

Hardinge bridge to Padma bridge – 100 years of major river crossings in Bangladesh

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ABSTRACT: The Hardinge Bridge was formally opened on 4th March 1915. The history of this important crossing is presented, covering the 100 years which followed. This has included movement of the River Ganges (Padma) and associated river training work repair; war damage & reconstruction; change of use; upgrade; and maintenance. This is a classic life history of a bridge over a long period of time. Other major bridges covered in the paper include the initial crossings of the Teesta, Meghna and Jamuna Rivers. The background to the Multi-purpose Crossing of the Jamuna River is given, with particular reference to the Aricha Nagabari Power Inter-connector, and the proposed project to supply gas to the Western Zone. A description of key aspects and constraining factors for the Jamuna Bridge itself is presented. Finally reference is made to the Shah Amanat Crossing of the Karnaphuli River, the first major cable supported bridge in Bangladesh.

1 INTRODUCTION

In 1703, Hydrographer John Thornton, on his “Mapp of The Greate River Ganges As it Emptieth itself into the Bay of Bengala” wrote in large letters across the map “The Rich Kingdom of Bengala”. This is a clear reference to the fertility of the alluvial plains of Bangladesh, threaded through by the Ganges and a multiplicity of major rivers.

Rendel (formerly known as Rendel, Palmer & Tritton and High-Point Rendel) has been involved in Bangladesh since the early days of the Eastern Bengal Railway Company (now Bangladesh Railway) which was formed in 1857. One of the larger projects undertaken for that company was the Hardinge Bridge over the Lower Ganges at Sara, which opened to traffic in 1915. In this centenary year of that outstanding undertaking, the projects described in the paper will include this crossing of the Ganges and extend to the current crossing of the Padma River below the confluence of the Ganges and the Jamuna rivers. A number of other projects undertaken by the firm during the course of these intervening years, including the Jamuna Multipurpose Bridge, will be described.

James Meadows Rendel, who founded the Consultancy in London in 1838, stated in his Presidential address to the Institution of Civil Engineers on 13th January 1852, that “The history of the Civil Engineer shows that mere technical knowledge of the details of a work, however critical and correct, will not of themselves lead to distinction. All undertakings must be examined with comprehensive views of their ultimate effects, not only as regards the immediate projectors and the present time, but on society generally and on the future.” Looking back on some of these projects can be an enlightening experience for us as Civil Engineers today. J M Rendel also referred at some length in his Presidential speech to the rapidly expanding work of the railway infrastructure worldwide. He included reference to his own involvement in the railways of this area of the world, noting the particular issues to be addressed in their development as the challenging ground conditions encountered and the mighty rivers to be crossed. However it was some years later that Sir Robert Gales, a partner of the firm, designed and supervised the construction of the Hardinge Bridge.

On first encountering a river such as the Jamuna or the Padma, it is inevitable that, as an engineer, one must feel a sense of humility. After dealing with the issues of the right guide bank of the Hardinge Bridge in 1933, B L Harvey stated that “It is impossible to be prophetic in dealing with the problems of the river Ganges and of rivers in the alluvial plains of Bengal.”

It is acknowledged that the names of rivers have changed between the first half of the twentieth century and the second. For example the length of the river between the west side of Bangladesh and its confluence with

the Jamuna was previously called the Ganges, and is now referred to as the Padma. As this paper covers both parts of that century, both usages have been retained.

Particular focus has been given in this paper to the Hardinge Bridge, in part in recognition of the 100 years since the opening of the bridge, but also to allow us to examine and recollect the considerable challenges and achievements of our predecessors those many years ago, and the project history.

2 THE HARDINGE BRIDGE

The 5,900 feet long Hardinge Bridge, described at the time as the largest bridge under construction in the Far East, carries two broad gauge rail tracks, connecting the broad gauge system south of the Ganges to the meter gauge system north of the river. It has provided a critical transport link between the fertile areas of the north-west area of Bangladesh and the south.

The first proposal for bridging the Ganges at Sara was put forward by the Eastern Bengal Railway in 1889. The proposal was entrusted to various committees, and consideration was also given to locating the crossing further upstream at Raita. By this time there was considerable pressure on the existing facilities for the transshipment ferries and barges, carrying the rapidly increasing traffic, mainly of jute and tea, due to the changeable character of the channel, the instability of the banks, and the considerable variation in river levels. It was clear that a bridge was urgently required. In 1908, Sir Robert Gales, a Partner with Sir Alexander Rendel, was appointed as Engineer in Chief for the project.

The selection of the bridge site required above all an understanding, such as was then possible, of the stability of the Ganges river course and its tributaries in the area. The river flows past more or less defined banks for over 1,000 miles before it arrives at the alluvial plains of Bangladesh below the Rajmahal and Garo hills. As background to the movements of the rivers in the plain, historic reference should be made to the detailed survey of these rivers published by James Rennell in 1781 (Fig.1). The most significant change between that date and 1908 was the abandonment by the Brahmaputra of its course east of Dhaka to that now occupied by Jamuna River 70 miles to the west. This movement appears to have occurred gradually over the period around 1805 to 1825. Between 1781 and 1908, there was no major change in the course of the Ganges (although local meanderings did occur). However going back further to the sixteenth century, it would appear that the Ganges flowed in a southerly direction further to the west of its present course, and entered the Bay of Bengal separately from the Brahmaputra.

It is clear that in selecting a bridge crossing site, considerable understanding had to be afforded to the nature of the river and its tributaries to avoid the river by-passing the bridge or damaging the approaches. A particular concern was that of the Ganges breaking through into the Baral river or other offshoots in Rajshashi upstream of Sara, leading to the Chalan Beel wetland depression. By careful mapping of relative levels along various alignments, Gale was able to satisfy himself that that would not occur, and furthermore it was observed that all spills (offshoots) above Sara were diminishing in volume, and the Chalan Beel was silting up. It was thus considered safe to proceed with the design of a bridge at Sara.

The nature of the fine micaceous sands overlying layers of silt required securing the banks before any bridge construction could be undertaken. Surveys indicated protection would be needed down to 100 feet below low water. Semi permanent hard points existed in Sara clay on the left bank three miles above the intended bridge site and in Raita clay on the right bank further upstream. However it was also evident that the clay in both these areas was being eroded each year. The Sara hard point was reinforced with 3,600 feet of revetment, while at Raita the revetment extended for 4,000 feet. This allowed shorter guide-banks at the bridge site, and the potential for construction of the guide-banks within one season (a luxury not found appropriate 80 years later for the Jamuna Bridge construction). Protection was also afforded on both banks by the railway embankments. Here formation-levels were raised to prevent such attacks as the river working deeply into the Lalpur bight and threatening the Gopalpur line just above Sara. In addition to their function in stabilising the river in the wider vicinity of the bridge, the river training works were required to prevent lateral movement at the bridge site itself. At the time of the design, it was noted that the river was moving eastward at approximately 200 feet per year.

Right and Left bank guide bunds were aligned parallel to the direction of river flow, and the bridge set at right angles thereto. They extended 3,000 feet upstream, and 1,000 feet downstream of the bridge, and were designed on the Bell guide bund principle. Along their length they consisted of a sand core, with the slope on the river side covered by a 9-inch layer of stiff clay together with a 3 inch layer of quarry chips on which a bolder revetment was laid. The revetment ranged from 2 feet thick at the top, 18 feet above high-flood level, to 3½ feet at the toe. A falling apron varying in thickness from 4½ to 8½ feet in thickness was extended 150 feet outward from the toe. The design provides that, as the river cuts away the sand from the outer edge of this apron, the stone falls in and automatically pitches a stone slope in continuation of the slope of the guide bank to a depth of 100 feet, the maximum known depth of bend scour. This protection pitching is continued on,

around the upper and lower ends of the guide-banks. The upstream section of the guide-banks was pitched with the heaviest stone available as protection against the large cyclonic waves. The quantity of stone was evaluated on the basis of the formula set down by Sir Francis Spring, and adopted for the design of many bridge river training works at that time.

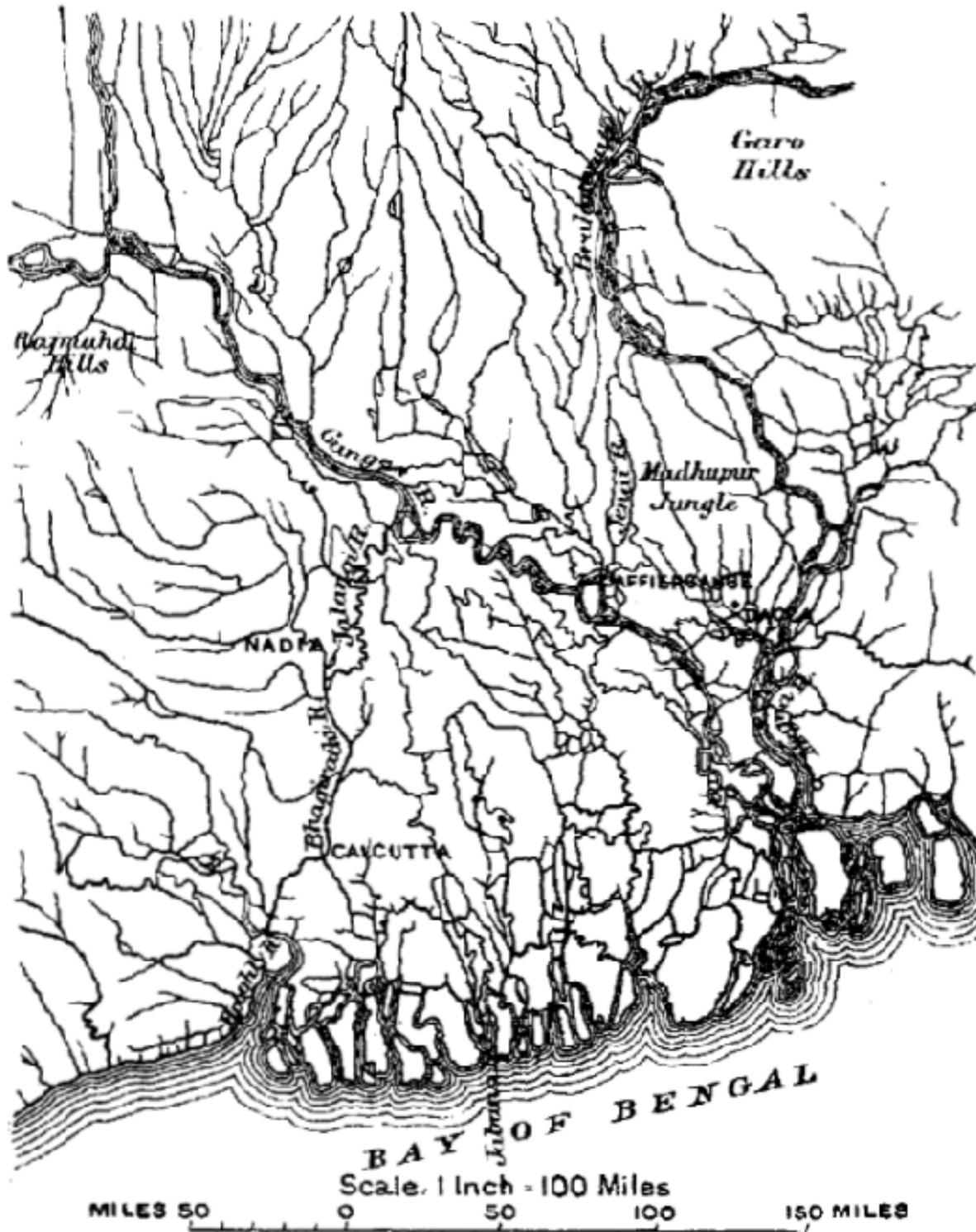


Figure 1. Delta of the Ganges, 1781

As was the case years later for the construction of the Jamuna Bridge, rock was not available close to the bridge site. Rock was transported by rail from the Pakur and Jainti quarries each approximately 230 miles dis-

tant. Also from the Phudkipur quarry 130 miles by steamer and flat boats. A total of 1.9 m tons of rock was brought to site, which included a reserve of 15% of the total.

With reference to recorded flood levels, river depths, the drainage area of the Ganges above the bridge site, and maximum velocities, a required sectional area of river was evaluated. While the Ganges has a flood width in many places of several miles, at the bridge site it has been effectively contained in a single channel, with a width between banks in the region of 5,400 feet. Further investigations of the various governing river parameters lead to a design with 15 river spans of 345 feet between bearings and 6 land spans of 75 feet, resulting in an overall bridge length of 5,894 feet.

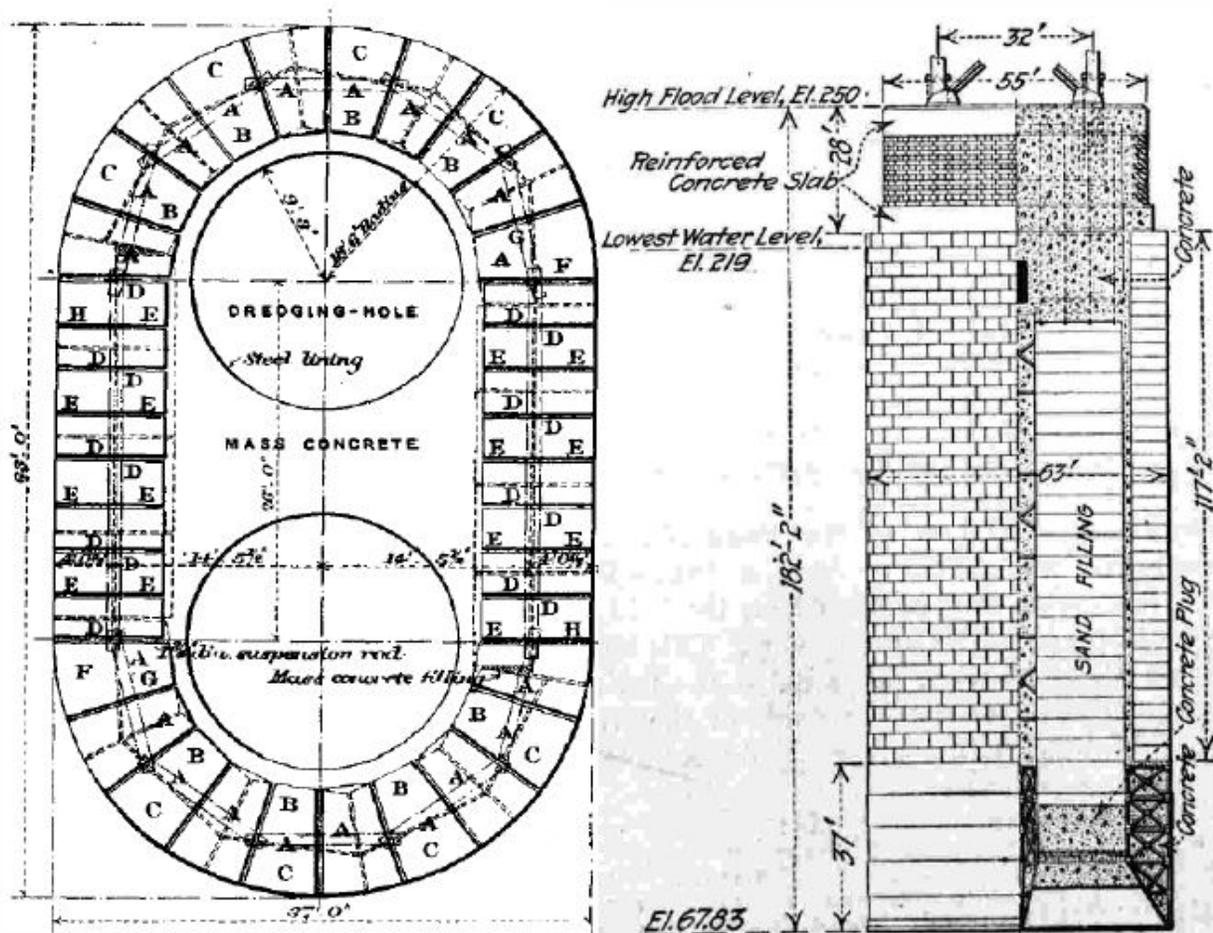


Figure 2. Details of the Deep Piers, including Layout of the Concrete Blocks of the Well-Steining

The main bridge piers were carried on wells sunk by open dredging to a depth of 150 or 160 feet below lowest low water. They were founded in sand 50 feet below the deepest known scour line of the river, and were claimed at that time to be the deepest foundations of their kind in the world. The wells were of semi circular ends of 37 feet in diameter with an overall length of 93 feet, and contained two steel lined dredging holes, 18½ feet in diameter (Fig 2.) The well curbs were constructed of steel filled with mass concrete. For founding in deep water, the curb was continued upward as a caisson by a series of 7 feet steel strakes, and thereafter filled with mass concrete. The concrete block well-steining was built up as the well sank. Finally the dredging holes were plugged top and bottom with concrete plugs, with sand filling in between.

The 359 feet through trusses of the river spans are simple girders of the modified Petit type, having a maximum depth at the centre of 52 feet, a width centre to centre of the trusses of 32 feet and weighing 1,250 per span. Construction of the spans was by way of 72 feet high girder erecting travellers moving from each end of the bridge and straddling the girders erected. They spanned 41 feet across the width of the spans (32 feet c/c), and ran along steel runways. For construction over chars or shallow water, the spans were erected on timber staging supported on piles. For the erection of the main channel spans, a service truss-span (Fig. 3) was floated in on pontoons and placed on the top of the masonry piers, moving from span to span as construction proceeded. The assembly of all the components of the spans required meticulous planning and supervision to en-

sure the final dead load camber was as specified. Cylindrical drifts with tapered ends together with service bolts were initially installed, to be replaced after the complete span had been erected by the 60,000 rivets required in each of the spans.

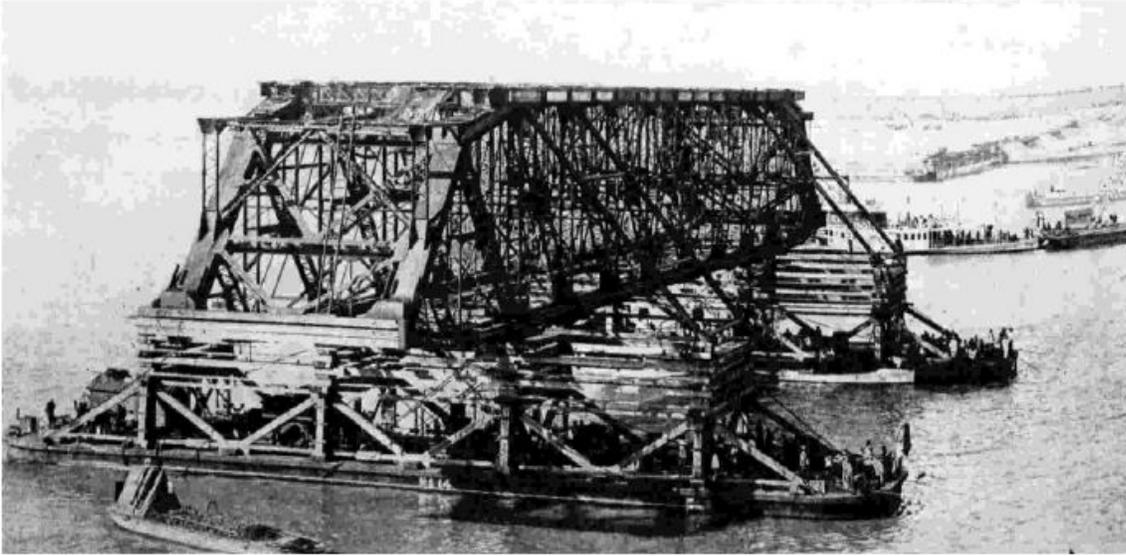


Figure 3. Float in of the service truss used for erection of the main spans

The steelwork for the superstructure was supplied from England and “shipped with the greatest regularity by fast liners”. “In the 1914-1915 season the last three spans were shipped from Liverpool in preference to East Coast ports, and successfully ran the gauntlet of the enemy cruiser “Emden” in the Indian Seas.” Two of the land spans had been captured in Luxemburg and one interned at Port Said and had to be replaced. The liner with half the last span was commandeered in Calcutta by Government, and was only unloaded by special favour.

Cholera was endemic in the area, but the jurisdiction of the Chief Medical Officer was extended beyond the immediate construction areas, and any outbreak in surrounding villages brought under control. Infection of the labour at the bridge site was thereby prevented. Malaria was successfully combated by a good drainage system, oiling stagnant water, periodic clearing of jungle, and a free supply of quinine.

The bridge was opened for goods-traffic on one track on the 1st January 1915, 3 years 5 months from the commencement of the erection of the first well curb. The Hardinge Bridge was formally opened for double line working of all classes of rail traffic on 4th March 1915.

Earlier mention was made of the course of the Ganges indicating that no major change has occurred since the surveys Rennell published in 1781. It was also indicated that at the time of the design of the Hardinge Bridge, the river was moving eastward at the bridge site at a rate in the region of 200 feet per year. The course of the river in the immediate area of Sara at intervals since 1780 is indicated on Fig. 5, and demonstrates the difficulties associated with the training of such a river. In 1915, the main channel of the river was hard up against the left bank at the bridge crossing alignment, although the Sara protection bank (the left bank hard point) and the Lalpur bight were well inland. Ten years later, the river had moved into the Lalpur bight, and by 1931, the sweep of the river into the embayment thus formed (in spite of the placing of large quantities of stone) caused the channel downstream to cross to the right bank and threatened a significant embayment 2 miles above the bridge. In consequence, the officer responsible implemented the construction of a guide bank at Damukdia on the right bank a short distance above the bridge, completed by June 1933.

The rise of the river that year was normal, but as seen on Fig. 6, the fall of the river was not. In the middle of September, a sudden fall occurred, followed by a rapid rise, these attributed to the failure of the monsoon and a subsequent deluge of rain lasting days and causing severe floods in the vicinity. The failure of monsoons and deluges of rain are not infrequent occurrences in the Ganges basin. However from previous experience the manner in which the river retained such force and characteristics down a distance of 1,000 miles could not have been expected.

In recognition of the dynamic nature of rivers in alluvial plains, from the time of completion of the bridge, watchmen were posted at each of the protection banks to patrol and report any unusual occurrence to the officer in charge. On completion of the watchman’s duty at dusk, 25th September 1933, all appeared well. At 5 a.m. the following morning a villager noted water flowing under the track on the right guide bank, and by 6

a.m. the site officer confirmed that there was a breach in the guide bank about 400 feet long and increasing rapidly. It was noted that the river was not only turbulent, but came in spasmodic rushes at almost regular intervals.



Figure 4. The Hardinge Bridge shortly after opening

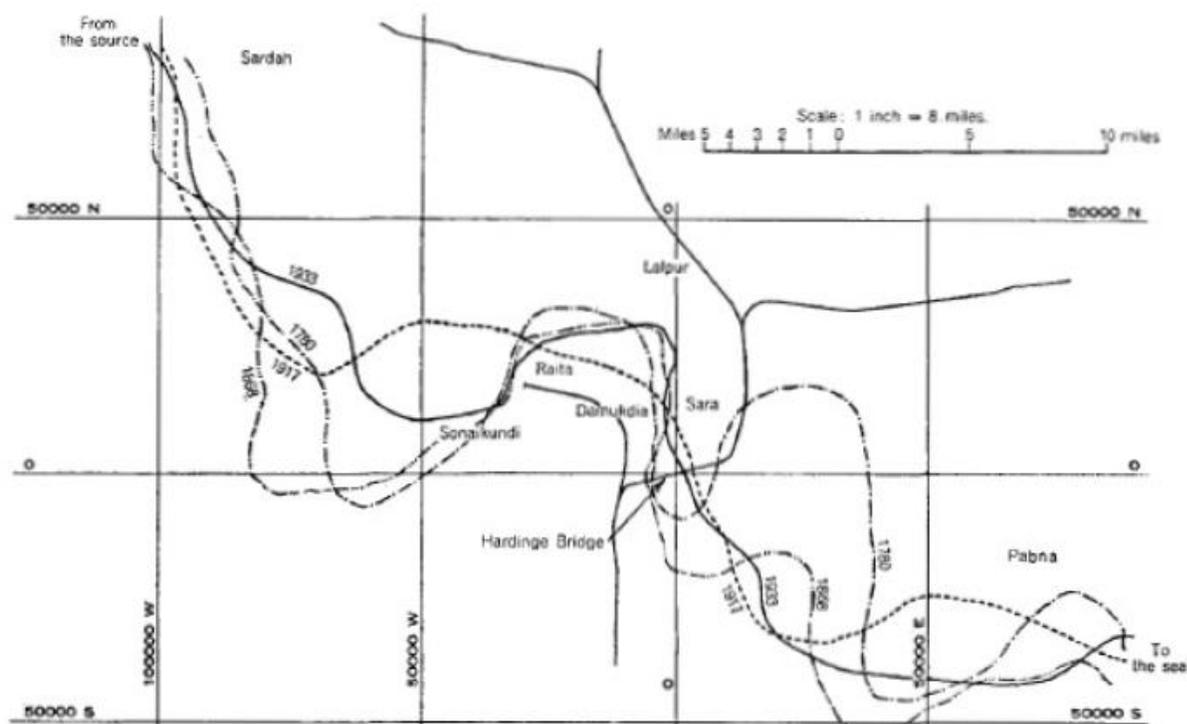


Figure 5. Course of the Ganges near Sara 1780 to 1933

The river appeared to sweep into the embayment like inhalations at intervals of about 2 minutes, and then, as if with each exhalation, carried away large tracks of land covered with jungle and trees. This continued until mid-day, when water surface in the embayment became calm.

The following morning, trains arrived loaded with boulders from the reserve depot, and emergency repair measures were attempted. However with the subsequent rise in the river, the flow of water over the back apron became so strong, that by 2nd October the northern end of the right guide bank was by then completely cut off from the mainland and had become an “island”. On 7th October a rapid fall in the river caused the breach to extend in just a few hours to 1,600 feet (Fig. 7).

Various theories for the right bank failure were promulgated, but the greatest and immediate concern was to design and complete works before the following June that would give the necessary protection for the 1934 flood season.

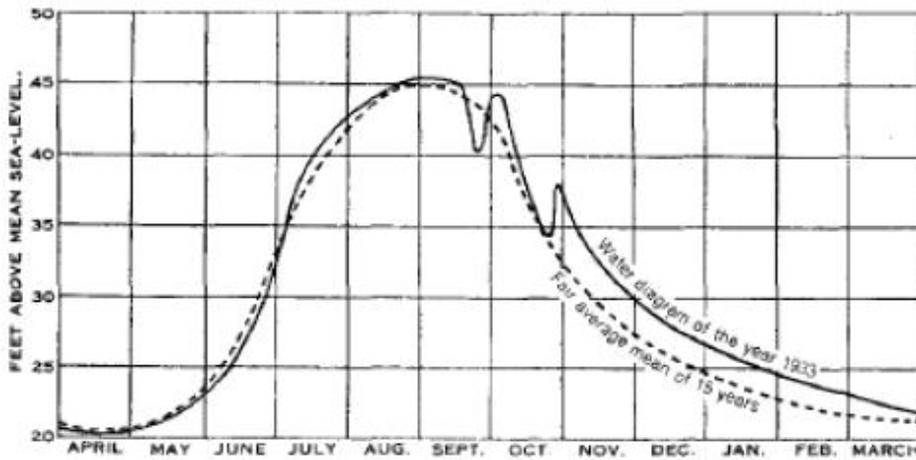


Figure 6. Hydrograph of the river at the bridge site in 1933, and 15 year mean

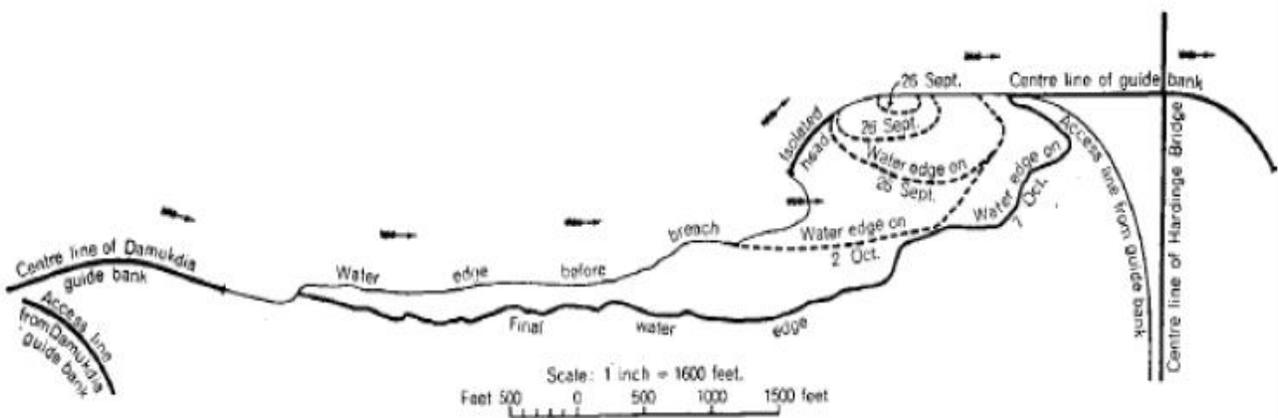


Figure 7. Right Bank of the Ganges at the bridge site, September/October 1933

Sir Robert Gales came to site, and after a searching preliminary inquiry, prepared the scheme to be undertaken (Fig. 8). It was considered that closing the main breach and the gap between the mainland and the “island” northern end of guide bank was not feasible during this period. The immediate threat to the approach bank of the bridge was removed by constructing a mole on a 400 feet radius to the upstream end of the remaining lower section of the right guide bank and where the embayment was comparatively shallow. The key element in the scheme was the construction of the “Backwater Bund” which connected the downstream end of the remaining “island” section of the right guide bund back to the mainland, closing off the channel of the Ganges passing behind the guide bank and through the breach.

These and other elements of the scheme were completed by June 1934, but given the experience of the previous year, inspectors patrolled the guide banks 24 hours a day. That year there were again abnormal floods and in October there were sudden falls in river levels, causing slips, but ones which were readily and rapidly dealt with.

Given the importance of the crossing, the Railway Board set up a committee, which confirmed that the remaining recommendations of Sir Robert Gales’ scheme should be implemented, including the closure of the main breach, but prior to commencement with the closure, investigations should be undertaken at the Irrigation Department’s laboratory at Poona. The results of the work of Sir Claude Inglis at Poona supported the wider scheme of Sir Robert Gales, and the restoration of the guide bund across the original breach proceeded to completion by June 1935.

During the 1935 flood season, higher velocities were recorded than in the previous year and a maximum flood level of only slightly less, but nothing untoward occurred. There were slips, but these were minor and efficiently and readily dealt with. Deep scour did occur that year around three of the piers, but not to a level of concern.

The above narrative describes what occurred in relation to the breach of the right guide bund in 1933. It was considered by Sir Robert Gales that a more focused response between 26th September and the 2nd October would have prevented what became a major failure of the right guide bank. Sir Claude Inglis of the Poona

Hydraulics Laboratory indicated that a major cause of the failure was the construction of the Damukdia guide bank which, while of apparent “common sense”, ignored the first principles of river-control. That is the opposing of the direct force of flow caused relatively harmless kinetic energy to be changed into highly destructive turbulent eddy-flow of an unstable kind, accompanied by surging, whereas the way to control flow should be by coaxing the river to swing in a large natural curve, around a fixed guide bank. The Damukdia guide bank not only ignored this basic principle, but also prevented the right bank from functioning in the manner in which it had been designed.

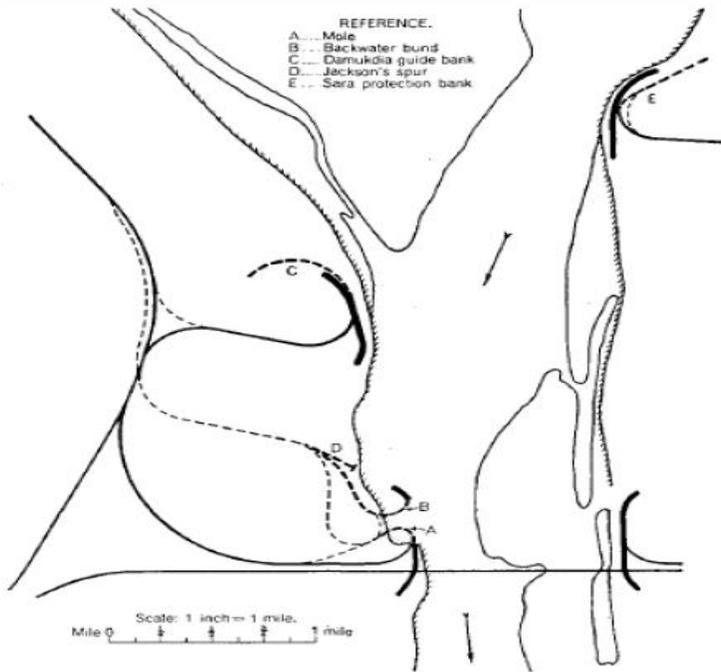


Figure 8. Scheme for Protection of the Bridge

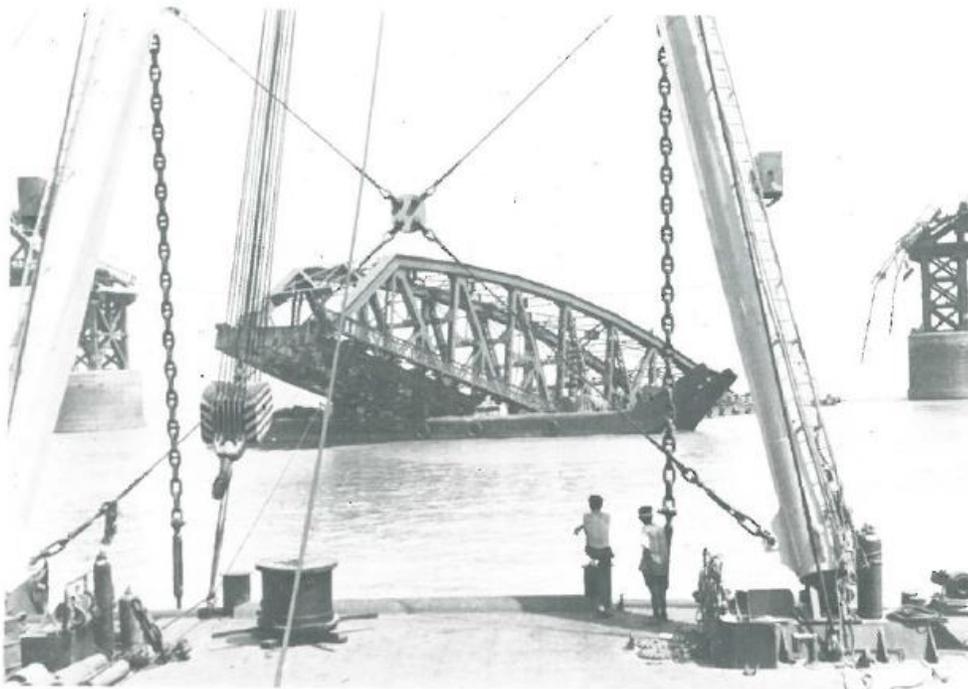


Figure 9. Span 12 of the Hardinge Bridge dislodged into the river during the War of Independence

In 1960, RPT designed a 132kV double circuit transmission line to be carried on pylons bracketed off the Hardinge Bridge girders. This required a reassessment of the existing spans and the foundations to contemporary design standards and to include these nominally increased loads.

During the war of Independence in 1971, the firm was requested to make an immediate assessment of the damage to the Bangladesh national transport system, with the objective of restoring essential links under aid programmes. At that time 276 bridges were either destroyed or severely damaged. The Hardinge Bridge rail link was broken, which, given the importance of the crossing, called for urgent action. Span 12 was dislodged into the river, and span 9 suffered severe damage. Of immediate concern was the danger the felled span posed in blocking the waterway, thereby increasing scour to the adjacent piers and potentially threatening the stability of the piers and spans. A 300 ton floating crane was brought in from Singapore and the span removed (Fig. 9). This was not without difficulty as a shoal had developed just downstream of the bridge, clearly caused by the fallen span and confirming the danger of increasing scour.

The link was restored in two phases, with assistance from Indian Railways, initially re-establishing a single line, using a span used for the second Godavari Bridge in Andhra Pradesh and modified to suit span 12, and by strengthening span 9. Work on the second phase required a period of closure, but advanced such that the bridge re-opened to goods traffic in August 1975, and subsequently to all traffic.



Figure 10. A recent photograph of the Harding Bridge (The 132kV transmission lines are evident.)

3 BHAIRAB BAZAAR RAIL BRIDGE ACROSS THE MEGHNA

The Bhairab Bazar rail bridge presented a further challenge of crossing a major braided Bangladesh river flowing in the alluvial plain. It forms an important link between Dhaka and the north eastern region of Sylhet, and also to Chittagong. The Meghna river just below Bhairab Bazaar is some 5,000 feet wide, and was narrowed to approximately 3,000 feet by river training works at the bridge site. There are seven primary bridge spans of 300 feet single track Warren Trusses which allow 33 feet headroom for the river traffic in this central waterway. These spans are supported on twin concrete well caissons sunk by open dredging within the outer caisson structure through layers of dense micaceous silty sand. Each side of this central section is connected to the approach embankment by shorter underslung truss spans. The bridge was opened to traffic on 6th December 1937.

Like the Hardinge Bridge, this rail link was broken during the War of Independence when two spans were destroyed by bombing.

4 ROAD ON RAIL BRIDGES

In 1979, RPT carried out a technical and economic study for Bangladesh Railways on converting the Hardinge, Teesta and Kanchan rail bridges to road and rail use. All three structures had been designed by the Practice, the latter two under the direction of Sir Alexander Meadows Rendel. The Hardinge Bridge has been described. The Bridge over the River Teesta (Fig. 12) was opened to single line metre gauge rail traffic 1st April 1901. It comprised thirteen Pratt trusses predominantly of spans of 157 feet, supported on elliptical wells 24½ feet wide by 30½ feet long sunk 100 feet below low water level. The 4,000 feet wide river was directed through Bell type river training works. The Kanchan bridge crosses the Punarbhaba river in Dinajpur, and again is a multi-span truss girder bridge. The investigation on all bridges demonstrated that the addition of road use to these rail bridges was technically and economically feasible. However, subsequent funding was not made available for the necessary modifications to proceed.



Figure 11. Bhairab Rail Bridge across the Meghna River



Figure 12. Sir Alexander Rendel's 1901 rail bridge across the Teesta river

5 EAST-WEST POWER INTERCONNECTOR ACROSS THE JAMUNA

Also in 1979, RPT were commissioned to undertake the design of the foundations for the East-West Power Interconnector across the Jamuna river at Aricha–Nagabari. The towers and conductors were designed under the

same commission by Merz and McLellan. A power crossing had been investigated some 20 years earlier, but had lacked economic viability. During the intervening period, relative generating costs between the eastern and western regions rendered the interconnection between the two networks a national priority, principally due to the abnormal rise in fuel oil costs in the 1970s. The purpose of the interconnection was to export cheaper gas generated energy from the eastern grid to the western grid, to improve system security, and to permit west-east energy transfer in the future, should that be required.

Earlier, in 1968, surveys and preliminary designs had been undertaken for the project and had suggested a crossing point on the Jamuna at Aricha just above the confluence of the Jamuna and Ganges rivers where the river is 12 km wide (Fig. 13). Immediately north of the Ganges upstream of its junction with the Jamuna is a low-lying belt containing quantities of clay which have inhibited the northward migration of the Ganges. Further north to the west of the Jamuna there is a region, the Barind Terrace, which consists of layers of silt and clay and is raised above the general level of the Gangetic plain. The Jamuna river meander belt is wide and irregular, but as it emerges from the Barind Terrace, it is narrower and more stable than elsewhere, also in part due to the silty clay deposits at Aricha on the east bank.

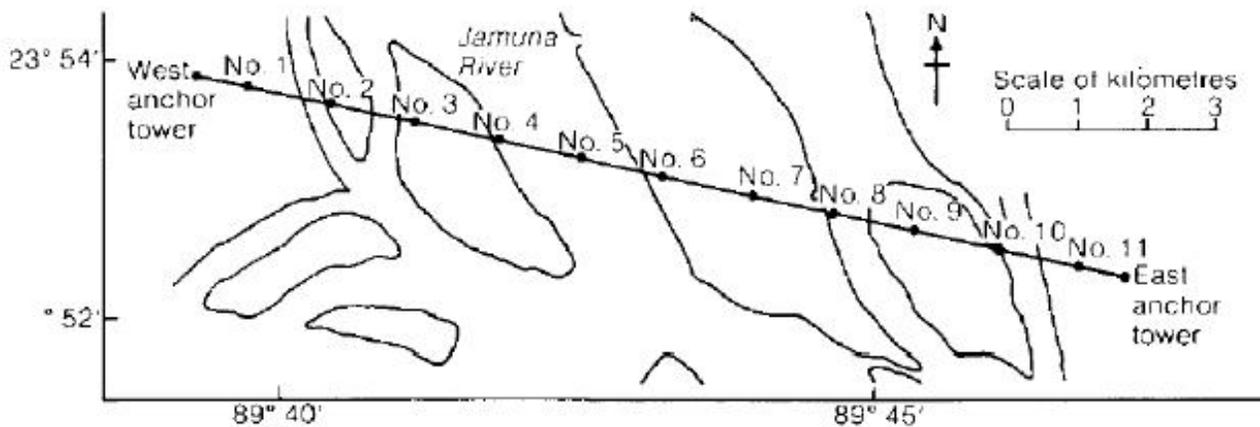


Figure 13. East-West Power Interconnector Crossing point suggested in 1968

The alignment recommended in the initial 1968 studies was approximately 10 km north of the Ganges at that time. By 1979, the river had migrated to within 2 km from that line (Fig. 14), and it was clearly necessary to establish reasons for this development. Records going back to 1830 were examined, together with satellite photographs taken in 1972, 1975 and 1976, and the viewing of old channels from the air. The Jamuna begins rising one month before the Ganges, and reaches its peak earlier. This causes the Jamuna to flow into the bed of the Ganges through several channels, followed by the washdown of sediment from the Ganges accumulated during the dry season. Further complications were caused by the massive landslide in Assam in 1949/50 causing increased sediment load to be deposited into the Jamuna River and associated rises in lowest water levels for years afterwards. It was not until the 1960s that the change came as far downriver as Aricha. A further factor affecting river movements has been the Farakka barrage which has reduced dry season flows in the Ganges since 1972, and concentrated the accumulation of dry season sediment to be swept down the river to meet the established flow of the Jamuna at the confluence.

Detailed examination of all these factors, of the apparent “established” nodal points in the rivers and the natural levee on the north bank of the Ganges allowed the consultants to conclude that the river would not encroach on the chosen line of the caissons in the foreseeable future.

The design of the caissons had to allow for river bed movements and local scour. The river is characterised by downstream migration of vast shoals of sands called chars, some of which are farmed or support established small settlements. The river might display braided channels between these chars, or a major char on one side of the meander might force the flow into a deep channel. If the channel was to migrate towards the clay of the east bank, this could lead to considerable water depths.

The lateral design forces imposed on the caissons were evaluated for the water currents, wind generated waves, forces due to sand waves, and seismic loading, together with the loading on the towers and conductors. It was also necessary to consider forces resulting from the tilt of the caissons. The behaviour of these 12 m diameter caissons founded up to 100m below water level in the weak soils of the Jamuna river bed is complex. Micaceous layers were found, but at depth, fine to coarse sand was encountered. Accordingly the theoretical

non-linear analysis undertaken was supplemented by model analysis undertaken in a centrifuge at the University of Manchester, to develop design bending moments and evaluate potential caisson movements.

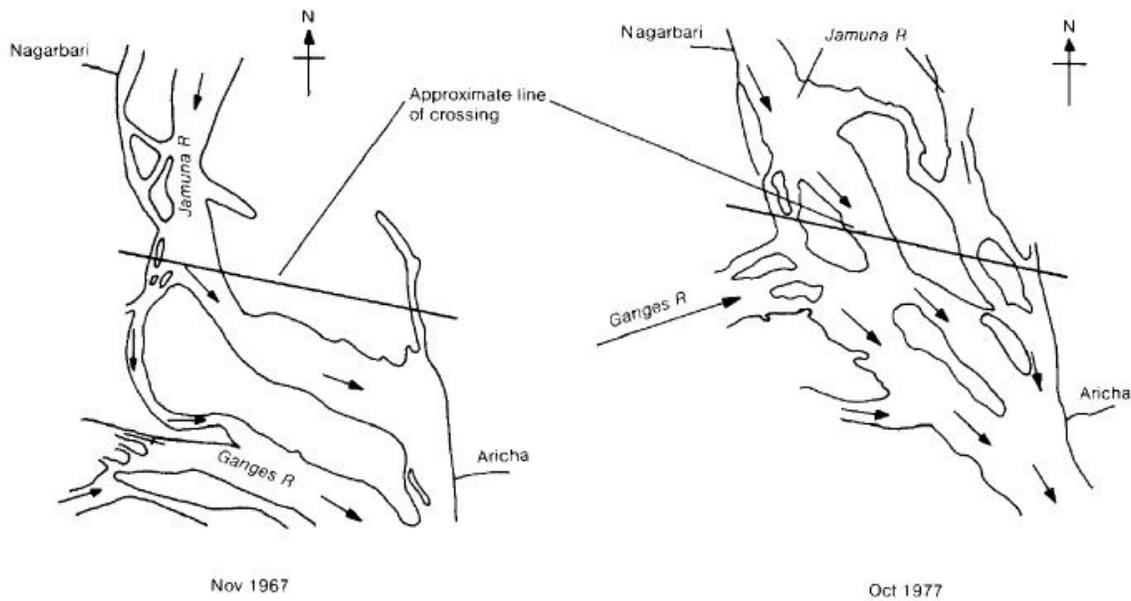


Figure 14. Migration of the Ganges in relation to the line of crossing

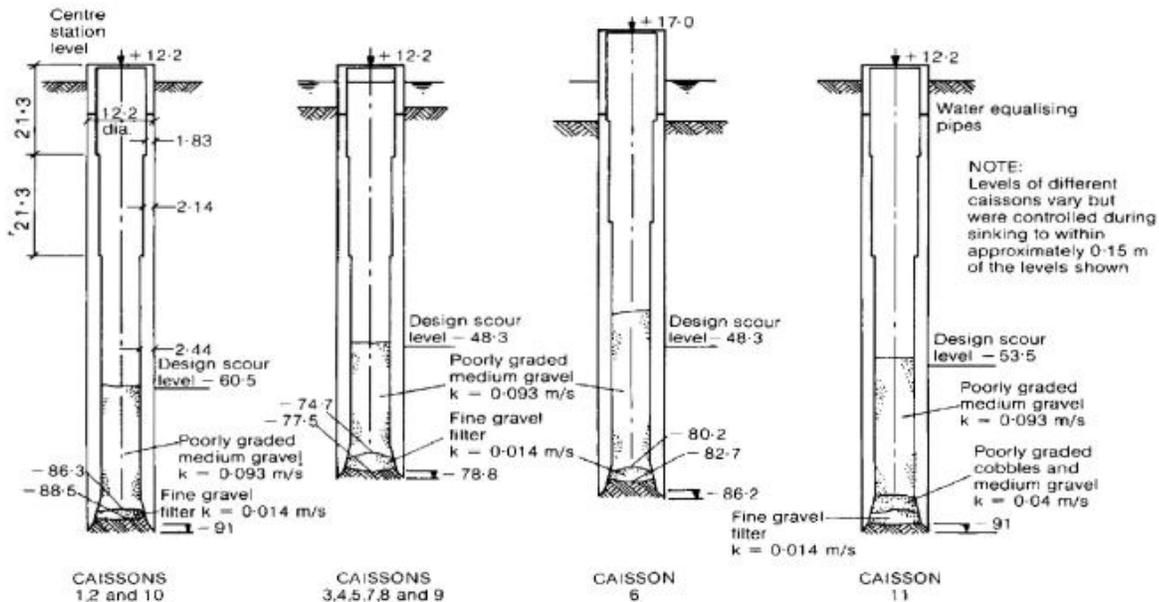


Figure 15. Typical sections through the caissons

Construction of the caissons commenced in 1980. They were sunk using an annular bentonite lubrication system throughout the sinking operation. Six of the caissons were founded in the river, and to facilitate the operation, sand islands were constructed through which to sink the caissons. Extreme weather conditions were experienced during the construction of the sand island for caisson No. 6 which resulted in constructing the caisson 21m to the west of the location intended. This required adjustment to the catenaries of the power cable and to the top elevation of the caisson. During the sinking of caisson No. 11, a blow occurred when the caisson reached level -78.3m, where most of the bentonite was lost to the centre of the caisson. Following detailed evaluation, the bentonite lubrication system was re-established and the caisson once again started to move, and was founded at a level of -91m (Fig. 15).

The founding of the last of the eleven caissons was completed in April 1982, the 111m tall towers by October, and the conductor stringing was completed by the end of November that year, an overall construction period of two years. Certainly at the time of construction, the foundations were the deepest caissons in the world and the key components of a project where the costs were recovered within 18 months by way of reduced fuel imports to Bangladesh.



Figure 16. Caisson in sand island during sinking

6 GAS SUPPLY TO THE WESTERN ZONE OF BANGLADESH

The success of the East-West Power Interconnector resulted in 1982 in the appointment of RPT, Pencol & BCL by PetroBangla to undertake the Study of the supply of Gas to the Western Zone of the country. In the transfer of gas from gas fields of the northeast region of Bangladesh, the primary obstacle was that of supporting a large diameter gas pipeline across the Jamuna River. Alternative locations were examined which were suited to the existing and potential gas networks of the east and west sides of the river, and which were appropriate for a stable river gas pipeline crossing. From these a site at Sirajgang was selected. A design for this crossing was produced, but with a disproportionately high construction cost.

Although outside the terms of reference, RPT prepared a design of an alternative crossing at that site, comprising a road bridge across the river, with the gas pipeline attached, and presented this to the Government. In this context, should the road crossing be economically justified, it was suggested that the transfer of gas across the river would cost little more than the cost of the pipe itself. The bridge was estimated to cost US\$ 420m and take four years to build. The Government accepted this suggestion, and sought funding from the World Bank.

7 THE JAMUNA MULTIPURPOSE BRIDGE

The Jamuna river, known as the Brahmaputra in India, is one of the world's great rivers. With its vast catchment area covering the eastern Himalayas, it ranks as the world's fourth largest in terms of peak discharge and second largest in sediment load. The Jamuna runs in a north-south direction, and following its confluence with the Ganges, continues, as the Padma and then Meghna rivers until its final discharge into the Bay of Bengal, dividing Bangladesh in two (Fig. 17).

The Jamuna is a braided river with its channels continuously changing course within the braid belt. It is flooded in most monsoon seasons and measures as much as 40 km in width in some places. Even at its narrowest point the braid belt is 15 to 20 km wide (Fig. 18).

The existing transport infrastructure within Bangladesh in the years immediately following Partition related largely to the structural needs of Bengal, not to the transport system subsequently required. Prior to the construction of the Jamuna Bridge, crossings over this river were made by ferries where long queues were a normal feature, and where capacity failed to meet demand. This was a major constraint on the post partition development of the agriculture of the north western zone, effectively isolating it from the commercial and industrial centres on the eastern side, including Dhaka and Chittagong in particular. There was also the need to provide facilities for the transfer of gas from the gas fields of Sylhet to the west, and for additional interconnection of power from these energy sources to the western side of the country.

In 1986, RPT, in joint venture with Nedeco and association with BCL were appointed by the UNDP to undertake location, traffic, economic and engineering studies for a crossing across the Jamuna or Padma rivers. During this period, the Consultants examined 14 potential crossing sites of these two rivers, and concluded that the most favourable location was at Sirajgang across the Jamuna, with the alternative being a crossing of the Padma at Mawa. This was followed by a Techno-Economic Study undertaken for the World Bank for a multi-purpose crossing at Sirajgang, which additionally included addressing environmental and resettlement issues, and leading to the preparation of the Tender Documents. In 1994, the Consultants were appointed as The Engineer for the project by the Government of Bangladesh.

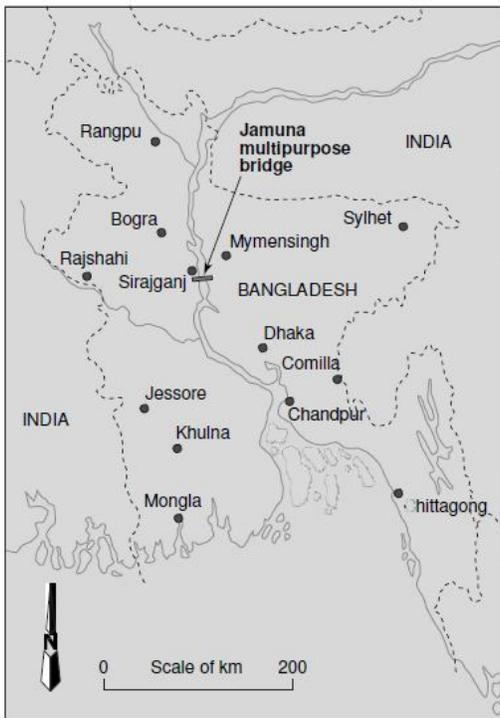


Figure 17. Jamuna Bridge location



Figure 18 Satellite image at the bridge site showing guide bunds and reclamation areas

The provision of a fixed crossing of the Jamuna at Sirajganj presented primary technical issues of the nature of the braided Jamuna river and the weakness of the foundation soils. In addition to these, a limited construction period was afforded by the Co-Financiers loan requirements. The design of a project of this nature not only involves the challenges of the considerations of direct design issues, but, of paramount importance, of the cost and construction constraints. These will be reflected in the ensuing paragraphs, but it is noted from the outset that this major infrastructure project would require large quantities of materials and substantial, potentially massive, items of construction equipment to be brought to the site in the middle of the country 300 km from the coast and where the road network had limited capacity. Although the rivers are wide and deep during the monsoon period, this is not the case during the low flow season. The water-borne equipment having large draft (e.g. off-shore piling barges, dredgers, and side dumping vessels etc.) would only be able to sail to or from the site during the 3 months of high water levels in the flood season. Additionally the power interconnector at Aricha–Nagabari imposed a height restriction during such high water periods, with passage dependent on the current location of the river channels in relation to the power catenaries. While the issues constraining the transport of equipment to site could generally be accommodated by careful planning, it would be necessary for the

supply of construction material to the site to be maintained throughout the year. In particular rock is not available in Bangladesh in the quantities required, with the nearest quarries being in India and Bhutan. In the event, rock came also from Indonesia, requiring transfer from ocean going vessels to shallow draft river barges, and requiring maintenance dredging of the navigation channels.

Reflecting the Ganges at the Hardinge Bridge, the control of the Jamuna river, where the maximum flow recorded is significantly greater, presented a major engineering challenge. The shifting deeply scoured channels of 40 to 45m depth during flood, the seasonal river level variation of 8 m, and river width at the selected Sirajgang site varying from 15km at flood to 5 km at low water, imposed considerable demands on the design. Also the seasonal construction period of approximately 6½ months caused by the river level variation created significant construction constraints.

The silty micaceous soils of the river bed extending to considerable depths at the bridge site, together with the high seismicity of the Bengal basin presented unusual foundation conditions. The scouring and liquefaction potential of the river bed, where the upper 70m is particularly weak, required very deep foundations. The micaceous nature limited the horizontal resistance of the soil, and rendered vertical units inappropriate. The conductors of the Aricha-Nagabari Power Interconnector are relatively insensitive to any horizontal movements at the top of the huge caissons. That however would not be the case for a bridge carrying road, rail and gas. The use of groups of very large diameter steel piles driven at a rake offered a solution to the resistance of the large lateral forces imposed on the foundations. Technology developed for the North Sea oil rigs presented the option of using steel piling of sufficient diameter to be effective for the lengths required and to be driven to the necessary depths using hammers developed in this context (Fig. 19).



Figure 19. Piling of the 3.15 m diameter piles at the Jamuna Bridge



Figure 20. Placing a pile cap

The project timescale also affected the choice of the inter-related design and construction issues leading to the adopted scheme. The massive piling units and the pile caps (Fig. 20) could best be handled by large floating equipment. For the river training works, it was only practical to construct one guide bank in one season. The key issue in achieving the optimum scheme selection was the economy of time and cost through the design, in particular the critical issues of bridge spans and bridge length. While superstructure costs generally increase with increasing span, the opposite is true for the foundations, and for this site, the minimum for the combined costs was found to be for spans in the region of 100m. Concerning optimum bridge length, evaluations were made for the 15km crossing for the total cost of bridge, embankment, and river training works, with designs incorporating bridge lengths varying from 3km to 15km. The hydraulic risk of outflanking was assessed for each case, and considered unacceptable for a 3km crossing. The solution selected was a bridge length of approximately 4.8km together with associated embankments and with river training works of 2.1 km and 2.2 km for the east and west guide bunds respectively. Existing “hard” points some distance upstream were to be

strengthened on both banks, and road and rail approaches constructed on the flood plain on embankments created by dredged fill and elevated above design flood level.

The total project, including rail was viable, but the incremental cost of rail was problematic. It was eventually accepted that if a road bridge went ahead without rail, the damage to the rail network of the country would be considerable, and finally rail was included. An earlier compromise in the bridge design specification of four narrow lanes of roadway plus meter gauge rail had allowed the project to proceed.

Market forces at the time of design indicated competitive pricing between steel and concrete, and designs for superstructures in both were included in the tender documents. The Consultants design incorporated sand filled steel piles where the D/t ratio was limited to below 40 thereby ensuring the piling would develop the full plastic moment of the pile section, and avoiding collapse through local buckling during a major earthquake. In the event, Hyundai Engineering & Construction elected to employ its large off-shore pile driving barge and use fewer but larger 3.15 m diameter steel piles up to 83m in length and filled with concrete. The piles were capped with precast concrete pile caps (Fig. 21), filled in situ, and on which cast in situ piers were constructed. The bridge was constructed in modules of seven 100 m spans, separated by expansion joints. The seismic loading was accommodated by shock transmission units at each free pier and energy absorbing steel pintels at all piers. The superstructure design was that of a variable depth single cell box girder formed of precast concrete segments. The overall bridge length comprised 49 spans of 100m.

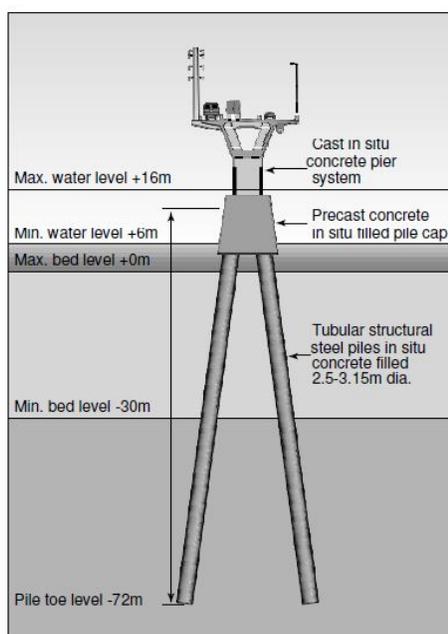


Figure 21. Cross section of the Jamuna Bridge

The layout of the river training works, as initially planned at feasibility stage, was based on a comparatively stable situation of the main river where only limited shifting of the river banks had been observed for some years. However in 1987-1989 it became apparent that the extreme floods of 1987 & 1988 had considerably disturbed the equilibrium previously existing in the selected bridge corridor. As can be seen in Fig. 22, a second major channel developed on the west bank, and both channels diverged east or west respectively.

To build within the originally conceived construction concept accommodating this second channel would require a bridge of at least 7.5 km in length, clearly adding significantly to the cost of the project. Accordingly consideration was given to the possibility of constructing one of the guide bundson a mid-river char (sand bank) or shallow water during the dry season. This was adopted, but it meant that, following the construction of the east guide bank in the first construction season, the location of the west guide bank could not be advised by the Consultants until the 15th October 1995, 19 months after signing of the bridge and the river training contracts.

The cross-sectional design of the guide banks required consideration of bend scour, slope stability, depth for economic dredging and protection of the slope. It is also recognised that, for training works of this nature in such a river and location, design modifications may be required during construction. In particular, notwithstanding extensive site investigations, unknown sub-soil conditions may need to be accommodated. While change in location was caused by channel shifting, and land acquisition constraints, cross-section changes were found to be necessary for the west guide bank. It became evident that the soil during and after dredging was

very sensitive to dynamic disturbance and flow slides occurred in rapid succession when dredged to a slope of 1-in-3.5. Accordingly the slopes were changed to 1-in-5 and 1-in-6, and adjustment made to the toe level of the falling apron (Fig. 23). Notwithstanding the change in slope, great care was exercised during the piling operations in the vicinity of the west guide bank. The 1700KNm of energy imparted by the Menk hammer to the pile caused considerable disturbance to the surrounding soils with potential liquefaction and failure of the recently constructed slope of the west guide bank. The risk was minimized by temporary backfilling of the trench in front of the guide bank, and by detailed monitoring of ground movements and attenuation characteristics by geophones during piling to ensure containment of these movements.

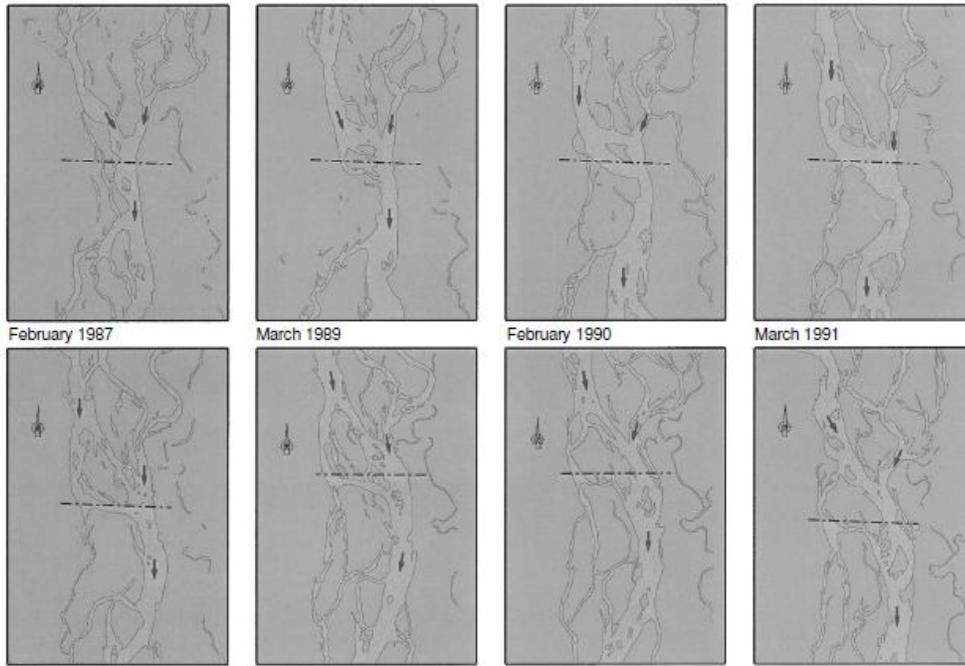


Figure 22. Satellite Images showing the development of a second major channel, 1987 – 1995

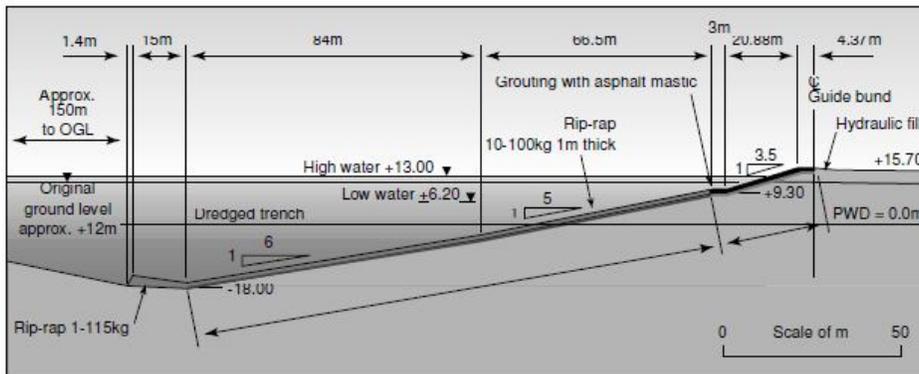


Figure 23. Cross section of West Guide Bund

The upper part of the slope (above low water) is protected by geotextile material. Below that, protection was provided by a fascine mattress fabricated on the banks, floated to the site attached to a frame of bamboo for buoyancy, and, after positioning, ballasted and sunk with the final ballasting layer placed by stone dumping barges (Fig. 24).

The river training works were completed in June 1997, the last span of the bridge in March 1998, and the Jamuna Bridge was opened to road and rail traffic on the 23rd June 1998.

Since the opening of the Jamuna Multipurpose Bridge, the levels of traffics traversing the crossing have far exceeded those used for the economic justification of the project, overwhelmingly endorsing the Government decision to proceed with the undertaking. It is clear that the positive impact of this project to the economy the North West region of Bangladesh has been considerable.



Figure 24. Floating out fascine mattress and sinking by ballasting with boulders



Figure 25. Jamuna Bridge under construction.

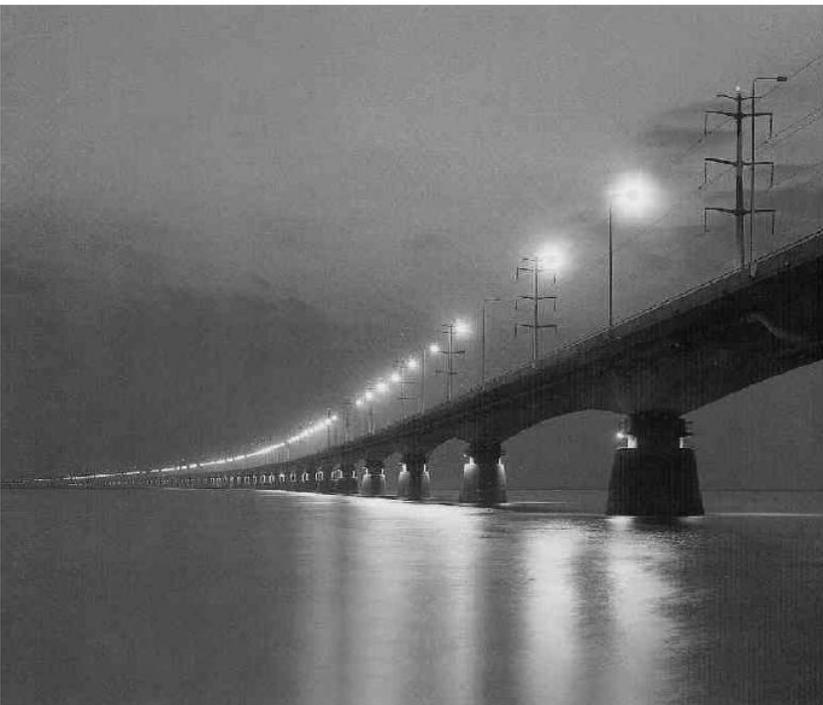


Figure 26. The completed Jamuna Bridge at night

8 PRIORITY “B” BRIDGES PROJECT

In parallel with the Jamuna crossing, RPT undertook a project for the United Kingdom bi-lateral aid agency, working with the Bangladesh Roads and Highways Department (RHD) on the design and the supervision of construction of 25 (later extended to 37) bridges. This involved a number of RPT engineers working in Bangladesh for several years with their RHD counterparts.

The aims of the project were to:

- i. select, on economic grounds, 25 (initially) bridges on the national highway system for reconstruction with spans ranging from 12.5m to 82.2m;
- ii. design and construct the replacement bridges to standards which will ensure that the bridges are durable and can withstand modern traffic loads, severe floods and earthquakes;
- iii. train Roads and Highways Department staff to use modern design technology and to supervise construction to adequate standards;
- iv. train local contractors' staff to plan and manage their projects effectively, to apply basic technical principles to ensure a durable product and to use modern plant and techniques;
- v. provide some new construction plant;
- vi. train RHD staff in bridge inspection and management techniques and to develop with RHD a computerised bridge management system.

The bridge superstructures consisted of universal steel beams and steel trusses; substructures were formed of reinforced concrete on piled foundations, precast and driven or bored and cast-in-place.

RPT & RHD undertook studies; hydrological and site surveys; geotechnical investigations; economic analysis; design; preparation of tender documents; supervision; computer programming; training.

Bridges were located from to the North East (Sylhet-Tamabil Road) and to the South West (Dhaka Mawa Road) of Dhaka.



Figure 27. Construction of one of the initially selected 25 bridges

9 PADMA BRIDGE

As indicated earlier, the transport network of Bangladesh had related to that existing prior to Partition, and accordingly the Government set as one of its priorities the integration of the country through newly developed transport and energy links between the major sectors of the country. The Jamuna Multipurpose Bridge effected that first major link, namely that between the North West of the country and the Eastern region. Following the success of this project, in 1999 the Government of Bangladesh appointed the RPT/NEDECO/BCL team to undertake a study of a Multipurpose Bridge crossing of the Padma River, below the confluence of the Jamuna and Ganges rivers, to connect the South West region to Dhaka and the Eastern Zone.

The Padma river is one of the mightiest rivers in the world with the conjoined flow of the two major rivers of the Ganges and the Jamuna, and such a crossing will present exceptional engineering challenges. However the technical experience learned from undertaking the Jamuna Bridge can be employed to good effect to allow this challenge to proceed with confidence.

The Consultants established that the traffic base for the proposed Padma Bridge was not only substantial but the economic viability was even greater than it had been for the Jamuna Bridge; that the practical sites were limited to Mawa and Goaluno of which Mawa was indisputably superior; and the engineering issues were not dissimilar to those which proved solvable for the Jamuna crossing.

Recommendations were:

- i. the Padma project should be progressed at Mawa
- ii. the base case should be a four lane road bridge with facilities for future BG rail and power and gas lines
- iii. potential environmental and resettlement should be addressed at an early stage
- iv. early action should be taken with respect to land acquisition

The clear definition of the location of the bridge was decided at the Inception Report Workshop on 29th August 1999. The primary characteristics of the bridge were defined in four main aspects, namely the type of foundations, the extent of river training works, the length of the bridge and the type of superstructure. These key issues have been maintained.



Figure 28. The Padma Ferry Ghat at Mawa – April 1999

10 THE SHAH AMANAT CROSSING OF THE KARNAPHULI RIVER

The Shah Amanat Bridge over the Karnaphuli River is a significant landmark in the port city of Chittagong. Following initial studies it was decided by the Roads and Highways Department and their Consultants to procure the new bridge on a design-and-build basis. Rendel, working with the contractor, produced the tender design for the successful MBEC-ACL-COPRI joint venture, and subsequently developed the detailed design for the 950 m long crossing.

The crossing spans the Karnaphuli River immediately north of Chittagong port, and connects the main city of Chittagong to the southern side and district of Patiya and to Cox's Bazaar further south. The site lies in the flat coastal region of Chittagong at the foot of the Chittagong Hills. The Karnaphuli River drains part of this hill system and deposits alluvial and deltaic strata in the adjoining flat plain. At the bridge location, the Karnaphuli River generally flows in a main channel approximately 280 m wide, extending to 950 m of flood channel during the monsoon season. The river is tidal and fluctuates in level by up to 5.9 m.

The 950 m long crossing is aligned on a 3,200 m horizontal curve (Fig. 29 b). It comprises three 200m extradosed main river spans with central stay cable towers, two 115 m side spans, and a 120 m approach viaduct (Fig. 29 a). These carry two high speed carriageways of 7.3 m, two 1.65m slow lanes (for rickshaw and bicycle traffic etc.) together with two pedestrian footways.

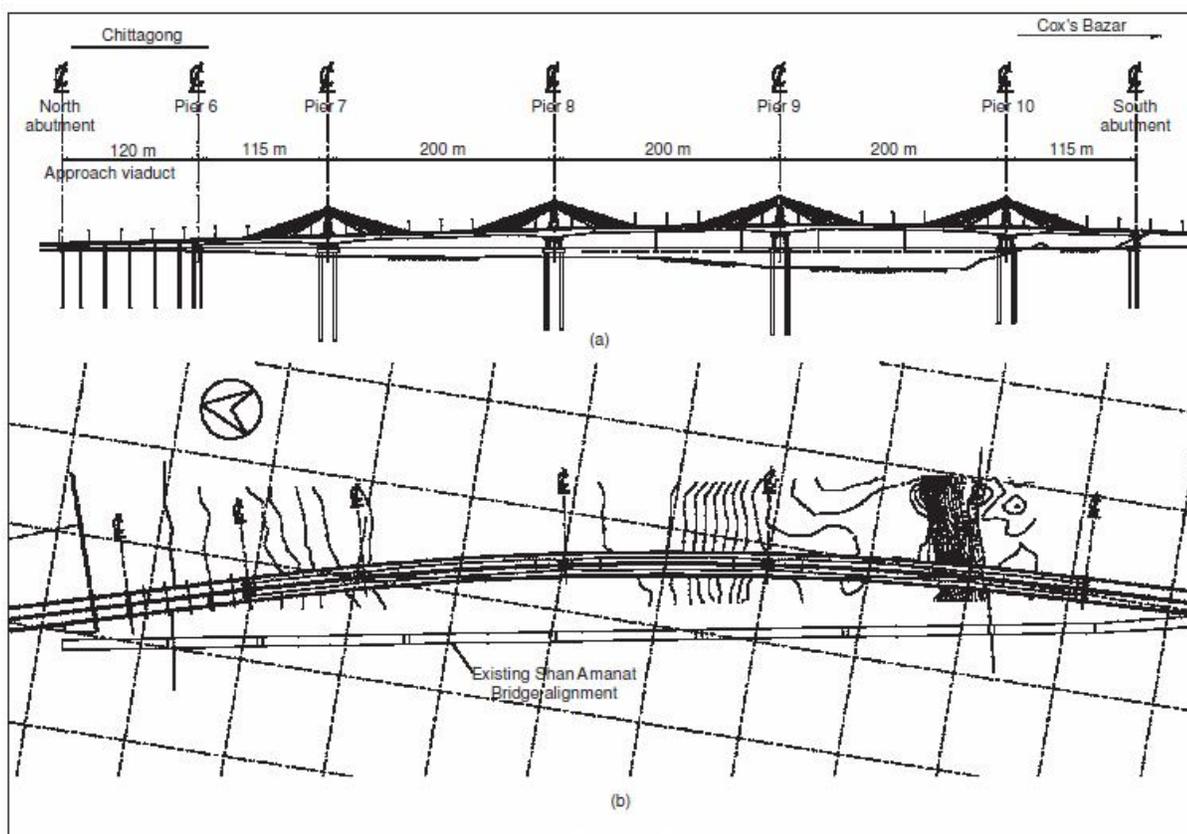


Figure 29. Elevation and Plan layout of the Shan Amanat Bridge across the Karnaphuli River

The Shah Amanat (or Third Karnaphuli) Bridge is the first major cable-supported crossing constructed in Bangladesh. Given the alluvial nature of the river bed, pre and post award ground investigations were undertaken, and preliminary pile designs were developed using the geotechnical properties thereby derived. Unlike the Jamuna river bed, virtually no mica was found in the Karnaphuli soils. This design was optimised using vertical bored cast in-situ reinforced concrete test piles of smaller diameter (1.5m) than the intended final design. Piles of the anticipated 3m diameter, could be expected to be displaced in the region of 300 mm vertically before developing the necessary end bearing, which is a significant component where depths of scour and liquefaction could reach 30m. With such displacement, much of the skin friction could be lost and accordingly it was de-

cided to post-construction base grout the piles. Three test piles were base grouted and their characteristics compared with three ungrouted piles. This verified the design approach and the final pile design.

Each of the main river piers are founded on four 3m diameter vertical piles, base grouted post-installation and up to 77 m in length. These reinforced concrete bored (under bentonite slurry) piles cast in-situ, were started by driving a permanent steel casing 10 m into the river bed from a gantry crane supported on a piled working platform at each of the river pier locations. The pile caps were constructed using a suspended cofferdam with bottom shutter, sealed by tremie concrete. The four inclined columns and the main pier “table tops” were cast in-situ.

This extradosed bridge structure is characterised by a 25 m central tower, integral with the deck, supporting six stay cables located at distances between 36 m and 76 m longitudinally from the piers. The cable deviator saddles within the towers are located at heights between 19 m and 24 m above deck level. The bridge deck consists of a prestressed concrete single cell box girder supported on four vertical load bearings at each of the main piers. This arrangement allows some of the superstructure imbalanced moment to be carried into the sub-structure, thereby reducing the mid-span moment variation. The deck is prestressed longitudinally by internally bonded prestressing tendons.

The pipe steel saddles are provided with a “blocking” system to prevent slippage due to unequal forces in the stay cables under live loading. Dampers are provided at cable anchorages to minimise fatigue effects due to wind vibration.

Traditional steel form travellers were used for casting the deck in segments. The towers, made integral with the deck, were cast in three pours and cambered transversely to account for eccentric loading from the stay cable resulting from the bridge curvature in plan. Deck construction was continuously monitored to ensure the required vertical and horizontal profiles were achieved, and adjustments continuously made. Deck closure stitches were carried out in the required sequence using the travelling formers.

Construction of the project commenced in July 2007 and was completed to time and budget in May 2010 (Fig. 30). The bridge has been well received by local and national government who regard the construction of the first major cable supported bridge in Bangladesh as a symbol of progress. It has already become a significant new landmark in the important port city of Chittagong.



Figure 30. The Shah Amanat Bridge across the Karnaphuli River at Chittagong

11 CONCLUDING REMARKS

A review of the river crossings described in this paper reflects advances made in the design and construction of bridge crossings of major rivers over the last 100 years. Additionally, looking back on an important project such as the Hardinge Bridge provides a most valuable perspective and case history still relevant today, and one from which there is much that can still be learned.

For all major infrastructure projects a balance must be decided at the onset as between direct initial capital investment and ongoing maintenance costs. The latter will relate in the first place to monitoring, which governments throughout the world are notoriously reluctant to fund adequately. Clearly this is an issue of considerable importance for river training works for the particularly challenging crossings of the rivers of Bangladesh.

River crossing infrastructure may also be faced with requirements of adapting to changing use. World wide, many bridges originally designed for rail were subsequently modified to carry road, either alternatively or sometimes additionally. In the case of the Jamuna Bridge, where the inclusion of rail on the bridge was rejected by one of the co-financiers throughout the design period, a residual issue remains. The compromise specification for the bridge width and loading of a narrow roadway and meter gauge rail allowed the project to proceed. However while particular local Broad Gauge rolling stock can cross the bridge, for International BG trains using the Trans Asia Railways in future some strengthening of the superstructure will be required.

Notwithstanding the unstable nature of the rivers of the alluvial plain of Bangladesh, and even the damage of war, the bridge crossings over the Teesta (1901), Ganges (1915) and Meghna (1937) rivers have demonstrated their robust nature as they continue to serve society today.

Looking to more recent times, the crossings of the Jamuna river, including the energy connections, and the Shah Amanat crossing of the Karnaphuli river have already demonstrated the very positive economic and social impacts such infrastructure investments can make. As we look forward to the construction of the Padma crossing, and its place in the Asia Highway, we can with confidence anticipate considerable benefits to Bangladesh from that investment.

The Rendel authors are most grateful to have been invited to record the involvement of their firm with crossings of all the major rivers of Bangladesh, including those across the Teesta, Ganges, Meghna, Jamuna, Karnaphuli and Padma Rivers.

REFERENCES

- John Thornton, J – English Pilot, Third Book (London 1703)
James Rennell – A Bengal Atlas (1781)
James Meadows Rendel – 1852 Presidential Address to the Institution of Civil Engineers, London. (Proceedings of the ICE, January 1852)
W R Shaw – The Teesta Bridge (Proceedings of the ICE, Paper No. 3352, Session 1901-1902)
Sir Robert Gales – The Hardinge Bridge over the Lower Ganges at Sara, and Discussion (Proceedings of the ICE, Paper No. 4200, November 1917)
B L Harvey – The Restoration of the Breach in the Right Bank of the Hardinge Bridge, and Discussion (Proceedings of the ICE, Paper 5045 November 1936)
G P Warriar – Restoration of the Hardinge Bridge in Bangladesh, and Discussion (Proceedings of the ICE, Paper No. 8016 August 1977)
L W Hinch, D M McDowell, P W Rowe – Jamuna River 230kV Crossing – Bangladesh, Design of foundations (Proceedings of the ICE, Paper No. 8867 November 1984)
J A Chandler, J Peraino, P W Rowe - Jamuna River 230kV Crossing – Bangladesh, Construction of foundations (Proceedings of the ICE, Paper No. 8869 November 1984)
RPT, Pencil, BCL – Gas Supply to the Eastern zone Study – May 1983
M R Lane – The Rendel Connection - Quiller Press, London 1989
R G R Tappin, J van Duivendijk, M Haque – The design and construction of Jamuna Bridge, Bangladesh (Proceedings of the ICE, Paper 11704 November 1998)
RPT/Nedeco/BCL – Padma Bridge Study – February 2000
D Astin, H Xie, A Gillarduzzi – Design and construction of the Third Karnaphuli Bridge, Bangladesh (Proceedings of ICE, Paper 900050 December 2010)