecting colossal problem of erosion of Malda district lying on the outer side (left bank) of the meander. On several occasions, the marginal embankments were breached causing colossal flood damages (Mazumder 2000). The river has moved about 8 km inside Malda district wiping out thickly populated villages near the left marginal embankment. 450 people died and property worth about rupees 1000 crores was damaged in 1998 flood 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 of the left bank. Near Manikchak, as many as 10 nos of retired embankment (Fig.6) were constructed to prevent migration. Avulsion of the mighty river Ganga upstream of the barrage may cause change in its course and it may join low lying rivers like Pagla, Kalindri and Mahanadi. 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. More than Rs. 1000 crores have already been spent in the training of river. But these conventional measures are found to be ineffective due to very weak soil in the left bank and the highly concentrated flow there. Alternative methods of river training have been recommended (Mazumder 2001) for protection of the bank and safety of the barrage.

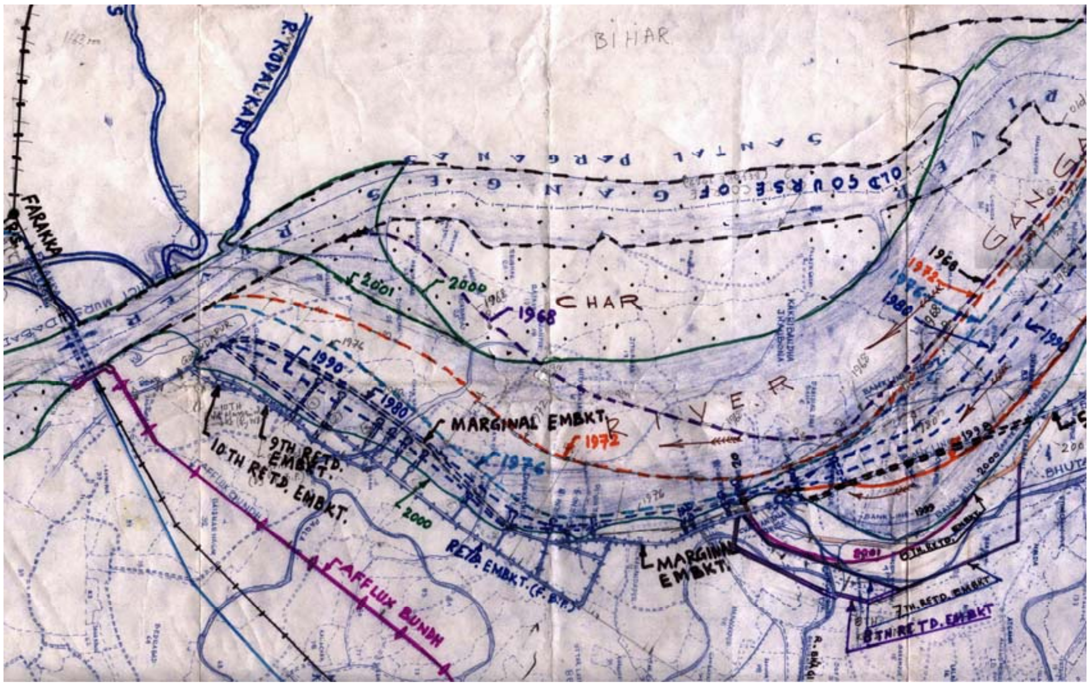

Fig. 6 : Migration of Meander towards Left Bank Upstream of Farakka Barrage

Downstream of Farakka barrage, the 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 outerside 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, NH-34 will be washed out. 96 nos of submergible 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 as per the recommendations of Pritam Singh and Keskar Committee.

Kosi Barrage on River Kosi

Kosi barrage was constructed on river Kosi (a tributary of Ganga) in 1963 with the objective of irrigation, flood control and hydro power generation. 85% of its catchment lies in Nepal and the rest 15% in India. Prior to the construction of barrage and flood embankments (about

263 km including eastern and western embankment), the river was highly unstable due to sudden expansion of flow (Mazumder 1993) at Chatra where the river enters in the flat flood plains of Bihar after its journey in the gorges in Nepal. During the period 1731 to 1954, Kosi had shifted 113 km laterally from east to west covering 7680 km^2 of land in north Bihar and about 1280 km^2 in Nepal mainly due to the deposition of the sediments brought by the river from the mountainous terrain of Nepal to the flood plains of north Bihar. Two canal system (Eastern and Western Canals) were built upstream of the barrage for irrigation and hydropower, apart from serving an existing irrigation canal at Chatra in Nepal. Afflux bundhs were also constructed to protect the area upstream from inundation due to afflux. The downstream flood embankment starting from barrage up to its outfall (at Kursela) were constructed to channelise the river within a khadir width of 16 km with a view to contain the river within these embankments and prevent shifting of the course which had been causing devastating damages in Bihar. The river is aggrading both upstream and down stream except a short stretch immediately downstream of barrage where it is degrading. The principal cause of aggradation is the tremendous sediment load brought by the river annually estimated as 95 million tons. Earlier before the construction of the flood embankments, a large portion of the sediments used to be deposited in the flood plain. After the construction of embankments, most of the sediments are getting deposited on the khadir bounded by the flood embankments.

Because of the instability, the river has caused breaches of both embankments and it is threatening to create an avulsion and trying to merge its course with low level rivers on the east side. In spite of constructing 284 numbers of impermeable groyen to train the river, it is causing breaches of the banks causing floods and damages to the crops. On the upstream side, 50% of built in capacity of the eastern canal is not available due to heavy siltation of the canal and the river reach between Chatra and Hanumangarh Barrage site . If the current rate of aggradation and instability of the river is not controlled both upstream and downstream of barrage, the river will continue to attack the embankments causing breaches and flooding. Training of such an unstable river is going to cost so heavily that it will be almost impossible to contain the river within the flood embankments. (Chitale, 2000)

RIVER BEHAVIOUR NEAR BRIDGES

A large number of major, medium and minor bridges have been constructed on rivers all over the country. For economy, the waterway provided under the bridges is often restricted and is less than the normal waterway corresponding to design flood discharge. In the north and north east India, the Khadir width of a river is found to be larger than the regime width mainly due to meandering or braided type channels. In such wide flood plains, the waterway is usually restricted to Lacey's regime width or even less by constructing approach embankments and guide bunds as shown in Fig. 5. The various effects of such waterway restriction has been discussed elsewhere (Mazumder, Rastogi et al 2002). Due to asymmetric approach flow upstream of the bridge, the river may hug on to one of the banks and deep embayment is observed near the head of guide bunds leading to high erosion and damage of the approach embankments and the guide bunds. Costly protective works like stone pitching over graded filters (now-a-days being replaced by packed stones in nylon gabions laid over geofilters), spurs, etc. are to be constructed for training/protection. Even then there is damage and sometimes outflanking of the bridges, if the waterway is highly restricted. Fig. 7 illustrates outflanking a bridge on stream Danab Khola in Nepal. This submergible type bridge (causeway) was built over a large number of hume pipes (for passage of dry weather flow). Additionally, transition structures made of stone gabions were constructed near the abutments causing high degree of restriction of normal waterway. Finally the bridge was outflanked on either side as shown in Fig. 7. High afflux (due to excessive restriction of waterway) is responsible for backwater and aggradation upstream in the same manner as already discussed under barrages. Due to sedimentation, the channel becomes wider and shallower resulting in lateral instability. Fig.8 illustrates development of a bowl form both upstream and downstream of a bridge on a stream in M.P. state highway, due to high degree of restriction of waterway. The stream may finally outflank the bridge on either side of the abutment. Sometimes, there is high tortuisity of flow upstream as shown in fig. 9 which shows the meander upstream of Ekti River Bridge on NH-31C. The approach flow in such bridges with guide bundhs is often found to be unsymmetrical. Flow separation occurs at the head of guide bund and there is high obliquity and non-uniform distribution of flow along the bridge length causing deep channel formation, as observed in the case of an old bridge on NH-27 across Ghagra river near Ayodhya.

Fig. 7 Outflanking of a vented causeways on the stream 'Danab Khola' in Nepal

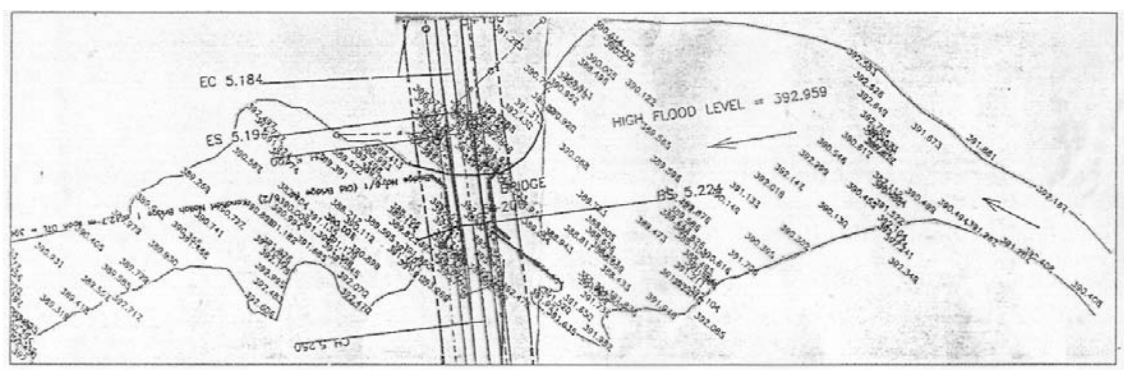

Fig. 8 Formation of a Bowl upstream and downstream of a Bridge (on M.P.State Highway) due to excessive restriction of waterway

River behaviour on the downstream of a bridge is closely linked with the behaviour of river upstream. If the river hugs on to the left bank upstream, it hugs on the right bank downstream due to a typical meander formation with the bridge acting as a fixed nodal point as observed near barrages also. Unlike barrages/weirs, there is no energy dissipation device downstream of a bridge. When there is choking of flow (due to high degree of asymmetry and non-uniformity of flow), often there is choking of flow and a hydraulic jump forms down stream. The jump may be skewed one resulting in poor energy dissipation and wall jet type flow along one side and a large eddy on the other side. Energy dissipation occurs through interaction of the eddy with the jet flow. Obviously, the flow distribution all along the eddying /jet flow will be non-uniform resulting in erosion of the bank on one side (jet side) and deposition of sediment on the other side (eddy side). Such a flow develops cross-slopes and may often result in meandering depending on strength of the bank adjacent to the jet flow.

Although flow contraction (upstream of bridge) is an efficient process, flow expansion (downstream of the bridge) is not. Depending on the extent of constriction (upstream) and rate of expansion (downstream), the flow may be unstable. Such unstable flow may wander within the flood plains causing devastating erosion of banks and approach embankments. It is advisable not to constrict normal waterway more than 2/3rd (corresponding to expansion ratio of 1 ½ times) beyond which flow may be unstable (Mazumder 2001)

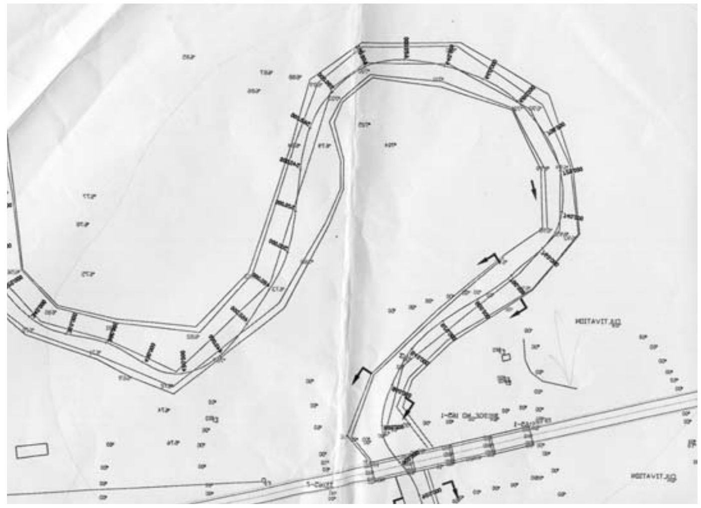

Fig. 9 Meandering of Ekti River Upstream of the Bridge on NH-31c due to excessive restriction of waterway

CONCLUSION

In spite of elaborate and very costly river training measures adopted, some of the hydraulic structures are creating unforeseen problems arising out of flow instability, meander formation, deep scour along one bank and deposition (formation of chars) on the other bank. Uncontrolled erosion and deposition process in the vicinity of hydraulic structures has created serious problems of river training and threat to the people living nearby. Conventional measures of river training by flood embankments and groyens are not found to be effective especially in case of Farakka and Kosi barrages. Too much restriction of normal waterway by constructing conventional guide bundhs and approach embankments have in some cases created serious problems of stability and outflanking. Understanding river behaviour is important in the planning, design and maintenance of hydraulic structures.

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References:

1. Blench, T. (1957) "Regime Behaviour of Canals and Rivers" Butterworth Scientific Publishing, London
2. Chitale, S.V. (1981), ": Shape and Mobility of River Meanders" Proc. XIX Congross of IAHR, Vol. 2, pp 281-286, New Delhi
3. Chitale, S.V. (2000) "Future of the Kosi River and Kosi Project'J. of Institution of Engineers (I) Vol. 81, Dec, 99 109-114

4. Diplas, P. (1990), "Characteristics of Self Formed Straight Channels" J. of Hyd. Engg., ASCE, Vol. 116, No. 5.
5. Engelund, F. (1973), "On the Origin of Meandering and Braiding in Alluvial Channels", J. of Fluid Mechanics Vol. 59, No. 2, PP 289-302
6. Garde, R.J. (2004), Aggradation and Degradation in Alluvial Streams", Theme paper pub in Seminar on Silting of Rivers – Problems and Solutions org. by Ministry of Water Resources through Central Water Commission and CW & PRS, Pune, Feb 12-14, New Delhi
7. Garde, R.J. and RangaRaju, K.G.(2000) "Mechanics of Sediment Transport and Alluvial Stream Problems" 3rd Ed. New Age Int. Pub.Pvt. Ltd. , New Delhi.
8. Hickin, E.J. and Nanson, G.C. (1984) "Lateral Migration of River Bends" J. of Hyd. Engg. ASCE, Vol 110, No. 11, pp 1957-67
9. Lacey, G. (1929) "Stable Channel in Alluvium" J. of Instn. Of Civil Engineers, U.K., Paper no. 4736,Vol. 229, PP 259-292
10. Lane, E. W. (1957) "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.
11. Lane, E.W. (1955), "The Importance of Fluvial Morphology in Hydraulic Engineering" Proc. ASCE, Paper 745, pp 1-17, July.
12. Mazumder, S.K. and Joshi, L.M. (1981) "Studies on Modular Limit of Critical Flowmeter, Proc XIX Congress of IAHR , New Delhi
13. Mazumder, S.K. (1985) "Effectiveness of Impermeable type Groyens in River Training with particular reference to River Kosi in India" 2nd Int. Conf. On "The Hydraulics of Floods and Flood Control" org. by British Hydromechanics Research Association, Fluid Engg. Centre, Cambridge, England 24-26 Sept.
14. Mazumder,S.K. and Sen, P. (1991) "Design, Operation and Maintenance of Diversion structures in Alluvial Rivers", J. of the Instn. Of Engrs. (India),. C.E. Division, Vol. 72, Part CV 3, Sept.
15. Mazumder, S.K. (1993) "River Erosion Downstream of a Barrage" Proc. on "River Scour" org. by CBI & P at Varanasi, 28-29 April
16. Mazumder, S.K. (1993), "Stability of River Downstream of Hydraulic Structres" Proc. of VIII APD- IAHR Congress, Vol II org by CW&PRS Pune, Oct. 20-23, pp 273-282
17. Mazumder, S.K. and Praveen Kumar (1995) "Local Scour Downstream of a Level Apron with and without Hydraulic Jump" Proc. 6th International Symposium on River Sediments and org. by CBI & P, New Delhi, Nov. 7-11
18. Mazumder, S.K. (2000) "Role of Farakka Barrage on the Disastrous Flood at Malda (West Bengal) in 1998" Proc. 8th ICID Intl. Drainage Workshop 'Role of Drainage and Challenges of 21st Century Vol. III, sponsored by ICID –CIID & Min. of Water Resources and org. by ICD & WAPCOS, New Delhi Jan 31 - Feb 4, New Delhi
19. Mazumder, S.K. (2001) "Training of River Ganga Near Farakka Barrage: Proc. of National conference on Hydraulics and Water Resources HYDRO –2001, org by Indian Soc. for Hydraulics (ISH) & CWPRS, Pune, Dec. 6-7

20. Mazumder, S.K. and Pramod Kumar (2001) Sub-critical Flow Behaviour in a Straight Expansion", ISH Journal of Hyd. Engg. , Vol. No. 1, March
21. Mazumder, S.K., Rastogi, S.P. and Hmar, Rofel (2002) "Restriction of Waterway under Bridges", J. of Indian Highways, Vol. 30, Nlo. 11, Nov.
22. Mazumder, S.K. and Dhiman, Rajni (2003), "Computation of afflux with particular reference to Widening of Bridges on roadway" , Proc. National Conf. Of Hydraulics and Water Resources, HYDRO-2003, CW&PRS, Pune, Dec.
23. Mazumder, S.K. (2004)" Aggradation/Degradation of Ganga near Farakka Barrage", Proc. Seminar on "Silting of Rivers- Problems and Solutions" org. by Min of Water Resources, Govt. of India, New Delhi Feb. 12-13.
24. Ordgaard, A.J. (1986), "Meander Flow Model 1: Development" J. of Hyd. Engg., ASCE, HY-12, pp 1117-1136
25. Rozovski, J.L. (1957) "Flow of Water in Bends of Open Channels" Acadamy of Sciences of the Ukranian SSR,. Translated in English by Prushansky, Y. Israel Programme of Scentific Translation.
26. Sanyal, N, (1980) "Effect of Embankment of River Kosi" Proc. Int. Workshop on 'Alluvial Rivers' org. by Univ. of Roorkee, march 18-20.
27. Schumm, S.A. 1980) "Plan form of Alluvial Rivers" Proc of the International Workshop on Alluvial River Problems held at Univ. of Roorkee, March 18-20.
28. Wang, P. et al (1992) "Numerical Prediction of Transverse Bed Slope and Bed Profiles in Curved Alluvial Streams" Proc. of APD – IAHR VIII Congress at CW&PRS, Pune, Vol. II, Oct 20-23
29. Wang, P. Zaho Shiquiang, Fangduo, Ciajinde (1994) "Computation of Depth Averaged Longitudinal Velocity and Boundary Shear Stress in Channel Bends" Proc. of APD- IAHR, IX Congress, Vol. 2, pp 409-416, Singapore.
30. Yalin, M.S. and Ferreira, D. Silva (1999) "Regime Channels in Chhesionless Alluvium" J of Hyd. Engg. Research, Special Issue on Fluvial Hydraulics, IAHR, Vol. 37, No. 6
31. Zimmermann, C and Kennedy, J.F. (1978) "Transverse Bed Slope in curved Alluvial Steams" Proc. Institution of Civil Engineers, London, pp 525-538