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Saga of hundred years of Hardinge bridge

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ABSTRACT: The Hardinge Bridge across River Padma is a remarkable achievement in Civil Engineering. This bridge is 5328 ft. long, one of the longest in its time, has 15 spans of 345 ft 1½ in. apart from three land spans of 75 ft. on either end. 345 ft. span for double line Broad Gauge traffic was itself a record holder at its time and even today is exceeded by few others in the subcontinent.The Bridge, built with extreme caution against any breach by the turbulent flows of the river in those days, met with a serious threat on its existence during the late floods on 25th September, 1933, when a breach of 400 ft occurred in the right guide bank, that eventually extended to 1600ft on 7th October, despite day and night work by engineers and workmen, whose services were requisitioned as an emergency measure. Rehabilitation work required 2 years of intense activity.The bridge again suffered multiple crippling damages during the war of liberation in December 1971: the ninth span from Bheramara side had a direct missile hit that blew off 60 ft of the steel span, leaving it listing dangerously; the twelfth span collapsed on its nose on one end as a result of blowing off of explosives padded on the bridge members by the retreating Army as a part of the scorched earth policy to prevent movement of freedom forces. The fifteenth span and the supporting pier number three also were damaged but these were not of grievous nature. Indian Railways took up the challenge of restoring this vital link before October 1972 and appointed BBJ who completed the difficult restoration task over three different stages, completing the permanent restoration in 1975 August. All these restoration works were done by technocrats in close collaboration with Bangladesh Railway engineers, who worked unceasingly in challenging conditions to meet the demands of the country's economic developm ent.The paper presents technical highlights on all three phases of the bridge's existence. This calls for a national homage to an engineering marvel that continues to serve the country unfailingly.

1 INTRODUCTION

The Hardinge Bridge across river Padma is a remarkable achievement in Civil Engineering globally, and merits a special celebration on its 100th year. The Hardinge Bridge across Padma carrying double track Broad Gauge line was inaugurated for double line working and all classes of traffic on the 4th March 1915, by Lord Hardinge, the then Viceroy of India, after being opened earlier for single line working for goods traffic on the 1st January, 1915. This bridge is 5328 ft. long, one of the longest in its time, has 15 spans of 345 ft. 1½ in. apart from three land spans of 75 ft. on either end.The hundred year life of this Bridge has been full of dramatic events that can make its biography more attractive than a fiction.

The Bridge built with extreme caution against any breach by the turbulent flows of the river Padma in those days, met with a serious threat on its existence during the late floods on 25th September, 1933, when a breach of 400 ft occurred in the right guide bank, that eventually extended to 1600ft on 7th October, despite day and night work by engineers and workmen, whose services were requisitioned as an emergency measure. The tracks were finally linked on June 1935 and had to be kept under continuous surveillance for the next few years, and dumping of stone ballast during monsoon fury continued.

Bad luck struck again in the December of 1971, during the birth pangs of Bangladesh, after a successful bloody war of Independence. As the war intensified the bridge suffered multiple crippling damages: the ninth span from Bheramara side had a direct missile hit that blew off 60 ft of the steel span, leaving it listing dangerously; the twelfth span collapsed on its nose on one end as a result of blowing off of explosives padded on the bridge members by the Army as a part of the scorched earth policy to prevent movement of freedom forces.

The fifteenth span and the supporting pier number three also were damaged but these were not of grievous nature.

The newly formed Government had a big, apparently insurmountable, challenge in hand and sent out appeals to the International community of engineering fraternity for restoring this vital link before the Jute export season in 1972. Indian Railways took up the challenge and appointed BBJ (the Braithwaite Burn and Jessop Constn Co) who completed the difficult restoration task over three different stages, completing the task in August, 1975. All these restoration works were done by Indian technocrats in close collaboration with Bangladesh Railway engineers, who worked unceasingly in challenging conditions to meet the demands of the country's economic development.

The Bridge that has seen history unfolding under its folds over a century, celebrates also its 80th year after the first calamity caused by nature and the 40th year (Ruby Anniversary) after its rebirth from a crippling damage caused by the war of Independence!!

This paper presents the remarkable engineering achievements in all three phases of the hundred year life of the bridge, namely: (I) during the original construction, (II) fighting the attack by the river in 1933 and (III) restoration of the damages caused during the War of Liberation in 1971.

2 THE ORIGINAL CREATION

2.1 *Planning*

The Hardinge Bridge connects the standard 5-foot 6-inch gauge system of the then Eastern Bengal Railway south of the Padma with the metre-gauge system north of the river. It comprised of fifteen river spans of 345 feet 1½ inch, with three land spans of 75 feet at each end. It carried a double line of standard gauge between the girders and a pedestrian walk 5 feet in width bracketed off the down-stream girder.

A proposal for bridging the Padma at Sara was first put forward officially by the administration of the Eastern Bengal Railway in 1889. The reference resulted in the appointment of a committee which, after consideration, outlined the chief dangers to be feared and reported a bridge to be feasible. In 1902 the preparation of a detailed project was entrusted to Sir (then Mr.) F. J. E. Spring, K.C.I.E.

Sir F.J.E. Spring is credited with the monumental effort in studying the flood delta of Bengal, which covered large number of waterways, and then assessing the hydraulics successfully. The project report identified the danger and difficulties of the project and expressed the opinion that a bridge could be constructed at Sara with proper precautions against identified risks.

Sir Robert Richard Gales was appointed Engineer-in-Chief of the project, and his Majesty's Secretary of State for India sanctioned the construction of the Lower Ganges bridge (Padma now) at or near Sara in December, 1908.

The bridging of the river at Sara was initiated with three main considerations,

1. the safety and stability of the approaches : the line from Calcutta to the bridge on one side, and from the bridge to Santahar on the other,
2. the stabilisation of the course of the river in the vicinity of the bridge, and
3. the safety of the bridge itself.

2.2 *Hydrology*

The drainage-area of the river upstream the site of the bridge is 3, 61,000 square miles. A maximum high-flood level at the site, estimated 50 feet above mean sea level was established after thorough investigation. A gauging by the Mississippi method taken on the 22nd August, 1910, with a flood-level of 47.77 feet, showed a discharge of 19, 26,080 cubic feet per second. This is probably one of the largest discharges hitherto gauged by exact methods in the main channel of any river. Four gaugings were taken, and a curve drawn through them when plotted showed a probable discharge of 25, 00,000 cubic feet per second at maximum high-flood level.

The maximum velocity in flood recorded before the construction of the bridge was 12.8 feet per second with a mean velocity of 9.34 feet per second. The sectional area of the river in maximum flood, excluding spill over high banks, was 2, 54,750 square feet. Possible scour of the river bed with the obstructions introduced by the bridge foundation were estimated for successful design of the supports inside river bed.

2.3 *Wells and Piers*

The wells adopted are rectangular in plan, with semi-circular ends, and measure 63 feet in length and 37 feet in breadth, with two dredging-holes 18 feet 6 inches in diameter. Owing to the great depth of the wells, and the consequent heavy load on the foundations at the bottom of the wells, it was considered desirable to lighten the structure as much as possible, and the pier accordingly consisted of two portions, a masonry plinth extending from the top of the well to high-flood level and a steel trestle weighing 140 tons above that point. This design facilitated the use of a service-girder in the erection of the main spans. The masonry pier consists of a lower slab of reinforced concrete resting on the stening and concrete top plug bonded all together, a shaft of brick-work with concrete-block facing, and a top slab of reinforced concrete. In plan the pier is 55 feet in length and 29 feet in breadth, with semi-circular nosing. The construction, with trains on each track, gives a maximum load of 9 tons per square foot on the sand foundation at the foot of the well, but without allowanec for skin-friction keeping in view possible scour effect. No sinkage has occurred in any of the wells since their completion. (Figure 1)

The main span piers are all on extremely deep well foundations, perhaps the deepest in this area, because of the deep scouring nature of the river bed in high discharge conditions. The wells are of precast concrete blocks in a double D shape. Founding depth of normal piers are 150 ft. below low water level, and for piers adjacent to guide banks (i.e., piers 1 and 15) they are 160 ft. below low water level. The piers are of brick masonry with concrete fascia blocks. The solid piers end at +250 ft. river level (high flood level). Above that, steel trestles 34 ft. 6 in. high have been erected with four columns below the four bearings, suitably braced and provided with adequate capping beams to take the jacking loads during maintenance.The steel columns were designed as hollow square box, and, very prudently, filled with concrete inside.

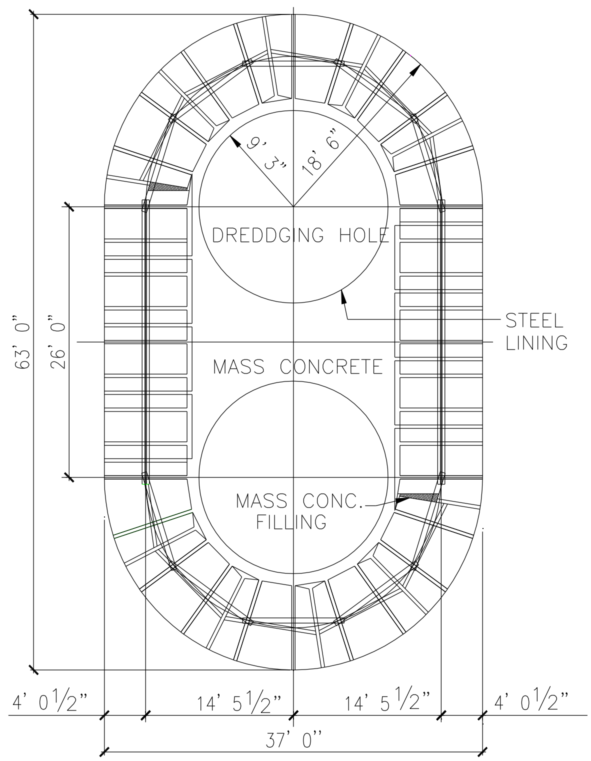

Figure 1. Layout of Concrete Block in Well Steining

2.4 *Girders*

The main spans are through type girders of the modified Petit type 345 feet 1½ inch from centre to centre of bearings. They are 52 feet deep and weigh 1,250 tons per span. They were designed under the then Government of India rules considering the following scale of loading:

(i) chord members, standard B+23 percent,
(ii) web members, standard B+40 percent,
(iii) floor members, standard B+50 percent.

This is equivalent in respect of the main girders to a train of wagons weighing 1.6 ton per foot, hauled by two locomotives with 20 ton axle-loads at each pair of the coupled wheels, and in respect of the floor system locomotive with 23 ton axle-loads at each pair of the coupled wheels.

The girders were assembled on a service girder that was floated in position on special portions to final position for eventual erection by taking help of the steel trestles in pier position.

2.5 *Planned Completion*

The bridge was opened for goods-traffic single-line working on the 1st January, 1915, i.e., 3 years and 5 months from the commencement of the erection of the first well-curb, was formally opened for double-line working and all classes of traffic on the 4th March 1915. The working season was for the most part from 15th October to 15th June.

Completion of this giant bridge in the short period during the early Twentieth century, and part of it during the First World War, that affected trade and commerce world wide, is sort of a miracle that was possible only with the meticulous planning and deployment of engineering skill of the highest order as would be difficult to replicate even today with great strides in technological development. Some of the aspects that helped this achievement under the dedicated leadership of Sir Robert Gale were:

i. Prior planning of the source of construction materials that were not available in the delta region. Quarries were identified and reserved in advance for construction grade sand and stone and arrangement made for their transportation to site by rail/ road/ waterway, which had to be created anew for many stretches.
ii. Arrangement of extensive infrastructure for the working force like well planned living quarters, hospital, water supply and treatment, sanitation, workshop, power house and other services on both banks of the river in advance. This paid rich dividend in retaining the workforce at site and getting their dedicated service and also avoided onset of epidemics that were very common in those times.
iii. Advance decision for using concrete in the foundations and piers, in place of brick that needed coal fired kilns, by using small sized stones that were available when sourcing boulders for the protection work.
Employment of electric power throughout the construction of the bridge for major functions like well sinking, concreting, operation of plants and equipments, girder erection and the like, even though use of electrical plants were not tried earlier. For this purpose giant power houses were commissioned on both banks and work could proceed simultaneously from both sides.
iv. Use of precasting technic for making concrete blocks that were extensively used for construction of well and piers--again use of a technology hardly known in those days.
v. Use of adequate number of plants and machinery to ensure rapid progress and provision of back up spares to avoid stoppages during breakdown. Complete control were placed on sinking of wells which, due to the uncertainties offered by under bed obstructions, delay work. Special protection was provided, around wells during sinking, from scour, by pitching stones around. Pumping or “Running” was resorted whenever sinking got slowed down.
vi. The girders for the bridge were fabricated at Liverpool with the steel produced in plants in England and transported by ship. For close coordination of the entire manufacturing process and despatch, senior staff was posted there and close contact maintained with site organisation and their progress. Ship movement was affected due to war and particularly due to swift attacks by the dreaded German cruiser Emden. Three land spans were captured and one of them had to be replaced on emergency basis.
vii. For fast assembly of the girders and accurate camber achievement drifts were extensively used. Hydraulic Riveting was used wherever possible for improved assembly.

All the above attributes helped in speeding up the project that needed 27,500 tons of steel and 1,700,000 field rivets for the structure. The total cost of the spans was £1,393,000 and cost of river Training works £705,650.

3 TAMING OF THE RIVER – DISASTER STRIKES THE BRIDGE

3.1 *River Movements*

The river Ganges, from its source on the southern slopes of the Himalayas, flows in a south-easterly direction between more or less defined banks, within which it has flowed for centuries, for a distance of about 1,100 miles before it arrives at the alluvial plains of Bengal, below the Rajmahal hills. From there it has, during the more recent centuries, flowed in innumerable courses and channels. Figure 2 indicates the channels it has occupied at four different periods, and this alone should show the difficulty one could have in "training" the river as to ensure that it will always, in spite of its wandering elsewhere along its course, flow through a bridge that has been built across it.

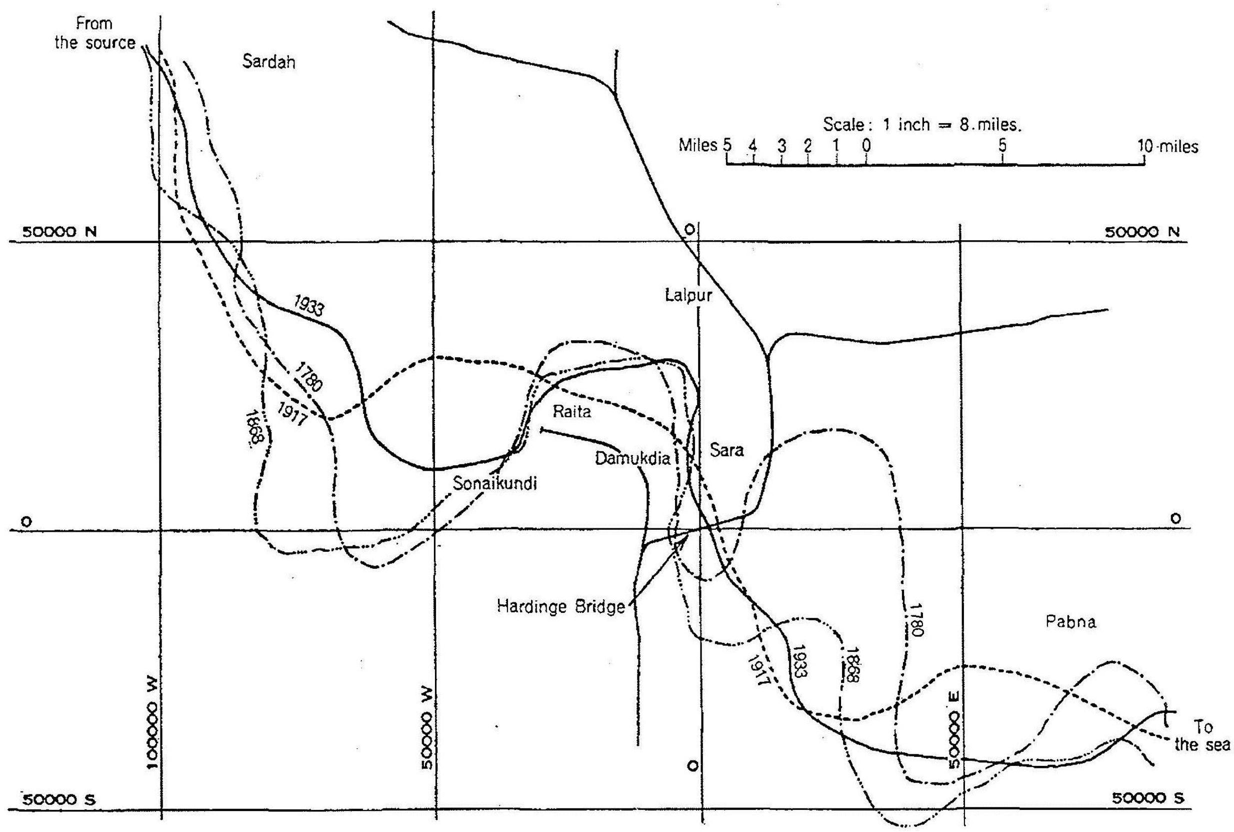

Figure 2. General Map showing river movement over years

The main protection works of the bridge, namely the guide bunds for retaining the river within the limits of the bridge, were designed on the Bell bund principle with certain modifications arising from local conditions. The body of the guide bunds was of sand, the slope on the river side being covered by a 9-inch layer of stiff clay, and on top by a 3-inch layer of quarry chips on which the facing of boulders was laid. At the foot of the slope just above low-water level an apron of loose boulders was provided on the floor so that, when scour occurred at the toe of this apron, the boulders would fall in.

When the river occupied its final position, the north end of the Sara protection bank, flanking the Lalpur bight, was well inland from the water's edge; but in the year 1925 the main river, moving eastwards into the Lalpur bight, came into contact with the unprotected river bank northward of the Sara revetment. This bank did not provide the resistance expected of the stiff Sara clay and in the year 1931, the upper end of the revetment, to which large quantities of stone had been added, was enveloped, isolated and sunk during the flood season. The sweep of the river into the embayment thus formed, assisted by the eddies caused by the obstruction of the sunken work, directed towards the right bank a current which threatened a serious embayment about 2 miles upstream of the bridge. The eddy downstream of the sunken work was found to have a diameter of 800 feet and soundings showed a depth of 170 feet below low-water level. At that point the matter was referred to the Consulting Engineers, Messrs. Rendel, Palmer and Tritton of London, and on their advice in 1933 the protection bank was curved back to promote smooth flow, to avoid further damage to the bank and to prevent the dangerous eddies, whilst the Damukdia guide bank was constructed.

The cost of this and other protective works done in the year 1933 was approximately £150,000. It was decided that for the Damukdia guide bank, and for future works in the vicinity, all aprons should be designed to meet a scour of 160 feet depth. The Damukdia guide bank was completed in 7 months, on the 1st June 1933, and a feeling prevailed that all was well with the bridge and that the danger of its isolation by the river advancing further westwards in this vicinity had passed for ever. This smug feeling of achievement was proved utterly wrong by the river shortly afterwards.

3.2 *Attack on the Bridge*

The behaviour of the river was normal during the rise of the year 1933, but, unfortunately, it was not normal during the fall. Figure 3 shows the average hydrograph of the river as well as the diagram for the year 1933; this brings out the fact that the main fall normally commences early in October. In 1933, however, the main fall appeared to commence early in September; this was attributed to the failure of the monsoon, in Northern India. Fig. 2 also shows, however, that something abnormal occurred in the middle of September, for after falling a matter of 5.20 feet, the river started a late rise with great rapidity in the third week of September. The reason for this was the fact that there was, after the failure of the monsoon, a deluge of rain, lasting several days and causing severe floods, in areas surrounding Delhi in Northern India, and this flood water found its way into the upper reaches of the Padma. The result was an abnormal rise at the end of September, creating conditions at the bridge which were without parallel or precedent. Heavy rain in Northern India frequently occurs, but there was no reason to suspect that this particular rise would come down a distance of 1,000 miles and still retain a force which, in the light of subsequent events, proved to be the cause of the destruction of the right guide bank of the Hardinge bridge.

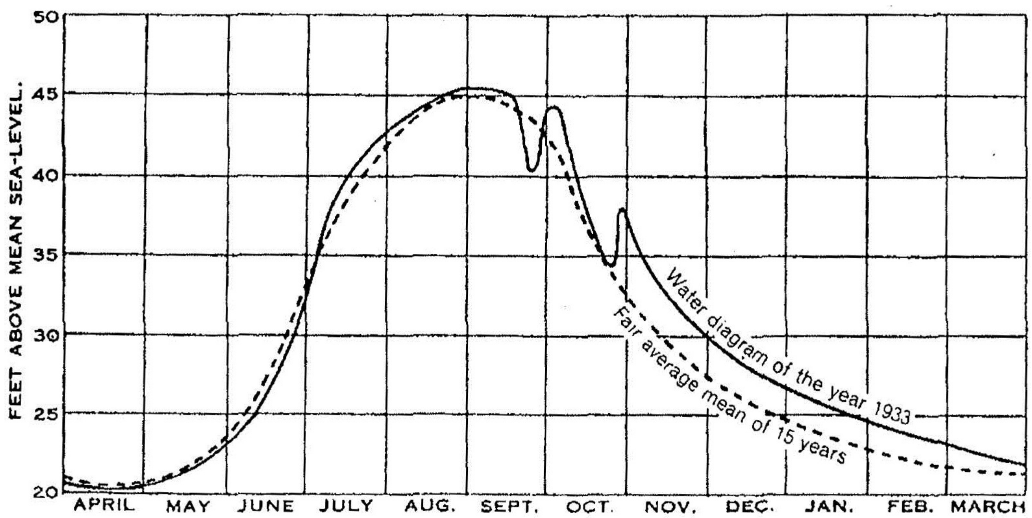

Figure 3. Hydrograph of river in the year 1933

There have been, as a matter of abundant precaution, ever since the completion of the bridge, watchmen at each of the protection banks, whose duties were to patrol it and to report any unusual occurrence to the designated officer in charge of the bridge. The watchmen's duties normally end at dusk, and on 25 September they reported, that all was well. It is likely that the damage really started late the same night or early on 26 September. A villager, who usually proceeded to his work at 5 a.m., over the bridge, gave the first intimation to the stationmaster at Paksey station on left bank. The stationmaster hurried to a point from where he could view the right guide bank, 11 mile away, saw what looked like a breach, and was sending out an SO S telegram to all concerned. About 6 o'clock in the morning the officer-in-charge of the bridge crossed the river in a motor boat to see whether the report was correct He returned to the left bank to report the disaster to Bertram Lionel Harvey, who was the Engineer-in-Chief for the river Protection work, posted at Paksey. He immediately went across the river and saw a most terrifying sight: there was a breach in the guide bank 400 feet long, and this was increasing rapidly each minute in the direction of the bridge, whilst an embayment had formed behind the guide bank in which there was turbulent water from 50 to 60 feet deep;

There was neither labour nor stone at the site to make any serious attempt at preventing the breach extending. The force of water was so strong that the 73-lb. double-headed track lying down the slope of the breach with its end in the water snapped off like a carrot with a loud report in two or three instances. The embayment through the breach, had reached a length of 1,000 feet, leaving an embayment behind 700 feet wide and 1,400 feet in length north to south.

By the next morning material trains, loaded with boulders from the reserve depots, and a labour force arrived, and pitching into the breach and down both slopes of the guide bank was started and continued in shifts day and night. On the back slope an apron was thrown out, and on the front the existing original apron was strengthened by stacking additional stone on it. The river, however, continued to rise, and by the 2nd October the flow of water over the back apron on the isolated portion of the guide bank had become so strong that it eroded the mainland and entirely isolated the head into an island. This unfortunately gave the river free flow into the embayment from the north and very soon widened the gap between the isolated head and the mainland to the extent of nearly 500 feet in a matter of a few hours, and eventually in the following days to 1,000 feet.

On the 7th October there was a fall of 14-inches, and with the high velocities resulting from the rush of water back into the main channels, a sudden attack developed just after dark. In spite of the mass of stone that had been pitched during the previous fortnight the breach extended in a few hours an additional 600 feet, thus making the total length eventually 1,600 ft. From the 8th October onwards, as the river fell gradually and there were no further changes in the conditions, a survey of the bed was taken in hand and a contour plan of the whole vicinity of the damage was prepared. This plan showed that a deep pot-hole had formed just below the stump of the guide bank, about 1,000 feet upstream of No. 2 pier, its depth being below the danger level of the pier. This, and the whole situation, showed that the great bridge was left in a very vulnerable condition and, as such serious issues were involved, the Railway Board cabled to the High Commissioner for India requesting him to procure the services of Sir Robert Gales, the original builder of the Bridge, to come to India and advise them as to what should be done.

Sir Robert Gales arrived in Paksey on the 3rd December, 1933, and after a searching preliminary inquiry, a scheme was drawn up by him for an immediate start to be made on to work, which he set forth in detail later in his report to the Railway Board.

3.3 *Restoration of the Breach*

The Railway Board had in the meantime decided that, in addition to having the advantage of the recommendations made by Sir Robert Gales, for the further works necessary they would seek the opinion of a committee of engineers in India under the chairrnanship of Sir James Williamson, Agent of the Bengal and North Western Railway, who had had considerable service and experience on river-training work in the watershed of the Upper Ganges. They confirmed the recommendation made by Sir Robert Gales that the main breach in the right guide bank should be closed as early as possible, but considered that, before further works were undertaken; experiments should be carried out in the Irrigation Department's experimental laboratory at Poona.

The main work in the season 1935 was therefore to carry out the recommendation of Sir Robert Gales, which was confirmed by the committee of engineers, namely, the restoration of the guide bank across the original breach. This restoration is of the same design as the mole, being a dyke of stone, sealed behind with clay and backed with earth, which is held from spreading by a pile-and-matting barrier. The quantities were, however, considerably greater than in the mole, for the bank was 1,600 feet long and the average depth of water at low level over the length was 65 feet. To visualize this bank of earth and stone, it has, at its maximum section, a base 150 yards wide and a height of 105 feet, and this decreases only very, slightly over the greater part of its length.

The floods of 1935 reached the highest level for the year in the third week of August and were only 6 inches below the previous year’s abnormal high-flood level. The highest velocity recorded in this flood was 13.6 feet per second with a discharge of 1,500,000 cusecs. This final round of protection work proved effective in protecting the bridge across which traffic was again resumed, but this extracted a huge cost. The monetary cost of this restoration work climbed to £ 930,200, which was more than the original spending on Training work.

3.4 *Current Situation*

The conclusions drawn by Engineer Harvey in his interesting technical paper was “that the condition of the river towards the end of the flood season of 1935, the waywardness of its channels for several miles upstream the bridge, and the daily-varying course of the main current near the bridge itself, present a most interesting study. Channels above Raita appeared to be moving rapidly into new, or rather into old, alignments which, should they develop, change the whole regime of the river, because the position of these upstream channels will influence the alignment of the main stream at the bridge, where the indications are for it to move away eastwards. In fact, the river appeared to be in a state of unstable equilibrium and might rapidly assume an alignment through the bridge which will solve the problems of those who remain to look after it. This statement is intentionally (and advisedly) made in an indefinite and guarded manner, because the Author is fully alive to the fact 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”.

Engineer Harvey’s conclusion has, however, proved prophetic as the next 80 years of the bridge existence established. Much water has flown under the bridge ever since, the discharges diminishing over the years and the threat to the guide bunds receding, not because the rainfall pattern has changed, but with the ever increasing population of the subcontinent diverting the river water to the needs of irrigation, power generations and supply of drinking water as is happening globally.

4 VICTIM OF THE WAR – INNOVATIVE RESTORATION WORK

4.1 *Damages*

In December 1971, towards the close of the war of liberation, Hardinge Bridge suffered serious damages on four of the 15 main spans, two of which were beyond ordinary repair or rehabilitation.

The steel supporting trestle common to spans 1 and 2 was damaged by an artillery shell attack. Steel plates of both the upstream column of the trestle were wrenched off the inner core of concrete and the bracings on two faces of the trestle were blown off. The span 15, the last span on the Paksey end suffered damage to the bottom chord of the penultimate panel, one deck panel, and the fixed bearing. Both the above damages looked repairable within reasonable time.

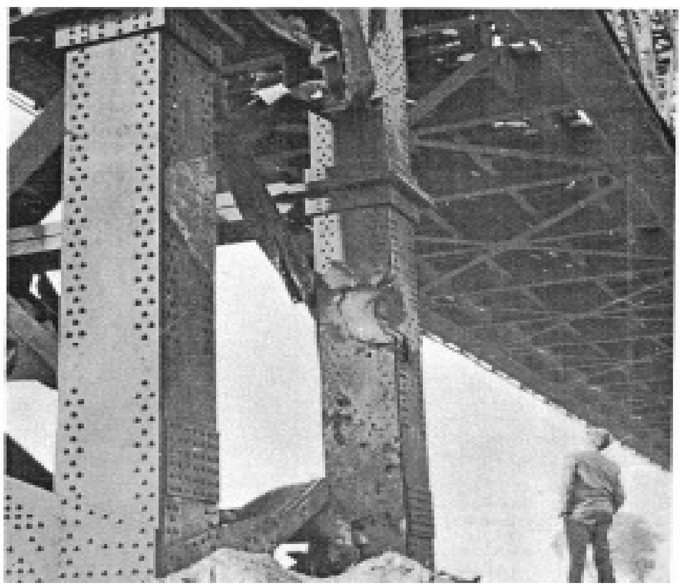

Figure 4. Damage to Pier

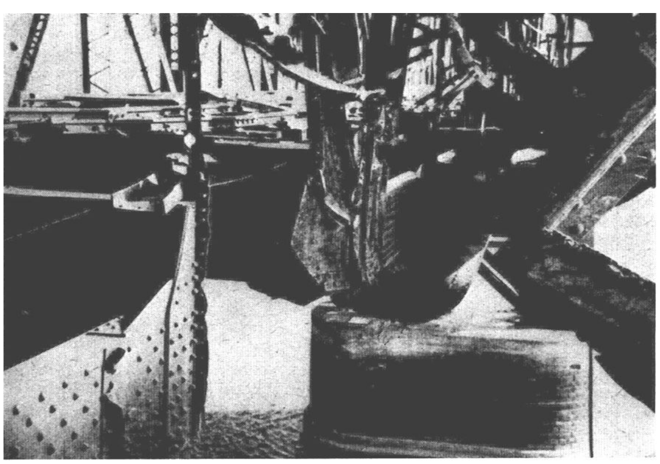

Figure 5. Damage to Span 9

However, the most serious damage happened to span no.12 from Bheramara end, which was cut into two, due to accidental deterioration of explosive charges on all chords and webs on the second panel at end of the span. This resulted in one end of the span dropping nose down into the river, while the other end perched precariously on top of the pier, after slipping down from the bearings on top of the trestle. Members of the truss system, visible in the portion projecting above the water, appeared deformed beyond repair.

Span No.9 from the Bheramara end suffered an unusual damage due to the missile attack that blew off 60 feet length of the bottom chord of the downstream truss alongwith the web members in the central region of the same truss. The severity of the blast completely damaged the deck system in the central panel. Readings taken after a month of the damage showed that the downstream truss had sagged by 4 ½ inches, while the up-stream truss had sagged by only one inch. The span had also titled out of vertical at the center towards the downstream side, by a slope of 1:250. The truss appeared unstable and looked vulnerable, to collapse, even though it sat solidly in position.

4.2 *Planning of Restoration*

After a thorough inspection of the damaged spans no.9 and 12, it was decided to have an extensive review before planning innovative solutions for making this precious bridge useful once again. National requirements of Bangladesh made linking of this bridge imperative before the jute export season in October 1972. As the time available was extremely short for such major unconventional repairs, it was decided to make repair work in two distinct stages. It was apparent that a new span of identical capacity and shape has to be fabricated and introduced in the gap created for the span 12, a process that will require very long duration. Repair work; therefore, have to be done first for temporary linking, within built provision for permanent connectivity.

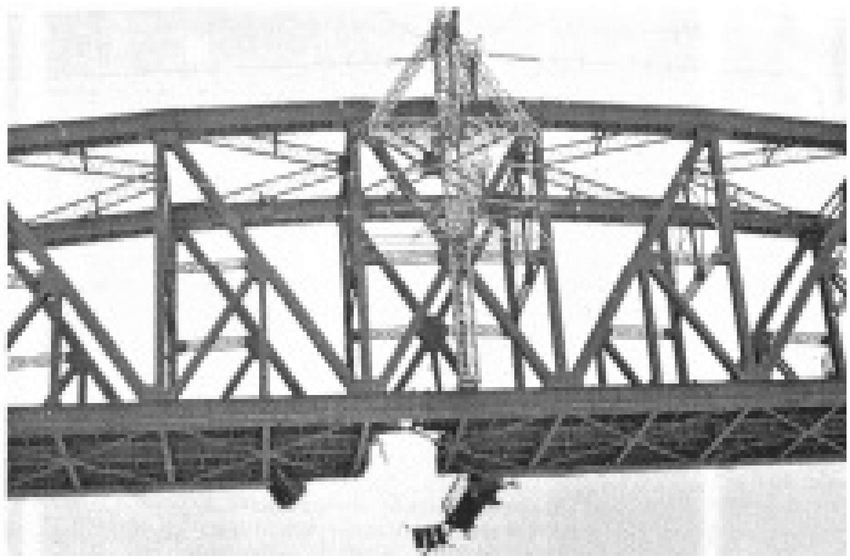

Figure 6. Damage to Span 9

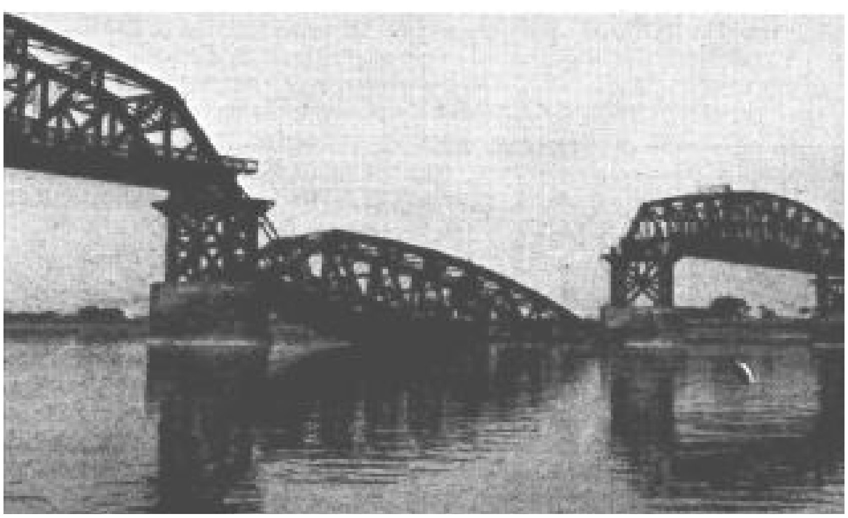

Figure 7. Fallen Span 12

The planning was that initially, span no.9 will need to be rehabilitated after proper analysis of the deformed structure, for ascertaining whether any member has been overstressed beyond its elastic limit. A temporary span need to be introduced to fill the gap created in span 12 for restoration of single line traffic. The repair work of trestles between span 1 & 2 and that of span 15 being of ordinary nature can be done in parallel. The second stage work was planned to be implemented after preparation of a new design of the span 12 with steel materials of current grade which are much superior than those used for existing span. Fabrication of such steel work will be done to create an identical structure to maintain the aesthetics of the bridge.

Once this plan of work was discussed, finalized and approved by Government of India and Government of Bangladesh, work was taken up on emergency basis.

It was recognized that span no.9 would have to be taken up on immediate basis:

i. Work could be started from Bheramara end, which was accessible from the workshops in India through road and rail connectivity
ii. The restoration for span 12 could be undertaken after the rail connectivity is completed through the repaired span no.9
It was further recognized that span no.9 repair work would involve extensive operations from the river and therefore this work needed to be completed before high flood season in July/August.

4.3 *Repair of Span no.9*

Despite damages to the central part of the span and tippling of the fixed bearings, as a result of the explosion, it was conjectured after close inspection of all the joints and the main structural members, that the damages have not overstressed the rest of the span members and those unaffected would be able to take design load once the span is completely rehabilitated.

Analysis of the span with its multiple degree of redundancy created by the presence of robust bracings proved to be difficult manually. Help was sought from IBM mainframe 7044-1401 computer at IIT Kanpur. The following analysis was planned :

i. Analysis of the undamaged structure for dead loads
ii. Analysis of the damaged structure with reverse of the forces obtained from the first analysis applied at nodes joining damaged members and in the direction of the members to simulate the span condition on the removal of the affected members. The actual state of stress could be obtained by the superimposition of the stresses obtained from the two analyses.

The analyses were performed by the stiffness method, assuming that the entire structure acts as a space frame. However, the sway bracing members in the portals and bottom lateral bracing members were idealized as truss members because of their relatively small bending rigidity. There were 128 joints and 359 members. The stiffness formulation resulted in the solution of a matrix on the order of 768 with a maximum half bandwidth of 90. The analysis led to the happy conclusion that none of the unaffected members had reached yield stress as a result of the damage to the span. The relative displacements of the bottom chord nodes in the upstream and downstream trusses were compared with the observed readings and it was observed that the structure as idealized was stiffer than the existing structure. This increased stiffness could be ascribed to two factors. The joints were assumed perfectly rigid in the analysis, while there is certain flexibility in the structural conditions. Encouraged by the revelation that the undamaged members had not suffered any overstressing, salvage operations were begun to restore the span to its original position.

The repair scheme of the bridge had to be chosen against the background of the extraordinary situation that had been created by the damage to this major bridge. In view of the urgency of rehabilitation of the bridge, all possible repair schemes were reviewed keeping in mind immediate indigenous availability of plant and materials in Bangladesh and the then India. A further constraint was provided by the River, which is known for its strong current (13.5 fps) and swift rise in level during the monsoon season. A hydrograph of the river section at the bridge shows a rise of 26ft in the water level during the monsoon months between May and August. Though inspection had started in January, work could be awarded to the executing agency only in March leaving less than 4 months for planning and completion of the rehabilitation work. It was concluded that the repair work can only be done with the help of steel barge located under the span. Floatation would be used to push the truss back to its initial configuration prior to replacement of the damaged members. The stress condition in the damaged structure, when subject to estimated jacking loads of 240 tons each at nodes L8 and L14 of the downstream truss, roughly in 1/3 points, was ascertained after necessary analysis. It was decided to connect the span with adjacent spans through temporary link members along top chord and with comprehensive members between the ends of bottom chords for holding the span during repair work.

Two wagon ferry barges belonging to Indian Railways, each capable of supporting 24 nos 20-ton capacity wagons, were brought to the site from India and were strengthened at the bridge site to withstand loads of upto 300 tons, applied centrally. The barges that had been designed for carrying uniformly distributed wagon loads were stiffened by introducing additional longitudinal and transverse girders inside the hold to ensure stiffness in both directions as can transfer a centrally applied load uniformly on to the water mass. A system of steel grillage was introduced on the top of the deck to distribute the load from steel trestle onto a 10m square area. The truncated pyramid shaped steel trestles of adequate height to reach underside of bridge and capable of supporting 300 tons were erected on each of the barges and the barges located under the downstream truss at appropriately middle third points. The barge had been made stationery, in the flowing river, by dropping concrete anchor blocks on all sides and by securing the barge with wire rope from the anchor blocks rested on the river bed.

As normal jacking operation was found to be impossible from the barge, it was decided to use hydraulic flotation principle for application of load on to the girder. Prior to start of jacking operations, space between the top of grillage on the top of the trestles and underside of the span was jammed with steel back plates. Inner chambers of the barges were filled with water. The compartments created inside the barges allowed systematic synchronized pumping of water from inside, with the help of electrically operated centrifugal pumps each placed close to the manholes of the six compartments of the barge. Water was pumped out of the two barges simultaneously. Pumping was alternatively carried out on the outer chambers and the central chambers to ensure uniform pressure distribution under the barge and to develop minimum moment on the barge section. As the water was being pumped out, an equivalent jacking load was transferred onto the bottom chords of the span, lifting the span back to its original position.

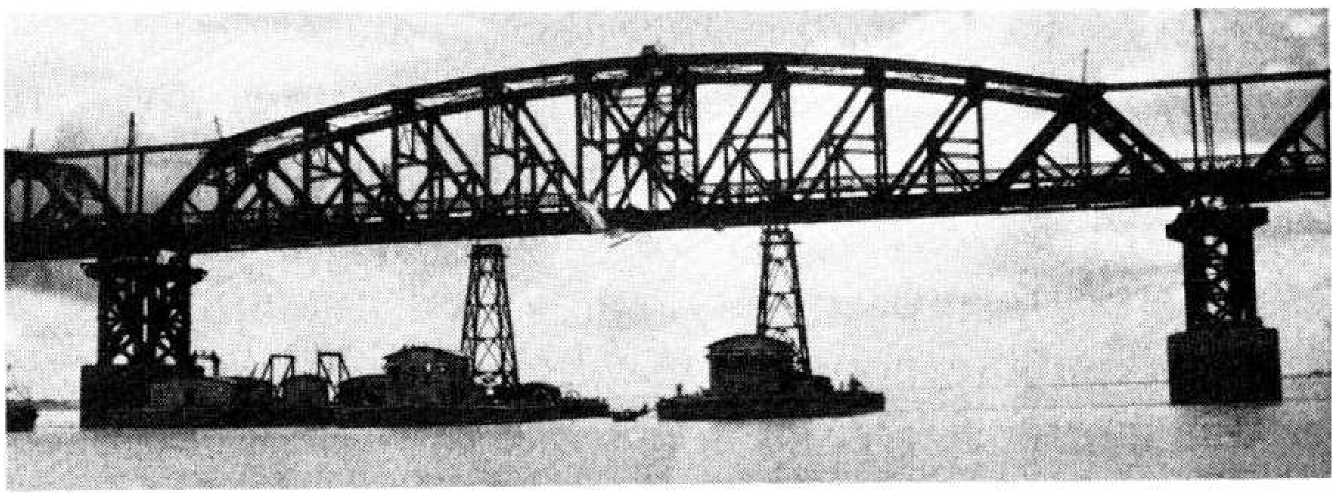

Figure 8. Repair of Span 9

The raker joints at both end of the span were carefully opened out for introduction of specially designed link plates with pin holes. Similarly at ends of span 8 and 10 link plates were connected. Specially fabricated link members were introduced between spans 8 and 9 and span 9 and 10 for providing connectivity with adjacent spans. Buffer blocks were introduced between ends of bottom chord. The first phase jacking operation was carried out in the month of June when the river was already rising. This unique operation which was carried out for the first time ever, was fraught with suspense, uncertainty and tension for all the technocrats involved in the operation. However, the spans responded amazingly well and with the jacking operation the span came back to its original shape. After the jacking operation the upstream girder recovered camber and downstream girder became level. This was considered appropriate and as per theoretical estimate. All members of the span, it was proved, were indeed working within the elastic limit. Once the spans were connected with adjacent spans, the operation of replacing damaged members was taken up. Despite unfavourable weather condition and lack of proper illumination, all members were carefully removed and all missing members were replaced. Final closing was planned in middle of July, when the river level was rising furiously. The height of the trestles had to be systematically truncated to match the rise in level of river water.

After the closing of the span, links and buffers were systematically removed and railway track made through upto the beginning of the span 12.

Work on removal and replacement of the damaged members began simultaneously from both ends so that all the adjustments could be accommodated in the central bottom-chord joint prior to closing the truss. After erection of all of the truss members, the span was once again jacked up with the help of the barges on 13th of July with weather conditions providing a break, and the central bottom-chord joint was closed to keep the secondary deformities to a minimum. The links, introduced to provide additional support to the span, were then removed by jacking up the adjacent spans at their far ends one by one (pin holes at the link ends were kept slotted to facilitate this operation).

The entire operation of restoration of span no.9 was conceived with ingenuity and innovative thinking at every stage, making best use of elements of nature. It was extremely rewarding for the technocrats that the entire operation went through as per plan reconfirming all the assumption made about the behaviour of the span.

After the trusses were repaired, the damaged deck members were replaced and one track and was made operational to feed construction and job materials to span 12, where the 345 foot gap had to be bridged. Since fabricating a new double-line, 1250 ton span (with the complicated construction involved in petit truss) would have taken much longer, it was decided to introduce a temporary span to bridge this gap so that single-line traffic could be restored.

4.4 *Temporary linking*

For doing temporary linkage, 300-foot-long spans, fabricated by BBJ for a bridge still under construction across the Godavari river in India, some 930 miles away from the Hardinge Bridge site, were utilized. These high-tensile steel-truss girders are designed for single-line broad-gauge (5½-foot) railway traffic and two lanes of roadway running on the top concrete slab deck of the span. It was found that the Godavari girders, without the concrete deck and the roadway live loading, would be capable of withstanding the 45-foot increase in span necessary for bridging the 345-foot gap at Hardinge Bridge. Two additional panels totaling 45 feet were fabricated, and one 300-foot span from Godavari was directed to the Hardinge Bridge site to make up the necessary 345-foot span. To facilitate the cantilever erection of this modified span, another 300-foot span was brought from Godavari and erected inside the 55-foot high, 32-foot wide petit truss span (11th span) for use as an anchor span.

It also became necessary to erect a 45-foot long erection bracket at the far end of the 12th span to keep the cantilever erection stresses within the permissible limit. Specially designed and electrically operated derrick cranes were installed on the top chord of the Godavari span to erect the anchor span as well as the cantilever span. Upon completion of the 345-foot cantilever span, the same cranes dismantled the anchor span and loaded it to go back to the Godavari Bridge in order to keep the erection schedule unaltered at that site.

The temporary span was lowered by 5 feet 8 inches, and the upstream track was slewed at either end to shift the railway track to the center, since the modified span was located along the center line of the bridge. This was done to facilitate the second-stage construction when a new span, identical in appearance to the existing ones, will be created – keeping the railway traffic uninterrupted during the entire erection process.

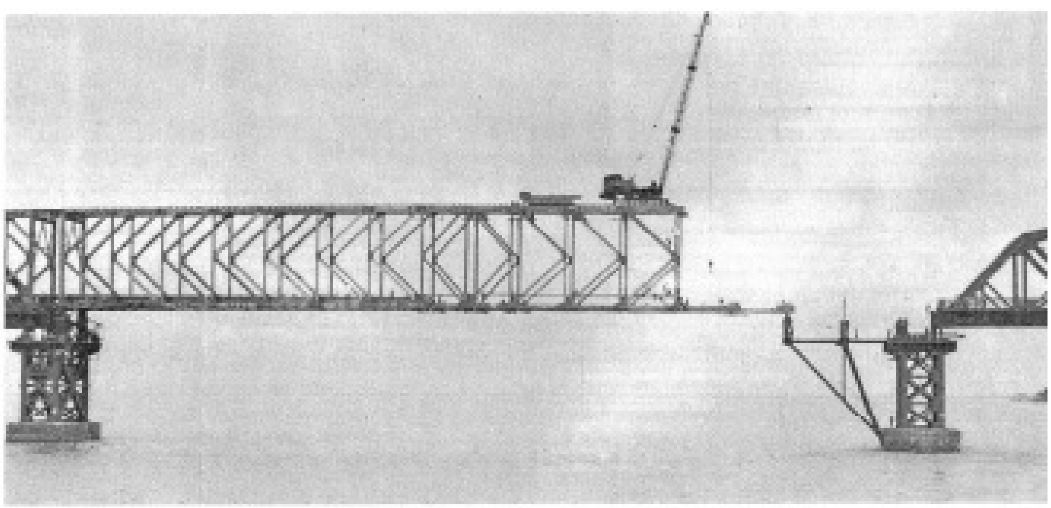

Figure 9. Temporary Linking

4.5 *The Permanent Span no. 12*

The design and detailed drawings of the original spans, available with the archives, were studied for the preparation of the design of the permanent restoration span. From point of view of aesthetics it was decided that the new girder should have identical geometrical configuration as the existing spans, Alterations in the dimensioning of the new span members were, however, permitted to effect maximum possible reduction in the dead load of the girder.

The design live load adopted for the old spans have meanwhile substantially changed with the increase in the haulage capacity of the locomotives and higher effective speeds. The basic axle loads originally adopted for the existing girders and those now followed by Indian Railways were compared and it was found that the axle loads enhanced by impact effect as currently adopted by the Indian Railways compared favourably with those originally followed.

The span length of the girders centre to centre of supporting trestle columns was maintained identical to the design span of the existing girders.

The problems of erection of the new span was very much aggravated as the twelfth span crosses the deepest channel of the river with velocity in the region of 14 ft./Sec., during high water season. The existing girders used 1250 M/T of fabricated Mild-Steel in each span with maximum permissible stress of 18000 lb/sq.m. The weight was too large to permit convenient erection of one single new span and economy in weight of steelwork was considered essential by use of improved graders of steel currently available. Use of high tensile steel (u.t.s. 35T/m2) together with readily available mild-steel (u.t.s. 28T/m2) was planned to achieve optimum balance between weight and cost of the steelwork. The aesthetic considerations required that the underside of the bottom chord be maintained at same level as the existing spans and the depth of the cross-girders had therefore to be left unaltered. The entire deck system was designed in mild-steel constructions. The bracings in various planes and the sub-members of the main truss were also designed in mild-steel.

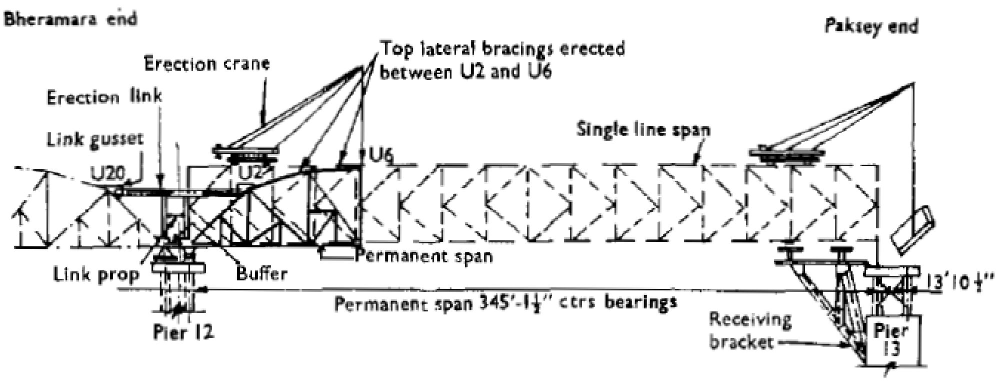

Figure 10. Erection in progress

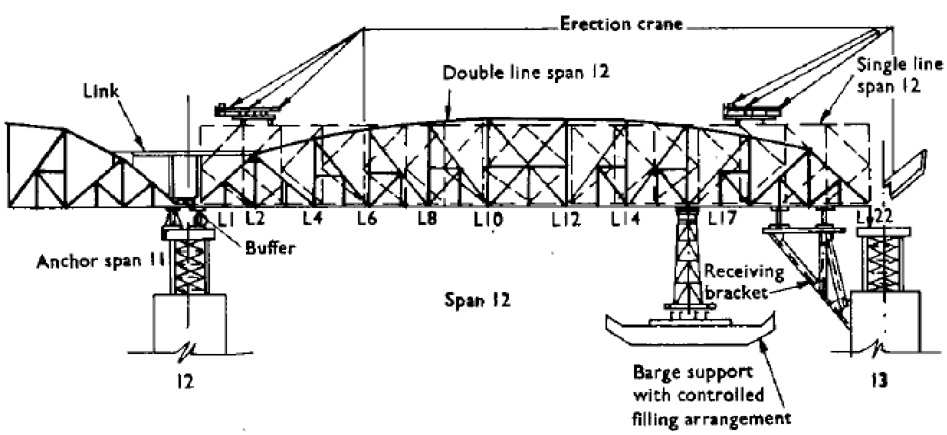

Figure 11. Erection completed

The bearings of the original spans were 1676 mm high and were composed of very large steel castings, extremely uneconomical to manufacture in small numbers. This design of bearings was found to be undesirable both from the point of view of technical and economical considerations. The bearing was redesigned to reduce its height to 746mm and a fabricated stool with concrete infil and machined top and bottom surfaces introduced to make up the difference in height. The new shallow bearings were also made of cast steel and of the conventional rocker and roller type. The roller bearings have been enclosed in oil-baths to eliminate maintenance and greasing problems and to obviate the difficult jacking operations for such heavy spans.

The foot-path on the down stream face was redesigned to carry precast slabs spanning between footway stringers, in turn supported on brackets cantilevering from the main truss at node points and a concrete wearing course was provided to ensure better maintenance. This is a variation from the foot-path design of the existing spans using steel troughing with mass-concrete infil having much heavier dead-loads.

The scheme for restoration of the span had to keep in view the minimum inconvenience to railway users. After studying the traffic census across the bridge, it was concluded that to effect least dislocation of goods traffic the working period should be restricted to the months between February and June.

Immediately beyond the bridge at north end is Paksey Station on 14m high bank. This limited the area that could be made available for use as girder assembly yard. About 1000 MT of steelwork for permanent girder and 200 MT of temporary erection materials, all fabricated in workshops in Kolkata were transported by special trains across the bridge and unloaded in the girder yard.

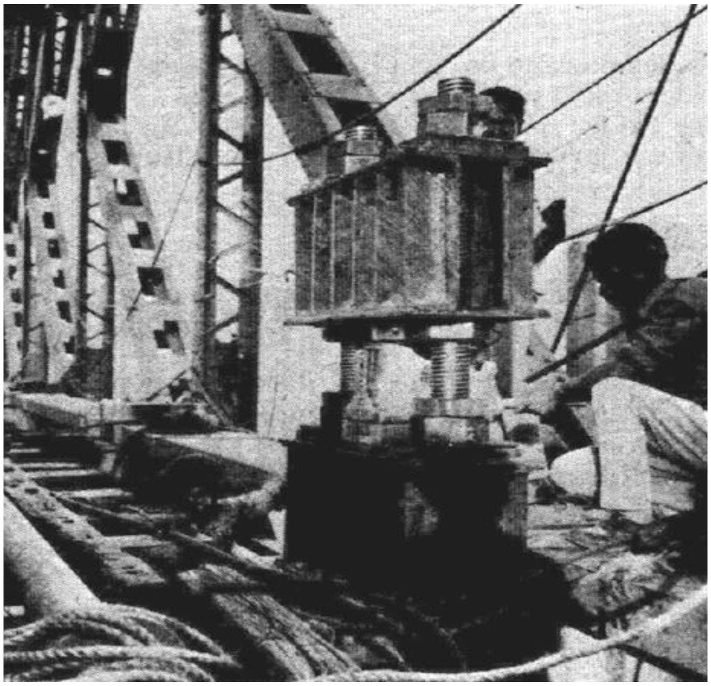

Figure 12. Warrier Paper – Clamping Device

The erection scheme was formulated by examining possible alternatives within the boundaries stated earlier. Providing any support from river was ruled out in view of the unfavourable river conditions. Floatation of girders was not practicable as the temporary span was already in position. Cantilevering of the span from the adjacent existing spans by securing the new span through link members provided the only possible solution. Lower permissible stress for the steel used in the existing spans restricted the maximum forces that could be introduced during cantilevering operation. Though considerable reduction in the dead weight of the new span was achieved by use of higher grades of steel, the forces in the anchor span during cantilever of full length of the new span was found to be too large to be carried by the grade of steel in existing spans. Transference of some load onto the temporary span during erection was therefore decided. The existing temporary girder had considerable spare load carrying capacity, once rail traffic was withdrawn from the span and maximum utilization of this spare capacity was made with the help of a special load transference device which transferred considerable amount of load to the temporary span and in turn helped the stresses in the anchor span to be kept within limits. This arrangement enabled the erection scheme to be independent of river conditions.

With the help of the clamping device, a vertical load of about 280T was effectively transferred to the temporary girder. Even with the use of this clamping device for relieving cantilevered forces, six panel length of bottom chord for the anchor span originally designed for tensile force had to be specially battened and laced to improve their slenderness ratio for resisting the compressive stresses developed.

As cantilever erection proceeded beyond the clamping device and before it reached the bearing position on the trestle capping beam, additional support was available from the bracket left in position during Stage-I erection.

The attachment of anchor span to new span was by traditional link and buffer arrangement. The link forces were high being around 1400MT. The top chord ends of the anchor spans were opened out to attach H TS link places with machined pinholes for introducing the 280mm dia. HTS steel pins required for transferring the forces from the tensile link member to the anchor span.

On completion of cantilever erection, the new span was jacked up to release the link members and the span was supported on the bearings; the clamping device was earlier released in the initial stages of the jacking.

After the new span was supported on the piers, the temporary span was jacked up from its supports and allowed to rest on the cross girders of the new span. Steel and hard timber packing were introduced between the bottom chord of the temporary girder and every cross girder of the new span to effect uniform transference of load all through the length of the new span.

Considering the urgency of opening the bridge to traffic, all the clearance work at Paksey yard including loading back of the dismantled temporary girder materials and tool and plants were undertaken simultaneously with the dismantling operations. Wagons were placed in advance in the yard for loading back these materials and this train of wagons was one of the first to be taken across the bridge leaving the Paksey station ready for immediate use by the user Railway.

The testing of the bridge was conducted by running special trains on both tracks and deflection observations were found to be highly satisfactory.

5 CONCLUSIONS

The story of Hardinge Bridge, starting with remarkable construction story in early Twentieth century, its restoration after being threatened by the mighty river and finally recovers from war damages in 1971 deserve to be well chronicled for the future generation of Engineers of its new home country.

ACKNOWLEDGEMENT

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