AN ENGINEERING MARVEL IN THE CAPITAL OF INDIA

V. N. HEGGADE

Abstract

The recently inaugurated over river Yamuna, Signature Bridge is an iconic bridge of its kind which is giving an illusion of being in perpetual motion in the tradition of Calatrava's Bridges in motion to the onlookers where very high importation of technology is involved.

The very complex geometry of the slanted steel pylon with its three-dimensionally varying Indian welcoming (Namaste) pose involves high precision fabrication, machining and drilling including the trial assemblies of fabricated segments which were carried out in China from economic considerations under strict vigilance and supervision.

The unprecedented nature of design of foundations, bearings and the pylon called for ingenious and first time construction engineering & methodology to be evolved whether for hybrid foundations, concrete technology, erection of large capacity & special type of bearings, fabrication, trial assemblies, welding including very long & critical in-situ welding of pylon base & finally segmental erection of three-dimensionally varying pylon.

Keywords: Back-stay anchorages, Cable-stay, Hybrid foundation, Slanted pylon, Segmental erection.

1. INTRODUCTION

The conception of new 8-lane bridge across river Yamuna, 600 m downstream of the existing barrage cum bridge at Wazirabad, Delhi was a culminated decision of Delhi Government for making a landmark structure in Delhi and to develop the surrounding area. This necessitated the development of approaches (Western as well as Eastern) on both sides of conceived signature bridge (Figure 1). Western and Eastern approaches as depicted in Figure 1 were a separate contract (depicted as 1) from that of main Signature Bridge contract (depicted as 2).

Infrastructure plays a significant role in the economic growth for a rapidly developing country like India. In last three decades, longest, tallest, biggest and many iconic bridges have been built in China. However, recent appetite for iconism among the rulers clubbed with huge investments in infrastructure has given rise to an exciting time ahead for bridge builders and it looks like the next three decades belong to India.

Figure 1: General arrangement of approaches and main bridge.

It is not necessary that a bridge has to be longest, tallest, etc. to be iconic, but when the identity of the surroundings are known by the bridge and development start taking place around, the bridge attains its iconic status. Signature Bridge at Delhi is envisioned to be one of such bridges.

2. CONCEPT AS EVOLVED

The area under the bridge is envisioned to be developed later as a park and the Yamuna River is to be converted in to lake like dimensions with river channelisation to enable boating facilities and other tourist attractions. So, the conception and design of iconic structure had to enhance the character of tourist attraction.

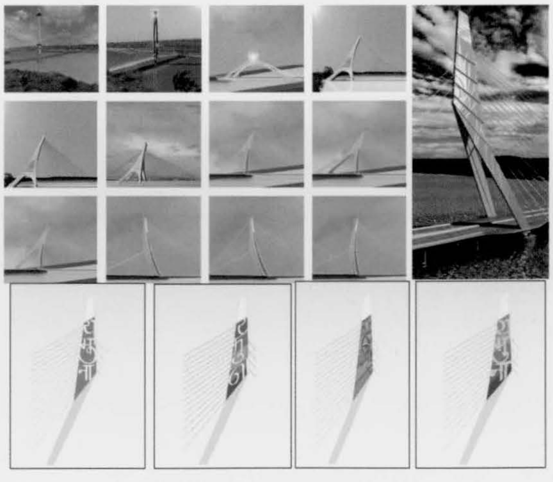

Figure 2: Concept evolution.

During the phase of convergence (Figure 2), many options were tested before arriving at a solution which is almost twice the height of Delhi's another heritage structure Qutub Minar.

Graphics on the bridge structure, peacock's feather particularly on the Pylon was to symbolise Indian culture but also to reflect modern and progressive India.

Signature Bridge is an elaborated cantilever spar cable-stayed bridge (Figure 3), comprising of an asymmetrical inclined Namaste shaped steel pylon of 154 m height. Total length of the cable-stayed bridge from expansion joint to expansion joint is 575 meters, with main cable-stayed span of 251 meters supported with 15 set of cables on one side and counterbalanced by 8 back-stay cables attached at a rocker bearing on Pier 23. The bridge steel and concrete composite deck has dual carriageway of 4 lanes (14 m) each with about 1.2 m. central verge, space for anchoring cables, maintenance walkway and crash barrier on either side of central verge. The outer-to-outer width of the bridge is around 35.20 m and the approach spans are about 36 m long. Spherical bearings are provided on all the piers. Pendulum bearings are provided for back-stays.

The steel pylon of around 154 meters from top of the bearings consists of two legs made up of steel boxes which merge into one upper pylon body zone made up of a load bearing skin stiffened by internal stiffeners and bracings, where the cable supporting the main span and the back-stays are anchored. Each of the pylon legs consists of a hollow steel box which are roughly 50–80 meters high. The upper end is the kink diaphragm which is the transition from pylon leg to the pylon body.

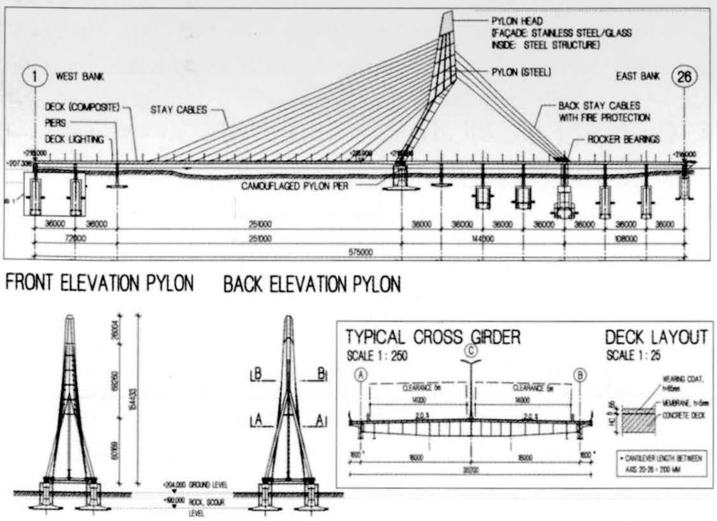

Figure 3: General arrangement of Signature Bridge.

It also has a pylon head, made up of beams and columns in steel structure with a glass cladding. Major part of the steel for pylon is of grade S355. In very highly stressed anchorage zones, S460 grade steel is used. Each leg of pylon rests on spherical bearings to transmit vertical loads of around 17,000 t.

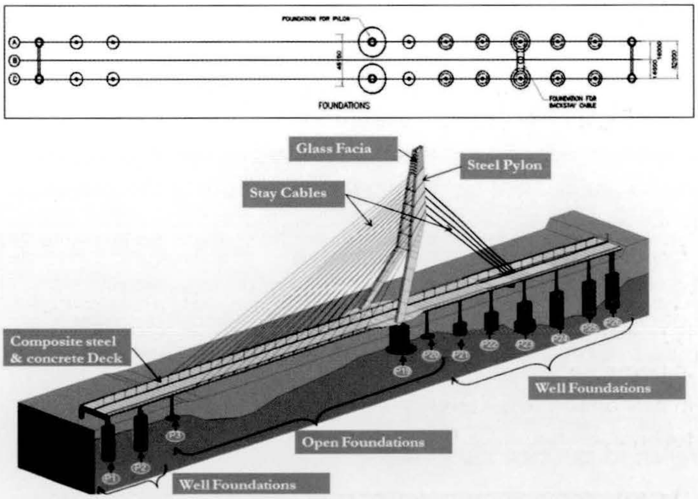

Figure 4: Details of the foundations.

The deck spans 32 m in transverse direction caters for eight lanes of traffic, four lanes in each direction. The composite deck consists of two main girders (I-shaped) in longitudinal direction and cross girders at 4.5 m spacing along the deck. Spans are of 13.5 m long on the cable supported part, 36 m on the approach spans which are supported over concrete columns. Most part of the deck slab is made up of full-depth prefabricated concrete elements of varying thickness from 250 to 350 mm, stitched in-situ over steel girder flanges. In highly stressed areas, near pylon base and back-stay anchorage, in-situ concrete up to 700 mm thick is used.

The cables are made up of bundles of parallel 15.70 mm strands of class 1770 MPa, protected against corrosion with hot dip galvanisation & outer PE-pipes. Depending on the location, the number of strands per cable varies from 55 to 123 nos. at the main span and is 127 nos. for each back-stay.

Under the axis A and C, the independent foundations are provided up to the depth of 20 m below ground level as generally rocky stratum was geotechnically determined at that level.

There are six numbers of open foundations (Figure 4) resting on rocky strata at a depth of about 20 m. The diameter of the main pylon P19 foundation (2 nos.) is 23 m with pier dia. of 5.5 m and that of lateral spans having foundations at P20 & P3 (2 nos. each) is 7 m with pier diameter of 2 m. The remaining 16 numbers are well foundations with the varying diameters of 8 to 9 m while back-stay foundation P23 has hybrid foundation which is a combination of piles and wells with the tapering well diameter from 17 m to 15.50 m.

3. REALISATION OF SPECIAL FOUNDATIONS & SUBSTRUCTURE

The signature bridge P19 pylon foundation has two massive independent open foundations to support peculiar pylon legs (Figure 5) that are resting on rock at around 20 m below the ground level. The foundations are 23 m diameter having an edge thickness of 2.5 m and tapering to pier diameter of 5.5 m in a height of 2 m, thus making the total depth of the foundation to 4.5 m.

For each foundation 28 m square × 18 m deep sheet pile cofferdam (Figure 5) was constructed by driving AU 25 sheet piles by vibro-hammer. As the excavation progressed in stages through sandy and clayey strata, till the rock level at around 19 m depth was reached, the cofferdam was stabilised by struts and walers at four designed levels.

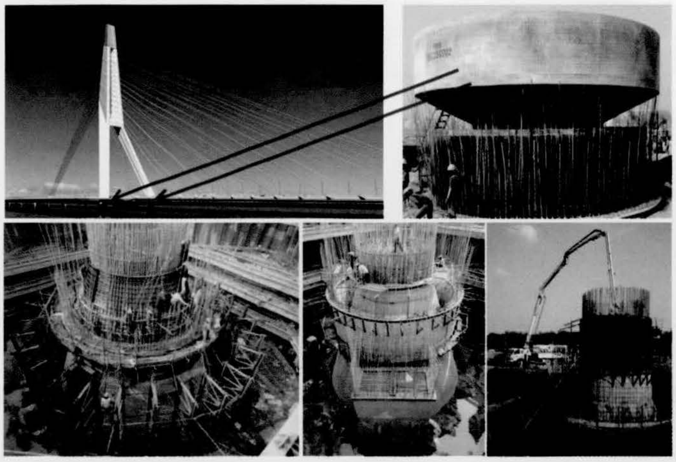

Figure 5: Foundations, pier and pier cap during construction of P19.

Since the sheet piles could not get sufficient embedment in to the rock, the same were pinned by toe pins made up of 230 mm diameter pipes having ISMB 200 sections inserted and pressure grouted.

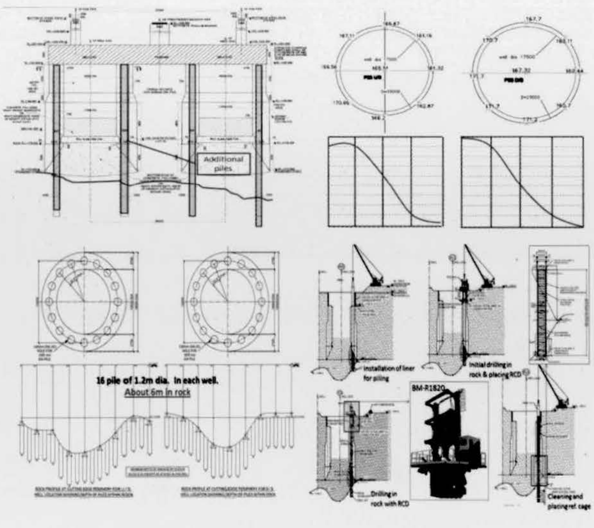

Figure 6: Hybrid foundation for P23.

The back-stay P23 foundation is a very critical foundation, as the same has to neutralise uplift of 6300 t under critical load combination (Figure 6). Originally, the foundation was designed as 2 independent wells with maximum diameter of 17.5 m each connected by a common well cap of thickness 4.5 m. The wells were designed on the basis of single boreholes at the center of gravity s of the wells and was terminated at around half meter above rock line, assuming horizontal rock line. The geotechnical investigations carried out around the periphery of both the wells revealed drastically sloping rocky strata which warranted a change in the design.

In the revised design, 16 numbers of 1.2 m diameter was provided in each well through the steining and anchoring into rock by 6 m. Wells were sunk by jack down method of sinking and as the steining was built up with 1.3 m diameter voids left in the steining, so that 1.2 m diameter piles could be done later through these voids. Bored cast in-situ piles were done using specially imported Reverse Circulating Drilling (RCD) rigs. The sequence of construction is depicted in the Figure 7.

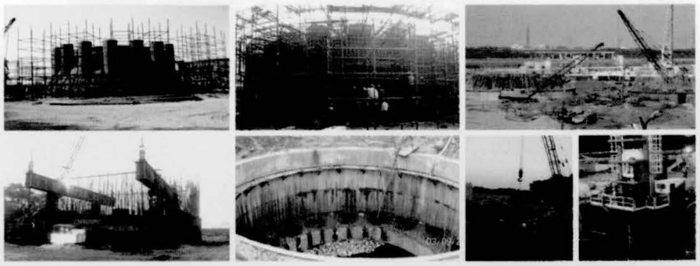

Figure 7: Stages of construction of P23.

Well cap of length 42.320 m, breadth 16.320 m, depth 4.50 m was cast with great care as bed level of well cap was approximately 10 m deep from the surrounding level and 2850 m^3 of concrete embedded with 500 t steel was to be poured in one go.

4. CONSTRUCTION ENGINEERING

In an item-rate contract like Signature bridge, starting from the final design, the bridge has to be constructed based on a system of detailed construction design called Construction Engineering (CE), which is the complex activity aimed to define and design the entire construction process as well as the construction of structures and equipment needed to build the bridge. While the final design assumes that the bridge is a completed single structure, CE must take into account the evolution of bridge construction and the numerous intermediate partial structures that arise grow and evolve during construction.

4.1. Assessment of Fabrication Complexity

Construction of superstructure involved fabrication and erection of about 14500 t of structural steel for permanent deck and pylon and around 17000 t for temporary enabling structures. The distinct characteristic of Signature Bridge is its pylon integrated with the composite deck and hinged at pier top level. The pylon with its harp shaped body, leaning backwards, would be the most unstable structure during construction stage.

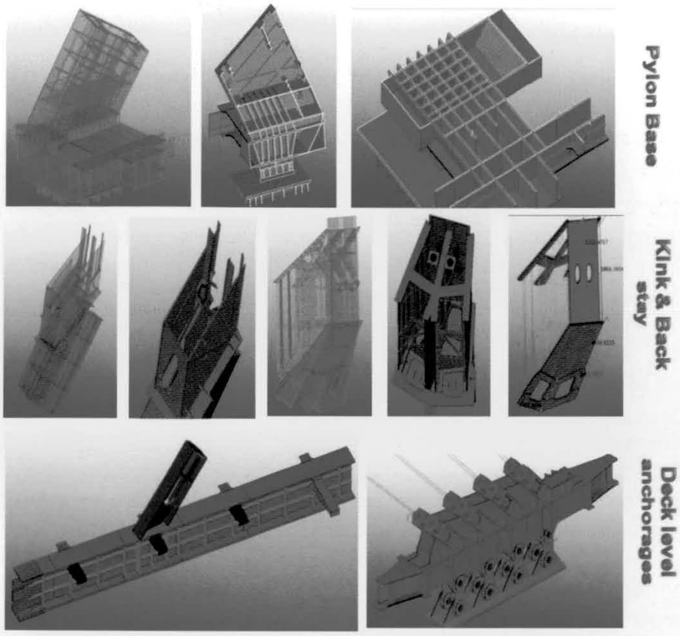

Figure 8: Fabrication complexities deciphered through digital model.

Pylon is a three dimensional complex structures having inclination in all planes. It is made up of irregular panels welded out of varying steel plates of different grades. To thoroughly understand the complexities of the structure, dimensional weights of the elements to be fabricated, transported and erected, a true to scale digital model (Figure 8) of the bridge was prepared in Tekla (steel detailing software).

Deck was comparatively easier, but the same was also modelled to understand the integrated parts with pylon, such as tie beam, rocker bearing and anchorages.

As an outcome of the digital model, it was understood that, pylon was a complex structure consisting of main panels made up of highly irregular stiffened and plated box sections of varying sizes. As per original design, maximum panel sizes were about 6.5 x 6.5 x 15 m and weighing from 60 t to 560 t.

To overcome the hurdle of restrictions on transportation, the pylon was divided into sub-panels of transportable size by introducing additional splices. Except for some welded joints at site, all additional splices were introduced as bolted connection.

Adopting the most appropriate welding procedure was very important to avoid distortions and deformations for welding of pylon segments and deck girders, and to ensure high level of accuracy and quality. Fabrication accuracy would directly affect geometrical dimension of the whole segment after their trial assembly, which were to be precisely matched within 1/10 of mm. Number of non-destructive tests such as dye penetration test, ultrasonic test, etc. were carried to ensure the desired quality of the product.

Two methods for drilling of holes were specially devised. Pre-drill holes on the web plate of the connection during panel fabrication and post-drilling method was applied for other holes which were marked and drilled with templates after fit-up, welding, rectification and milling of segments.

All the compression joints were designed to transfer load through bearing contact surfaces along with splice connection. To achieve appropriate bearing surfaces, all the contact surfaces in compression such as main girder edges, pylon horizontal joints were machined to have a surface planes not more than 0.3 mm per meter. Longest machined surface was as long as 32 m for pylon kink.

The deck structure is made up of standard segments consisting main longitudinal external girders, anchor boxes and cross girders. The anchor boxes being a load bearing member are welded to main girders by full penetration thick weld. The splicing between the longitudinal girders are through splice plates & HSFG bolts and bearing contact that required high precision machined surfaces.

The pylon included four parts (Figure 9): steel leg segments, main body, pylon head segments. Steel leg was divided into 11 large segments L0 to L10, among which L1 to L6 were made up of two small blocks each. Main pylon body was divided into 5 large segments MB1 to MB5, each of which was made up of two small blocks. Front cable pylon was divided into 5 large segments F0-1B to F4-1B while rear cable pylon was divided into 5 large segments B0-1B to B4-1B.

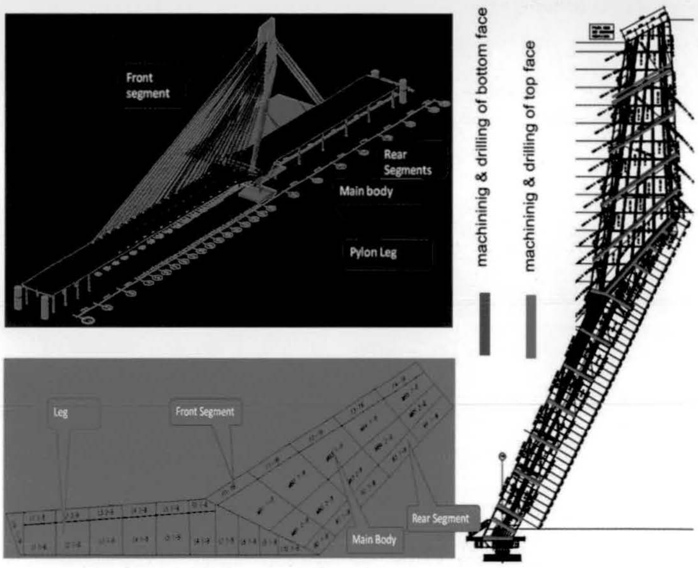

Figure 9: Components of pylon and machining surfaces.

Fabrication and erection of steel pylon segments were divided into three steps: panelling fabrication, shop assembly and trial assembly, trial assembly on site into large blocks for erection, erection and bolt connection on site.

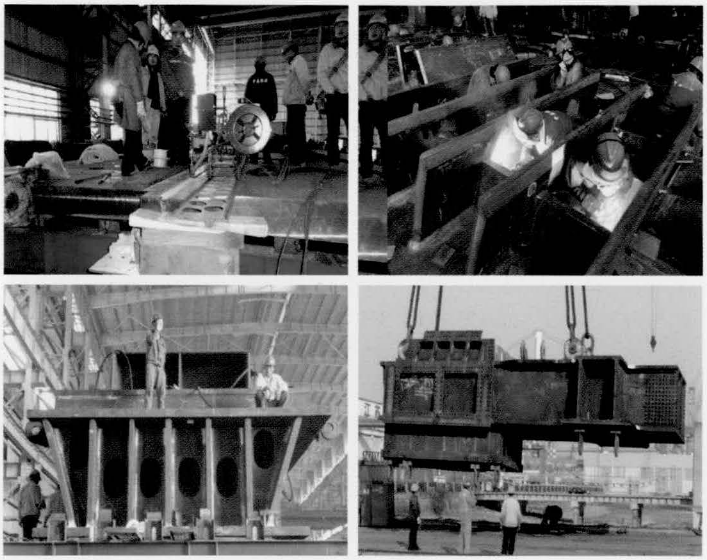

Figure 10: Pylon base fabrication.

In pylon base (Figure 10), the structural configuration of the stiffeners and the varying thickness of the plates from 80 mm to 250 mm were very much painstaking for fabrication.

The kink segment (Figure 11) was the most important part in fabrication. After having finished the fabrication of panel units and truss structure of the segments, the fit up of the segment was done on the jig as per the designed mark on the ground. The outside plate was to be designed as the base surface and the fabrication was carried out by the side way. The fit up, welding and shop assembly of the kink was done at the same time. After acceptance of the assembly, the temporary splicing plates was fit up and the kink segment was marked, taken off from jig and sent to machining area.

Figure 11: Fabrication, machining and trial assembly of pylon kink.

Steel leg segments of L101-B, L91-B, L81-B, L71-B was included in the second batch preassembly (fit up and welding of the connection parts of leg and main body). L6 1-B and FO 1-B segments which included in the first batch, had to be included in the second batch as the starting guide reference to guarantee continuous linear shape of leg segments and main body. Fit-up, welding and preassembly procedures for pylon main body segment are almost the same with those for the transition segment.

4.2. Engineering for Erection

The pylon is composed of two legs, box girders, inclined backwards and inwards and connected at a level of +63 m by a main body that is a vertical shaft with variable cross-section, which hosts the top anchorages for the stay-cables. The legs have a rectangular box girder with a constant width of 2.50 m and height varying from 7.20 to 9.60 m. The main body, still a box girder, has a maximum width at its base of 20 m and a minimum width at the top of 13 m. The two legs are hinged at the base so they would be unstable during erection, unless some sort of device was provided. The pylon was divided into segments with weights varying from 40 to 250 t. The joints between segments were flanged bolted joints with machined flanges. The connection between the main body and legs is created using flanged joints, machined at the workshop, with a total length of 32 m.

The main design problems to be solved in order to erect the pylon were essentially:

- how to stabilise an inclined structure hinged at its base during construction;
- how to recover structure deformation during erection;
- how to install large, heavy box girder segments that had to be placed, one above the other, in a position with double inclination;
- how to manage the temperature effect, together with the tight tolerance of a bolted structure.

Figure 12: Temporary supports for erection.

After working out several alternatives, it was proposed to erect pylon using a 1,250 t crawler crane, while the pylon would be supported with specially designed temporary struts (Figure 12) until the system is stable after installation of permanent cables. Segments weighting more than 40 t to 250 t were required to be erected.

Deck girders were supported over temporary trestle and erected using a Goliath gantry running over the same trestles along the bridge. Pre-cast deck panels were erected over girders using same Goliath gantry for deck erection (Figure 13) towards the river side while girders and precast panels were erected on land side with crane.

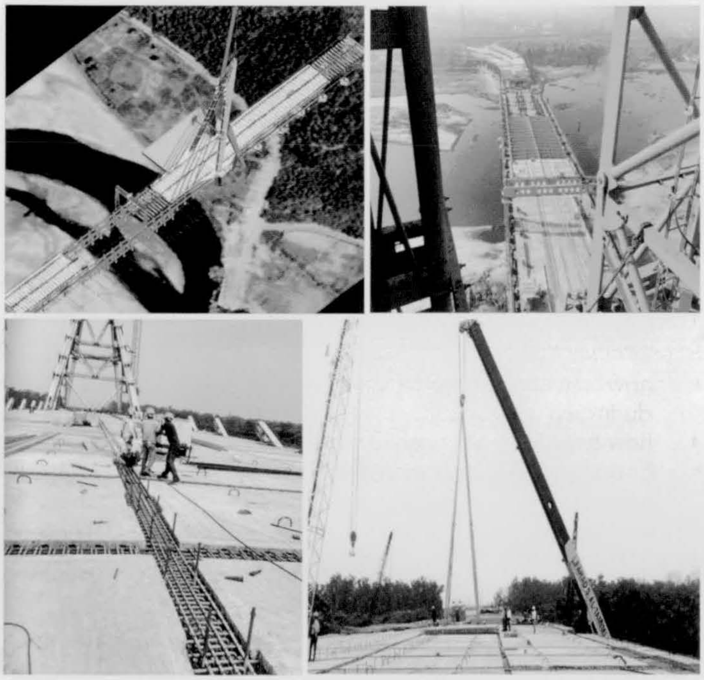

Figure 13: Deck erection by Goliath gantry and crane.

The majority of the deck concrete was in precast panels stitched by cast-in-situ concrete on top of the main girders and cross beams, except in the highly compressed P19 and P23 locations (pylon and backstay anchor) where slab thickness was varying from 250 mm up to 700 mm with seven layers of reinforcement.

The correct positioning, with double inclination, of pylon segments was achieved by a specially designed turn table (Figure 14) which allows two rotations to enable the segment to be positioned such that it can be lifted vertically in a ready to place configuration. In this manner, the segment would travel from take-off to landing on the preceding segment, always in the same three-dimensional positions, which is the 3D final position. A set of centring devices helped the final positioning.

Figure 14: Specially designed turn table for rigging three-dimensionally varying pylon segments.

The pylon position changed (Figure 15) rapidly during the day, with movements around 20 mm in longitudinal and vertical direction and up to 40 mm in transverse direction. Displacements followed the same trend during the day. Apart from survey tolerances (total station and operator), movements due to temperature, sun exposure, wind, vibrations, could also influence final acquired points coordinates. Survey data collected at different time during the day (also one or two hours) could also lead to apparent inconsistencies.

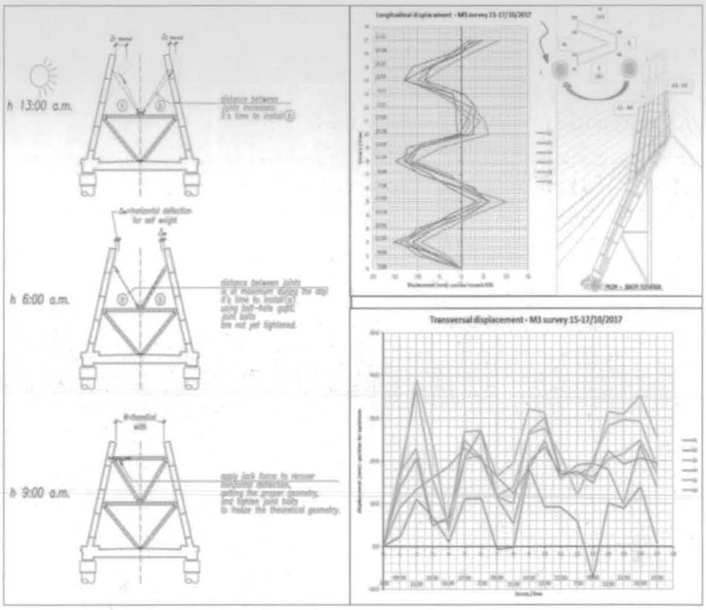

Figure 15: Pylon movement due to environmental effect before and after merging of pylon legs.

Stay-cable system consisted of 19 pairs of cables with varying number of strands minimum being 55 to maximum of 127 of 15.70 mm diameter with GUTS of 1770MPa. The reference lengths of the cables (deck bearing plate to pylon bearing plate distance) varied from 85 m to 285 m.

The passive anchors being at deck location, the active anchors from where stressing was to be done was at the location of pylon main body. Strands in the cables were tensioned using iso-elongation method. This method utilises mono strand jack attached with a load cell, hydraulic pump, dynamometer for calibration of pump-jack system.

As the pylon grew in stature, the working locations of HSFG bolting, pre-tensioning, shifting of jacks and other accessories had to be enabled by specially designed platforms, cage ladders and passenger hoist equipped tower crane. The connection between growing pylon and tower crane was engineered in such a way that there is no unscheduled horizontal force either on pylon or on tower crane.

At the time of writing this paper, the bridge has been commissioned to traffic (Figure 16) while the balance, particularly glass façade of the pylon head is expected to be completed in March 2019.

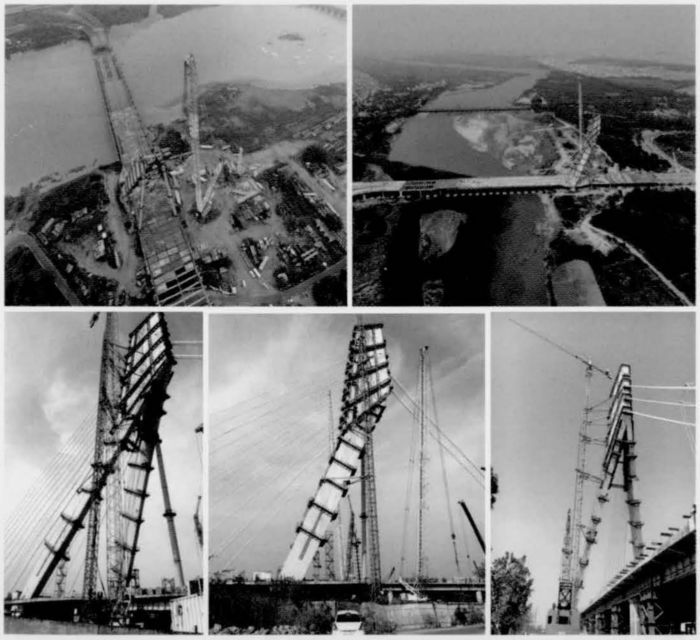

Figure 16: Pylon growing in stature.

5. MEGA PROJECT ASPECTS IN CONCLUSIONS

This new symbol of Delhi which is inaugurated on 4th November 2018, upon completion, has set a standard for iconism in India.

Bridge construction is always complex and challenging task. Perhaps designing the permanent structure part of the bridge like Signature Bridge is relatively simpler than Construction Engineering. Huge sizes, three-dimensionally varying inclined tower and enormous weights to be lifted, compound the complexities.

This warrants a detailed and holistic study of construction methods, rigging plans and fabrication of structure to suit construction methods along with constantly checking of the structural behaviour. As the segmental construction of three-dimensionally varying pylons being attempted first time and being not time tested, there were many unforeseen issues which could be overcome by only proper Construction Engineering.

The nature of the contract necessitated domain experts from 10 countries with diverse backgrounds, cultures as such demanded very savvy and innovative managerial skills in terms of co-ordination and contract administration that perhaps are not taught in the best of management schools.

6. ACKNOWLEDGEMENTS

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- Consultant for Contractor and Construction Engineering: DMA - Studio de Miranda Associati - Milan - Italy

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V.N. HEGGADE is presently Technical Director of Gammon Engineers & Contractors (P) Ltd. He has over 34 years of experience of designing and constructing bridges, energy structures like chimneys & cooling towers, marine and hydraulic structures and more.

He is a recipient of 'International Association of Bridge and Structural Engineering (IABSE)-Prize' in addition to national Awards like Pandit Jawaharlal Nehru Centenary award from Indian Roads Congress (IRC); Pre-stressed concrete design Award from Institution of Engineers, Indian Concrete Institute (ICI) Awards for best publications and Indian Buildings Congress (IBC) Award for built environment.

He has more than 125 papers to his credit and is a member of various IRC and BIS committees and also a Fellow of Indian National Academy of Engineering (FNAE). He is also a member of Indian Member Committee of Federation Internationale Du Beton, IMC fib. He has been an invited and a keynote speaker in national and international forums. He has a passion for tall and long structures and he is an ardent advocate of sustainability and aesthetics in construction.