

Cable-Stayed Bridge as an Alternative
for Medium and Short Span Bridges

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Abstract

Cable-stayed bridges are usually thought of as signature bridges and not generally considered as serious option for most regular short-to-medium span bridges. This stems mainly from the belief that such bridges are expensive and too elaborate for the function required. However, in many circumstances, cable-stayed bridges can provide benefits at a relatively moderate increase in cost. Some of the benefits include the following:

- long spans with minimal deck thickness
- the elimination of piers
- increased traffic safety
- the minimization of environmental impacts and construction schedule limitations for river crossings
- enhanced appearance

In addition, greater use of this form of construction would allow our contractors to perfect methods of construction that would drive down the cost for future cable-stayed bridges.

After a brief literature review on short-to-medium span cable-stayed bridges, this paper will discuss the advantages of considering cable-stayed bridges as an option. The recently constructed Elbow River Bridge will be used as an example to demonstrate the possibility of using a cable-stayed bridge as a successful option for medium-span bridges, where deck thickness is an issue and river piers need to be eliminated.

The Elbow River Bridge is located near downtown Calgary, Alberta, and is the first vehicular cable-stayed bridge in Alberta. The bridge is owned by the Calgary Exhibition and Stampede and provides local access to Stampede grounds. The cable-stayed bridge was selected because of limitations in deck thickness, a tight construction schedule, and the attractive appearance. The Elbow River Bridge has a single span of 48.5 m. The deck is a cast-in-place post-tensioned concrete slab with a width of 12.66 m and an average thickness of 0.55 m. The cables are anchored at the east end of the bridge through two pylons. The deck was cast in a single stage because the contractor used existing steel girders as shoring to span the river and support the deck forms during the slab pour. This paper will discuss situations where cable-stayed bridges may be considered as realistic options for small-to-medium span bridges.

Text

Introduction

Building a signature bridge was not one of the original objectives discussed in early 2008 during the planning stages for the Elbow River Bridge. The main criteria was to build a river crossing with a total length of about 50 m that could be designed and built in approximately one year, to satisfy the geometry requirements, and of course to stay within the client's budget.

The Elbow River Bridge is owned by the Calgary Exhibition and Stampede and provides local access to Stampede grounds. This Bridge was recently named as “Christie Crossing” in memory of Nat Christie, one of the Calgary Stampede’s most notable past presidents. The Stampede grounds are the location for Calgary Stampede, a popular cultural event that occurs every year in July and attracts many tourists. The construction of the bridge could not start until after the 2008 Stampede and the bridge had to be open to traffic for the July 2009 Stampede. The owner hired the consulting engineer (CH2M HILL) and contractor (Graham Construction), and they had to work together to design and build the bridge.

The bridge deck had to meet tight geometric requirements. It had to be high enough to stay above the flood level while the bridge’s road surface had to be low enough to get underneath the nearby Spiller Road Bridge. This left a maximum of 700 mm for deck thickness. With the common girder options, these requirements could only be met by placing one or more piers in the river. To help meet the tight schedule, the contractor wanted to avoid having a pier in the river because it would eliminate the need for permits and the imposed schedule limitations for in-stream work. Eliminating the pier would require a clear span of about 50 m. Truss bridge and cable-stayed options were suggested as alternatives within the owner’s budget. The client preferred the cable-stayed option from an aesthetic point of view.

The bridge was successfully designed and built in the given time period. The client was very satisfied with the bridge and it won the Consulting Engineers of Alberta Showcase Award of Excellence in Transportation for 2009. The total cost of construction was about \$5.6 million. The bridge was efficient and aesthetically pleasing. The success of this project indicates that cable-stayed bridge might be a viable option for other medium and short span bridges.

Literature Review

Although cable-stayed bridges are usually only considered when long spans are required, there have been several cases where they have been used to span smaller distances. This topic has been discussed by Walter et al. [1] in *Cable-Stayed Bridges* in a chapter about small and medium spans. They provided a summary table for bridges with spans between 27 m and 150 m. Some of these examples, such as road bridges, footbridges with wider decks, and bridges with higher span to depth ratios are shown in Table 1.

Classical cable-stayed bridges have two or three spans with one or two towers. For three-span bridges the optimum side span length is 0.40-0.45 of the length of the main span (2). The height of the tower above the deck is usually 0.2 times the length of the main span. It is possible to have shorter or no side spans by anchoring the back stays at short side spans or anchor blocks. These options, however, would be less cost-efficient than balanced options.

Close spacing of cables can reduce longitudinal bending moments in the deck and the deck thickness. Walter et al. [1] discussed cable-stayed bridges with slender decks and the laboratory tests conducted to study the behaviour of these bridges. Their test model simulated a bridge with a 200 m span, a width of 14 m, and a 0.5 m thick concrete deck, giving a span-to-depth ratio of 400.

Different construction methods have been used to erect cable-stayed bridges [2]. One of the main advantages of these bridges is that they can be progressively erected on self-anchored cantilevers without interfering with roads or rivers underneath the structure. A deck can also be erected from two longitudinal precast edge girders and solid slab members with longitudinal and transverse post-tensioning. In the case of the Elbow River Bridge, existing girders from a previous project were used to support the forms for a cast-in-place concrete deck.

In recent years there have been many innovations in the structural design and architecture of cable-stayed bridges, including more slender decks, eccentric suspension of decks from cables (cables at one side of deck), curved bridges, and bridges without backstays (cables at one side of pylon only). Construction methods have also improved, making these bridges more cost-effective.

Cable-Stayed Bridge as an Alternative

For most applications, cable-stayed bridges will not be price competitive. The construction and the material costs are generally higher than conventional girder bridges. Consider the normal type of urban interchange bridge illustrated in Figure 1. In Calgary this type of bridge would commonly be constructed with two continuous 40 m spans using 2.0 m deep NU-type precast concrete girders. The bridge would be built in stages with the deck being post-tensioned in two stages. This type of bridge would be an economic, reasonably attractive solution. One problem with this type of bridge is that the centre pier can be a safety concern. Even when the pier is outside the clear zone, in about 20% of cases where traffic leaves the road it travels beyond the clear zone. Unfortunately, bridge piers have suffered many instances of vehicle impact over the years.

The cable-stayed alternative would remove the central pier and make the main highway safer. Another advantage is the bridge could be constructed over the main highway with minimal disruption to traffic, whereas a conventional bridge often requires some detouring. Normally a cable-stayed bridge would be considered more attractive. However, this is subjective and dependent on the surrounding area. The main disadvantages of cable-stayed bridges include their cost and the transfer of a collision hazard from the main highway to the lower speed secondary road. With the off-centre configuration shown in Fig. 1, there are some inefficiencies associated with locating the pylon on one side of the highway. The cost per square metre would be reduced considerably if the pylon had been placed in the centre of the main highway, creating a balanced structure.

Figure 2 shows a river crossing where a balanced cable-stayed bridge arrangement can achieve maximum efficiency for this type of structure. This sketch shows a 180 m river crossing. A conventional river crossing could be achieved using full length 2.8 m deep NU girders and two river piers. The cable-stayed alternative could have a much thinner deck section, perhaps 0.5–1.0 m. In this situation the cable-stayed bridge becomes much more price competitive. The pylon could be constructed from one river berm and bridge construction, using precast bridge deck units, could be carried out from the same berm using cantilever construction methods. The conventional three-span bridge would probably require two berms with berm construction and deconstruction occurring during predetermined periods when river work can be carried out. Although still a more expensive option, the cable-stayed bridge can provide a more attractive solution in a setting that often allows the designer to design a more visually appealing structure.

Reducing the Cost of a Cable-Stayed Bridge

The objective of this paper is to encourage engineers to consider the possibility of using cable-stayed bridges for relevant situations. As with all types of new bridge designs, there is increased efficiencies and cost savings as contractors learn how to construct them cheaply and as engineers learn to design them economically. This, in part, explains why NU girder bridges have almost become the default bridge type in many jurisdictions. In Edmonton,

steel girder bridges are perhaps more common. Contractors, engineers, and owners become familiar and confident with bridges that they have experience with. Reusing previous information and details decreases design cost, construction costs, and risks. However, concept bridge options have become very limited.

Cable-stayed bridges could become an economic rival to conventional bridges in some situations as engineers learn how to efficiently design them and develop standard details, as contractors develop tried and tested construction techniques, and as owners gain confidence in them. The bridge that was built at the Elbow River was constructed using a basic formwork system owned by the contractor. This proved to be cost-effective for a span of about 50 m. For other spans, other techniques could prove more economical. If cable-stayed bridges were more common, the main bridge contractors would probably develop their own standard formwork system or precast segmental units construction system. Suppliers, such as precast concrete suppliers, would invest in formwork systems that could serve this need. Likewise, steelwork fabricators could develop lightweight steel deck systems with simple anchors. Cable-stayed bridges can be an effective mix of steel and concrete. Pylons, for example, are often constructed from structural steel to allow a thinner section while accommodating complex cable anchors.

Cost Comparisons

Although cable-stayed bridges provide many advantages such as flexibility, innovative engineering, challenging construction, visually striking structure, slender decks, and large span arrangement variations, they have to also be cost-effective. However, unlike regular pier and girder bridges, the price per square metre is dependent to a great extent on the efficiency of the bridge configuration and not purely on its square area. Consider the bridge in Figure 1. From end of approach slab to end of approach slab this bridge could typically cost around \$7,000/m². If this were a bridge spanning 100 m with a central pier (Figure 2) there would be an extended deck section but the cables would be the same (configured differently) and the anchor block would be removed. With this arrangement the bridge cost would be reduced to about \$4,500–5,000/m². As the bridge becomes longer, the cost per square metre of a cable-stayed bridge decreases, becoming closer to \$4,000–4750/m².

Another option that might be cost-effective for single span bridges with pylons at one side is a cable-stayed bridge without backstays. In this case the costs for the anchor block, the back cables, and all the earthwork corresponding to anchor block components are eliminated but the pylon has to be designed to take the extra bending moment.

Table 2 provides a cost comparison for some bridges recently constructed in the United States. Comparisons are based on 2009 costs. The costs are then increased by 15% to account for higher expenses in Canada. Although these prices are approximate, they can give a rough idea of expected costs. It should also be noted that all of the bridges in Table 2 are pedestrian bridges and bridges with narrow decks usually have higher cost per square metre. In comparison, conventional girder and pier bridges usually cost in the range of \$2,750–\$3,000/m² and typically rise to \$3,500/m² for river crossings. Except for large water crossings, the cost of cable-stayed bridges is higher in Alberta than conventional bridges but the gap will close if the cable-stayed form of construction becomes more commonly used.

The Elbow River Bridge

There is limited experience in the design and construction of cable-stayed bridges in Alberta. The recently completed Elbow River Bridge is the first vehicle cable-stayed bridge in Alberta. Following are details of its design and construction that describe some of the challenges and rewards of using this type of structure.

1. Geometry and Components

The Elbow River Bridge is in the Stampede grounds near downtown Calgary, Alberta. It has a single span of 48.5 m (50.6 m end-to-end) over the Elbow River. Figure 3 shows an overall picture of the bridge and Figure 4 is a three-dimensional image. The bridge carries two lanes of traffic and a sidewalk. The deck is carried by six cables at each side. It is supported on pot bearings at the west abutment and integral with pylons and abutment at the east. The cables are supported on 23 metre-high pylons. Four pairs of back cables at each side provide the force balance. Anchor blocks are located at about 20 m from the base of the pylon and are designed for the vertical component of the back cable forces. The horizontal component is transferred through struts to the base of the pylon where it is balanced against the horizontal force in the deck.

The deck is cast-in-place post-tensioned concrete with a width of 12.66 m and an average thickness of 0.55 m. It was post-tensioned both laterally and longitudinally. Figure 5 shows a cross section of the deck. For more information on deck details and post-tensioning see Azarnejad et al. [3].

West and east abutments are on 18 and 88 HP piles respectively. The back wall of the west abutment was constructed after the deck slab was post-tensioned. The bridge is connected to the roadways through 6 and 7.4 m approach slabs at the west and east. Each anchor block is supported on six 780 mm diameter caissons. Uplift is taken partially by the weight of the anchor block and partially by the skin friction in the concrete piles. Each block is post-tensioned using DYWIDAG post-tensioning bars. Figures 6 and 7 show elevation drawings of the anchor block and Figure 8 shows a picture taken during construction. The compressive struts that carry the horizontal force between the anchor blocks and deck slab are supported on piles and connected horizontally through crossbeams to reduce effective length. Crossbeams are protected by floating slabs.

Pylons have a rectangular cross section of 1.26 m by 1.2 m and are made of two segments. The bottom part is reinforced concrete and is integral with the deck and foundation. The cable anchorage segment is a steel box made of welded plates with two additional plates welded inside the box. The pylon head is connected to the lower section through anchor bolts. Each pylon anchors six cables from the front and eight cables (four pairs) from the back. Cables go across the pylon through steel pipes and are anchored at the other side of the pylon. Pipes are welded to the plates in the box. Figure 8 shows vertical cross sections of pylon head at the front and back cables locations. Dimensions of the pylon cross section were determined from the space needed for anchorage devices. In the conceptual design stage, pylons were total reinforced concrete or concrete with embedded steel segments. Later, in the design and construction stage it was decided to make the pylon head totally from steel so that it could be manufactured separately. It would make the construction easier, faster, and more accurate.

2. Design

A number of different methods and software were used to analyze and design the Elbow River Bridge. For more information on analysis, including methods and results, see Azarnejad et al. [4]. The conceptual design was performed by Jiri Strasky. He used basic hand calculations to determine the initial geometry and then used the ANSYS finite element program and a three-dimensional model with shell elements to check load effects.

Detailed design was done by CH2M HILL using mainly SAP2000 software. A combination of two and three dimensional models with frame and shell elements was used to check load effects for different limit states. Frame elements provided beam-type results such as bending moment and shear force that were used to check ultimate member capacities and crack widths at service. The shell model was mainly used to check stresses and forces at cables. The staged construction module of SAP2000 was used to include nonlinear, time-dependent, and staging effects. Anchor blocks were analyzed with a strut and tie model and a detailed finite model of the block using solid elements. The pylon head was designed based on the results from the overall model and Jiri Strasky checked it using a detailed finite element model. After completion of detailed design, Jiri Strasky conducted an independent check.

The design was based on the Canadian Highway Bridge Design Code (CHBDC) (CAN/CSA S6-06) [5] and recommendations from the Post-Tensioning Institute (PTI) [6]. For cable-stayed bridges PTI recommends checking for cases of exchange or loss of one cable, which is not included in the CHBDC. The bridge was checked for both ultimate and serviceability limit states. The deck was designed as a partially prestressed member. The criteria was to keep the stresses under cracking strength for permanent loads and to check crack width for service conditions including live load and temperature changes. The program CRACK developed at the University of Calgary [7] was used to obtain stresses at cracked sections and crack widths were calculated from CHBDC formulas. The strain compatibility method was implemented to design deck sections because axial forces from cables or post-tensioning were important components to be considered.

3. Construction

The tight schedule was one of the main challenges of the project and influenced many of the decisions about the structure and its components. Conceptual design started in March 2008 leading to detailed design in May. The construction, however, could not start until after the Calgary Stampede in July 2008 and the bridge had to be open to traffic for the July 2009 Stampede. The owner hired the consultant and the contractor separately and they had to work together during the project. Finalizing geometry and layout caused some delays at the start of the project that resulted in the team having one year to design and build the bridge.

One of the factors that led to the selection of the cable-stayed bridge was the contractor having steel girders from a previous project that could span over the river and support the forms for a cast-in-place deck. This would save time and eliminate the necessity for a temporary support in the river or cantilever construction, which is normally used for cable-stayed bridges. There was also the advantage of having a deck that could be poured in a single operation. This, however, put an additional time restriction on the project. If the bridge was not self-supporting by the flood season in May-June, the flood could wash away the forms, causing the bridge deck to collapse into the river. Figure 9 shows a picture of bridge with steel girders supporting the forms. This picture was taken during the form removal operation in spring.

Due to time restrictions and the risks involved, the construction had to start before the design was finished. The design team had to provide the drawings and design data in stages as required by the construction. Cable-stayed bridges work as a whole system, unlike other bridges, so it is not possible to separate the design of substructure and superstructure.

Considering nonlinearity, time staging, and time dependent effects the structure needs to be analyzed as whole and different components be checked to make sure the system worked. This put additional pressure on design team and risk on the project.

Because the bridge was the first of its kind in Alberta and a new experience for both the design and construction team, the process was challenging. Many design decisions had to be made as the construction was progressing to avoid any delays. The team did not have the time to explore all of the possibilities that might have optimized the cost or design any further.

An example of the design being changed during the process is the design of the west abutment. In the conceptual design stage, the west abutment was considered an integral abutment. In the detailed analysis stage it was observed that HP piles could not take the simultaneous uplift and bending due to a combination of cable forces, temperature changes, and creep and shrinkage. The team decided to use a conventional abutment with sliding bearings instead. Further analysis showed that the bearings could be subjected to wide range of forces from high compression to large uplifts due to extreme load combination as described by the CHBDC. Tie-down bearings are normally used in cable-stayed bridges with permanent uplifts. These bearings have a large depth and could have affected the whole geometry, so they could not be used at that stage of design and construction. It was then decided that pot bearings would be used. Pot bearings can take uplift but have to be under compression for permanent loads. It took time to try different numbers and positions of the bearings to eliminate uplift under permanent loads.

With all of the challenges and risks involved in the project, success was only possible with close collaboration of the parties involved. Fortunately, the project progressed without any significant problems and the bridge was open to traffic in July 2009. The bridge was completed later in August.

Summary and Conclusions

Cable-stayed bridges have several advantages such as a wide range of span lengths and arrangements, the possibility of limiting and eliminating piers, slender decks, flexibility in the construction schedule, reduction of environmental impact (especially for river crossings), increased traffic safety, and enhanced appearance. Although they are usually considered for longer spans, when conventional bridge girders cannot be used or are not economical there have been many cases where cable-stayed bridges have been used to span shorter distances.

Cable-stayed bridges for medium and short spans may not be able to compete with conventional girder systems from a cost point of view, but there might be many occasions where the benefits warrant the extra cost. This could include following cases:

- Limitations in deck thickness due to geometry, vertical clearance, or flood levels
- Traffic safety, construction schedules, or environmental concerns could benefit from eliminating piers
- Construction has to be done independent of the traffic or river below the bridge
- Complex bridge geometry
- Aesthetics are an important requirement

The Elbow River Bridge was a case where the extra benefits of a cable-stayed system were the main factors in type selection. It was not the objective to build a signature bridge, but to build a river crossing that would have a slender deck to satisfy geometry and flood

requirements and could be built in one year. Eliminating the pier in the river would avoid the permit requirements and restrictions caused by the short window of time provided for working in the river. The attractive appearance was an additional benefit.

Cable-stayed bridges are becoming more common in Europe and the United States. They are not very common in Canada yet. The Elbow River Bridge was the first vehicular cable-stayed bridge in Alberta. This contributed to the project's higher costs. With more local design and construction experience the gap between the costs of cable-stayed option and conventional bridges would be smaller. The main objective of this paper is to encourage engineers to consider cable-stayed bridges as options, especially when the benefits warrant the added cost. It is the belief of the authors of this paper that the effective use of cable-stayed bridges is still in its infancy. There are so many options that need to be explored, from the use of cable-stayed bridges incorporating stress ribbon decks to simple one-sided cable-stayed systems without anchor blocks. With more experience we can optimize designs and details and develop cheaper construction methods that in time may make these bridges cost competitive.

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- Contractor: Graham Construction and Engineering Inc.

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Tables

TABLE 1
Examples of medium and short span cable-stayed bridges

Name, Country, and Operational Date	Deck Depth, Width (m), and Material	Spans (m)	Pylon Height (m) Above Deck	Span/depth (main span)
Schillerstrasse footbridge, Germany, 1961	0.65, 5.5, steel	24, 68.8	18.5	106
Julicherstrasse road bridge, Germany 1963	1.2–1.65, 26.4, steel	31.8, 98.7, 31.8	16.5	70
Pont de la Bourse footbridge, Le Havre, France, 1969	1.07, 5.5, Steel	31.6, 73.4	37.8	69
Footbridge over the Bundesalle, Germany, 1971	0.65, 6.4, steel	44, 20	23.9 top of cables to ground	68
Footbridge at Villingen, Germany, 1972	0.6, 6.4, concrete	31, 66.5	21	111
Franklinstrasse road bridge, Germany, 1974	0.8–1.7, 23, steel	41.6, 125.3, 42.3	19.5	74
Footbridge over the Neckar Mannheim, Germany, 1975	0.6, 6.44, concrete	56.5, 139.5, 56.5	29.1	233
Kwang-Fu road bridge, Taiwan, 1977	1.8, 14.3, concrete	67, 134, 134, 67	17.5	74
Diepoldsau Road Bridge, Switzerland, 1985	0.55, 14.5, concrete	40.5, 97, 40.5	22 (top of cables)	176

TABLE 2
Cost comparison for recent pedestrian bridges in the United States

Name, Completion Year	Type	Overall Length, Main Span, Width (m)	Cost (\$US)/m² (2009)	Increase 15%	Picture
I-5 Belt line, 2008	Cable-stay	153, 61.8, 4.3	3875	4456	
McLoughlin, 2006	Thru-arch	92, 73.4, 3.6	4951	5694	
Grants Pass, 2000	Stress-ribbon	200, 84.7, 4.3	2260	2600	
McKenzie R., 2001	Suspension	204, 131, 5.6	3767	4332	
Willamette R., 2000	Suspension	184.7, 103, 4.3	5812	6684	
Delta ponds, 2009	Cable-stay	231.6, 51.8, 4.3	3767	4332	

Figures

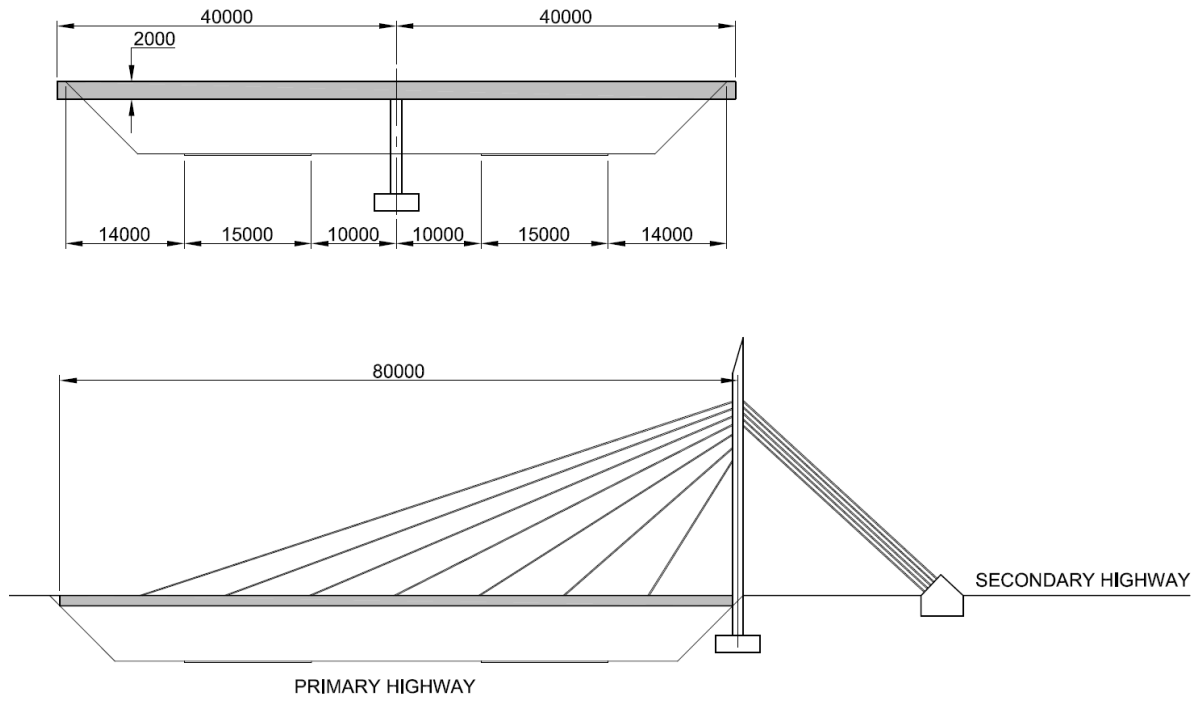


FIGURE 1 – TYPICAL URBAN INTERCHANGE BRIDGE

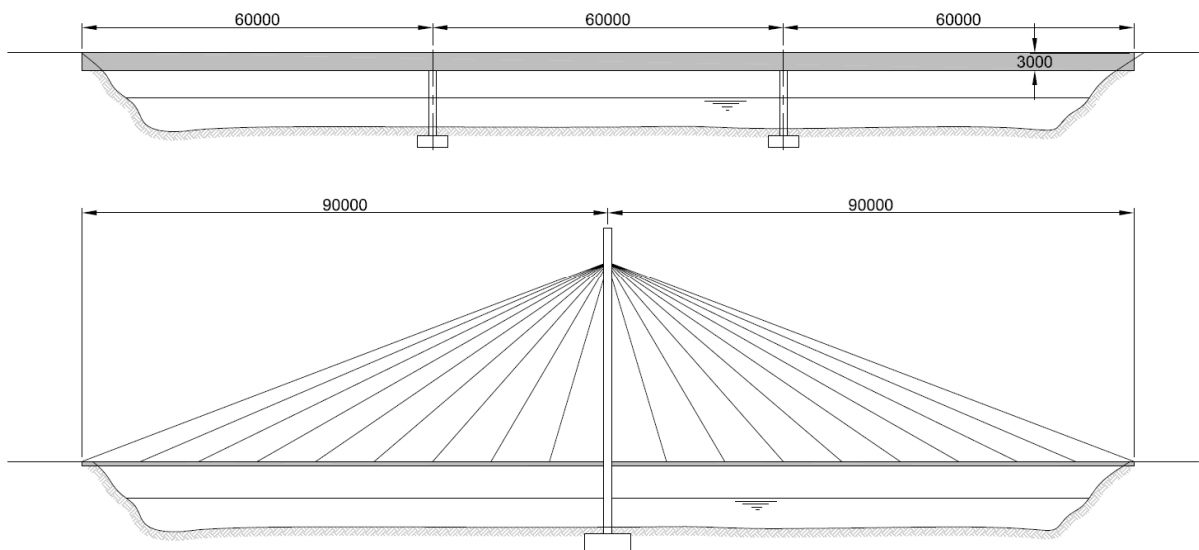


FIGURE 2 – TYPICAL RIVER CROSSING



FIGURE 3 – ELBOW RIVER CABLE-STAYED BRIDGE

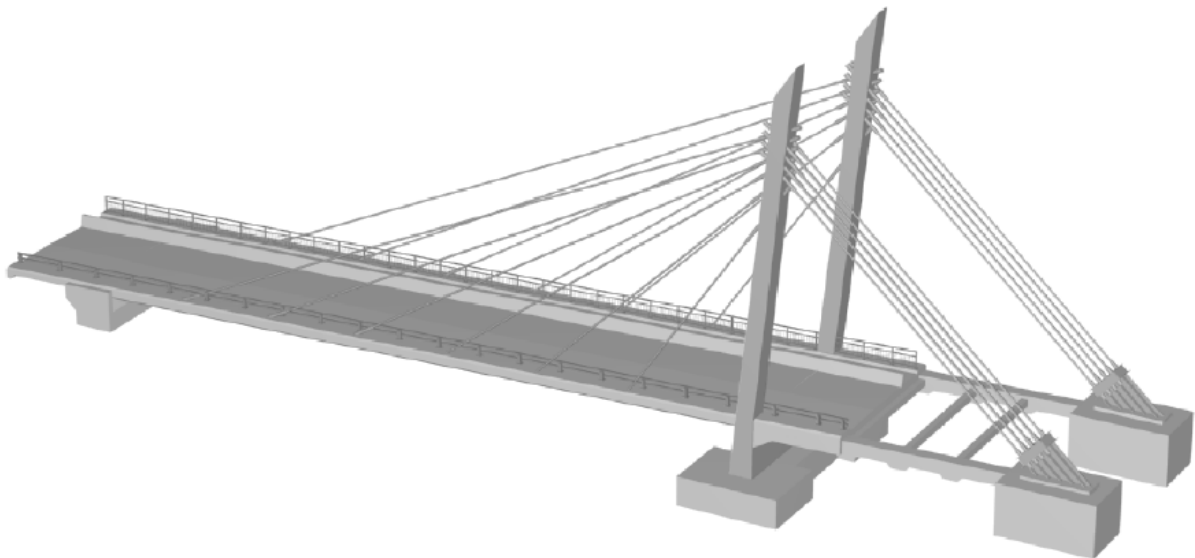


FIGURE 4 – THREE-DIMENSIONAL IMAGE (PILES NOT SHOWN)

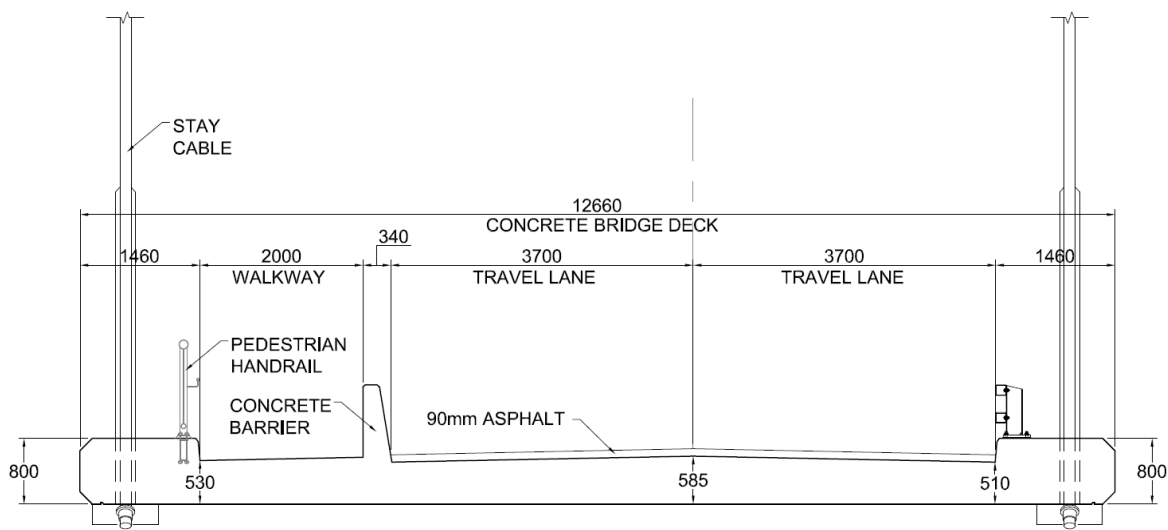


FIGURE 5 – DECK CROSS - SECTION

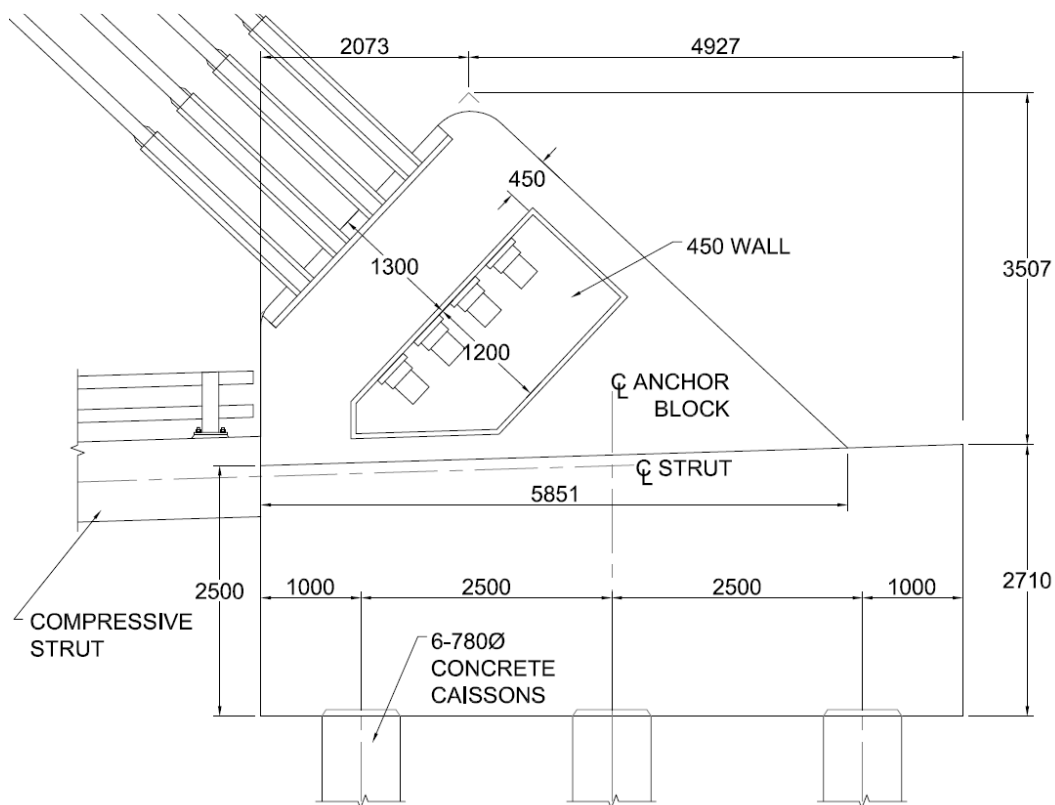


FIGURE 6 – ANCHOR BLOCK GEOMETRY

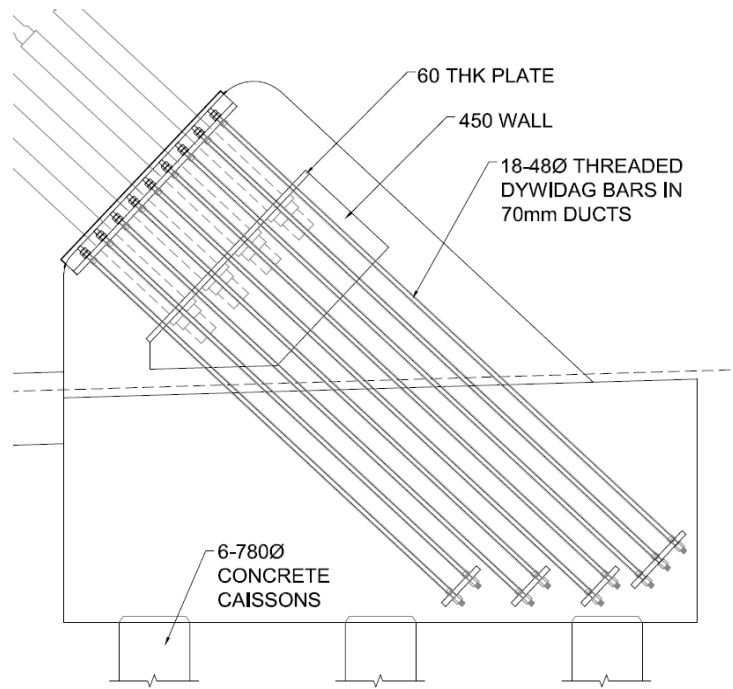


FIGURE 7 – ANCHOR BLOCK POST-TENSIONING



FIGURE 8 – ANCHOR BLOCK DURING CONSTRUCTION

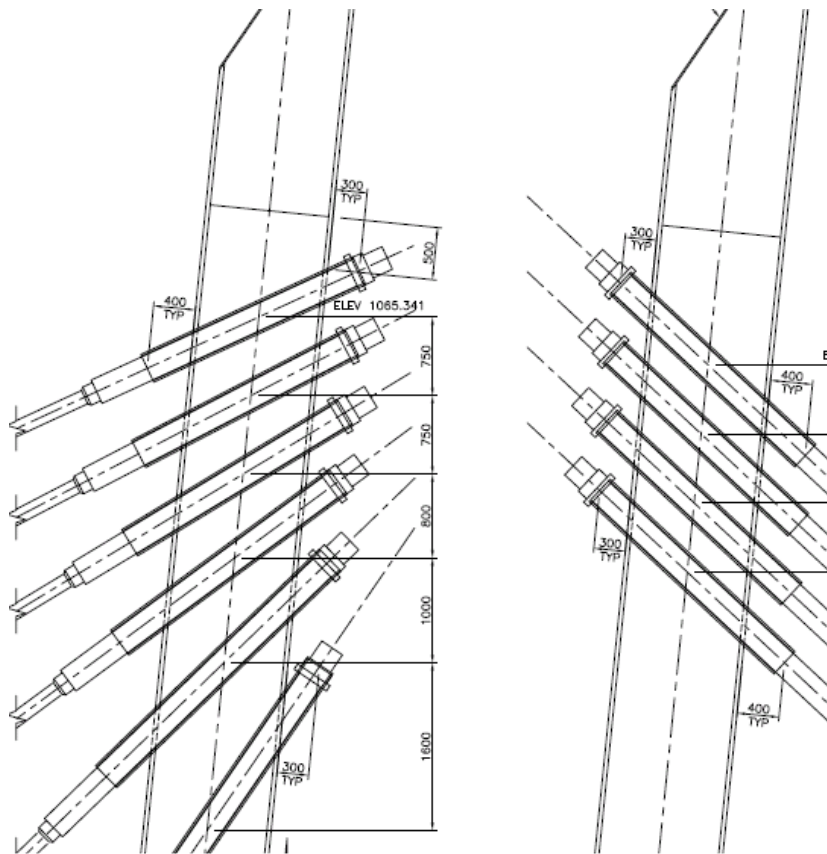


FIGURE 9 – PYLON SECTIONS



FIGURE 10 – PICTURE OF STEEL GIRDERS SUPPORTING THE FORMS.