Locating the Jamuna River crossing of a 230 kV electrical transmission line in Bangladesh

Victor A. Sowa, PhD., PEng
Jacques Whitford and Associates Limited, Vancouver, B.C.

Abstract: Much of the country of Bangladesh in the Indian Sub-Continent is a huge delta formed by the Jamuna-Ganges-Meghna River System. A 230 kV electrical transmission line, a lifeline project, was required to cross the Jamuna River which is a large braided river that is up to 20 km wide during the flood season. The transmission line crossing of the Jamuna River, where the river is about 10 km wide, consisted of 11 transmission towers, 90 m high and 1,220 m apart. Each tower is supported on a single large 10.7 m diameter caisson, with the depth of the caissons ranging from 91 to 112 m. The river delta soils in the vicinity of the transmissions line crossing of the Jamuna River are primarily sandy soils that are highly erodible. River bank erosion of up to 400 m in a single year is not uncommon. The major challenges of crossing this river were to select a relatively stable river location; to locate the anchor towers far enough back from the river banks to accommodate future river bank erosion; and to minimize the possibility of the river developing a new channel during flooding, bypassing the entire river crossing. The engineering process used in selecting the final crossing location is described.

Introduction

The Brahmaputra-Jamuna River is one of the largest rivers in the world. It rises in Tibet on the northern slopes of the Himalayas, flows through Tibet, crosses the Himalayas into Assam, and flows southward to enter Bangladesh. The Brahmaputra-Jamuna River then flows generally in a southerly direction, discharging into the Bay of Bengal.

Along the way the Brahmaputra-Jamuna River is joined by the Teesta River, the Ganges River, and the Meghna River. This river system in Bangladesh is known by various names in different parts of the country. For the purposes of this paper the area of interest is in the vicinity of the confluence of the Jamuna River and the Ganges River, and the river will be referenced simply as the Jamuna River.

The Jamuna-Ganges river system, in terms of the volume of flow during the flood season, is the second largest river system in the world. The maximum recorded flow for the Jamuna River was 92,300m^3/s (3.3 x 10^6 cfs) and the maximum flow for the Ganges River was 73,000m^3/s (2.6 x 10^6 cfs).

The Jamuna River system essentially divides the country of Bangladesh into two; the western and the eastern regions. The river is a major obstacle that inhibits the development of the country in many ways. There has been a strong need to construct an electrical transmission line to cross the Jamuna River to connect the western and eastern regions of the country. As a result the 230 kV East-West Interconnector Project came into being, connecting Ishurdi in the west to Ghorasal in the east as shown on Fig. 1.

The main physical obstacle to constructing the East-West Interconnector was the crossing of the Jamuna River. At the time that this project was designed and constructed there was no bridge crossing the Jamuna River in Bangladesh. Ferries were the only means of crossing the river, and even the railroads crossed the river using the ferries.

Engineering studies of the East-West Interconnector Project were undertaken at various times, but it was not until 1970 that a complete engineering study was undertaken by a consortium of Acres International Limited and Consulting Engineers (Pak) Limited on behalf of the Bangladesh Power Development Board. The results of this study are summarized in the 1968 and 1970 Acres reports listed in the references.

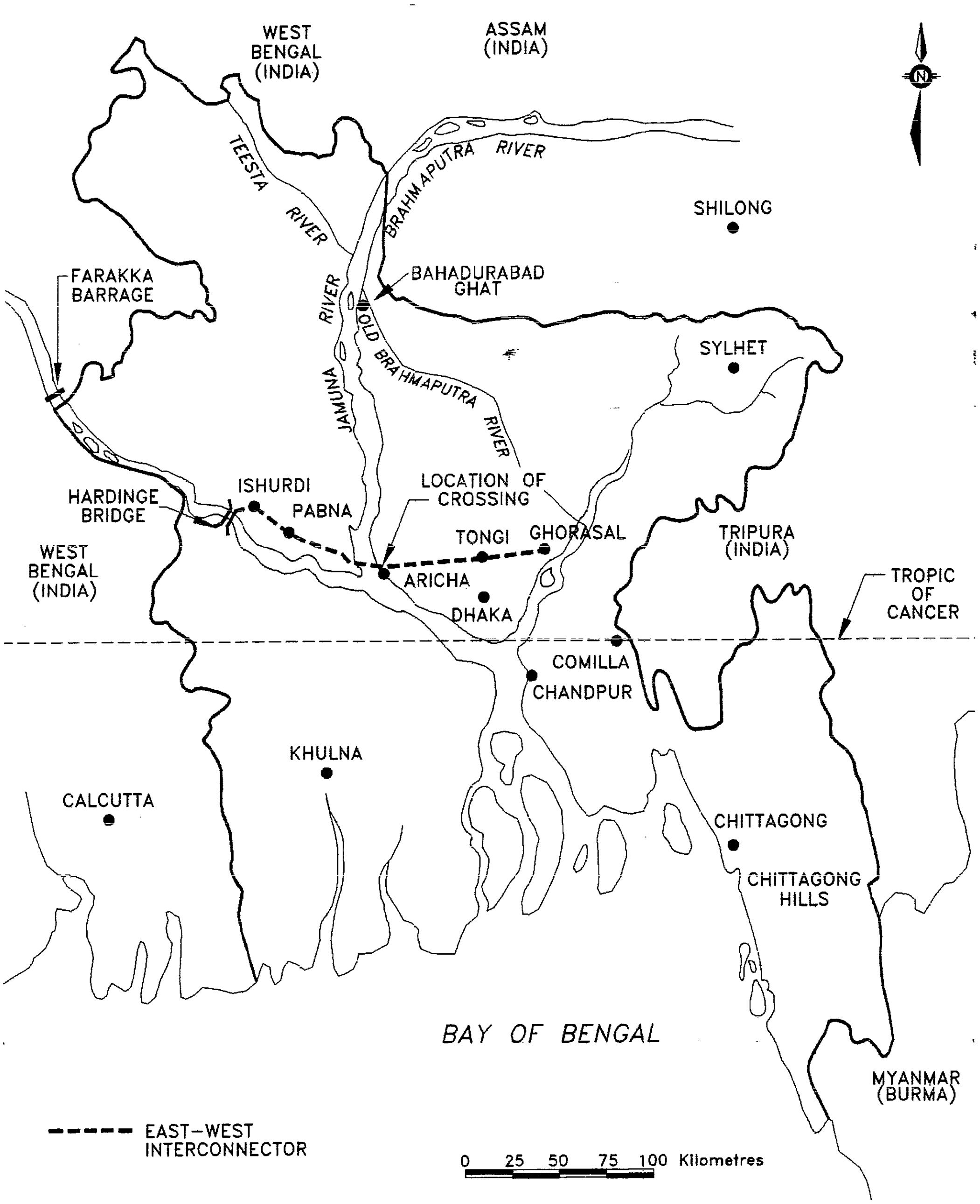
The engineering study commenced in 1967 and was concluded in 1970 with the submission of a final engineering report and construction documents. The engineering study included the results of site investigations, primarily geotechnical, geomorphological, and hydrological, that were undertaken during 1967, 1968 and 1969.

Shortly after the completion of the East-West Interconnector Project engineering study, Acres International Limited became the General Consultants to the then East Pakistan Water and Power Development Authority (EPWAPDA). EPWAPDA was the forerunner to the Bangladesh Power Development Board that was formed later to look after the power development in Bangladesh.

Acres International Limited, as the new General Consultants to EPWAPDA, could not continue their involvement with the East-West Interconnector Project during the construction phase because monitoring their own project was a conflict of interest. As a result, the project had to be taken over by other consultants.

During the process of selecting alternate consultants and obtaining funds for construction of the East-West Interconnector Project, political events delayed the project.

Fig. 1. Map of Bangladesh and the location of the East-West Interconnector electrical transmission line.



The partnership of West Pakistan and East Pakistan became strained and they separated, with East Pakistan becoming a new country in 1971 known as Bangladesh.

The creation of the new country of Bangladesh delayed much of the development in Bangladesh as the country adjusted to its new role. Eventually, the economics of proceeding with the East-West Interconnector Project became increasingly attractive. In 1979 the Bangladesh Power Development Board appointed consultants from Great Britain, namely Merz and McLellan; and Rendel, Palmer and Tritton to continue with the East-West Interconnector Project. Their terms of reference were to review and update the design to current standards, and to carry the project through to construction.

The original Acres International Limited design called for a river crossing of the transmission line supported on 11 transmission towers spaced at 1,220 m. The 90 m high transmission line towers were to be founded on deep cantilever caisson foundations 10.7 m in diameter. The design depth of the caisson foundations ranged from 91 to 96 m, with one of the caissons extending to a depth of 112 m. The original location of the electrical transmission line crossing of the Jamuna River is shown on Fig. 2. Fig. 2 also shows the location of the towers and the caisson foundations, and drill holes undertaken during the Acres study.

After reviewing the project, the new consultants made relatively minor changes to the main physical elements of the Jamuna River crossing design. The design by the new consultants also called for a river crossing of the transmission line supported on 11 transmission line towers spaced at 1,220 m. The 111 m high transmission towers were founded on deep cantilever caisson foundations 12.2 m in diameter. The design depth of the caissons ranged from 91 to 103 m.

Construction of the East-West Interconnector Project based on the Rendel, Palmer and Tritton design was completed in 1982. Four technical papers describing the design and the construction of the East-West Interconnector Project appeared together in the same issue of the *Proceedings of the Institute of Civil Engineers*, in 1984. The geotechnical aspects are covered in one of the four papers, namely the paper by Hinch et al. (1984).

The author of this paper was part of the original Acres International Limited design team and was responsible for the geotechnical design of the East-West Interconnector Project. This paper is based on the results of the engineering work undertaken by the author for the project, and is based on the information available and analysis undertaken at that time (Acres 1970). The author has written a previous paper, (Sowa 1999) on the same project but on a different aspect. While some of the first part of this paper is similar to that presented in the author's earlier paper, it is given here to provide some background and for the sake of completeness.

A suitable location for the transmission line crossing of the Jamuna River was recognized at the outset as one of the most important design issues to be resolved for the East-West Interconnector Project. The intersection of the shortest distance between the electrical substations at Pabna and Tongi (Fig.1) with the Jamuna River would normally be the river crossing location of choice. However, the banks of the Jamuna River are generally highly erodible and river bank erosion in the range of 400 m in a single flood season had been observed. Unless the crossing location was chosen carefully, the designers faced the daunting prospect that the river crossing could be by-passed by the river a few years after construction. Consequently, it was recognized that there could be considerable departure from the usual concept of selecting the shortest distance crossing if a more stable river crossing location was identified.

The East-West Interconnector Project is important to the development of Bangladesh and the project is certainly an important lifeline in Bangladesh. The security of the Jamuna River transmission line crossing is a key lifeline component.

This article focuses on the background and the basis for the final selection of the Jamuna River crossing which was an aspect of design that was not considered in detail by Hinch et al. (1984).

The geomorphology of the river delta development is described first to provide the background for understanding river migration and the stability of the river banks. River bank erosion and migration along an extended length of the Jamuna River is examined next to locate the most stable reach of the river for a potential crossing site. Some of the results of the geotechnical site investigations, the soil stratigraphy, river scour, and river bank instability are presented and taken into consideration as part of the final crossing selection. The rate of river bank erosion is studied in detail at the potential crossing site to select the specific location of the crossing, and the extent of the crossing length required to take into account future erosion during the economic life of the project.

Geomorphology of the Bangladesh River Delta

General

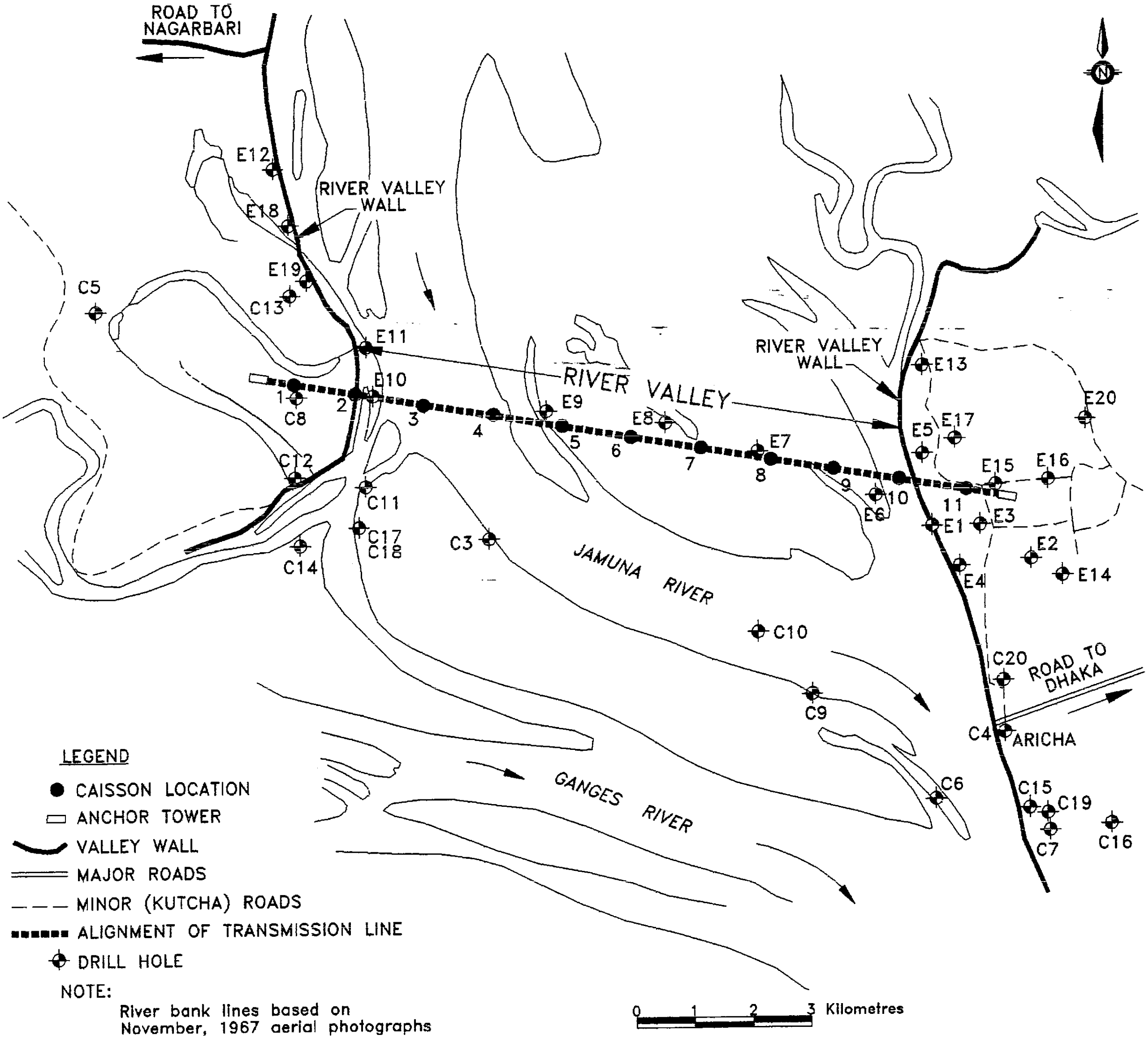
In order to select the most suitable river crossing location it was essential to develop a better understanding of the characteristics and the behaviour of the Jamuna River. This, in essence, meant understanding the geomorphology of the rivers and the formation of the river delta in Bangladesh. The evaluation of the geomorphology of the Jamuna-Ganges-Meghna delta is described in the following. Much of this description is based on the work undertaken by J. M. Coleman while a member of the East-West Interconnector Project team and this work is summarized in Acres (1968) and Coleman (1969).

Migratory behaviour of rivers in Bangladesh

Much of Bangladesh is a very large delta formed by the Ganges, Jamuna and the Meghna River systems. The Bengal Basin geological unit is located mainly in Bangladesh. Apart from isolated, higher-lying remnants of the old Pleistocene surface, the terrain is comprised of flat-lying recent alluvial sediments dissected by numerous tributaries and distributaries of the major river systems. Recent alluvial sediments are found at the Jamuna River crossing and along most of the transmission line route.

The rivers in Bangladesh are of the meandering or braided channel type, and a characteristic feature of most of the rivers is the tendency for rapid migration and meandering. The migration of rivers continues largely unabated since there is very little flood control and construction of river training works. At the outset, it was concluded that river training works sufficiently extensive to control the Jamuna River in the vicinity of the transmission line crossing would be uneconomical. The design of the transmission line crossing of the Jamuna River was based on the assumption that river migration would continue during the service life of the Interconnector Project.

Fig. 2. Jamuna River transmission line crossing area and the location of drill holes.



The sediments transported by the river systems of Bangladesh consist of primarily of sand, silt and some clay. The great quantity of easily eroded sandy sediments which are deposited annually, combined with the large river flows, cause rivers to constantly adjust the river bed configuration to accommodate differing flow regimes. This has resulted in the major river systems occupying and abandoning numerous river courses.

A feature of the river valley of a huge braided river such as the Jamuna River, is that the river valley includes large sand "chars" (sand islands or sandbars) which can be up to several kilometers in size. The sand chars, although having the appearance of being relatively permanent land because of intensive cultivation and the presence of large villages, are actually of a temporary nature. In many cases, a sand char does not remain at the same location more than a few years before being eroded.

The rate of river bank erosion and therefore the rate of river migration is dependent on a number of factors, including the volume of river flow, the river type, the direction of the river flow at any particular location, and the composition of the river bank sediments.

Assuming that all other factors are equally important, the erosion of river banks proceeds more slowly when the banks are comprised of clayey soils rather than sandy soils. Furthermore, the greater the thickness of clayey strata in the river banks, the slower the rate of erosion.

Since the rate of river bank erosion is significantly governed by the presence of the clayey soils, it is essential to understand the basic processes underlying the deposition of these soils in the Bengal Basin delta.

Deposition of erosion resistant clayey soils

The rivers in Bangladesh overtop their banks annually during each flood season, and flood approximately 40 percent of the total land area. The capacity of the rivers to transport sediment is the greatest during the flood season. When the river banks are overtopped, the floodwater carries the sediment in suspension. The finer the sediments, the greater the distance that the sediments are transported over the flooded land area. The fine to medium size sandy soils are deposited in the river channels, and the finer sandy and silty soils are deposited on the river banks forming the natural river levees. The finest silts are deposited further from the banks, and the cohesive clayey soils are deposited the greatest distance from the rivers. A fresh deposit of floodwater alluvium is deposited annually following each flood. Eventually, if other factors remained static, the elevation of the ground surface would build up to a level corresponding to the highest flood level.

The total depth of the alluvial sediments in Bangladesh in the project area is greater than 3,000 m. Consolidation of these sediments is occurring on a continuing basis and results in the gradual settlement of the ground surface. Equilibrium of the settled ground surface is maintained by the compensating deposition of fresh sediment following each flood. The process of consolidation, deposition of sediments, if uninterrupted, could result in the accumulation of thick deposits of cohesive clayey soils. The migrating rivers, however, usually erode the cohesive clayey sediments before they become very thick, and replace these sediments by coarser-grained sandy soils transported in their channels. As the rivers continue to migrate further from their previous courses, the entire cycle of deposition of finer and finer alluvium sediments is resumed and other strata of cohesive clayey soil sediments are built up.

The thickness of the cohesive clayey soil strata along the overland portion of the transmission line route for this project generally did not exceed about 6 m, indicating that river migration interrupts the sedimentation process before an additional thickness of clayey soils can accumulate. As frequently occurs, there are exceptions to the idealized concept, and considerably thicker strata of cohesive clayey soil were found. The thickness of cohesive clayey soil at one location along the east bank of the Jamuna River near the crossing is approximately 28 m at Aricha. The development of thicker cohesive clayey soil deposits can occur for a number of reasons, of which two reasons are cited below.

Some areas escape the erosive action of a migrating river for geologically longer periods of time than others, and thereby permitting the development of thicker deposits of cohesive soils. This may arise because of geological conditions or hydraulic conditions. Secondly, thicker deposits of cohesive clayey sediments also develop during infilling of ox-bow lakes, which are formed when a meander loop of a river channel becomes abandoned. Owing to the higher elevation of the natural levee around the ox-bow lakes, only the finest soils, (clay and fine silts) are transported during the flood over the top of the levees to settle in the ox-bow lakes. The depth of the cohesive clayey soil in these cases is limited to the depth of the abandoned meander channel.

Migration of the Jamuna River

Historical extent of Jamuna River migration

In relatively recent historical times, the Jamuna River discharged into the more southeasterly channel of the Old Brahmaputra River as shown on Fig. 1. About 200 years ago, over a period of years, the Brahmaputra River changed course significantly, jumping westward about 60 km to occupy the Teesta River channel which became the new channel of the current Jamuna River. The Teesta River is now a tributary of the Jamuna River. Some discharge, although considerably diminished, still continues to flow down the Old Brahmaputra River. The reason for the change of the course of the Old Brahmaputra River is not known, but a major earthquake in 1762 and a catastrophic flood in 1787 may have been contributory causes.

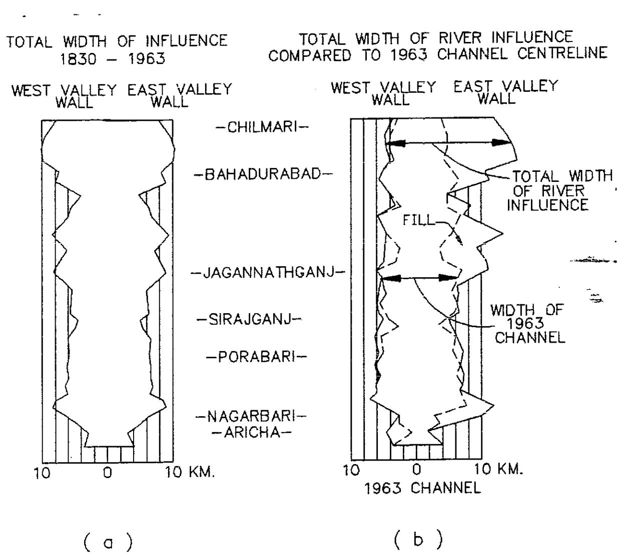
Surveyed river bank line maps and navigation maps, some, dating back to 1830, as well as aerial photography have been used by Coleman, (Acres, 1968) to prepare a series of plans showing historic bank lines of the Jamuna River. The bank line maps have been combined to produce the drawing shown in Fig. 3. Fig. 3a shows the maximum extent of the Jamuna River bank lines and migration in its new channel since 1830. The bank line mapping extends along about a 200-km river length from Chilmari in Assam, and Bahadurabad in northern Bangladesh to Aricha.

The information given in Fig. 3a illustrates that the Jamuna River has exhibited intense activity since 1830, migrating laterally between valley walls that in some reaches are now as much as 20 km apart. The river valley, as defined for the purpose of this paper, refers to that portion of the delta within which the river has flowed since occupying its present course.

The extent of bank line migration shown on Fig. 3a illustrates that a number of reaches are more stable than the general trend. The smallest extent of bank line migration is, by far, located at Aricha. Since the smallest overall extent of river migration is at Aricha, the location of the Jamuna River crossing was selected to be at Aricha.

Fig. 3b shows the width of the 1963 river channel influence compared to the total river influence since 1830. The dashed lines indicate the 1963 river channel influence. The 1963 channel is significantly narrower in the northern reaches of the river compared to the southern reaches, except at Aricha. At Aricha the 1963 river channel influence is about one-half of the past river influence. The practical aspect of this observation is that at Aricha, during the 1963 season, there was a relatively large width of sand islands within the extent of past river activity that could have been used for land-based construction of the caisson foundations.

Fig. 3. Historical width of river migration of the Jamuna River.



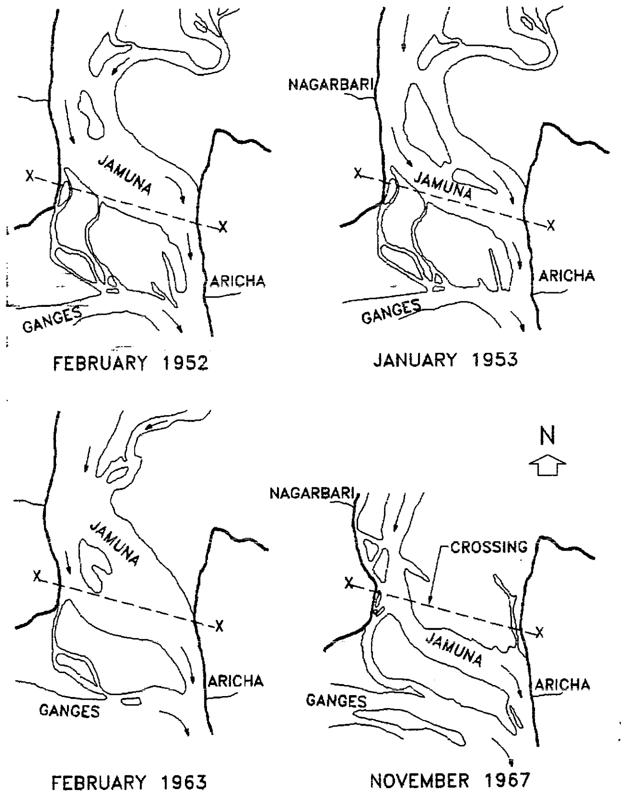
Recent Jamuna River migration at Aricha

The information in the preceding section indicated that the Jamuna River is the most stable in the Aricha area. Consequently the location of the transmission line crossing was selected to be at Aricha. More detailed information on recent river bank line migration and the sand island migration in the river channel is illustrated on Fig. 4. Fig 4, which presents the river bank line and sand island configurations for 1952, 1953, 1963, and 1967, was prepared by Coleman (Acres, 1968). The river valley walls on both sides of the river are also shown in heavier outline on Fig. 4 as well as the location of the crossing. The information on Fig. 4 shows that along the west side the river was actively eroding the west valley wall in the vicinity of Nagarbari in 1952, and 1953. Later the area of active erosion on the west side moved down further south, and sand islands are formed opposite Nagarbari.

In 1952 and 1953 the river was actively eroding the east side of the river valley wall at a relatively sharp bend of the river, just north of the crossing location, as shown on Fig. 4. With time the active erosion continued to move further south. By 1967 a large sand island had formed opposite the east river valley wall area that was being actively eroded in 1952, and the most active area of the river erosion, with the sharpest bend in the river current, was located opposite Aricha.

Over the time period of 1952 to 1967, as the main channel of the river moved south, the large sand island opposite Aricha eroded considerably. At the same time, new sand islands have grown elsewhere, including the large sand island at the crossing.

Fig. 4. Recent Jamuna River bank line changes at Aricha.



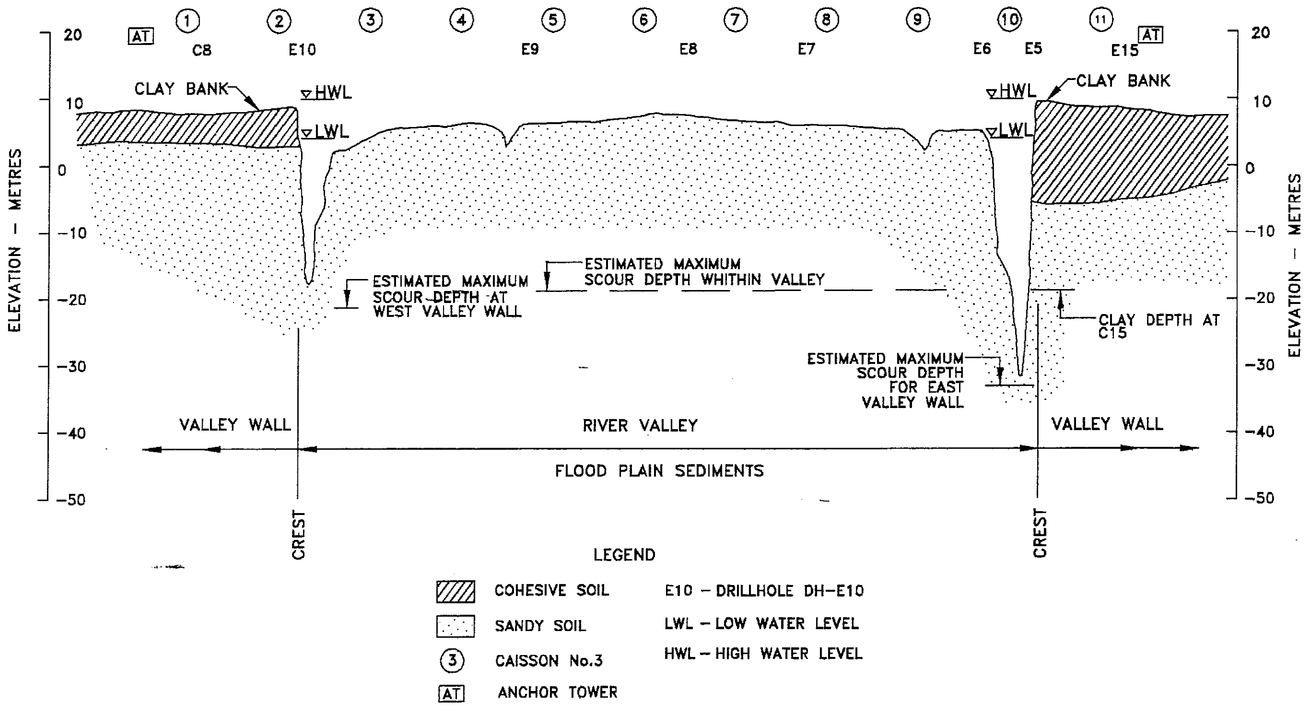
The most stable reach of the Jamuna River, based on geomorphological principles, is located at Aricha, and consequently the Jamuna River crossing was located at Aricha. Although the Aricha area is the most stable location on the Jamuna River, the size of the potential crossing site is still large, about 9 by 16 km, which is an area of about 140 km^2. The next challenge was to establish the most suitable specific crossing location within the large Aricha area. The final crossing location will need to accommodate the river erosion for the economic life of the project. The approach used in meeting this challenge is the subject of the remainder of this paper.

Geotechnical conditions at the Jamuna River Crossing

Soil stratigraphy

Fig. 2 shows the location of the transmission line crossing of the Jamuna River, the tower and caisson foundation locations, and the river channels for the Ganges and the Jamuna Rivers. Fig. 5 shows a cross-section along the alignment of the transmission line crossing and a simplified foundation soil stratigraphy. The location of the "river valley walls" and the "river valley" are shown on

Fig. 5. Soil stratigraphy and river cross-section along the proposed Jamuna River crossing.



both Fig. 2 and 5. The river valley is considered to be that portion of the delta within which the river has flowed since occupying its present course.

The basic soil stratigraphy at the river crossing consists of clayey soil over sandy soil at the valley walls. The thickness of the upper clay in the valley walls is variable, typically 5 to 18 m, as illustrated on Fig. 5. The sand islands in the valley between the valley walls are comprised of sandy soil. The upper sand strata in the sand islands may be siltier, but the siltier sand is underlain by cleaner sand.

The presence of the clayey soil in the river valley walls increases the erosion resistance considerably. Since the river is restrained in moving laterally, the energy of the river is directed downwards in eroding a deeper channel.

The sediments in the river valley within the depth of the river scour have been reworked and redeposited very recently, within about the last 200 years since the Jamuna River changed course. Since these sediments are sandy, they are readily erodible. The sediments comprising the river valley walls, although still considered as recent sediments in geological terms, are thousands of years older than the very recent sediments within the river valley. The results of radio-carbon dating undertaken on two samples of organic matter obtained in the Aricha area at depths of 18 and 90 m indicated the organic matter to be 2,100 and 29,000 years old respectively.

Foundation Soil Conditions

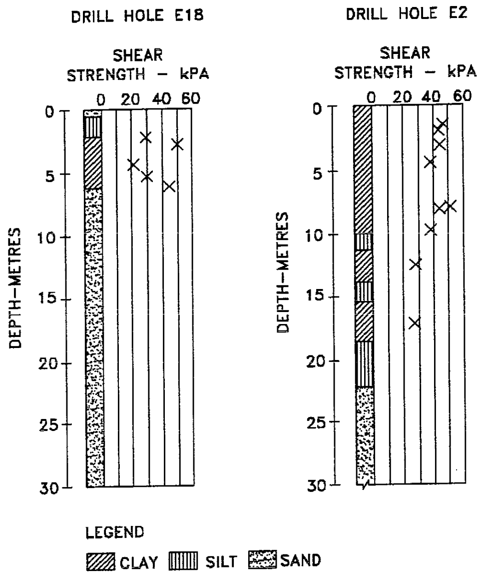
As can be seen from the stratigraphic plot shown on Fig. 5, the foundation soils at the crossing location are broadly determined by their location. The foundation soils in the river valley are primarily sand, fine to medium, which generally increase in density with depth. Coarser sands and gravels are encountered at depth. The foundation soils in the valley walls, starting at the top of the river banks, consist primarily of clayey strata which overlie sandy soil. The sandy soil in the valley walls also generally becomes denser and coarser with depth.

The thickness of the clayey soil along the west river valley wall is generally 4.5 to 6.0 m, although a thickness of 9 to 10.5 m has been observed. The thickness of the clayey soil along the east river valley wall is generally 12 to 28 m. The thicker clay soil (28 m) along the east valley wall occurs near Aricha. The thickness of clayey soil north of Aricha in the vicinity of Caisson No. 11 and the east anchor tower is in the range of 12 to 17 m.

The clayey soil near Aricha is massive and consists primarily of clay. However, the clayey soil near the east end of the crossing, in the vicinity of Caisson No. 11 is more stratified with silt layers between the clay layers. The silt layers are generally 1.0 to 1.5 m thick, but can be thicker. The presence of silt layers in the stratified clayey soil in the vicinity of Caisson No. 11 will reduce the erosion resistance compared to the more massive clayey soil at Aricha, but the amount of the reduction is unknown.

The river sands are generally uniformly graded, particularly the sand that has been eroded and redeposited by the Jamuna River. The grain size of the river sands generally fall into a narrow range. Typically, the uniformity coefficient, U, for the sand deposited by the Jamuna River ranges from 1.5 to 3.0, but larger values

Fig. 6. Typical soil summary plots for clay bank.



occur when silt was present. The D_{50} grain size ranges from 0.1 to 0.3 mm. Non-cohesive sand soils that are fine-grained and uniformly graded such as these soils are easily eroded.

The density and the shear strength of the sand was determined from the results of standard penetration tests, and direct shear box strength tests and triaxial shear strength tests. For the purpose of river bank stability evaluation, the sand is considered to be loose to medium dense, with an angle of shearing resistance of 30 degrees.

The cohesive soils are often comprised of approximately 5 to 25 percent clay content, and usually these sediments have been designated as a clayey silt or a silt with some clay. In spite of the relatively small clay content, it is this constituent which has a profound influence on the engineering properties of the sediments, being responsible for the significantly greater erosion resistance. The clayey soil is of medium to high plasticity.

Typical summary plots of the soil conditions for the west and east valley walls are shown for Drill Holes E18 and E2 respectively on Fig. 6. Although other drill holes are closer to the west and east anchor towers, the selected drill holes are representative of the foundation soil conditions and also include a larger data set of undrained shear strength results for the clayey soil. As can be seen from Fig. 6, clayey soil strata extend to about 6 m in Drill Hole E18 on the west valley wall, and to a larger depth of 18 m in Drill Hole E2 along the east valley wall. Some silt strata are interbedded within the clayey soil.

The undrained shear strength of the clayey soil is also shown on Fig. 6. The undrained shear strength in Drill Hole E 18 ranges from about 21 to 50 kPa, with an average of about 35kPa. The undrained shear strength in Drill Hole E2 ranges from about 26 to 52 kPa, with an average of about 39 kPa.

The undrained shear strength of the clay soil in the crossing area ranges from 9.6 to 96 kPa, but most of the shear strength values were within a smaller range of about 30 to 35 kPa. The variability in undrained shear strength values are sometimes erratic in a given soil profile since the strength is probably a by-product of desiccation.

The undrained shear strength of the clayey soil in the river bank probably governs the overall stability of the cohesive portion of the river bank during the erosion of the bank, since the rate of erosion is too rapid to allow the drained conditions to develop.

River scour

The depth of river scour will vary and depend on a variety of factors, including the velocity of flow, angle of attack of the river current towards the river bank, and the soil type. For the purpose of design, the maximum depth of river scour within the river valley in the sandy Jamuna River bed for a moderate river bend condition was estimated to be 29.5 m. The maximum design scour depth within the river valley is illustrated on the soil stratigraphic plot on Fig. 5.

The depth of river scour increases as the radius of curvature of the river bend decreases. Furthermore, the presence of clayey soil in the river banks along the valley walls not only increases the resistance to river bank erosion, but because the clay bank forces the energy of the river downward, the depth of scour increases.

The radius of curvature of the river bend along the west valley wall is expected to be smaller and more severe than within the river valley. For the condition of a more severe river bend, and for the thickness of clayey soil applicable along the west river valley wall, the estimated maximum depth of river scour is 32 m. The river bend curvature is expected to be even more severe along the east valley wall. For the combined effect of a sharp river bend and for the larger thickness of clayey soil, the estimated maximum depth of river scour along the east valley wall, is 44 m. The maximum estimated depth of river scour along both valley walls is illustrated on Fig. 5.

The actual depth of river scour was observed during hydrographic surveys undertaken during the flood stages in 1967, 1968, and 1969. The maximum observed river scour depth within the river valley during the three years of hydrographic survey undertaken for this project was 19.8 m compared to the maximum estimated river scour depth of 29.5 m. The maximum observed river scour along the west valley wall was 28.3 m, compared to the maximum estimated river scour of 32.0 m. The maximum observed river scour along the east valley wall was 42.7 m, compared to the maximum estimated river scour of 44 m.

River bank instability

The banks of the Jamuna River erode and fail on a continuing basis during each flood season. The basic failure process for the different river bank configurations is described in the following. Understanding the process of river bank failure will assist in understanding the river bank erosion process, will assist in the selection of the final river crossing location and also the long-term set back distance required for the anchor towers.

Erosion of the banks of Jamuna River is a continuous process of river erosion causing over-steepening of the river banks, or undercutting, or both, resulting in failure of the river banks. The submerged failed river bank mass slides towards the toe of the submerged river bank, and temporarily stabilizes the lower slope. In time, the river erodes the slide debris on the lower slope, and the entire process starts all over again. While this process continues all year, the erosion process accelerates considerably during the flood season. Also the rate of erosion depends on the type of soil which comprises the river bank, with the rate of erosion being the fastest for sandy soil, and the slowest as the thickness of the clayey soil increases.

Observations during flooding indicate that the river banks either fail as numerous small blocks of soil sliding into the river, or as a large mass of soil sliding as a single unit. The sliding soil mass can range from soil blocks a few cubic metres in size, usually characteristic of the river banks comprised of sandy soil, and up to soil blocks 3 to 15 m wide and 15 to 60 m in length, for river banks comprised of clayey soil.

The stability of the river bank slopes has been considered previously, (Sowa 1999). Some of the previous observations are included here, as well as other new aspects.

The characteristics of river bank failure is examined for three typical river bank slope profiles as shown on Figs. 7, 8, and 9. These profiles represent a range of slopes that are likely to be encountered during active river bank erosion. Fig. 7 represents a typical river bank slope on the sand island, near Drill Hole C3, located as shown on Fig. 2. Fig. 8 represents a typical river bank slope along the west valley wall near Drill Hole E19, and Fig. 9 represents a typical river bank slope along the east valley wall, near Drill Hole C15, both located as shown on Fig. 2. The river bank slope shown on Fig. 7 is termed the "sand bank" slope, and the river bank slopes on Fig. 8 and 9 are termed the "clay bank" slopes.

The three profiles of the river bank slopes were established by means of surveying and depth soundings during the flood season when the active river bank failure was occurring. The river level during the flood season corresponds approximately to the top of the river banks when essentially the entire river banks become submerged.

The shear strength parameters which govern the stability of the failing river bank slopes were established previously (Sowa 1999). The angle of shearing resistance considered to be representative of the looser siltier sand comprising the upper sand bank was 30 degrees. Representative values of the undrained shear strength of the clay soil were 30 to 35 kPa.

Sand bank slopes

The sand bank slope shown on Fig. 7 is representative of the river banks on the sand chars. The sand bank profile consists of approximately 6 m of silty fine sand overlying fine sand. The average slope of the river bank section on Fig. 7 is approximately 51 degrees above horizontal. The angle of repose of the silty fine sand is expected to be about 30 degrees. Since the bank slope is considerably steeper than 30 degrees, some other factor must be responsible for maintaining the steeper slope. Possible factors include a small amount of cohesion, or water seeping into the sand river bank from the rising river flood stage will increase the effective stress and consequently the bank stability. Alternatively, as bank slumping is occurring, negative pore water pressure may develop owing to soil dilatancy, creating a small temporary increase in effective stress.

Any of the foregoing factors, or a combination of these factors could account for a slope steeper than about 30 degrees. The effect of any of these factors can be considered in terms of an equivalent amount of cohesion.

The results of stability back analysis of the sand bank illustrated on Fig. 7 showed that for an angle of shearing resistance of 30 degrees, a small value of cohesion of about 2.4 kPa is sufficient to just maintain the slope of 51 degrees. This amount of cohesion is very small and can easily be accounted for by a trace of actual cohesion, or apparent cohesion as discussed above.

The erosion process for the sand bank slope shown on Fig. 7 consists of the river eroding the bank sufficiently to cause slumping of the bank. Since the sand is friable, the river probably completely breaks up the sandy soil chunks and the sand is either removed as a suspended load, or is spread on the submerged beach at the toe of the slope.

Clay bank slopes

A clay bank slope along the west valley wall is illustrated on Fig. 8. The upper clay stratum at this location is about 3.7 m thick and is underlain by fine sand. The upper portion of the slope is essentially vertical from "a" to "b" as shown on Fig. 8. The slope from "b" to "c" is mostly comprised of fine sand, and is at an angle of about 30 degrees which is approximately the angle of repose.

Failure of this type of river bank slope probably consists of erosion of the underlying sand slope, which then leads to undermining of the clay slope. The clay slope fails in tension, and then slides into the river onto the lower slope. The composition of the slope from "b" to "c", Fig. 8 could consist of some failed clay slope debris that has not yet been eroded. The failed clay slope debris provides

Fig. 7. Profile of river bank slope comprised of sand.

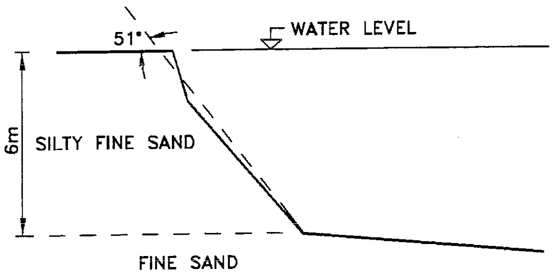


Fig. 8. Profile of river bank slope with thin upper clay strata.

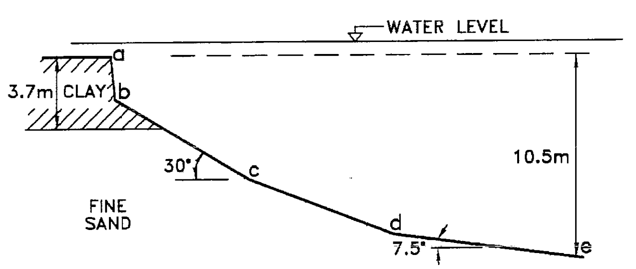
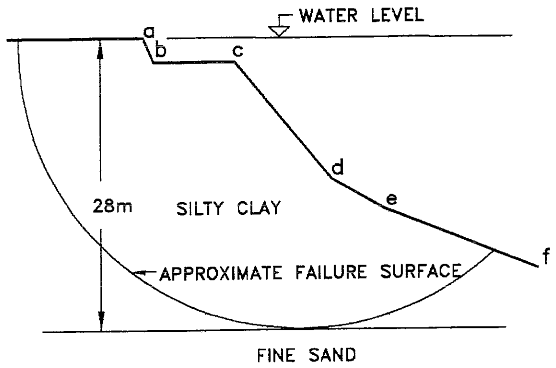


Fig. 9. Profile of river bank slope with thicker upper clay strata.



some "armour" or temporary slope protection against river erosion. It is probably a combination of erosion resistance of the intact clayey soil in the river bank and the "armour effect" of the failed clay slope debris that reduces the rate of bank erosion very considerably, compared to the sand bank slope condition illustrated on Fig. 7. Eventually the failed clay slope debris is eroded, and the cycle is repeated.

The river bank profile of an active eroding clay bank along the east river valley wall during river bank erosion and failure is shown on Fig. 9. The layer of clay soil is 28 m thick at this location and the clayey soil overlies fine sand. The stability of the clay bank was analyzed on a total stress basis. It is a reasonable to assume that the rate of erosion during the flood season is so rapid that the undrained shear strength condition is applicable. It was assumed that the failure surface is circular and tangential to the fine sand strata. The average value of the undrained shear strength of the clay soil obtained from the stability analysis for a bank on the verge of failure, was 31.1 kPa. This undrained shear strength value is similar to the representative measured values of 30 to 35 kPa.

Failure of this clay riverbank is probably similar to that described for the west valley wall as shown on Fig. 8. The portion of the clay slope in Fig. 9, "b", "c" and "d" may be a failed soil block that has slid down the slope. The portion "d", "e" and "f" may constitute failed clay bank slope debris that is providing temporary "armour" which reduces the rate of erosion. Failure of this slope also probably commences with erosion of the underlying sand stratum below the upper clay slope to cause undermining and the clay slope to fail. Again, once the clay slope debris "armour" on the lower portion of the slope is eroded, the entire process of river bank instability continues to repeat.

The failure mechanism of the clay slopes reported here have some similarities with river bank instability reported by Turnbull et al. (1966) for the Mississippi River, and by Ullrich and Hagerty for the Ohio River, (1986).

The estimated maximum depth of river scour along the east valley wall is about 44 m. If the thickness of the clay strata in the river bank exceeded the maximum depth of scour, the erosive energy of the river would be directed against an entire slope of clayey soil. The failure mechanism for an entire slope of clay would be different from the clay bank slope shown on Fig. 9. In the case of an entirely clay slope there is no underlying sand strata that can be undermined to cause the slope to fail more readily and more rapidly. Consequently, a river bank consisting entirely of clay would erode at a considerably slower rate, and, as a result, the river bank migration rate would be significantly reduced. Turnbull, et al. (1966) have observed this type of behaviour in the deltaic plain of the Lower Mississippi River.

River bank erosion at the crossing

It has been previously shown that the lowest rate of river bank migration is at Aricha, and that the transmission line crossing should be located at Aricha. Although the amount of river bank erosion at Aricha is the lowest along the Jamuna River, the rate of erosion is still relatively very large. Owing to the cost of the river crossing and the wide disparity in rates of river bank erosion, it was imperative to obtain a better understanding of the river bank erosion in the Aricha area. A study of the Aricha-Nagarbari area was made using aerial photographs to identify the position of the "river valley walls" and the "river valley" width for the Jamuna River. The results are illustrated on Figs. 2 and 5. The identification of the more permanent river banks is synonymous with the identification of the valley walls.

The amount and rate of the erosion of the valley walls was determined by comparing the position of the valley walls on sets of aerial photographs dated 1952, 1953, 1963, 1967 and 1968. The river bank erosion was measured at specific locations on the aerial photographs. The results are plotted on Fig. 10 which shows the cumulative erosion for both the west and east valley wall river banks. The specific locations where erosion was examined are shown on the key sketch. Not all locations where erosion was examined are shown for clarity, however, the measuring locations are in numerical order from north to south.

The maximum cumulative valley wall erosion on the west bank occurred at Station W4 as shown on Fig. 10. Between 1952 and 1968, the cumulative erosion at Station W4 was 954 m and this is equivalent to an average rate of erosion of 56 m per year. The maximum cumulative valley wall erosion on the east bank occurred at Station E7 as shown on Fig. 10. Between 1952 and 1968, the cumulative erosion at Station E7 was 478 m, and this is equivalent to an average rate of erosion of 28 m per year.

As can be seen from Fig. 10, the overall rate of erosion is greater for the western valley wall compared to the eastern valley wall. The lower rate of erosion for the east valley wall is due to the greater thickness of erosion resistant clayey soil in the east valley wall.

In addition to the river valley wall erosion shown on Fig. 10, the rate of river bank line migration at several locations during the 1969 flood season was observed and is shown on Fig. 11. In this case the river bank may either correspond to a river valley wall, or to a river bank within the valley walls. The river banks within the valley are comprised primarily of easily erodible sandy soil.

From the beginning of June to the end of October, the cumulative erosion at the observed locations ranged from no erosion at Station No. 12 to more than 300 m at Station No. 15. Stations No. 15 and 16 are located within the river valley on a sand island river bank that was being attacked actively by the river. Since these banks are comprised of highly erodible sandy soil, the rapid rate of river bank erosion can be expected. On the other hand, although the river bank adjacent to Station No. 11 was also being attacked vigorously, the substantially slower rate of river bank erosion, owing to the clayey composition of this bank, is evident.

The river bank erosion activity at Station No. 18 is of particular significance. A char (sand island) comprised of sandy soil abutted the valley wall at this location. Rapid erosion of 171 m occurred from June 1 to July 10 (40 days) until the river bank coincided with the river valley wall as predicted from the aerial photographs. After July 10, the rate of erosion was reduced considerably, and from July 10 to end of October (112 days), the amount of erosion in the valley wall sediments was only 17 m. This observation clearly demonstrates the higher erosion resistance of the more cohesive river valley wall soils.

A river stage hydrograph, which shows the elevation of the river level during flood, is also illustrated on Fig. 11, with the stage level scale given on the right-hand side of the figure. The stage hydrograph illustrates the build up of the flood level and then the recession over the June-October period. The rate of erosion is related to the flood stage with the largest erosion rates generally occurring during the rising flood stages.

It is believed that the rate of river valley erosion shown on Fig. 10 is related, in part, all other factors being equal, to the thickness of the clayey soil strata. To provide some correlation of thickness of clay strata with the rate of erosion, Fig. 12 has been prepared. Fig. 12 shows essentially the maximum average rate of erosion for different thickness of clay over the 1952-68 period, at locations where there is considerable exposure to river erosion. It must be recognized that the relationship in Fig. 12 is empirical and may only be used for general guidance in the Aricha area for longer time periods.

Selection of final crossing location

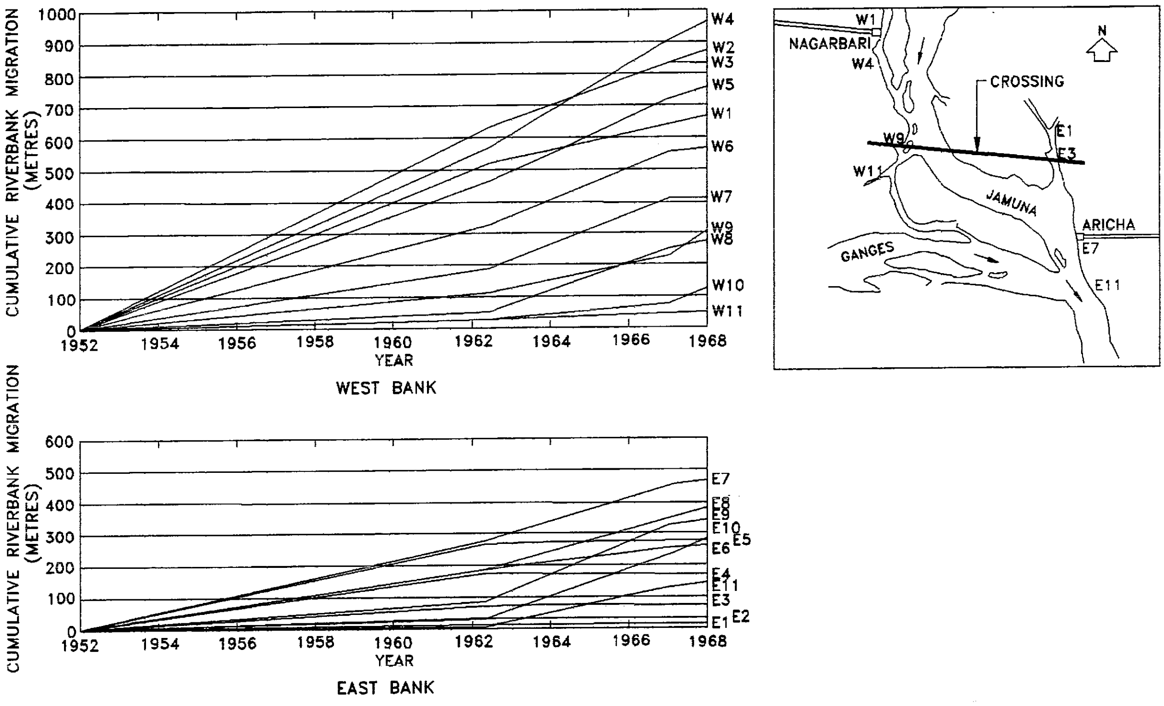
One of the basic project decisions that was made was that the Jamuna River crossing would be undertaken without any river training works since the cost of river training would make the project uneconomic. Consequently, all the foundations supporting the transmission towers for the Jamuna River crossing would be designed to withstand the maximum loads and the maximum river scour expected during the service life of the crossing. Furthermore, the Jamuna River crossing section with the deep foundations should extend sufficiently beyond the river banks so that the anchor towers are located beyond the estimated river bank erosion which will occur during the service life of the crossing. Some additional factors which influenced the selection of the specific alignment of the Jamuna River crossing and the position of the anchor towers, are as follows:

- The service life of the project was taken as 50 years.
- The 1,220 m span length between the towers of the Jamuna River crossing is sufficient to span most of the low-water river channels, consequently most caissons could be constructed as a land-based operation.
- The design allowed some flexibility in selecting the final caisson locations along the alignment just prior to construction, to take into account changes in river conditions.

An examination of Fig. 10, 11 and 12, as well as the previous information reveals the following significant features of river bank erosion:

- All other factors being equal, erosion is slowest where the clayey strata in the river bank are the thickest.
- Assuming that the river bank soil conditions are similar, the maximum erosion rate occurs at the location of the sharpest bend of the river.

Fig. 10. Recent river bank erosion by the Jamuna River at Aricha.



- The position of the sharpest bend of the river channel appears to move from north to south along each valley wall, in a cyclic fashion in response to the changing sand island configuration between the valley walls.
- The position of the sharpest bend of the river channel usually remains at the same general location for a short-term of several years before moving on. The selection of the short-term rate of valley wall erosion occurring at the sharp bend to estimate the total river bank migration for the longer economic project lifetime period is expected to be conservative. The adoption of the short-term rate of valley wall migration for a long-term estimate is equivalent to assuming that the sharp river channel bend will remain at the same location throughout the project service life, and this is unlikely to be the case.
- At the confluence of the Jamuna and Ganges Rivers, a sand island is invariably formed similar to the large sand island opposite Aricha as shown on Fig. 2. The main Jamuna River channel flows against the east bank in the general vicinity of Aricha owing to the influence of the Ganges River. Because of this condition, and the presence of a sand island somewhere between the Jamuna and Ganges Rivers, the Jamuna River will most likely continue to flow against the west bank somewhere near Nagarbari and deflect from this location eastward towards Aricha.

The maximum rate of valley wall erosion at the west bank over the 1952-68 period occurred at Station W4 as shown on Fig. 10, and is equivalent to a maximum average erosion rate of 56 m per year. The thickness of clayey soil strata in the vicinity of Caissons No. 1 and 2 and the western anchor tower is typically 4.5 to 6.0 m.

The maximum rate of valley wall erosion on the east bank over the 1952-68 period occurred at Station E7 as shown on Fig. 10, and is equivalent to a maximum average erosion rate of 28 m per year. The thickness of the clayey soil strata in the vicinity of Station E7 is approximately 21 m. The thickness of clay strata in the vicinity of Caisson No. 11 and the eastern anchor tower ranges from 12 to 17 m, and a value of 15 m was considered representative.

The clayey soil in the vicinity of the eastern anchor tower near Station E3, (Fig. 10), is stratified with some sandy silt and is not as uniform or massive as the clayey soil strata found in the vicinity of Station E7, or a little further south at Station E11. The thinner and more stratified nature of the clayey strata in the vicinity of the eastern anchor tower will probably result in a more rapid rate of bank line erosion than the average rate recorded at Station E7. This condition will be compensated to some extent since it is believed that the river activity will be less vigorous at the eastern terminal near Station E3, Fig. 10. The influence of the Ganges River will probably result in the river bend being located for longer periods adjacent to Station E7. On the basis of the foregoing, it is believed reasonable to assume that using the maximum average erosion rate of 28 m per year obtained at Station E7 over the 1952-68 period for the long-term condition will be conservative for the east crossing terminal, even though the clayey soil strata is thinner at that location.

Fig. 11. River bank erosion during the 1969 flood season at Aricha.

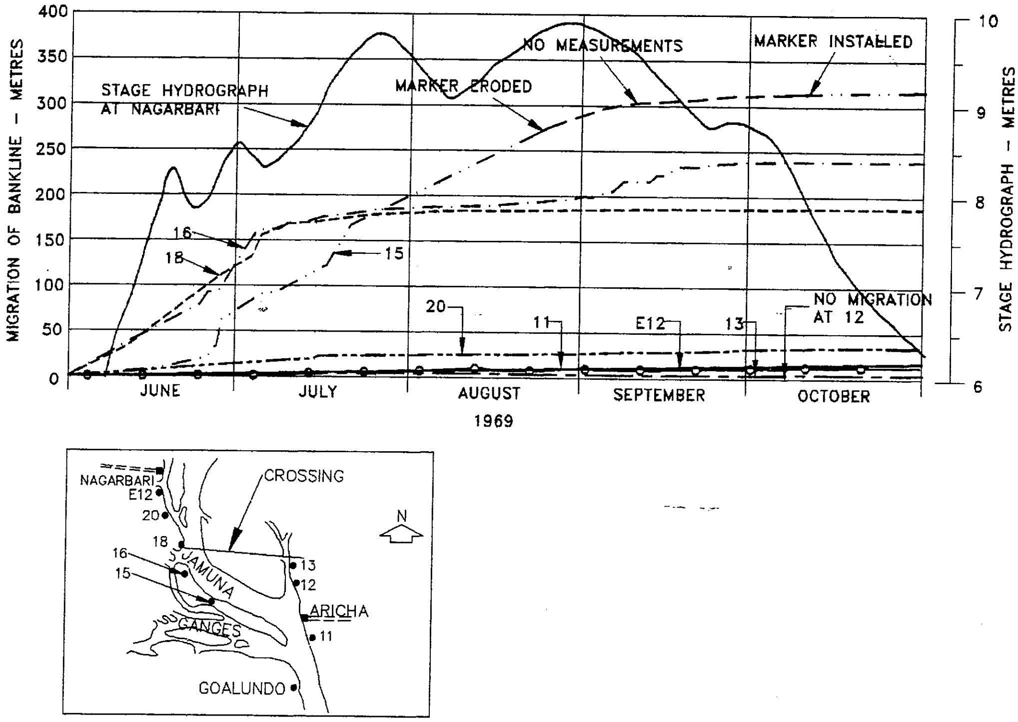
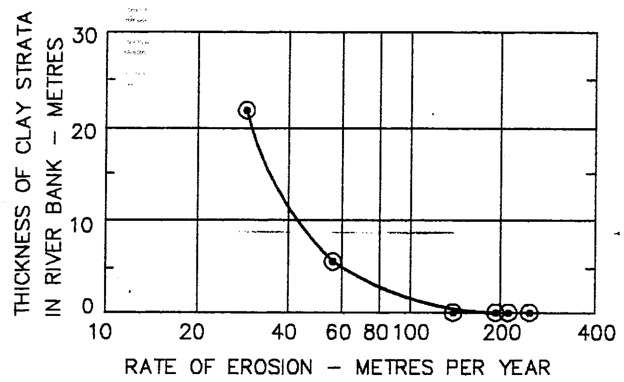


Fig. 12. Rate of river bank erosion versus thickness of upper clay strata.



In consideration of the proceeding factors, the final location of the transmission line crossing of the Jamuna River is shown on Fig. 2. In conjunction with the criteria noted previously, the best location of the crossing places the anchor towers furthest from the valley walls in an area with the thicker strata of erosion-resistant clayey soil.

The perpendicular distance from the west valley wall to Caisson No. 1 is 1,460 m and the distance from the valley wall to the western anchor tower is 2,210 m. On the assumption that the maximum average rate of river valley wall migration is 56 m per year, the estimated time required for the river to erode to Caisson No. 1 and the western anchor tower is 26 years and 39 years respectively.

The perpendicular distance from the east valley wall to Caisson No. 11 is 610 m and the distance from the valley wall to the eastern anchor tower is 1,265 m. On the assumption that the maximum average rate of river valley wall migration is 28 m per year, the estimated time required for the river to erode to Caisson No. 11 and the eastern anchor tower is 22 years and 45 years respectively.

The western anchor tower was located near Drill Hole C8, as shown on Fig. 2, within the abandoned meander loop. The clayey soil in the meander channel in Drill Hole C12 is 10 m deep and is thicker than at Drill Hole C8. The western anchor tower is located at a reasonable distance from the Jamuna River, and this location also provides a buffer zone against possible future northward migration of the Ganges River.

The eastern tower was located near Drill Hole E15 as shown on Fig. 2. The clayey strata are approximately the thickest in this general area and become thinner in a southerly direction. Furthermore, the anchor tower should not be located much further north because, as can be seen from Fig. 2, the valley wall widens considerably about 4 km northward. In the event that there is a major change in the flow pattern of the Jamuna River, erosion of the valley wall 4 km north of the crossing could proceed more rapidly if the thickness of the clayey strata in this vicinity is thin.

In summary, the final location of the transmission line crossing of the Jamuna River is as shown on Fig. 2, and this location was selected for the reasons given. It is estimated that the rate of valley wall erosion is such that approximately 39 and 45 years will elapse before the river banks are eroded back to the western and the eastern anchor towers respectively. This time period is estimated on the basis that the maximum rate of erosion observed from 1952 to 1968 will apply throughout the project life. Since it is believed that this assumption is conservative for the reasons given, it is reasonable to assume that the actual time period for river bank erosion to the anchor towers will take longer, and may approach or exceed the economic project life of 50 years.

The selection of the river crossing location was based on the premise that the past behaviour of the river is the best basis for predicting the future behaviour. In view of this, instituting a program of bank line migration observations was considered mandatory to confirm the continued validity of this premise, and to take appropriate action if future river behaviour is significantly different.

The new consultants responsible for the final design and construction reviewed the location of the Jamuna River crossing in some detail when they undertook their design review, taking into account the configuration of the river channel and sand islands in the river at the time of their review. They also considered the position of the Ganges River and the possibility of the Ganges moving northward, among other factors at the location of the crossing.

It interesting that more than 10 years after the original recommendations were made by Acres (1970) for the location of the Jamuna River crossing, and after considerable river activity during that time, the final crossing location selected by the new consultants was essentially the same location, Hinch et al (1984). It appears that the principles that were applied to select the initial crossing location as summarized in this paper were validated and were still sound and applicable.

Summary and Conclusions

An electrical transmission line connecting the western and eastern regions of Bangladesh was required to cross the Jamuna River, which is one of the largest rivers in the world. The Jamuna River has a very high rate of river bank migration and river bank erosion. This meant that selecting a suitable location for the crossing the Jamuna River was a major challenge. Examination of historical records dating back to 1830 demonstrated that the most stable reach of the Jamuna River over a 200-km length was near the village of Aricha.

While recognizing that the most stable section of the Jamuna River was at the Aricha area, the Aricha area is still very large, about 140 km^2, and a much more detailed evaluation was required to select the final alignment of the crossing. Furthermore, although the most stable reach of the Jamuna River was in the Aricha area, the rates of river bank erosion are still very large. The maximum average rates of the river bank erosion over the 1952 to 1968 period were established for the Jamuna River in the Aricha area. These erosion rates were used to locate the anchor towers at a sufficient distance from the river banks to accommodate the future river bank erosion for the economic life of the project.

The final Jamuna River crossing location for the transmission line is shown on Fig. 2. The estimated maximum average annual rates of erosion of the west and the east river valley walls were 56 and 28 m respectively, but the actual annual erosion rates during the project life may be less. River erosion is not expected to affect the western and the eastern anchor transmission line towers for approximately 40 years or more.

Acknowledgements

The author is grateful to the Bangladesh Power Development Board and Acres International Limited for the opportunity to become involved with the engineering of the challenging East-West Interconnector Project, and for their permission to publish this paper. The author also wishes to acknowledge the assistance received from Jacques Whitford and Associates Limited with the production of this paper, and the support of his colleagues at Jacques Whitford and Associates Limited.

References

Acres International Limited and Consulting (Pak) Limited, 1968. Preliminary Design Report on the East-West Interconnector Project. Report to the East Pakistan Water and Power Development Authority.

Acres International Limited and Consulting (Pak) Limited, 1970. Report on the East-West Interconnector Project. Report to the East Pakistan Water and Power Development Authority.

Coleman, J.M. 1969. Brahmaputra River: Channel processes and sedimentation. Journal of Sedimentary Geology, August, pp.129-239.

Hinch, L.W., McDowell. D.M., and Rowe, P.W. 1984. Jamuna River 230 kV crossing – Bangladesh. I. Design of foundations. Proceedings of the Institution of Civil Engineers, **76,** Nov., pp. 927-949.

Sowa, V.A., 1999. The influence of unstable submerged riverbank slopes on large caisson foundations in the Jamuna River. Proceedings of the 13th Annual Vancouver Geotechnical Society Symposium, May 28, 1999.

Turnbull, W.J., Krinitzsky, E.L., and Weaver, F.J., 1966. Bank erosion in soils of the Lower Mississippi Valley. Journal of the Soil Mechanics and Foundations Division, Proceedings, ASCE, Vol. 92, No. SM1, Proc. Paper 4632, January, 1966.

Ullrich, C.R., and Hagerty, D.J., 1986. Surficial failures of alluvial stream banks. Canadian Geotechnical Journal, **23** (3), pp 304-316.