ANALYSIS AND CONTROL OF EROSION OF RIVER GANGA UPSTREAM AND DOWNSTREAM OF FARAKKA BARRAGE

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ABSTRACT

It is necessary to understand river behavior upstream and downstream of hydraulic structures for proper planning designing and maintaining anti-erosion works. Morphology of the river, its aggradation /degradation and the meandering processes has been discussed. Uncontrolled erosion and deposition of sediments creates lateral instability of river, meandering and migration of river course. Migration of river Ganga towards the left bank upstream and right bank downstream of the barrage has resulted in unprecedented erosion of the left bank towards Malda (West Bengal) upstream of the barrage and its right bank towards Murshidabad (West Bengal) downstream of the barrage. Hydraulic analysis is made of the river behavior upstream and downstream of Farakka barrage as a result of sediment deposition upstream and inadequate energy dissipation. The protective measures adopted so far are found to be, by and large, ineffective. The underlying reasons for the failure of the anti-erosion measures adopted by the project authorities have been critically examined and some alternative measures for erosion control have been suggested

INTRODUCTION

Farakka barrage-about 2.6 km long- was constructed in the year 1967 across river Ganga with the objective of forcibly diverting flow from the parent river Ganga to its tributary river Hoogly. The river Hoogly (initial stretch of which is known as Bhagirathi) was drying up due to silting of it's off take point at a place called Jangipur (at a distance of about 40 km downstream of the barrage), resulting in gradual reduction of fresh upland flow from Ganga. Hoogly River flows through West Bengal for a length of about 500 km from its off take to its outfall in Bay of Bengal. It is the lifeline of west Bengal as it is the principal source of water for drinking and industrial uses for Kolkata and Howrah cities and many other important towns located on either bank of Hoogly which is a navigable and a tidal river. Kolkata port located on river Hoogly was drying up due to siltation, as the fresh water upland discharge was reducing. The tidal reach was increasing and the cost of water treatment (due to salinity) and the dredging cost (for maintaining its navigability) were rising excessively year by year. Under the recommendation of CW&PRS (Pune) and advise of experts from India and abroad, Ministry of Water Resources, Govt. of India, decided to construct the Farakka barrage on Ganga and Jangipur barrage on Hoogly for diverting 1135 cumec flow to Hoogly river through a Feeder canal which is about 34 km long. as shown in Fig.1(a). The cost of the project at 1973 price index was nearly Rs.2, 000 million.

After Sahebganj (in Jharkhand state) where the River Ganga changes its course from west-east to north-south direction, the river had been changing its course even before the construction of the barrage, except at two nodal points, namely, Rajmahal (about 40 km upstream of barrage) and Farakka - places where the river course was found to be more or less stable. During the pre-barrage period, the main course of Ganga between Rajmahal and Farakka was along the right bank and the stretch was almost straight. Downstream of Farakka, however, the main course shifted towards the left bank of the river. After the barrage was constructed, the main course of the river upstream of barrage has shifted towards the left bank and that on the downstream side it has shifted towards right bank as shown in fig.1 (a) and 1(b).With continued erosion of its left bank upstream and right bank downstream of the barrage, the river has developed a typical meander with left bank on the outer side of upstream bend and the right bank on the outer side of downstream bend. There is a severe embayment of the river Ganga upstream of the barrage and it may cause outflanking of the barrage if the erosion upstream can not be arrested immediately. It has already merged with river Pagla, one of its tributaries and it may finally join another mighty river Mahananda (Fig. 1a), whose high flood level is about 1 m below that of Ganga at Faarakka.

During the period 1968 to 1990, the upstream meander has migrated towards left bank by about 3 km eastward with an average migration rate of about 136 m per year. Between 1990 and 2005, it has further

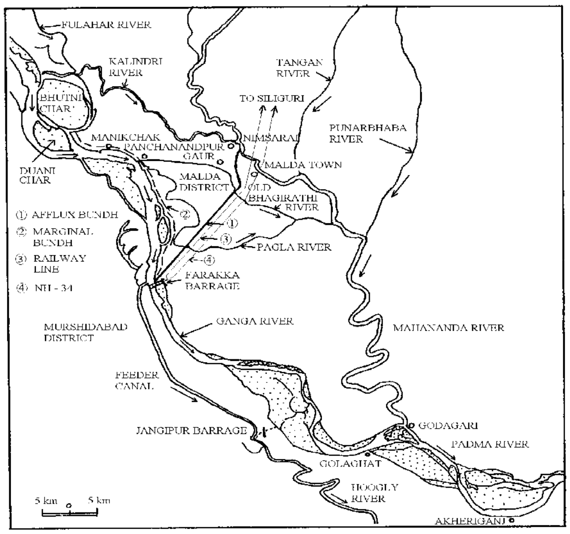

Fig.1 (a) River Ganga and its Tributories near Farakka

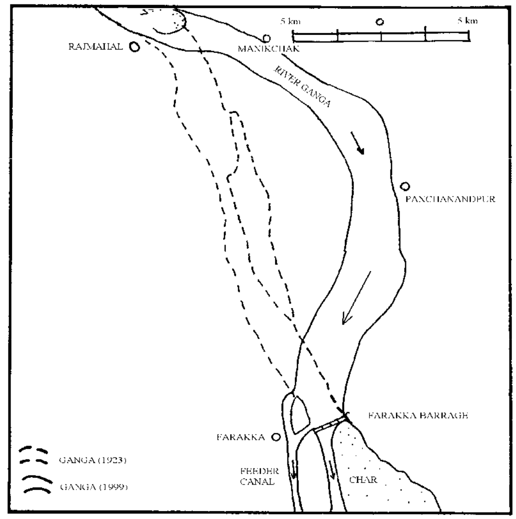

Fig.1(b) Change in Course of River Ganga Near Farakka Barrage during 1923-1999

migrated about 4 km eastward which corresponds to an average migration rate of about 266.m per year. This unprecedented rate of meander migration is about 10 times more than that predicted by Hickin and Nanson (1984), perhaps due to the interaction between the river Ganga and the barrage. On the downstream side, the right bank of the river also has similar erosion problem. Several towns have been completely wiped out and in certain stretches the distance between the railway line and bank has been reduced to 200 m or so compared to an earlier distance of 5 km and more. Continued erosion of the river upstream and downstream of the barrage has resulted in colossal loss of agricultural and household properties and subjected the poor people living on the banks to unimaginable sufferings. Properties worth several thousand million rupees have been lost or damaged both upstream and downstream of the barrage If the erosion and embayment on the left bank continues upstream, there is a possibility of change of the present course of Ganga wiping out thickly populated areas in the Malda district of West Bengal. The marginal bund has already been severely damaged. The afflux bund, the railway line and the national highway NH-34 (Fig.1a) - both connecting north-east India with the rest of the country- have also breached several times resulting in loss of both agricultural and household properties subjecting the people living in Malda district in West Bengal to unprecedented miseries. If the river course changes upstream, the barrage and the feeder canal will be useless and the Hoogly River will again go dry. On the other hand, if the erosion of right bank continues downstream, the railway, the roadway, the feeder canal and the Jangipur Barrage are likely to be washed out. The river may either join parent Ganga or may merge with Hoogly River. In either case, there will be further loss of life and properties and the purpose of the barrage and the feeder canal will be lost.

Ministry of water resources appointed two commissions (Pritam Singh Committee in 1980 and Keskar committee in 1996) to study the problem of Ganga river erosion both upstream and downstream of the barrage and suggest remedial measures. Total cost of the short term and long term measures (yet to be implemented) suggested by the committee is about Rs.10,000 million.

Considering the gravity of the situation and complexity of the problem , it is necessary that an in depth analysis of the erosion problem should be made with all relevant field data, especially regarding incoming and outgoing sediment load and sediment deposition upstream since the river course, the meandering and the erosion of the banks are inter- related. Author wishes to discuss the problem, analyse the various issues involved, state the various reasons for ineffectiveness of the conventional measures of bank protection adopted so far and suggest some alternative measures for short and long term solution of the problem.

RIVER MORPHOLOGY / AGGRADATION / DEGRADATION

Understanding the behaviour of any given stream is complicated due to interrelated geomorphologic, hydraulic and hydrologic parameters. The interrelation between plan form, hydraulic and sediment parameters and relative stability of a river is illustrated in Fig.2 (a) & 2(b) (Schum, 1981). It may be seen that the different plan forms of a river e.g. straight, meandering and braided course 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(a) (Lane 1957). A decrease in discharge combined with increase in sediment load will result in decrease in flow depth and increase in flow width as mostly observed upstream of hydraulic structures e.g. barrages and bridges Prediction of stream response to climatological or watershed changes is based on the fundamental relation given by equation- 1 (Lane,1955) 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 given by Eq.2.

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

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

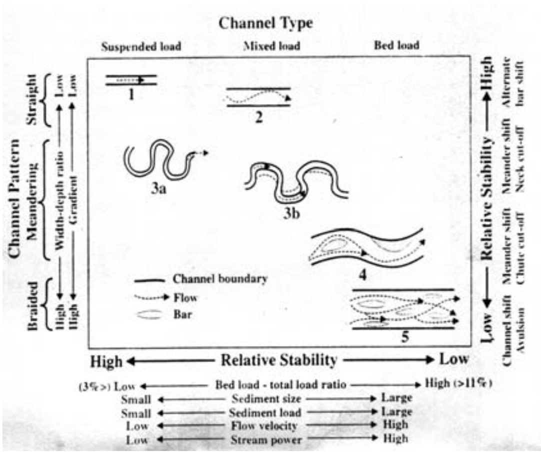

Fig.2(a) Interrelation between channel type, hydraulic and sediment parameters and relativestability of streams(Schwam,1981)

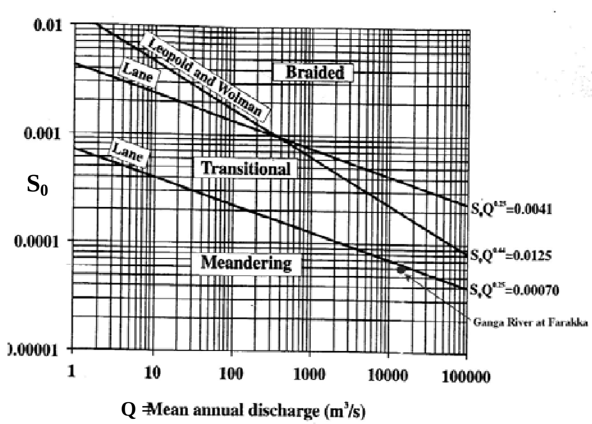

Fig. 2(b) Interrelation between stream form, bed slope and mean discharge(Lane, 1955)

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 ($Q.S_e$) and the sediment carrying capacity of the stream are reduced. As a result, there is deposition of sediments resulting in aggradations upstream of the hydraulic structure (as observed upstream of Farakka barrage), till such time the original slope is restored and the balance given by equation (1) is satisfied. In all diversion structures (like Farakka barrage), 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 aggradations (heavy silting has occurred on the left bank side of Ganga in the areas downstream of Farakka barrage pushing the river towards right bank side) and rise in slope till such time equation (1) is satisfied and the original stream power is restored.

Downstream of hydraulic structures, there is erosion of stream bed and degradation 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. Corrioli's coefficient(α) is increased and hencethe kinetic energy of flow $\alpha \ v^2/2g$. It has been established (Mazumder 1993) that even 1% residual K.E. is sufficient to raise the 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. Due to deposition of sediments upstream of Farakka barrage, flow downstream is comparatively clear. There is also high intensity of turbulence due to imperfect jump (at low pre-jump Froude's number (F_1=2.4 at design flood). All these coupled with highly non-uniform flow distribution (due to skewed jump downstream) has caused heavy erosion of right bank downstream of barrage.

RIVER STABILITY AND MEANDERING 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 flow (Q) are presented by Lame (1957). A non cohesive stream bed composed of silts and sands is predicted to meander when

$$S_o\, Q^{0.25} > 0.00070 \quad \text{………} \qquad (3)$$

and braided when

$$S_o\, Q^{.25} > 0.0041 \quad \text{……. …..} \qquad (4)$$

A typical straight stream 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 on alternate river banks give rise to thalweg pattern. Uncontrolled erosion and deposition ultimately give rise to meandering processes as illustrated in fig. 3 (a). A lot of research work on bends in a meandering river have been carried out by eminent river scientists like Rozovsky (1957), Zimmerman and Kennedy (1978), Engueland (1973), Oddgard (1986), Wang (1994), Yalin (1999), Chitale (1981), Garde and Raju (2000). 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 u/s and d/s 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 :

$$M = f(\Omega, b, G, h, \tau_b) \qquad \text{….(5)}$$

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. 3(b), Hickin and Nanson concluded that the migration rate is maximum when meander stabilizes at an approximate value of r/w =2.5 and got the relation

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

Where, $M_{2.5}$ is the maximum rate of migration corresponding to r/w = 2.5. 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. Uncontrolled meandering may lead to outflanking of hydraulic structures and flow avulsion when the river shifts its course and it may join other low lying rivers -tendencies as observed in the case of Farakka barrage.

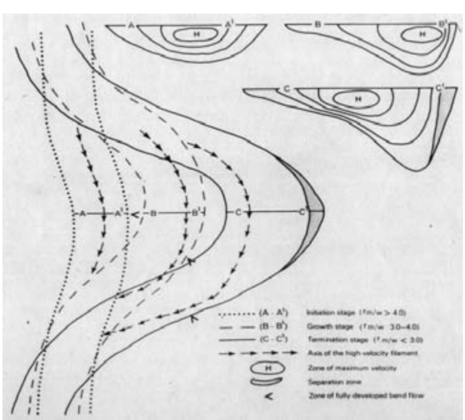

Fig. 3(a) Lateral Migration of meander and development of Stream Section in a Bend

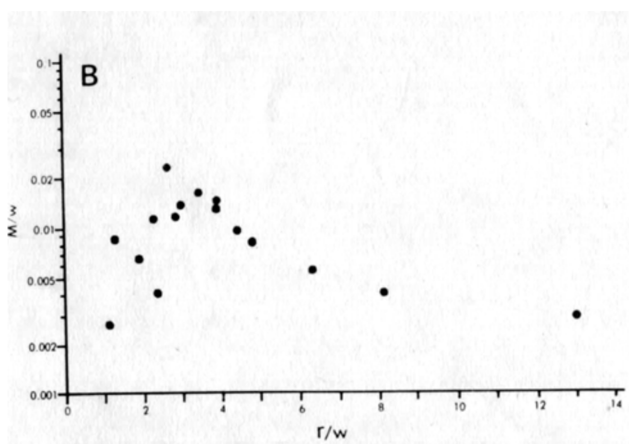

Fig. 3(b) Variation of Migration Rate (M) with Relative curvature (r/w) in a Meander

In north and north - east India, most of the streams are found to be moving in a wide flood plain formed principally due to the formation. of meandering/braided channel. At Farakka, the width of flood plain (also called khadir) of river Ganga at design flood varies from 6 to 8 km. When a bridge or a barrage is constructed on such a wide flood plain, it is an usual practice to provide waterway of these structures limited up to Lacey'sregime waterway by providing approach embankments and guide bunds as shown in fig-4. (Length of Farakka barrage is only 2.6 km with guide bunds on either side). Such restriction of waterway (which may or may not be symmetrical) results in considerable afflux (Mazumder, 2003) and back water upstream of the hydraulic structures causing sedimentation and lateral instability of flow. The stream is found to form meandering/braiding flow pattern within the flood plain depending on the slope, discharge, sediment inflow etc (Fig.2). The main channel is often found to move along one of the banks eroding the same and deposition of sediments takes place on the opposite bank resulting in a meandering course. Uncontrolled erosion on the outer bank side and deposition on the inner bank side of such meandering approach flow lead to migration of meander on the outer bank side(Fig.3), especially where the banks are made of fine alluvial soil of extremely poor shear strength (τ_b) as in Farakka (d_{50} of bed material is about 0..15mm). Non-uniformity (obliquity) of approaching flow causes not only deep scour due to high flow concentration on the outer bank, it creates large cross-slope along the river width resulting in stronger secondary current and greater scour. Similar behavior of river Ganga is observed upstream of Farakka barrage. The main course of the river (about 1.2km width flowing along the left bank) is carrying almost all the flood discharge resulting in extremely high flow concentration and colossal erosion of the left bank lying on the outer side of the meandering bend upstream of the barrage The eroded materials as well as the large volume of incoming sediments have been deposited on the right bank forming a number of shoals/bed bars upstream of the barrage. With the progressive growth of the shoals (also known as bed bars) over the years and development of cross-slope, Ganga has already shifted about 7 km towards the left bank (Fig.1b and Fig.5). Deep scour to the extent of 50 m was observed on 3rd October, 2000 (as shown in Fig. 6(a)) resulting in wash out of almost all the spurs on the left bank constructed for the protection of the marginal embankment for marginal embankment erosion. There is an embayment and obliquity of flow approaching the barrage. The main flow separates at the head of left guide bund and shifts towards the diversion works on the right bank causing deep scour on the right side and silting on the left side in the vicinity of the barrage structure, threatening the safety of the barrage and difficulty in operation of 50% of the barrage gates on the left side

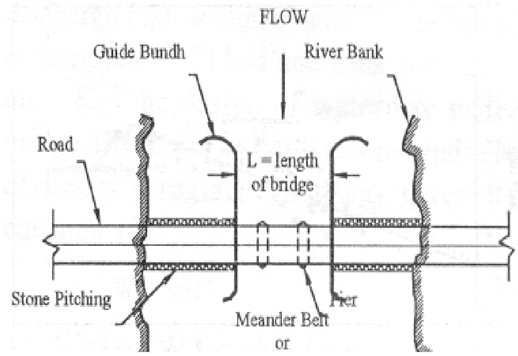

Fig. 4 Use of Guide dh for restriction of Water Way in the Flood Plain of a River

Hydraulic structures causes restriction of waterway (Fig.4) also - 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 (as in. Farakka barrage). Depending on the degree of such restriction of waterway, the flow may be free or submerged. In free flow, the flow is choked and the afflux is high (to satisfy the minimum specific energy requirement) and there is a hydraulic jump on the downstream side. Submerged weirs/barrages of low solid obstructions (like Farakka barrage) are generally made of low crest height with high head gates for the purpose of storage and sediment flushing. The flow over such low level barrage crests may be either free or submerged 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 always a difference in energy level (ΔE) across the structure. In case the actual energy loss ($\Delta E'$) 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 distortion downstream and it remains more or less uniform. If the energy dissipation is inadequate, there is residual kinetic energy of flow ($\Delta E- \Delta E'$), which causes non- uniformity in the flow distribution downstream. Author found (Mazumder and Sen, 1991) that in many of the low height barrages (e.g. Farakka) in India, the pre-jump Froude's number of flow F_1 lies between 2 to 4. (At design flood, F_1=2.4 in Farakka barrage). It is known that the hydraulic jump in this region of Froude's number is either undular or oscillating in nature and the jump efficiency is very low. As a result, the flow downstream has high degree of non-uniformity and flow distortion. Such distorted flow often swings periodically to either left or right bank side due to flow instability (Mazumder 1993). It becomes highly turbulent causing erosion of bed and banks on the side where the turbulent wall-jet like flow adheres to. Deposition of sediment occurs on the opposite bank creating cross- slope and meander formation. Similar phenomenon is observed on the downstream side of Farakka barrage, where high velocity jet like flow is found to erode the right bank after a skewed hydraulic jump- partly due to oblique approach flow (explained earlier) and partly due to inadequate energy dissipation in a skewed jump at low pre-jump Froude's number(F1) of flow. The eroded materials have deposited on the right bank causing strong cross- slope and meandering of the river downstream of the barrage. The main jet like flow is found to move along the right bank causing deep erosion and meander migration towards the right bank as illustrated in Fig.1(a) and Fig.6(b).

GANGA EROSION AND PROTECTIVE MEASURES NEAR FARAKKA BARRAGE

Farakka barrage is designed for a flood discharge of 70,930 cumec (25 lakh cusec) with a design afflux of 0.5 m. Further details of the barrage are available elsewhere (Mazumer 2004). With a longitudinal bed slope of 1 in 21,000 and a mean annual flow of about 14,000 cumec, the river is in a meandering state as indicated in Fig. 2 (b). On an average, 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 causing formation of several shoals/bed bars, meandering, cross-slope, strong flow curvature and lateral flow instability upstream of the barrage - the morphological processes already discussed. With the continued erosion of its left bank upstream and right bank downstream of the barrage, a typical meander has developed with Malda on the outer side of the upstream bend (left bank) and Murshidabad on the outer side of the downstream bend (right bank) with Farakka Barrage (a rigid structure) at the centre acting as a nodal /fixed point (Fig.1(a)&1(b)). As shown in Fig-5, the river has extensively eroded its left bank and developed a sharp curvature about 5 km upstream of the barrage. Figs.6(a) shows a typical cross-sections of the river in the meandering zone upstream of the barrage, indicating deep scour near the left bank. In 1972, a 30 km long marginal embankment was constructed along the left bank upstream of the barrage to stop erosion and further migration of the river towards the left bank. Subsequently, 27 numbers earthen core type impermeable spurs (duly protected with crated stones for preventing erosion) were constructed for protecting the marginal embankment with a view to train the river up to the barrage. But the embankment was breached on several occasions during high floods and most of the fending spurs have been washed out. The river has moved about 7 km inside Malda district (Fig. 2(b)) wiping out thickly populated villages near the left marginal embankment. 450 people died and properties worth about rupees 1000 crores were damaged. in 1998 flood alone (Mazumder 2000).

Near Panchanandpur, where the river has taken the sharpest bend and breached the marginal embankment on several occasion, retired embankments were constructed eight times around the breaches (Fig.5) in order to protect the people and the properties from flood damage However, all these retired embankments and majority of the spurs have been swallowed by the mighty river Ganga year after year. (It is likely that the proposed ninth retired embankment will also meet the same fate as the previous eight). The protection measures adopted for the 9 th retired embankment consist of bed pitching with crated stones and loose boulders in between the crated ones up to a length of 50 meter starting from the bank at RL +25m and ending at a point in the river bed where the river bed level is +3 meter. The apron is laid over tarja mat made of the Assam Bamboo skin. Submerged bed spurs of 3-meter height above the river bed and made of crated stones are constructed at a spacing of 100 meter. Since the marginal embankment (with its top at +27m) has already been washed out, the protective apron is ended at the existing bank level of 25m. If the design high flood with HFL+26.5 m occurs, the flood water will overtop the bank and it is likely to wash out all the protective works, particularly during back flow from country side to the river. If the erosion continues, there is a possibility of avulsion of the mighty river Ganga bypassing the barrage. If it happens, river Ganga will change its course and it is likely to join the low lying 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.

Downstream of Farakka barrage, the river Ganga has extensively eroded its right bank in Murshidabad district of West Bengal. The downstream meander has already migrated about 4 km on the right bank side resulting in development of sharp bend (Fig.1a) and cross-slope and deep scour near the right bank as shown in Fig.6(b). Extensive erosion of right bank has resulted in flooding, loss of human and animal life, loss of valuable agricultural lands and household properties, damage to roads and communication system subjecting the people to extreme miseries. It is threatening several townships located on the right bank of the river. About 26 km length of river bank was protected with stone pitching and 87 nos. of submerged stone spurs were built on the right bank of the river to control river erosion. 26 spurs and 15 km of pitching have been washed out and a number of spurs and the stone pitching have been badly damaged. If the erosion continues further, the river may may merge with the Feeder canal defeating the very purpose of the barrage. Railway line , NH-34 and Jangipur barrage will be washed out.

A master plan of riverbank protection, both upstream and downstream of the barrage, has been drawn to control erosion of river banks and prevent further migration of the river meander at a cost of about Rs. 927 crores as per the recommendations of Pritam Singh and Keskar Committee.(2000). Unfortunately, the recommended conventional protective measures, consisting of impermeable earth-core type spurs protected with stone pitching and crated stone bed spurs over stone mattress, have miserably failed to perform. Most of the impervious spurs are already destroyed due to heavy erosion at their heads and toes. They settle (due to scouring/winnowing of foundation soil) , crack and the high velocity current flows through the cracks eventually washing out the spurs. The river banks made of very fine non-cohesive alluvial soil are subjected to the fury of the river causing erosion of the bank. The sand and silt layers underneath the bank get eroded first and the top clayey bank caves in the scoured area due to lack of any support from bottom.

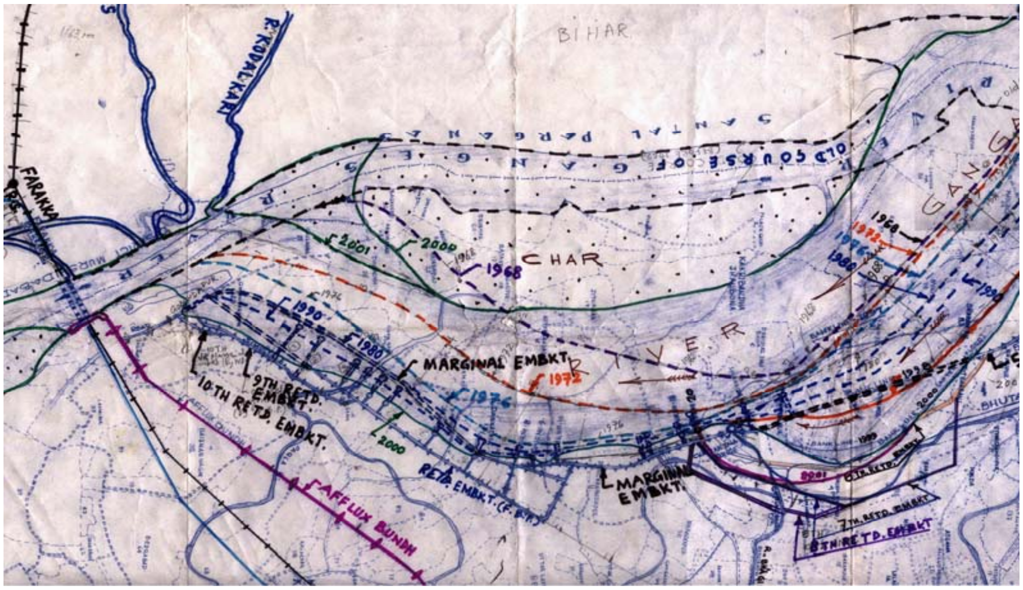

Fig. 5: Migration of Meander towards Left Bank Upstream of Farakka Barrage

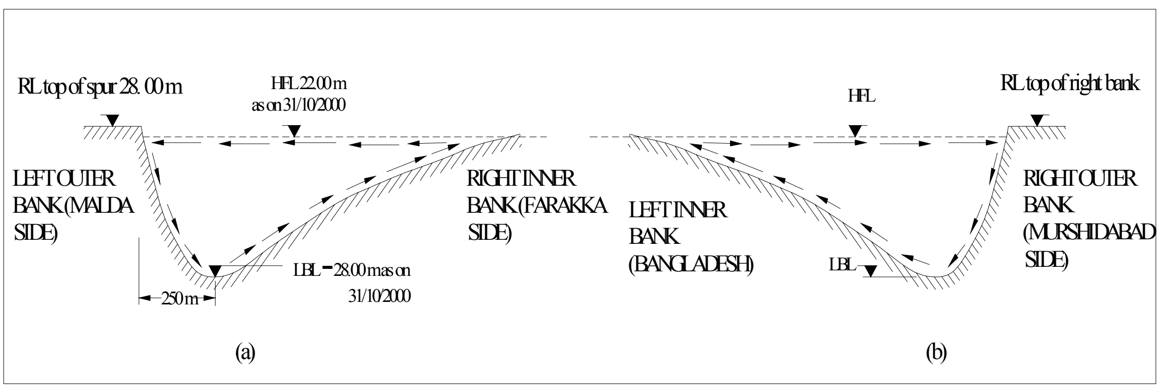

Fig.6 Showing Typical Cross-Sections with Secondery Current and Deep Erosion on the Outer Banks (a) Upstream and (b) Downstream of Farakka Barrage.

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The spurs which are designed as deflecting type originally are now behaving as attracting type due to scouring of the banks upstream of the spurs and consequent river embayment. Longer the spur, higher will be the flow concentration at heads and more vulnerable will be the spur heads to failure. Both Pritam Sngh and Keshkar committee have recommended use of still longer spurs for deflecting the current. This is going to cause so high flow concentration at spur head that it will be almost impossible to retain them in position. This may also cause further complications due to flow instability associated with high degree of contraction and subsequent expansion of flow around the long spurs. An unstable flow can change its course in any direction with slightest disturbance which is inherent in a stream.

The contemporary idea (propounded by Inglis) that stones dumped in the horizontal apron will be launched uniformly to protect the scoured area is a myth. Launching never occurs uniformly. The fine bed materials exposed to high velocity current (due to non-uniform launching) are removed/winnowed being entrained /trapped in the current moving over the uneven pitching.surface, resulting in scouring, winnowing and foundation failure. Another important reason of failure of spurs and stone pitching is improper choice of filter material. It is doubtful whether tarza mat with innumerable joints will act as appropriate filter/separator with so fine soil underneath. Fine base materials may be trapped/winnowed through the joints due to dynamic suction when high velocity stream flow over the pitching. Laying the stone apron and submerged bed spurs (made of

1mx1m GI wire crates) with tarja mat underneath result in innumerable joints (and possible gaps) between consecutive crates, while sinking them from burgess under a standing depth of water. It may cause further non-uniformity in pitcing and exposure of foundation soil due to lack of control, type of tools used, and the dishonest contractors/engineers engaged in construction.

RECOMMENDED REMMEDIAL MEASURES FOR EROSION CONTROL

- Long impermeable type spurs should not be constructed as it causes high flow concentration near its head.
- It is not understood why the project authorities are adopting the conventional measures for controlling erosion again and again in spite of the fact they are found not so effective. There is no sincere effort to analyze the causes of erosion and adopt alternative measures of erosion control - both short and long term.
- Impermeable spurs can not be kept in position due to deep scour at their head and toe. They are found to settle and crack and through flow occurs through the spur body resulting in their wash out.
- Permeable spurs of ballies or bamboos should be constructed for dampening of flow velocity which takes place due to energy dissipation in micro-turbulence downstream of the spurs.
- Properly designed filter below stone apron is essential to prevent loss of fines due to dynamic suction effect when high velocity current passes over the pitching.
- During launching of stone apron, the filter must also launch uniformly. This does not happen due to small size tarja mat with numerous joints and possible gaps between consecutive units.
- Use of synthetic geo - filter of proper mesh size (depending on size of base material to be protected) having long length and breadth (covering larger area) with sufficient overlap at junctions is going to be highly effective, both in launching as well as uniformity of laying
- Tarja mat, which is currently used as filter/separator, need thorough testing regarding its effectiveness as filter for the given bed and bank materials.of very fine size.
- Welded GI wire crates are not flexible and are susceptible to corrosion and rupture of joints. Either double twisted GI wire net or Nylon/polymer rope gabions (filled with assorted stones of much smaller size than the ones used now) are flexible, economic and will be helpful in maintaining uniformity after launching and highly effective in protection of river bed and bank.
- Submerged stone bed spurs are initially permeable but they soon become impermeable (due to arrest of sediments and debris passing through the spurs along with flowing water) causing high flow concentration at their heads and resulting in progressive failure of these bed spurs and the apron, starting from head end of the spurs. It will be desirable to omit them as they obstruct the flow and lead to development of stream curvature in vertical plain causing stronger dynamic suction and winnowing of foundation materials.
- Provide smoth apron made of nylon/polymer gabions (laid over synthetic geo- filter of appropriate mesh size as per BIS code-IS:8408) having sufficient weight as per codal provisions, so that the gabions can resist the drag. of flowing water and there is no loss of fines from the river bed and bank. .
- As a long term measure, the shoals/bed bars may have to be commenced near their pointed heads in order to arrest their progressive growth (shoals formed due to sediment deposition) which is responsible for flow curvature, development of secondary current, cross-slope, meandering and consequent scouring of outer bank of the meandering bend.
- Attempt should be made to measure annual deposition of sediments u/s and d/s of the barrage since the root cause of the problem is sediment deposition and consequent formation. of bed bars/shoals.
- Instead of 9th retired embankment, it will be wise to construct arrays of curved submerged vanes as per design procedure recommended by Oddgard and Kennedy.
- Since flow above 26,000 cumec is largly responsible for bank erosion, an attempt should be made to divert flow in excess of 26,000 cumec through Pagla or other natural or artificial diversion channel bypassing the barrage. It may be examined whether another barrage can be constructed u/s of Rajmahal for diverting excess flow in river Ganga through the Jharkhand state.
- Shear strength of embankment and bank soil may be artificially improved by use of geo-synthetics or geo-Jute textiles, cement –soil grouting etc. Afforestation of the bank will also help in ground improvement,.
- An attempt should be made to divert the main course of Ganga through its Fulahar side channel (silted up due to large amount of sediments brought by Fulahar river and deposited at its outfall of Fulahar branch on the left bank of Ganga). The main Ganga river course, which was earlier along its left branch near Fulahar, has now shifted to the right branch near Rajmahal hills. It is the Rajmahal side channel bend (on the right bank) that has triggered the subsequent other bends, namely, the left side bend (towards Malda) and the right side bend (towards Murshidabad) u/s and d/s of Farakka barrage respectively.

CONCLUSION

In spite of elaborate and very costly river training measures adopted so far, river Ganga is creating unforeseen problems due to uncontrolled erosion of its left bank upstream and right bank downstream of Farakka barrage.Uncontrolled erosion and deposition process in the vicinity of Farakka barrage has resulted in development of meanders and its migration towards Malda district in West Bengal (on left bank) upstream of the barrage and Mushidabad district in West Bengal (on right bank) downstream of the barrage resulting in flooding, loss of life, agricultural lands and other properties on both the banks If the erosion continues, .the river may outflank the barrage upstream or join feeder canal downstream, washing out the national highways, railways , the household and landed properties on either of its bank and the purpose of the barrage wil be lost. It is necessary to understand the basic mechanisms of aggradations / degradation, flow instability and meandering processes in a river like Ganga near Farakka for proper planning and design and of river training works. Conventional measures consisting of embankments, stone mattresses and groynes are found to be ineffective due to deep scour near the river banks. An in-depth analysis of erosion mechanism and failure of the protective works have been made and some alternative measures of erosion control have been recommended for consideration of the project authorities.

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