Design and construction aspects of a bridge over river Yamuna

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The Delhi mass rapid transport system comprises a rail-based system having a network of underground, elevated and surface corridors with a total length of 198.5 km. In phase I of this project, the metro line from Shandara to Tis Hazari crosses the river Yarnuna. The paper highlights the salient design and construction aspects of this bridge which was constructed by incremental launching method and is the longest continuous span railway bridge in India.

The proposed sector of Metro line from Shahadra to Tis Hazari crosses river Yamuna about 164 m downstream of the existing 8-lane road bridge near Interstate Bus Terminal (ISBT), Delhi. The formation is on a gradient of 0.654 percent and is about 6.4 m to 10.3 m above high flood level.

The Delhi Metro Rail Corporation (DMRC) invited bids for the construction of Yamuna bridge in mid-1998 on the design and build concept. The tender specified basic requirements that the completed structure should fulfill. The contractor along with his design consultant had to conceptualise the scheme and submit the same along with a lump sum cost.

Precasting of superstructure and jacking down of well foundations to enhance speedy construction of superstructure and substructure were some of the actions envisaged in the process of conceptualisation so as to complete the project in the stipulated period. Also, high standards of quality and durability were envisaged (see box on next page). The span configuration had to be in multiple of 46.2 m and there was a limitation on the diameter of the well which was to be of 10.0 m; these were the additional structural constraints imposed in the tender so that every pier and well foundation would be in line with the existing road bridge located upstream.

In response to the invitation of competition, a consortium was formed between Larsen and Toubro Ltd (L&T) and Tandon Consultant Pvt Ltd, Delhi. Based on the knowledge of the owner's requirements, various alternatives were investigated

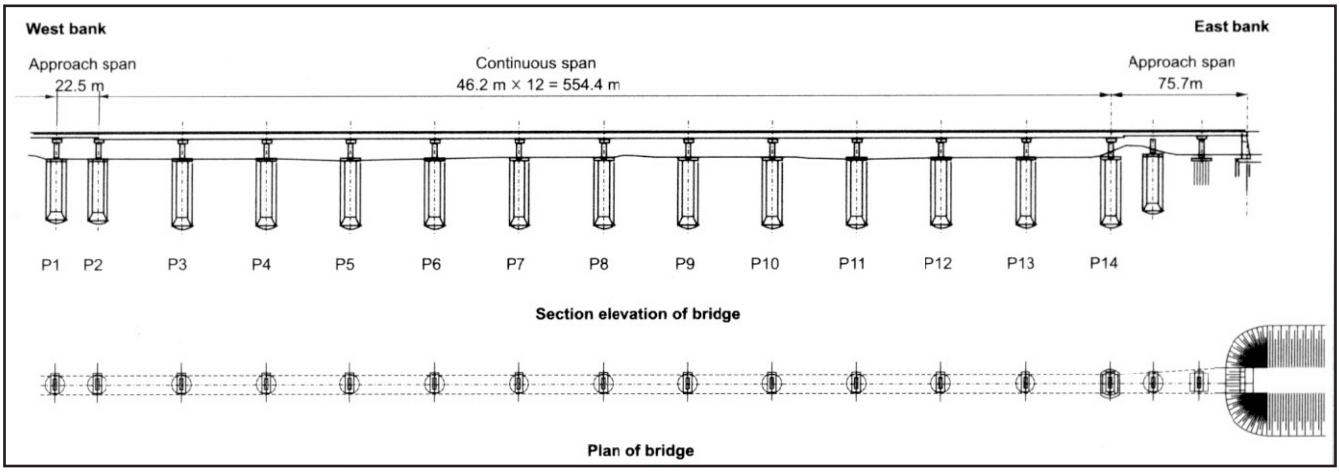


Figure 1. Yamuna bridge: sectional elevation and plan

such as twin precast for girders of full span length, precast post-tensioned beams, precast segmental construction. But the adoption was discarded as these schemes require lot of infrastructure and may result in project delay. The main advantage of design and built concept is that development of conceptual design can be formulated to suit contractor's available equipments and experience. A continuous single box girder carrying two tracks constructed by incrementally-launched technique was proposed as the final solution which proved to be the most economical and appropriate design with respect to the tender invitation.

Superstructure

Longitudinal arrangement

The bridge proposal composed of:

1. the river portion: consisting of 12 spans of 46.2 m each (Pier P-2 to P-14), which were founded on well foundation as depicted in Figure 1. For the construction of these spans, incremental launching technique was suggested .

2. the land portion: consisting of one span on west bank and three spans on east bank, which were proposed over ground supported formwork.

Innovative features of the Yamuna bridge

Superstructure

1. Longest continuous railway bridge (554.4 m) in India.

2. Third incrementally-launched bridge in India; second for Indian Railways.

3. Heaviest girder (13450 t) among all previously incrementally-launched superstructure.

4. Non-stop launching of superstructure in all seasons, even during floods.

5. First box girder in India carrying dual unballasted track.

6. The continuous constant depth box girder looks aesthetically elegant, stretching like a smooth ribbon from shore to shore.

7. Box girder was launched on specially-fabricated temporary bearing which was replaced by permanent bearing. Temporary transverse restraints were provided over every pier to guide the superstructure during launching.

8. POT bearings were installed after completion of launching.

9. Time cycle of launching of 23.0-m long segments was 10 days.

10. Both external as well as internal prestress was used for temporary condition (during launching) so as to develop central prestressing and after completion of launching, external prestress has been destressed and additional internal prestress draped in webs has been supplemented for service condition.

11. Intermediate blisters were provided to overlap external as well as internal cables, couplers being eliminated.

12. Complete box girder of 23.0 m length constituting one segment was cast in a single stage. For this, specially-designed internal as well as external forms of box girder were used.

13. Dowels for intermediate pier diaphragm were left at specified locations. Intermediate pier diaphragms were cast after completion of launching, so that collapsible internal shutter of full box length could be extruded out after casting, of box girder.

14. To reduce the cycle time, full length of reinforced cage of 23.0 m length segment was fabricated at ground level and lifted into position.

15 Curved precast parapet forming walkway and cable duct was provided on both sides of the deck. Vertical fluting was introduced on outer profile of parapet to break visually the large surface area. An open and light railing was also provided.

16. OHE mast and signal is supported on the parapet directly.

Substructure

1. Capsule-shaped piers with rounded-edged pier cap was provided to retain a soft profile.

2. Braking/tractive forces of train and full longitudinal seismic forces of superstructure would be transferred to substructure at one end. For this purpose end diaphragm of superstructure was extended out on both sides of box girder and sandwiched between concrete stoppers. The concrete stoppers were prestressed together so that they can share the horizontal loads. Twin wall shaped piers were provided underneath both stoppers so as to transfer the longitudinal as well as vertical load directly to well steining.

Foundation

1. An innovative technique for sinking of well — jack down method —was adopted for sinking 15 wells. Ground anchors were installed near the well steining which were used for taking reaction by specially-designed hydraulic jacks at top.

2. New national record was set when 142.5 m of well sinking was achieved in a single month in a single project.

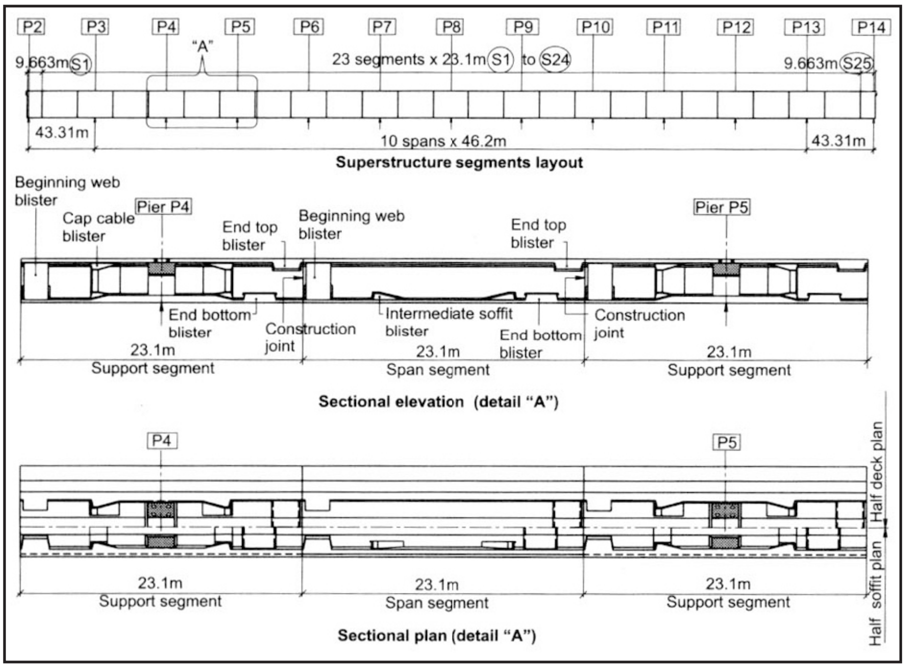


Figure 2. Segment details

Prestress details

During launching, each section of the superstructure was subjected to complete reversal of bending moments. The moment envelope as developed along the length of launching nose/girder is depicted in Figure 5. These bending moments have to be balanced by uniform axial prestressing of the box girder and the prestressing tendons were arranged accordingly. The number of cables above and below the neutral axis were thus inversely proportional to their eccentricity.

Three different types of cables in temporary and service condition were used, as indicated below:

1. E-type launching external unbonded tendons to be removed after the process

The deck of main bridge was proposed to be built in segments of one half of the length of one span. Consequently, all segmental lengths were of 23.1 m except at both the ends, which were 9.663 m long. The bridge was constructed in 25 segments and the same was pushed in stages after casting of each segment. In its final position, the construction joints were located at quarter span which reduced bending moments and shear forces, Figure 2. The length of segment decreases because of elastic shortening, shrinkage and creep of concrete during launching operations. In order to ensure that after launching the pier diaphragm location would be at its designated position, small adjustments have been made in every segment length. The adjustments were evaluated as 18 mm for the 23.1-m long segment in the front and 14 mm for the 23.1-m long segment at the rear. These extra values of segment length have matched very well with actual values recorded after launching and temperature corrections.

Cross-section details

A single box girder of 3.5 m constant depth with span-todepth ratio of 13.2 was selected as shown in Figure 3 for supporting the two tracks. Under frequent service loading, the box has to withstand only half of the total design live load corresponding to one track only, which generally enhances the fatigue resistance of superstructure.

Adoption of box section resulted in higher stiffness under bending and torsion, which is well suited for a continuous bridge. The selected configuration of box girder is also suitable for incremental launching as it increases the ratio of sectional modulus of top fibre to sectional modulus of bottom fibre which contributes to high structural efficiency, Figure 4. This is an essential requirement due to the high ratio of negative moment (producing tension at top) to positive moment (producing tension at bottom).

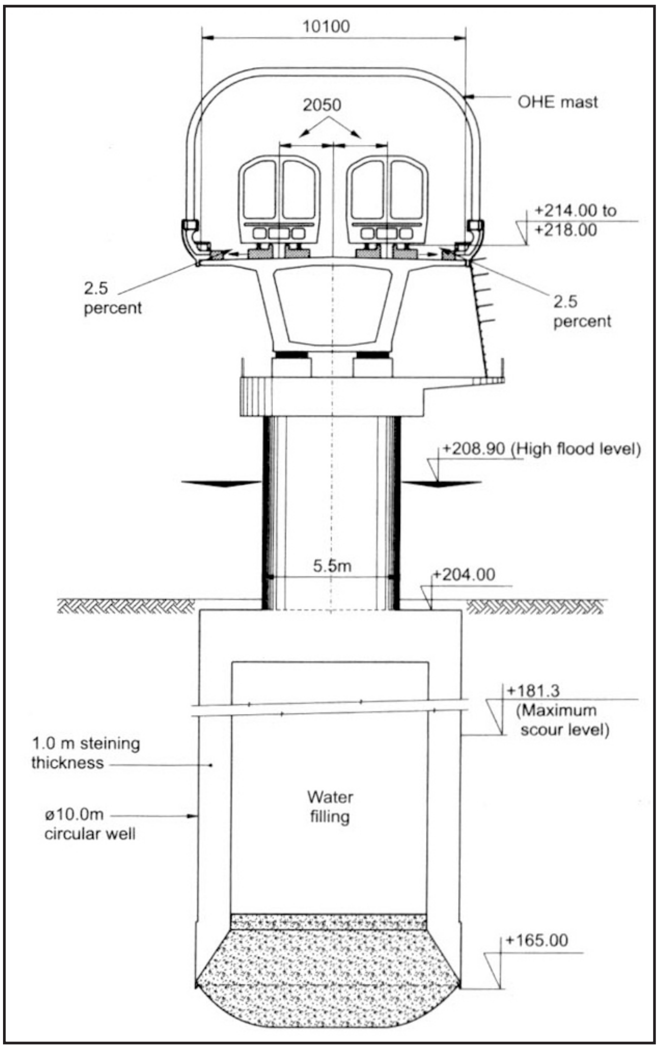


Figure 3. Typical cross section at pier

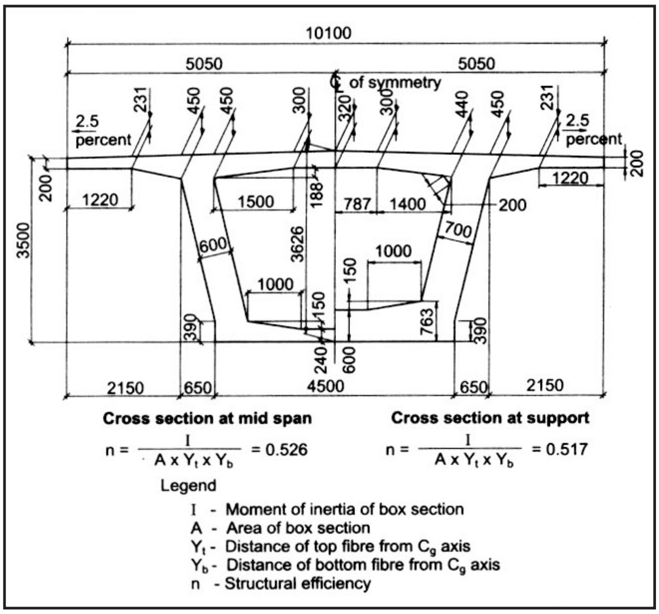


Figure 4. Superstructure cross section

2. S-type launching internal bonded tendons (grouted) to be retained for service condition.

3. FS-type internal tendons to be threaded and stressed after completion of launching and retained to cater to service conditions.

Launching cables

The cables that were used for launching purpose, Figure 6, were a combination of the following.

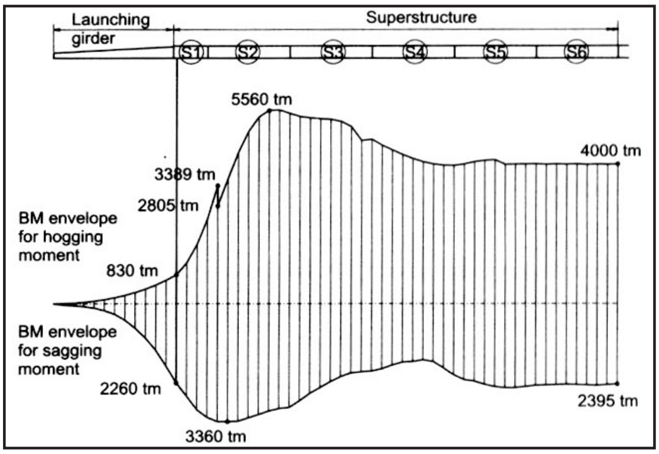


Figure 5. Bending moment envelope during launching

1. External unbonded cables (E-type) which were placed inside the box girder but outside the concrete section. These cables are straight in alignment and anchored only in the web blister provided at the beginning of segment. These cables were de-stressed after the completion of full launching and stressing of permanent internal bonded cables. Each cable of such type extended for two segments.

2. Internal bonded cables (S-type) which are straight in alignment. These were situated in the soffit and deck slab of box girder and were grouted and retained to cater to service conditions. Each cable of such type was extended for three segments.

The full launching prestress was imparted only after two more new segments were added because maximum moments were

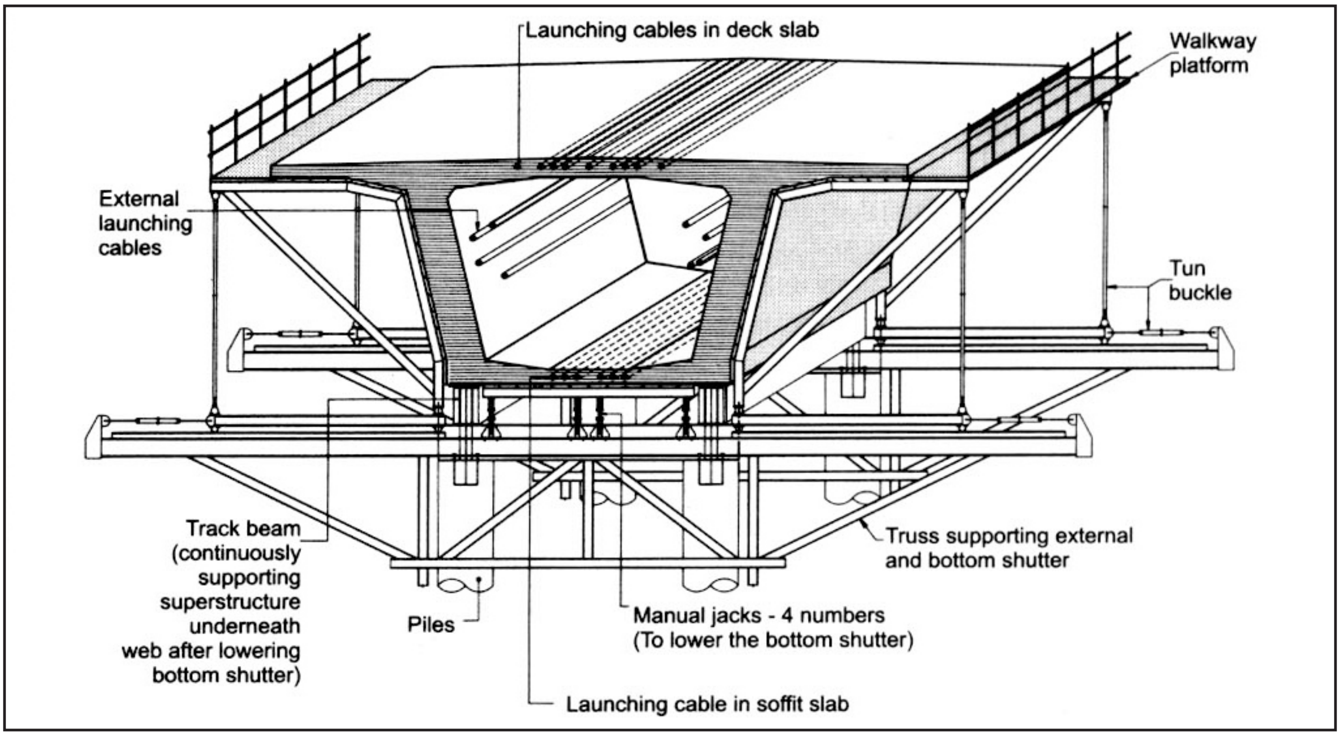


Figure 6. External formwork at casting yard

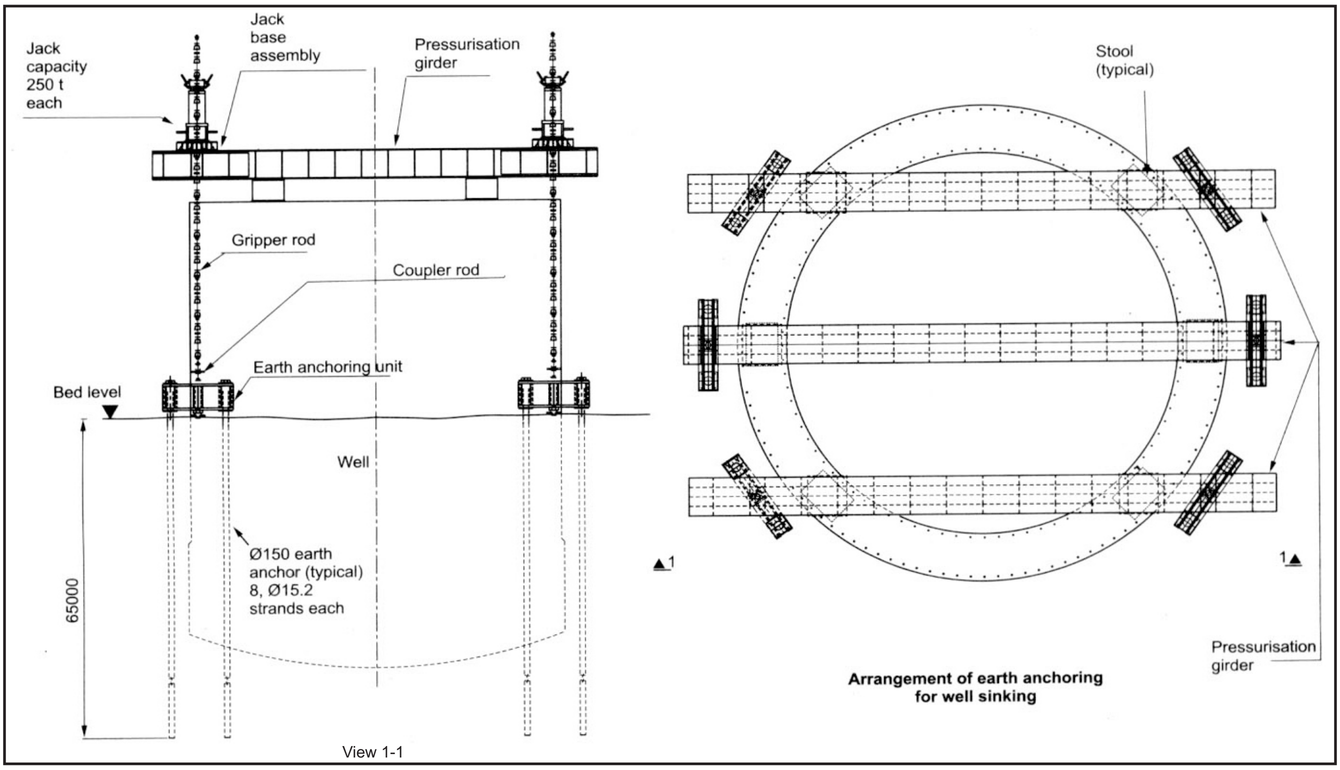


Figure 7. Principle of jack-down method used for well foundation

developed in a segment only after it was launched well past the pier P-14.

Permanent cables

In the final stage, additional cables have been provided to supplement the launching prestressing in order to carry the service loads. Permanent cables comprising profiled cables draped in the webs of the box-girder were provided for the purpose. In addition extra cap cables at support and span cables at soffit were also incorporated. For launching as well as service condition, 19T13 cables are used.

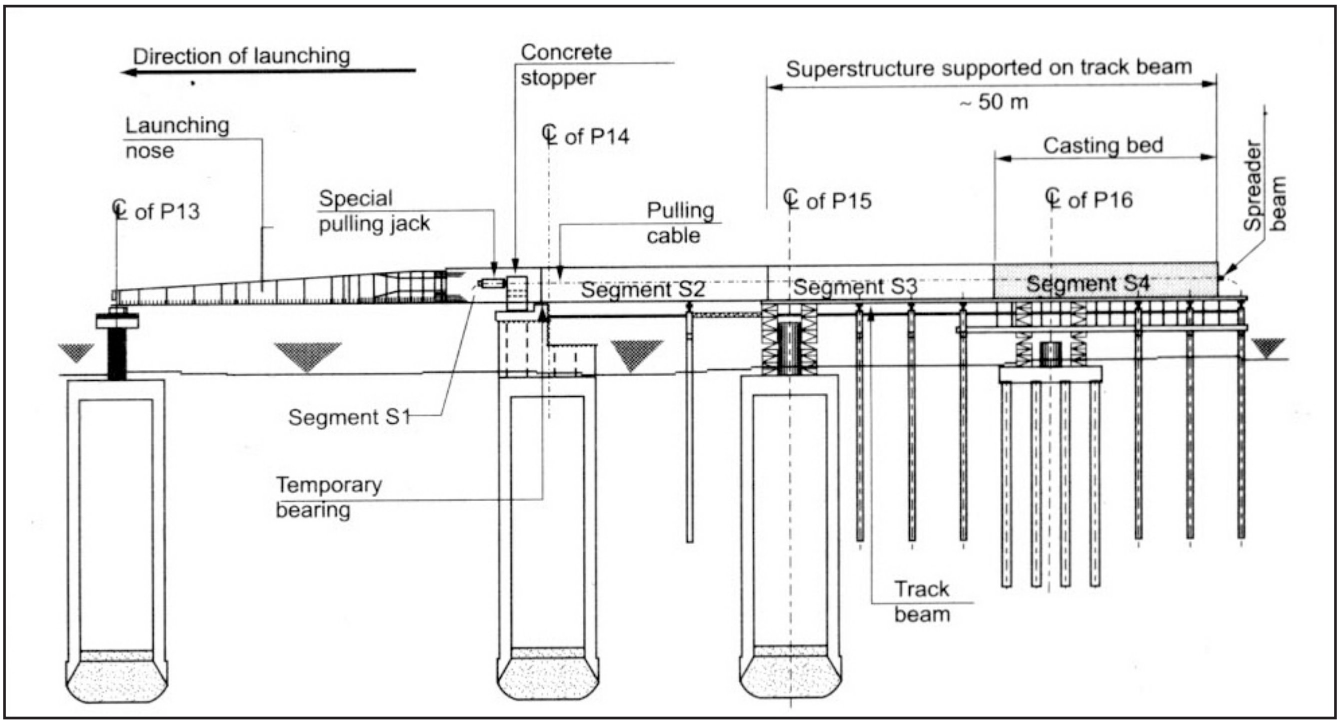


Figure 8. Pulling arrangement of superstructure

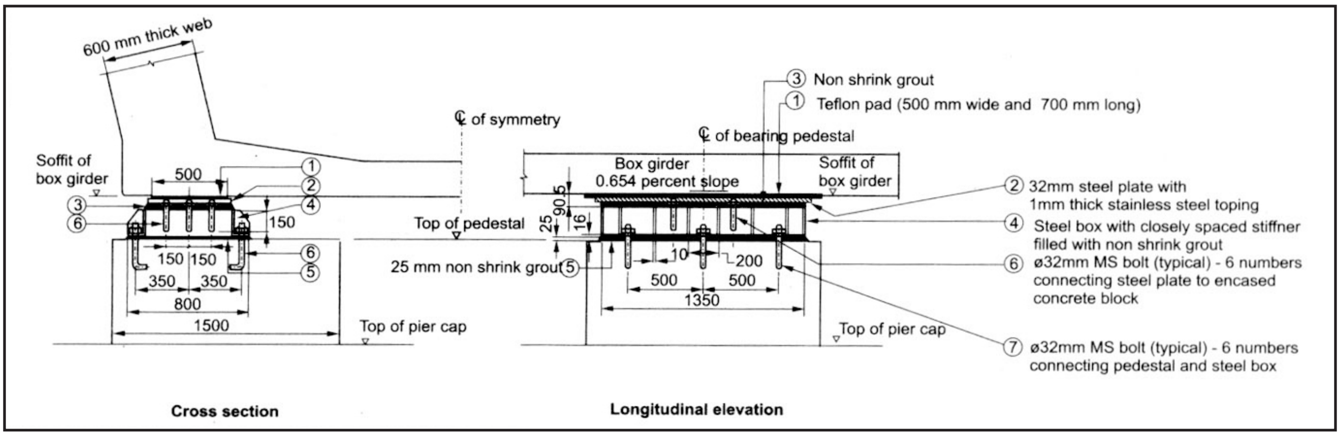


Figure 9. Teflon pad slides over temporary bearing

Launching nose

To control bending moments and stresses in the front part of superstructure to reasonable values, a light launching nose, consisting of steel members having 34.15 m length was attached to the front of the concrete structure. The launching nose was in the form of two pairs of tapered 1-girders braced in the horizontal and vertical planes weighing 67 t as shown in Photo 1 (see construction highlights at the end of the paper). The launching nose was attached to the concrete structure by prestressing bars so as to ensure that no tension developed across the joint at any stage of the launching process.

Substructure and foundations

The substructure consists of aesthetically-elegant cap-suleshaped piers with height varying from 4.0 m to 8.0 m.

Detailed soil survey was conducted at every pier location, which indicated more or less similar soil characteristics. The upper stratum comprised of fine sand (upto 10.0 m), followed by silty clay with small pebbles (upto 19.5 m). The lower stratum (19.5 m to 60.0 m) consisted predominantly of sandy silt of low plasticity and clayey silt of low to medium plasticity. Standard penetration test values ranged from 25 to more than 100, exhibiting very stiff to hard consistency of strata.

A well (caisson) having 10.0 m diameter with steining thickness of 1.0 m was provided for a depth of 39 m for most well foundations. The "jack down" method supplemented with air jetting/water jetting was used for sinking of well as shown in Figure 7 and Photos 2 and 3. The principle of this method is illustrated in Figure 7. is to push down the structure into the ground by applying pressure to counter the resistance of ground due to skin friction around the periphery of well and below the cutting edge. Soil dredging inside the well is carried out simultaneously. Ground anchors are installed around the well to counteract the thrust of hydraulic jacks, which are placed on the top of well, resulting in pushing of well inside the ground. Jacks are operated individually or jointly and are controlled such that the well is sunk plumb with minimum tilts and shifts. Superstructure and substructure were designed for seismic forces equivalent to 0.126g. Longitudinal restraint was provided at one end of bridge (that is, pier P14) whereas transverse restraint (using POT bearings) was provided over every pier to resist the inplane forces (seismic, braking and tractive). Longtitudinal restraint at pier P14 was provided in the form of concrete stoppers from pier head which sandwich extended diaphragn on both sides of the box girder.

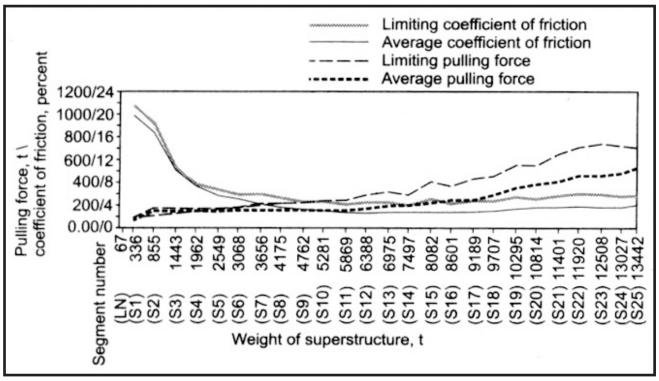


Figure 10. Plot showing recorded pulling force or coefficient of friction in different stages

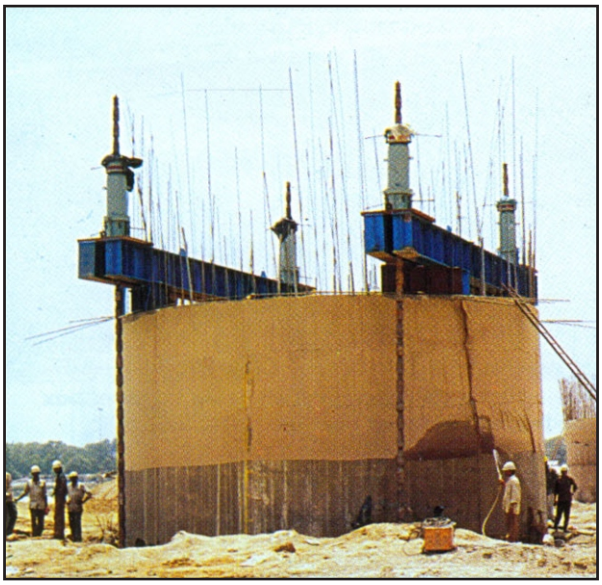
Special construction aspects

Typically the bridge super-structure is "pulled" 23.1 m at a time as shown in Figure 8. After the movement, the casting bed was cleared of the previous segment. The external forms were then cleaned and repositioned. Sliding panels were reinstalled on top of the track beam, Photo 4. Prefabricated reinforcement cage comprising of soffit slab and web, Photo 5, for full length of segment was lifted and placed in position (between external mould). The internal tunnel form was then placed in position and the deck slab reinforcement tied in position. The complete segment was poured in one stage, Photo 6. On achieving the desired strength, the external shutter was stripped off and the internal mould was extruded out of the cast segment. The bottom shutter was also lowered down so that the structure rested only along the continuous track beam located underneath web location. All the required launching cables were stressed and integration of the segment was achieved with previous segment.

A spreader beam outflanking the box girder was placed on the rear end of the last segment. Prestressing strands of 15.2 mm diameter connect the spreader beam to two synchronised special pulling jacks of 500-t capacity-each taking reactions

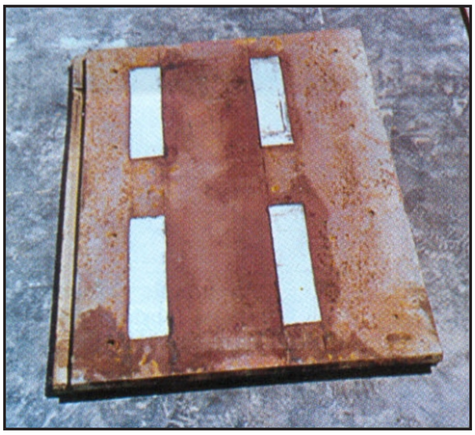
Yamuna Bridge: Construction Highlights

Superstructure with launching nose at its front

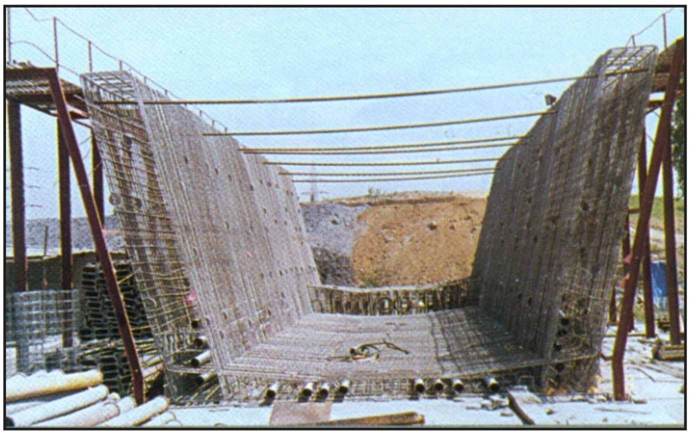


"Jack down" method of well sinking being employed

Gripper rod passing through cross beam and connected to central hole jack at top

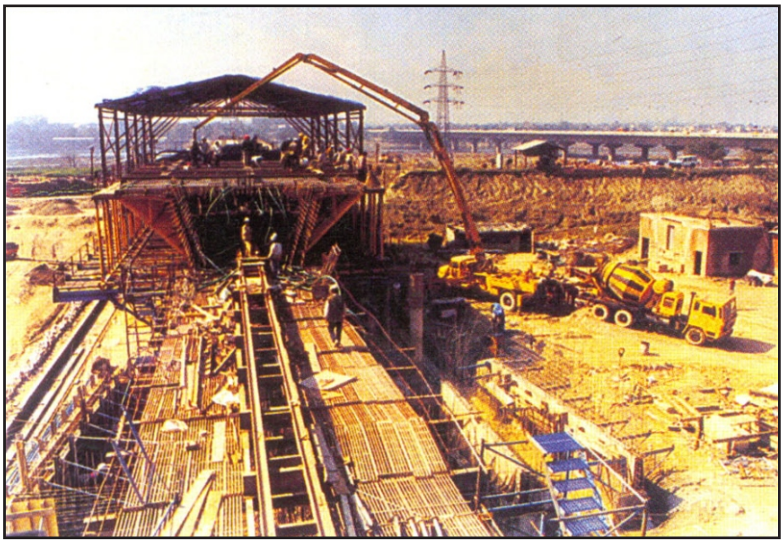


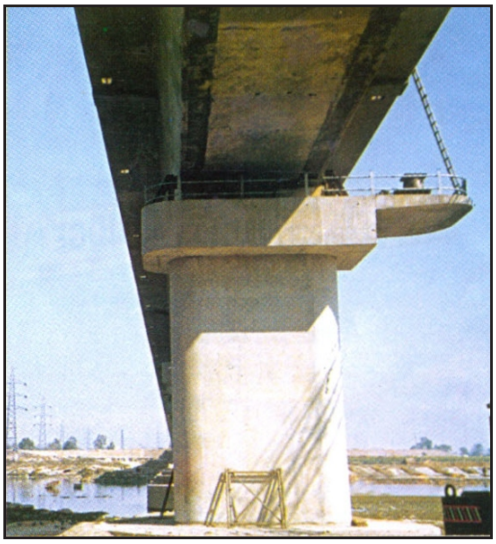
Inverted view of sliding panel showing PTFE modules positioned in recess provided in steel plate

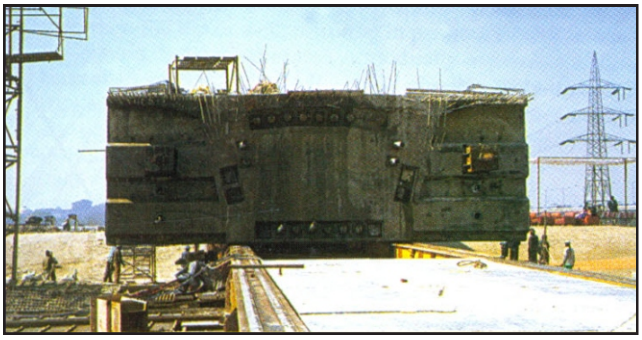


A view showing prefabricated reinforcement cage for the 23-m long segment

Yamuna Bridge: Construction Highlights


Concrete being pumped in the box girder from the transit mixer. The existing bridge can be seen in the background


Capsule-shaped pier with rounded edges


Last stages of superstructure launching is in progress as seen from rear end. Reaction was taken from concrete stopper over pier P14. Extended diaphragm at end of superstructure was connected to concrete stopper for launching purpose


View showing extended portion of end diaphragm of box girder sandwiched between concrete stoppers


Panoramic view of Yamuna bridge after completion

from the concrete stopper provided at pier P-14, Figure 8. A movement of 270 mm was achieved during each stroke of jack. The jack has the capability to de-lock the master wedges and re-lock the same after contracting in the ram. During launching operations, the plywood sheets (top face of sliding plates) were frictionally driven by the deck and could slide on the stainless steel in the casting yard.

At the top of every pier, a temporary bearing was provided with a stainless steel plate fixed at its top. Teflon coated elastomer bearing pads were introduced between the underside of superstructure and a temporary bearing during launching to reduce friction, Figure 9. The friction coefficient recorded showed considerable variation with every launching operation. The weight of girder increases with the length of girder but the ratio of area of contact surface between teflon pad to the girder weight required to be pulled keeps on reducing. This resulted in greater coefficient of friction (15 percent to 20 percent) during earlier launching operations and less coefficient of friction (3 percent to 4 percent) during launching operation at later stages. In the last stages an average force of 530 t was recorded for pulling the full girder for a weight of 13450 t. Pulling operation of the girder in the last stages is shown in Photo 7. Development of static and dynamic coefficient of friction recorded during launching of superstructure is depicted in Figure 10.

Conclusion

The successful completion of the new railway bridge crossing Yamuna river near ISBT, New Delhi has revealed that the introduction of incrementally-launched technique for spans ranging from 40 m to 50 m can be more cost-effective than any other technique traditionally used for major river bridges in India. The design of the bridge was done in such a way that it suits adoption of local material and available equipment. The adoption of "jack down" method for well foundation and incremental launching of the superstructure proved extremely beneficial an speeded up construction.

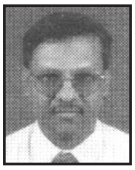
It is expected that the technology adopted may form the basis for numerous bridges across the rivers in India in the coming years. The project recently received the award in the category of "Innovative construction engineering including temporary works" from the Indian Institute of Bridge Engineers.

Credits

Owner	:	Delhi Metro Rail Corporation Ltd, Delhi.
Consultants	:	Tandon Consultants Pvt Ltd, Delhi —Structural design of incrementally launched bridge over river Yamuna, technical assistance at site
	:	Shirish Patel & Associates — Proof Consultants for Design
Contractor	:	Larsen & Toubro Ltd

Mr Lalit Menghnani began his career in the Indian Railways in 1983. He was assistant engineer and divisional engineer in Ratlam Division, Western Railways from 1985 to 1989 and was incharge of maintenance of Rajdhani route. As a deputy chief engineer in Konkan Railway from 1990 to 1996 he was involved in the construction of Panval Nadi viaduct and a number of tunnels. He is presently working as chief project manager, Delhi Metro Rail Corporation since 1998 and is incharge of construction of viaducts, elevated stations and Yamuna Bridge on rail corridor from Shandara to Barwala.

Mr Jatinder Singh Pahuja specialises in design of major bridges and flyovers. Some of these include viaduct for LRT system II at Kuala Lumpur and sharply curved clover leaf at ITO Delhi. He is currently leading the team engaged in design of elevated viaduct for Delhi Metro. He has contributed various papers enumerating the design requirements and state-of-art construction technique adopted in modern bridges. He is working as senior consultant in Tandon Consultant Pvt Ltd. He is working as a senior consultant in Tandon Consultants Pvt Ltd.



Mr C. Sankaralingam, who has been working with L&T for the last 20 years, was associated with various construction activities including design of various structures such as cement silos, construction methods for various projects, planning for the Malaysian bridges and Konkan Railway bridges. Presently, he is in the contract cell of the company's headquarters for monitoring and bidding of major bridge projects.

(Source: ICJ November 2002, Vol. 76, No. 11, pp. 703-711)