Optimised long spans for urban railways projects

Kumar Keshav, Rajan Kataria, Jean-Charles Vollery, Vaung Chhuo and Abdel Mhedden

Metro projects often face roads and river crossings, buildings and monuments as obstacles in the urban environment. Urban planners expect projects to integrate these into the overall built environment. Also, solutions in dealing with these should minimize impact on urban life, construction schedule and interference with the remaining parts of the project. Extradosed bridges are an attractive solution in certain urban projects. They allow building economical crossings over railway lines and can have 40-120 m spans.

Keywords: *Extradosed bridge, segment precasting, Pragati Maidan, Moolchand.*

The Delhi metro is one of the first rail networks in the world to use this structure for Pragati Maidan line-3 extension.

This structure was designed and built in a record time because of the use of standard pre-cast sections. In the process, the project used limited special equipment. Side spans were built with standard erection girders and the central span above the railways line was built by using cantilevers.

The Pragati Maidan 93 m span curved structure was built without interrupting the rail traffic. The structure was the second of its type in the world and first extradosed bridge in India and first on a metro project.

The second application of this bridge technology is at Moolchand crossing. For building this 65.5m span bridge in a congested part of the city, the Delhi Metro Rail Corporation Ltd. (DMRC) addressed the concerns of aesthetics and the need for integrating the structure into the urban built environment. A study of alternatives suggested that a single axial extradosed bridge would be an ideal solution both economically and aesthetically.

The bridge design saves time and cost as it uses typically 2 m height segments as used for standard spans and reduces the need for any special equipment. Aesthetically, the idea allows sleek structure. The bridge's 4-layer coloured extradosed cables, unlike its homologous Pragati Maiden counterpart, are not covered in a concrete wall. This is one more reason that makes this structure one-of-its-kind in the world.

The extradosed concept

Mathivat J. introduced the original idea of these bridges in the 80's. The bridge gets its name from the French word "Extrados" which means the upper or outer cover of an arch or top fibre. In this bridge design, prestressing tendons pass above the top fibre. Figure 1 compares the main characteristics of an extradosed bridge and other standard bridges.

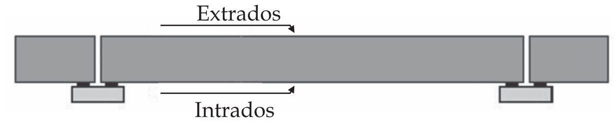
Table 1 compares the behaviour of non-covered extradosed prestressed cables with that of external prestressed tendons and cable stays.

The main advantages of extradosed bridge are:

1. Improved aesthetics over girder bridge

Table 1. Comparison of behaviour of cables

Cable type	Overtension due to frequent traffic load	Vibration due to wind
Cable stays	About 100 MPa (between 60 to 160 MPa)	Yes
Extradosed prestressed tendons	About 50 MPa (between 30 to 100 MPa)	Negligible
External prestressed tendons	About 15 MPa	No



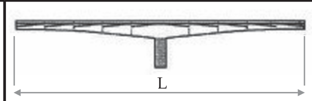
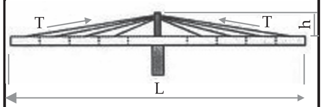
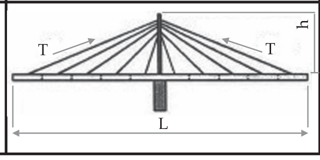
Description	Figure	The rate of tower height to center spin length
Girder bridge		-
Extradosed bridge		h/L = 1/15 ~ 1/10
Cable-stayed bridge		h/L=1/5

Figure 1. Comparison of bridge types

1.1 Reduced girder depth

1.2 Appearance of a cable stayed bridge

2. Simpler than a cable stayed bridge

2.1 Structural behaviour of a girder bridge

2.2 No force adjustment

2.3 Shorter pylon height

2.4 Simpler deviation saddle

2.5 Fatigue is not an issue in extradossed cables

About 30 % less concrete consumption compared to a typical pre-stressed concrete bridge.

In this bridge design, the economical span range is 40 and 200 m over railways and roads. The bridge over the Kiso River in Japan with a 275 m main span holds the world record for the longest span.

While highway projects had used the extradosed bridge technology, railways have seldom used them. The DMRC therefore is an exception in the world with 2 such bridges on its network: the Pragati Maidan Bridge and the Moolchand Bridge.

Pragati Maidan extradosed bridge

For extending the U shaped viaducts of Delhi Metro Line 3, DMRC needed to cross 5 railway tracks with such constraints as sharp plan curvature, vertical clearance for railway and impossible location of intermediate piers. In addition, for not interrupting the railway traffic, the bridge needed a minimum span of 93 m. Also the timeline given for bridge opening was less than a year.

Typical earlier designs of the DMRC's line 3 viaduct projects would have not overcome these constraints.

Project consultant Systra analysed options such as steel bridges and cable stayed bridges but did not select them because of high cost and long construction time; and instead proposed a new concept-extradosed bridge Figure 2.

This innovative and economic solution employs the same typical viaduct cross-section, uses conventional materials and allows faster construction than typical segmental bridges. The segmental extradosed bridge has been erected using the same construction method that is used for typical viaduct (span by span). The main span however uses cantilever construction Figure 3.

Foundations

All the piers and pylons have deep foundations with cast in situ concrete piles. The difficulty in moving utilities because of space constraints led to designing large pile caps with 20 piles per pylon, as shown in Figure 4.

The utilities that were not possible to shift were embedded in the 3 m deep pile cap.

The lateral piers' foundations are on 4 piles of 1.5 m diameter, typically as in the simply supported typical spans of the line 3

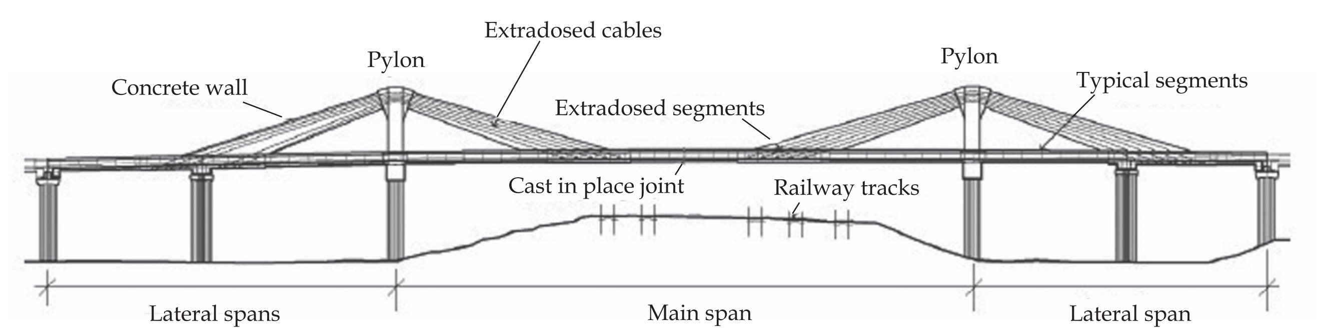


Figure 2. General elevation of extradosed bridge

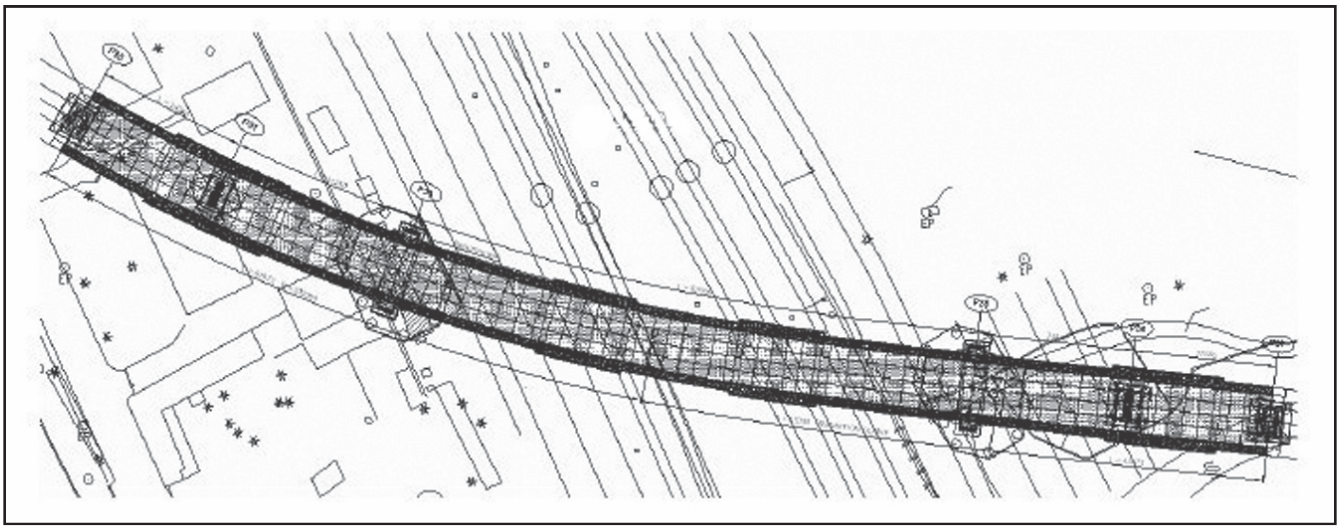


Figure 3. Extradosed bridge plan view

viaduct. The pile testing had earlier been for 30 m length, so keeping this pile length meant saving in pile testing time.

Substructures and pylons

A 2.4 m diameter portal with vertical circular shafts supports the bridge pylons. Figure 5 shows the 2.5 m deep rectangular transverse beam.

Above the beam, cast in situ pylon segments rigidly connect to the pylon. The outer pylon on the curved part of the bridge is vertically pre-stressed, to reduce transverse bending moments because of the curvature of the deck. The evacuation walkway located in the current area on the top flange of the U shaped deck, deviates laterally at pylons.

The superstructure connects to a thin wall to resist uplift forces on intermediate piers that would get generated while loading the main span in-service. The connection, a cast in place concrete between starter bars of the pier segments and the thin wall, allows longitudinal movements.

During construction however this connection is not effective; this is when the vertical pre-stressing bars resist uplift forces. On extremity piers, the super structure is simply supported on elastomeric bearings.

Seismic considerations

Rigid connections on all piers restrain transverse movements of the superstructure at pylons and at intermediate piers, and shear keys do the same on extremity piers Figure 6. Longitudinal movements are free only on extremity piers.

As Delhi is in Zone IV on seismic map, the codal provision requires nominal 0.24 g ground acceleration for design. The piers and portals design accordingly have a reduction factor of 2.5 in both longitudinal and transverse directions.

Horizontal earthquake forces were computed using spectral analysis and participation of frequencies were combined using the Complete Quadratic Combination (CQC), Figure 7. The transverse and longitudinal earthquake forces were combined following Newmark combinations. Vertical earthquake was not considered. Table 3 details the frequency of the main vibrations and Figure 8 is the 3D view of the calculation model.

Superstructures

The 2.14 m deck is continuous with five spans of 24.714 + 32.25 + 93 + 24.8 + 22.58 meters. From one extremity to about mid main span, the bridge curves with a radius of 302.5 m. It straightens out on other side lateral spans.

A transition curve connects the straight and curved parts. M50 concrete superstructure is rigidly connected to the pylons and simply supported on extremity piers.

On lateral spans, the deck connects to the intermediate piers to resist uplift forces created during main span loading.

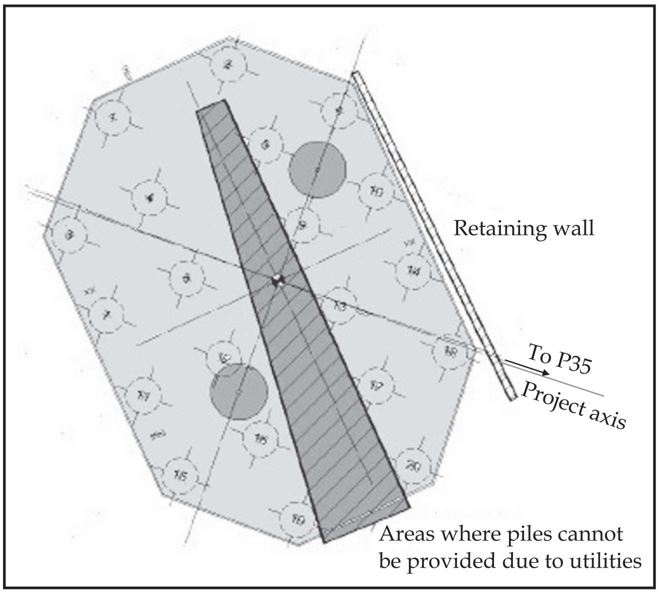


Figure 4. Plan view of pylons pilecap

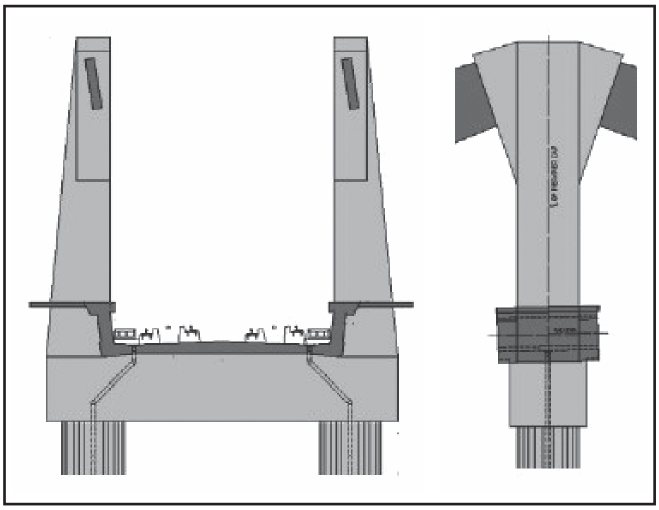


Figure 5. Pylons transverse and longitudinal elevation

The deck's precast segments are of the same crosssection as those of the typical DMRC viaduct, however the precast extradosed segments have thicker webs for extradosed cable anchorage Figure 9. The typical precast segments and extradosed segments are 3.5 m and 2.3 m respectively.

The prestressing layout of lateral spans is similar to that of the typical simply supported spans, with 12T15 tendons in the slab and webs (Figure 10). However, the difference is in the web tendons which are continuous from one extremity of the structure to the pylons. The main span uses different cables types namely 12T15, 19T15 and 4T15.

While cantilever has 12T15 cables in the top flanges of the typical segments; 19T15 extradosed tendons are anchored in the webs of the extradosed segments. In addition, 4T15 tendons are in the slab of all the segments and 12T15 continuity tendons are in the central part of the main span.

The segments on intermediate and extremity piers are transversally pre-stressed using 19T15 units (2 units for extremity pier segments and 3 units for intermediate ones). The extradosed cables are considered as typical prestressing tendons, for they are covered by a reinforced concrete beam;

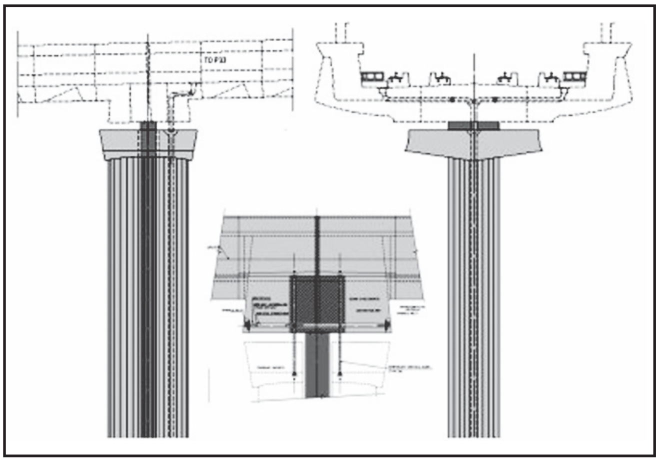


Figure 6. Intermediate piers elevation

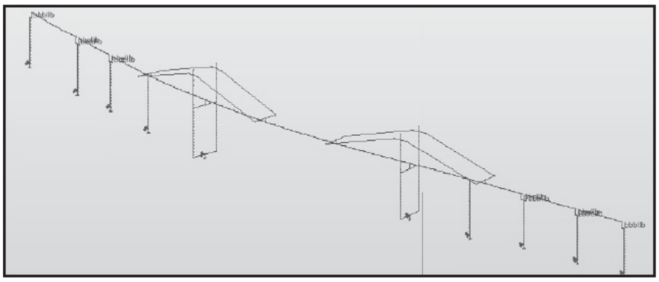


Figure 7. 3D view of the seismic calculation model

Table 3. Modal analysis main results

Mode number	Frequency (Hz)	Type
4	1.16	First longitudinal mode
10	1.40	First transverse mode
13	1.77	First vertical mode of main span

therefore they have no fatigue stress limitation. As extradosed cables deviate in the pylons through steel pipes, they are tensioned in two stages: first during cantilever construction and finally after concrete beam casting covering the cables. This introduces a permanent compression in these beams. When the main span is loaded during service, the beams remain under compression. The total vertical deflection under one loaded track (17 t per axle) including dynamic impact and torsional effects is 19.4 mm, whereas the maximum allowable deflection is 38.8 mm.

Construction

Substructures

The excavation for foundation encountered embedded utilities for the first pylon and a concrete sewer for the other pylon Figure 11.

Segments precasting

The precasting lines used earlier for the typical viaduct were also used for the extradosed bridge. The segments were

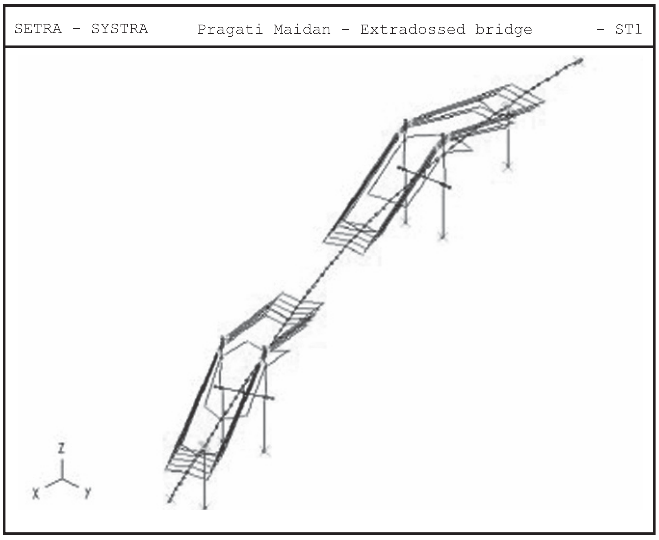


Figure 8. 3D view of the calculation model

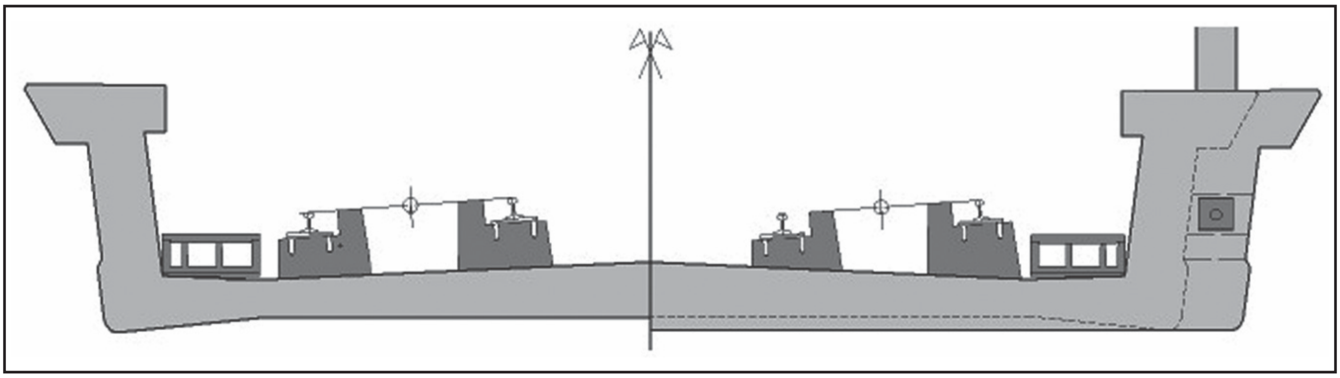


Figure 9. Typical segment (left) and extradosed segment cross-sections (right)

precast and match cast using long beds or long line method, and the pier segments were precast in short cells Figure 12. Each span was precast on a single line except main span which used two separate long lines. Special consideration was given for the geometric control of the main span segments. Typically, precast segments, extra-dosed segments and intermediate pier segments weigh 45 tons, 55 tons, and 80 tons respectively.

Lateral spans' erection

Lateral span erection used the same launching girders that were used for the simply supported spans Figure 13. The first lateral span was erected simply supported on lateral and intermediate piers, whereas the second one was simply supported on intermediate pier and connected to the pylon through a cast in place joint. Next, a cast in situ joint, the tensioning continuity tendons and the pre-stressing bars at intermediate pier segment made the two spans continuous.

Main span erection

Two 105-t segment launchers were used for erecting the main span used Figure 14. The first cantilever segment on each pylon was oriented at an angle in elevation so that at the end of the construction the two cantilevers are at the same level as designed Figure 15. While the typical segments are kept pre-stressed by internal cantilever cables, the extradosed segments are kept prestressed by the extradosed cables tensioned from the lateral spans. In addition to the internal pre-stressing, a temporary external tendon was tensioned between the pylon and the deck, from the 5th cantilever segment.

A reinforced cast in situ 0.4 m stitching segment connected the two cantilevers. The continuity 12T15 tendons in the webs were tensioned only when the stitching segment reached the required concrete strength.

The construction did not interrupt the railway's traffic of 200 trains a day. Following the removal of the segment launchers, the concrete beams were cast in place to cover the extradosed tendons. When the beams reached the required strength, the extradosed tendons were tensioned to full load to introduce a permanent compression in the beams.

Geometry control during construction

As the entire main span segments were precast, correcting geometric deviation would have been difficult. So controlling geometry during cantilever construction was one of the main

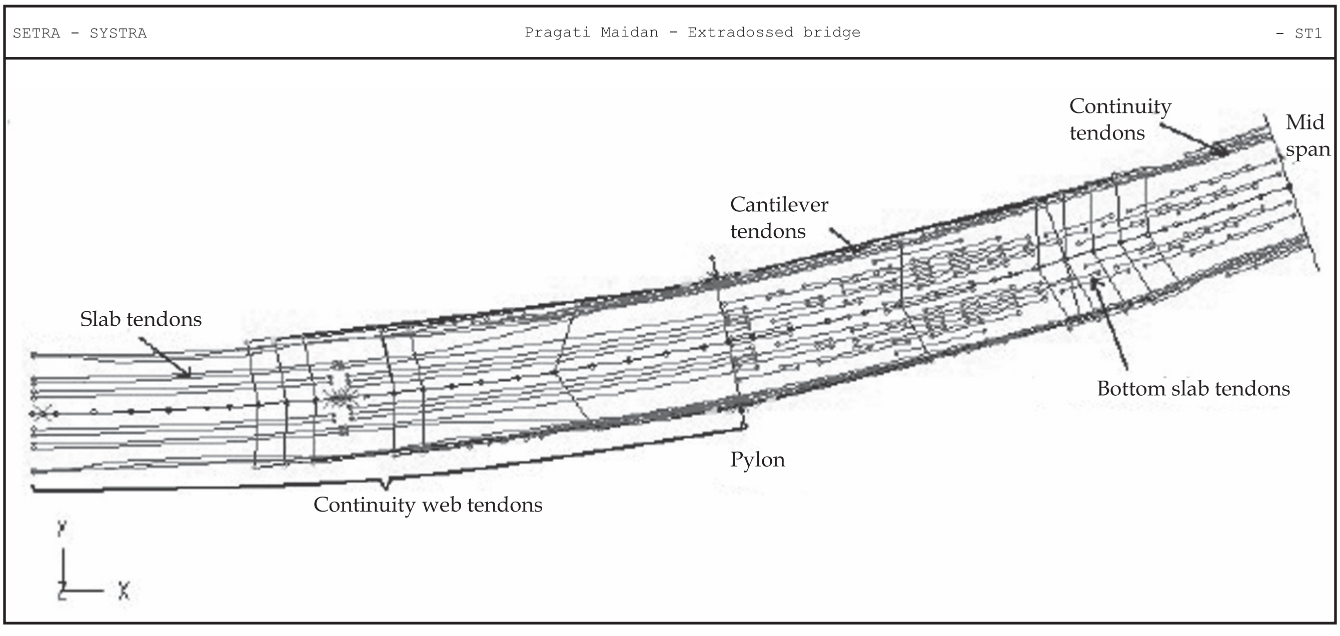


Figure 10. Longitudinal prestressing layout

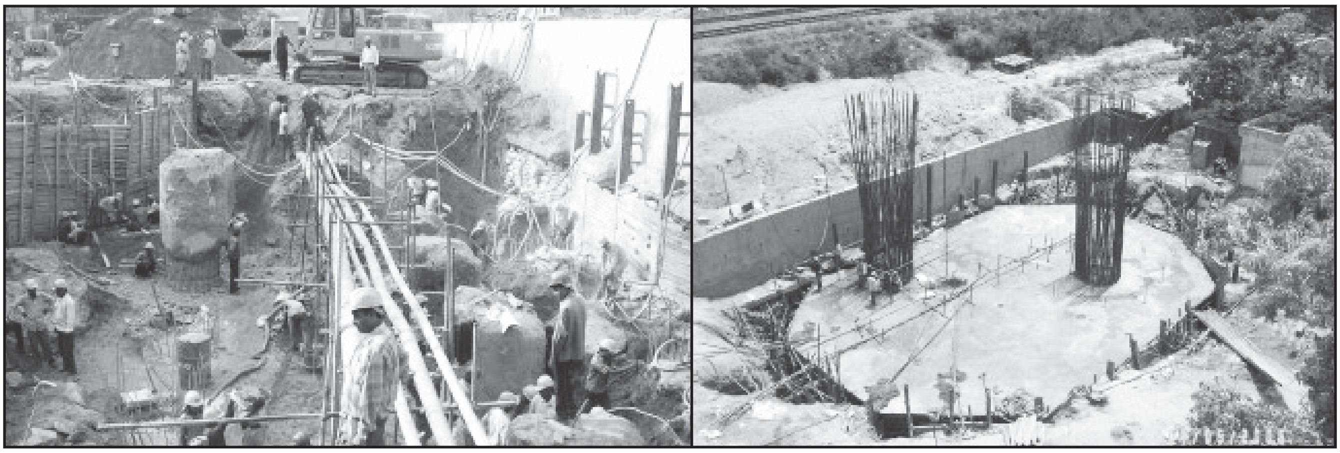


Figure 11. Works on pylon's foundations

preoccupations Figure 16. Because of the level difference between pylons and non-symmetrical bridge's slope, the first cantilever segment has been connected to the pylons with a cast in place joint orientated such that at the end of the construction, the two cantilevers are at the design level.

Construction schedule

The following helped achieve the schedule of project completion:

1. Design studies: mid December 2005 to end March 2006
2. Piling works: mid February to end April 2006
3. Piers and pylons: March to July 2006
4. Segments precasting: April to July 2006
5. Lateral spans erection: mid May to beginning August 2006
6. Main span erection: end July to mid September 2006
7. Concrete beams: end September to mid October 2006
8. Track and system works: mid September to end October 2006
9. Test and commissioning: mid October to mid November 2006

1. Line opening: 12 November 2006

Gammon India Limited as the main contractor built the extradosed bridge.

Second Example: The Moolchand extradosed bridge

The Delhi metro extension crosses at Moolchand. Considering the overall site conditions, a minimum span of 65 m was required. The original design had a standard balanced cantilever bridge.

The DMRC had two main concerns about this bridge namely the construction schedule and integrating the bridge with the landscape since it is a visible bridge.

Design consultant Systra proposed an innovative and economic solution, for fast track construction using the same cross-section as used in typical viaduct and using conventional

Figure 12. Precast segments on a long line

Figure 13. Lateral spans erection

Figure 14. Cantilever construction of main span

materials Figure 17. This bridge type could bring improvement in the aesthetics and integrate with the surrounding built environment. Figure 18 shows shows the difference in visual obstruction from a standard balanced cantilever bridge (left side) and the proposed extradosed bridge (right side).

The following are the main features of the Moolchand bridge:

1. Spans: 51 m – 65.5 m – 51 m
2. Single axial 4-layer extradosed cables
3. Pylon height: 8 m
4. Deck height: 2 m (same as standard spans)
5. Plan curvature: 1000 m

Design

Foundation

The foundations are classical construction with each foundation having six piles of 25 m length and 1.5m diameter Figure 19.

Substructures and pylons

For horizontal clearance of rolling stock and for aesthetic reasons, the 8 m high pylons are centrally placed on the superstructure. Four layers of extradossed cables, which are not covered by concrete for aesthetic reasons, are distributed from each pylon to the superstructure. The extradossed cables deviate in the pylons by steel pipe saddles. This allows the possibility of cable replacement for renewal if needed in future. Figures 20 and 21 show pier and pylon and Figure 22 gives cross section of the segment.

To protect the stem of the extradossed cables from vandalism and train derailment, 1.6 m high concrete walls are provided at the stem area Figure 23. Further, the bridge is designed to stand against accidental breaking of any of the extradossed cables.

Superstructures

The deck has a constant depth of 2.00 m and is continuous with 51+ 65.5+ 51 m spans The bridge curves with a radius of 1000 m, starting from around mid of main span to the extremity. A transition curve connects the straight and the curved part of the bridge.

The concrete used for superstructure is M50. The superstructure rigidly connects to the pylons and intermediate piers and is simply supported on extremity piers.

The extradossed bridge uses the same typical precast segments as standard viaduct by widening the top flange of 325 mm at each side for rolling stock clearance at pylon locations. At stay anchorage, the same segments are provided with concrete prestressed struts Figure 24.

Figure 15. Start of cantilever construction

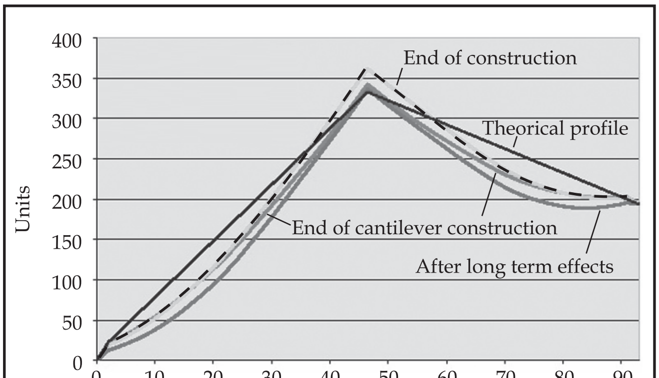


Figure 16. Main span construction geometry

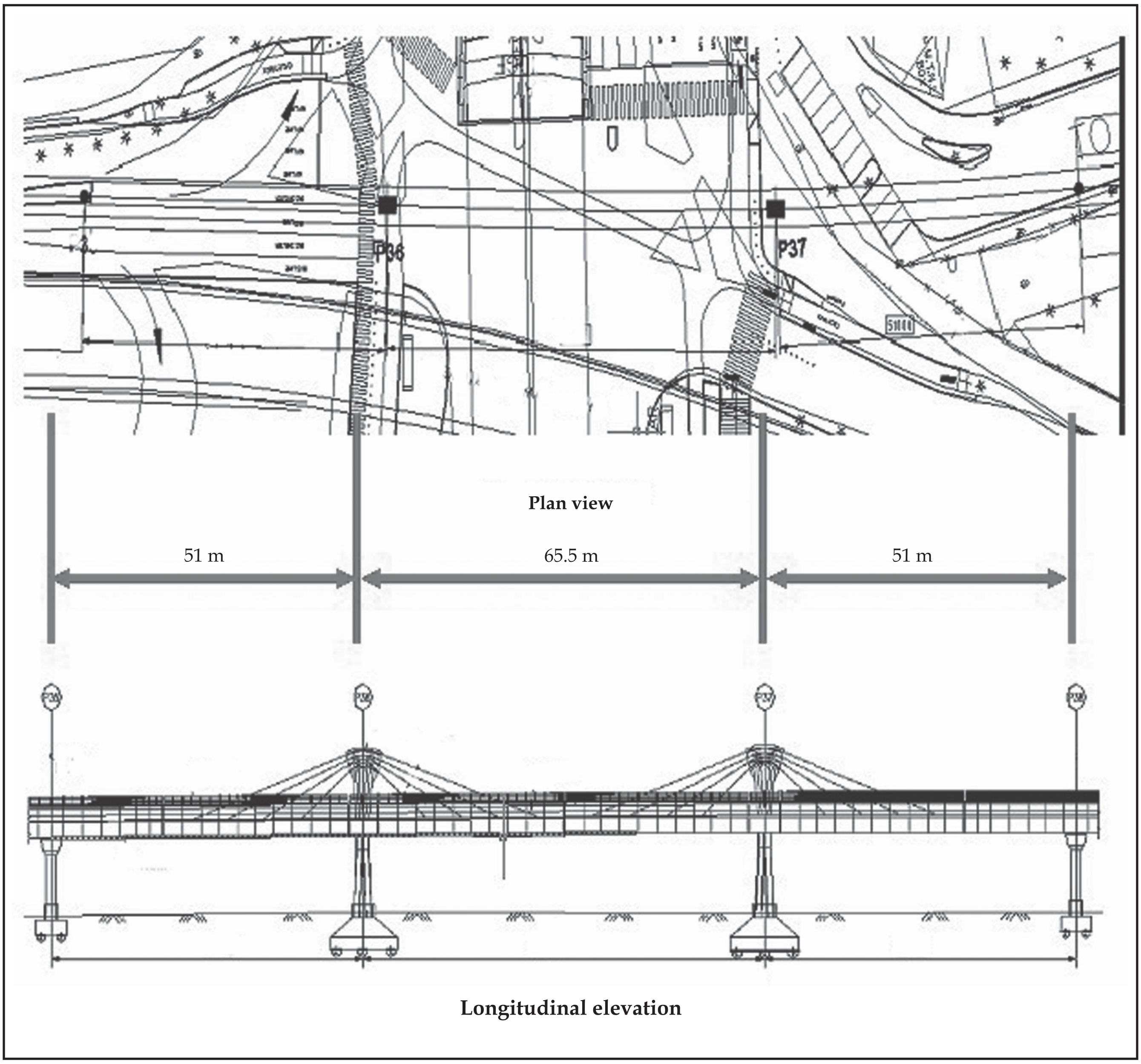


Figure 17. Plan view and longitudinal elevation of the Moolchand bridge

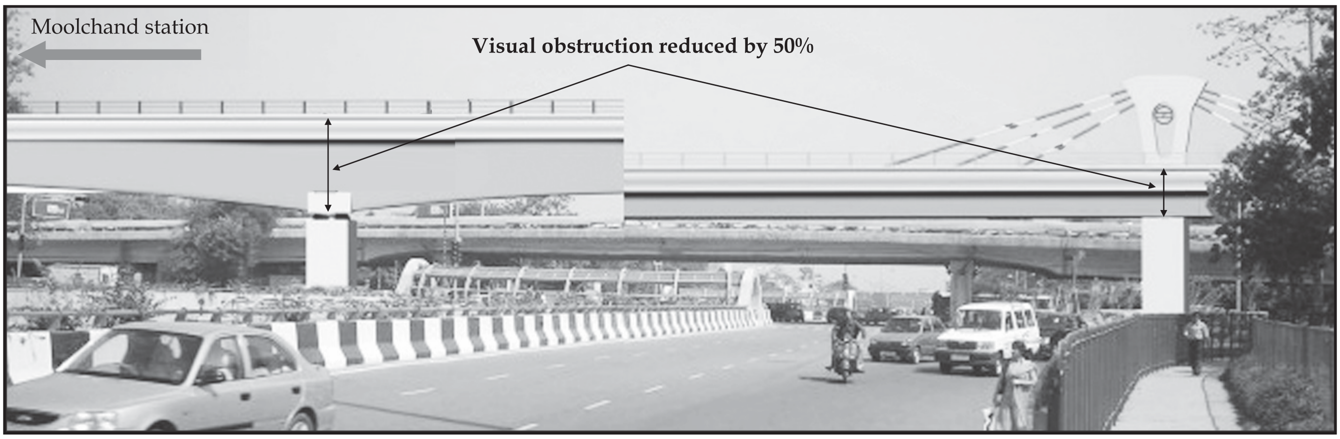


Figure 18. Moolchand bridge

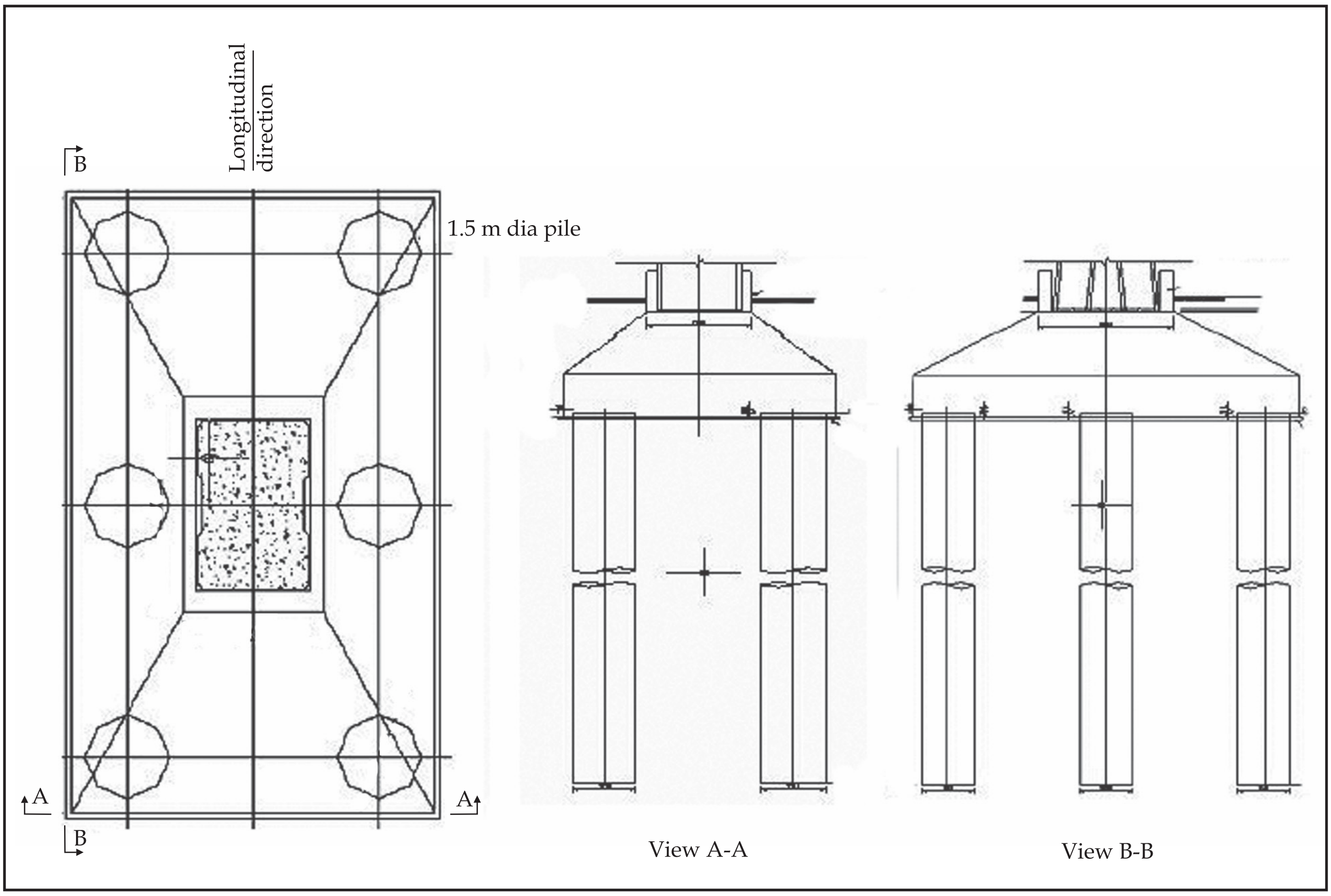


Figure 19. Foundation plan and elevation

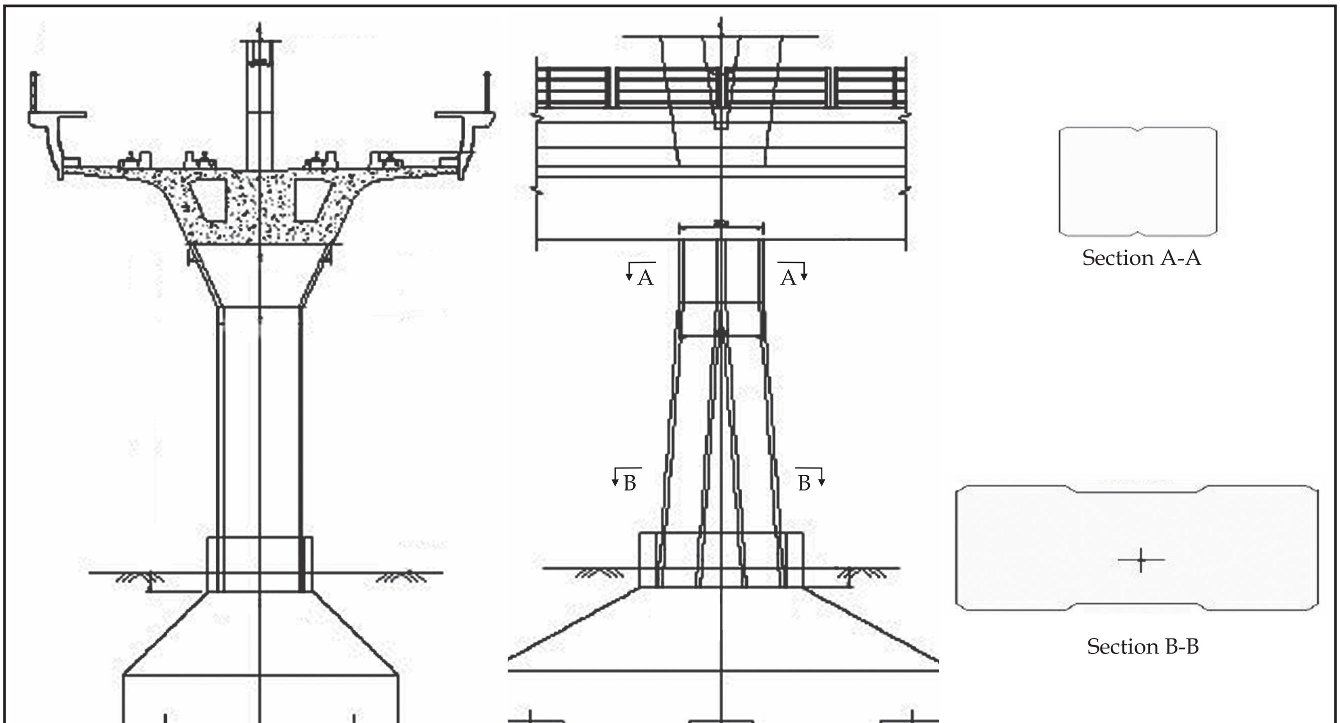


Figure 20. View of pier

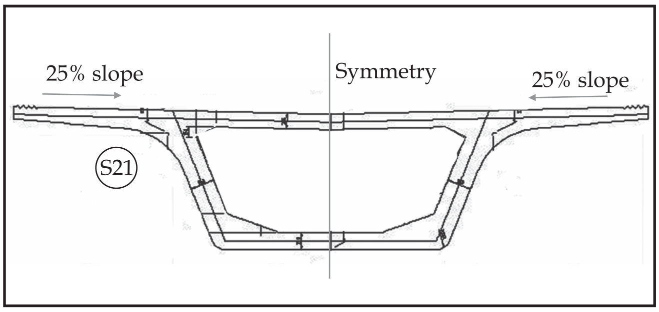


Figure 22. View of typical cross section

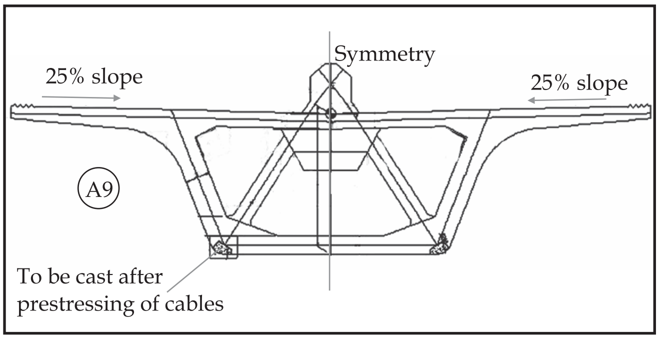


Figure 24. View of cross-section at cable-stay anchorage

Construction

The bridge erection was done by balance cantilever method. Pier segments and the first 3 segments at each cantilever are cast-in-place. Remaining portions at lateral span (around 18m from each end pier) are also cast in place.

Conclusion

Using pre-cast segments and typical construction materials, two innovative extradosed bridges have been designed and built (Figures 25 and 26). The projects prove that these

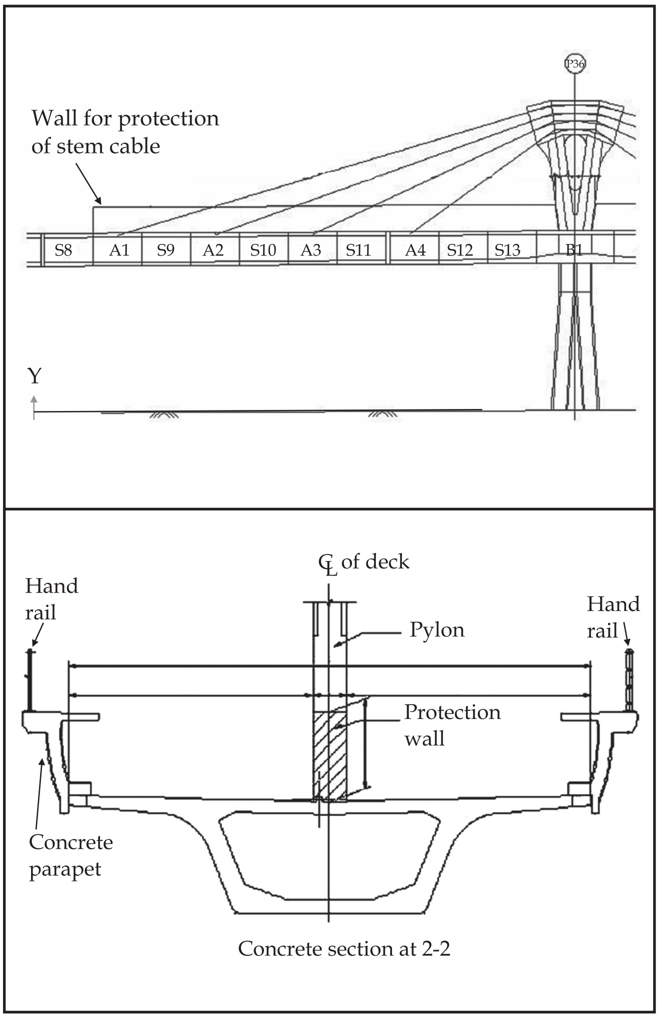


Figure 23. Elevation and section of protection wall

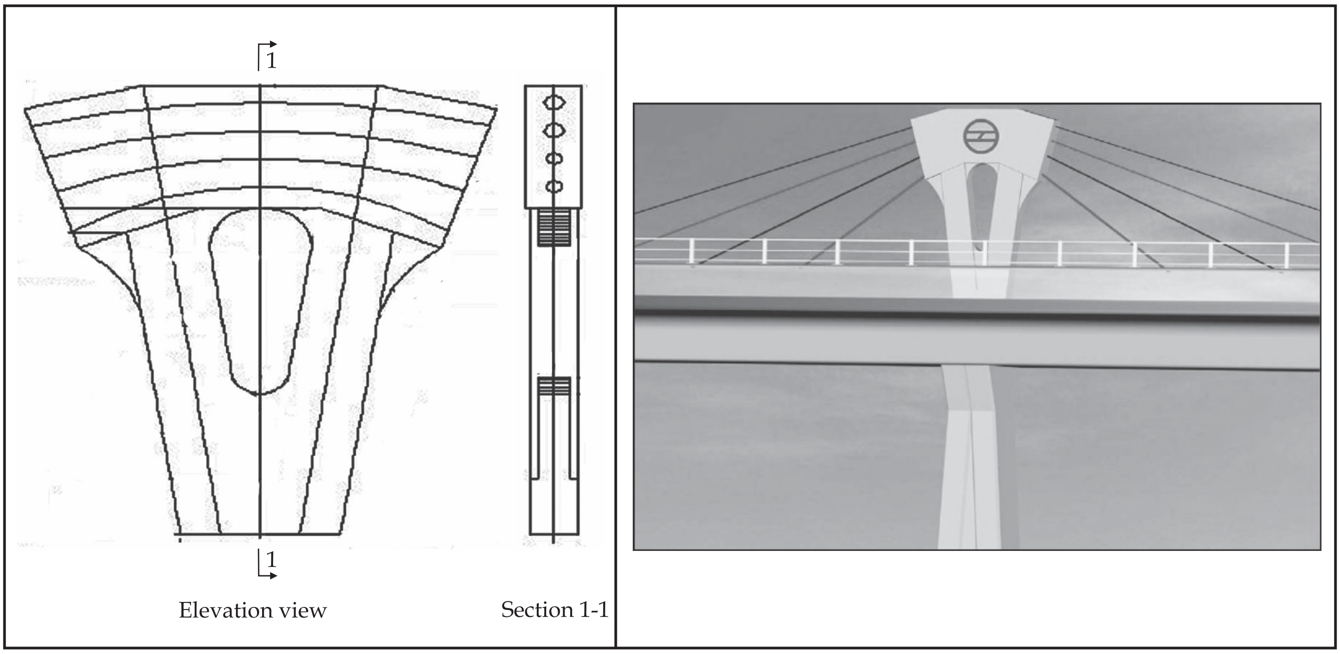


Figure 21. View of pylon top (left) Rendering of pylon (right)

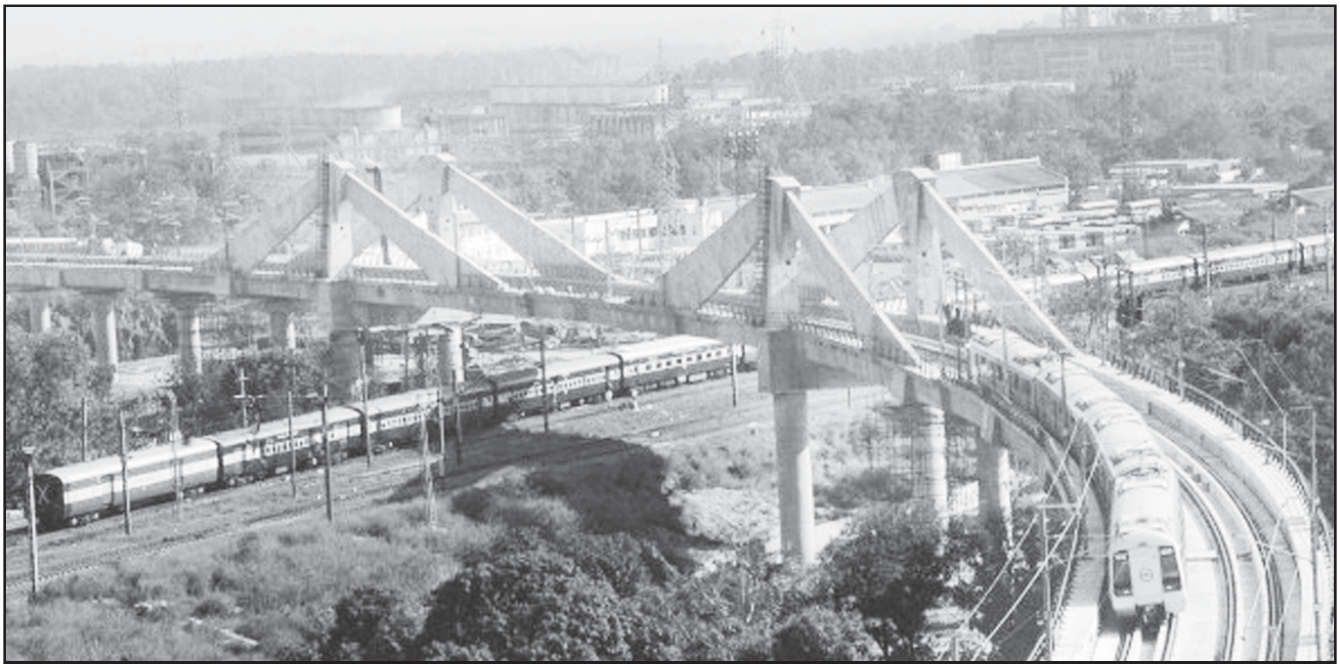


Figure 25. Aerial view of the viaduct

Figure 26. The Moolchand extradosed bridge

economic structures are not difficult to build, and the new idea offers potential for infrastructure development in the years to come. This also shows the U-shaped deck idea used by Systra for many metro rail transit (MRT) and light rail transit (LRT) viaducts can be extended to build longer spans and that extradosed bridges are aesthetically acceptable for medium and long spans.

Mr. Kumar Keshav, a civil engineer of the Indian Railway Service of Engineers (IRSE) cadre, served DMRC in various positions including Chief Project Manager and Chief Engineer (Planning). He has experience in project planning, monitoring and coordination, design, procurement, installation, testing and commissioning of ballastless tracks and prime consultancy works for metro projects. Presently, he is Director (Project & Planning).

Mr. Rajan Kataria received his Masters degree in Structural Engineering from The Indian Institute of Technology (IIT) Delhi. He has more than 30 years experience in the area of bridge engineering for Road & Railways. Presently, he is Chief Engineer/Design at DMRC Ltd. and has played a significant role in the structural design/proof checking of elevated structures and underground structures for rail corridor of MRTS project.

Jean-Charles Vollery is the Director Civil Work for Asia-Pacific, SYSTRA and Chief Executive of SYSTRA India

Vaung Chhuo is a Structural Engineer at SYSTRA

Abdel Mhedden is a Manager, Structural Department at SYSTRA India.

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