SELECTION CRITERIA FOR SHORT-SPAN BRIDGES CONSTRUCTION METHODS

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Abstract:

Short-span bridges crossing water ways, roads and varying topographies are necessary for transportation allover the world. Construction of such structures involves utilizing unique construction methods due to various characteristics like structural system, cost, constructability, resources and time. This paper covers different methods of short-span bridge construction by concentrating on different construction methods of every type of short-span bridges. Moreover, a comparative analysis is provided to show when to use every method of construction according to the conditions available. Two projects involving short-span bridges with different sizes and project conditions were studied and examined against the developed selection criteria in order to evaluate the validity of the applied construction methods in each case.

Keywords: Short-span Bridges; Construction Engineering; Bridge Engineering

1 INTRODUCTION.

A bridge is a type of structure that carries a road, path or railway across a certain gap or obstacle such as roads or rivers. Bridges appeared with the rise of ancient civilizations. In its earliest forms, the bridge was pieces of wood cut out of logs to cross a gap. The design and construction of bridges was revolutionized in Ancient Rome upon the discovery of the use of mortar, which allowed for the execution of stronger and longer bridges. Today the design and construction of bridges has improved and evolved to be safer, more economic, easier to construct, more durable and esthetically more pleasing.

A short span bridge is a structure with a relatively short clear span that transports roadways or pathways across a certain barrier such as water or other roads. The different types of short span bridges studied include segmental concrete bridges, arched bridges, steel bridges and timber bridges. The different systems, materials and construction methods of short span bridges that are discussed in this paper, and analyzed in terms of suitability to certain applications, economical factors and ease of construction method (Khan, 2015).

Segmental concrete bridges are made of repetitive structural concrete elements that are repeatedly joined together to form the complete bridge structure. This method is the most traditional bridge construction method, as it was used in history in many bridges. Builders have always found it easier and more efficient to create a larger durable bridge structure from smaller segments (Barker, 1981).

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An arch bridge has an aesthetical appearance. The shape determines how the bridge behaves structurally. Live loads & Dead Loads are transformed horizontally to the supports at each side, also known as abutments. Abutments then form reaction forces to these thrusts.

On the other hand, steel offers higher yield strength, better ductility and better ability to be welded, that sets steel above all the other alternatives for short span bridges. This is due to the benefits that the steel has over the other types of materials. Modular Bridge Technology is used meanwhile to allow for faster construction of the bridges, improve safety on site, reduce the disruption of traffic during construction, reduce the environmental impacts and costs, and improve the quality of construction. Currently, this technology is applied to all sectors of the bridge; substructure, superstructure, systems, and secondary elements (Durkee, 2003).

2 SEGMENTAL CONCRETE BRIDGES.

This type of bridges is the most traditional bridge construction alternative. Builders have always found it easier and more efficient to create a larger durable bridge structure from smaller segments. Segmental bridges today are used in several applications, such as the construction of highway projects in areas of already existing streets and urban density, or the construction of bridges across sites that are environmentally fragile and require specific care. Also due to their repetitive nature, segmental bridges are used in applications that are repetitive over a large scale, specifically if the site below the bridge is inaccessible for construction purposes. The different construction methods of segmental concrete bridges can be distinguished based on casting methods and erection methods. This section discusses both variations and their execution methods (Barker, 1981).

2.1 Casting Methods

There are two different casting options for segmental concrete bridges. These are pre-cast or cast-in-place. In both alternatives, a concept of “match casting” is used. Within this concept the segment of the bridge casted should be done in a way so that its relative casting position reflects the position it will be erected in in reference to the other segments. This means that any segment is cast following preceding segments in the same order they will be erected (Blank, Blank, & Luberas, 2003).

2.1.1 Pre-Cast Segments

In this method the different segments of the bridge are prefabricated away from the site, and then installed there after transportation to the site. When placing the segments in their place in the bridge structure the connections between the different segments need special care. There is a need to ensure that the different segments fit together well and that the final superstructure is protected against moisture, and that the segments are joined well to withstand compressive and shear forces at the joining point between them. To achieve all that, cement-based or epoxy grouts are used at the joining of the different precast elements. Epoxy on its own is not sufficient to transfer the shear forces at joining points of the segments. Therefore, shear keys are placed between the joining faces of the segments to ensure perfect lock between them, and to guarantee they are exactly aligned (Blank, Blank, & Luberas, 2003).

Within this method, finishing of any member can be done on the ground, before installation, which increases accessibility. Casting conditions are controlled in a plant allowing better quality control. The hydration reactions occurred before assembly which means that no cracks due to shrinkage or hydration temperatures occur while the member is loaded in its permanent location. In addition to that it is time-saving as several activities could take place simultaneously as the substructure could be constructed while at the same time pre-casting the segments if the bridge. This is not possible with cast-in-place segments. This method is more economic when the segments are smaller in size since forms of precast elements can be re-used while it is uneconomic to use this method for larger segments due to the uneconomic nature of transporting and installing prefabricated members having large or heavy segments. In addition to that, the high cost of pre-casting plant, the transportation, storage and installation, in some applications is higher than the cost of cast in place formwork and execution process (Khan, 2015).

2.1.2 Cast-in-place Segments

In this method the segments of the bridge are cast in their place in the superstructure of the bridge. This could be done using shoring members (whether wood or steel shores) to support formwork (conventional, ply-form or steel) or using travelling forms which is very common in use specially if the topography or the traffic conditions beneath do not allow shoring. Travelling forms are supported by a steel truss system with rails to allow the forms to be movable along the line of the bridge deck. Once a segment is cast in the forms, a time is allowed for the cast element to gain sufficient strength to be able to hold the self-weight of the element, so that the form could be moved to the cast the next segment (Dunn, 1996).

Cast-in-place process involves preassembling the reinforcement in cages then lifting the reinforcement cages using cranes to their intended positions. After that, if the concrete is to be post-stressed, the post-tensioning tendons are placed in their ducts before the pouring of the concrete. Then concrete is poured either using a crane hoisting concrete bucket or a concrete pump. Sufficient time is given for curing and for the segment to gain enough strength then the tendons in the segment are post-tensioned. The cycle is then repeated to cast the subsequent segment (Blank, Blank, & Luberas, 2003).

This method is most suitable for large heavy segments, where precast segments cannot be used since the segments are too large and/or too heavy to be transported. It is more economic if typical shoring methods are used however it loses this merit if the traveling forms are used due to their capital intensiveness unless there is a necessity for that due to the site conditions beneath the bridge under construction (Barker, 1981). Hence, this method is limited to cases where the lower conditions allow for false work erection and it is valid for spans reaching 80 m, using it in larger spans would be a waste of time and money due to the large amount of false work used (BBR, 2014).

2.2 Erection Methods

2.2.1 Span-by-Span Method

Span-by-span erection uses a steel truss assembly that spans between the piers of the bridge in order to carry and assemble the precast segments to be placed in the superstructure. This erection method starts by lifting the segments beneath the truss assembly using a gantry crane in their approximate positions. After that, the segments are aligned and their geometry is fixed and the connections between the segments are grouted (usually with epoxy-based grouts) (Dunn, 1996). Then the post-tensioning tendons that are stressed and the truss assembly are advanced to the next span and the cycle is repeated (VSL Inc., 2013). This method offers rapid assembly however the high level of mechanization makes it highly capital intensive and makes it more suitable when used in large scale projects having a large number of spans (VSL Inc., 2013). However, this large number of spans is of a limited length due to the time and effort consumed in connecting large number of successive segments within a span exceeding 45 m (BBR, 2014).

2.2.2 Balanced Cantilever Method

Within this method of construction the deck segments are placed and attached as cantilevers supported on the piers of the bridge, after constructing the bridge piers. The pre-cast segments are placed equally at both sides of the pier to ensure stability of the structure. The high moment that is initiated in the deck during the addition of more segments is resisted by post-tensioning the segment near and on the top of the pier, and extending this post-tensioning to the body of the pier itself, in order to stabilize the structure such that the connection between the deck and pier will be a moment-resisting connection. The segments added to the cantilever are most commonly placed using cranes. A launching gantry crane is very useful in situations where the land below the superstructure of the bridge is not accessible (VSL Inc., 2013).

If cast-in-place concrete is poured instead of pre-cast segments then there will be a need to use two traveler forms (one from each side of the pier) as shown in Figure 1.However, careful care should be taken as the traveler forms are advanced due to the fact that the full strength of the concrete is not achieved yet (Dunn, 1996). Hence, unless early strength concrete mixtures and curing procedures are used, striking and advancing the forms should take at least three days (as 50% of the strength would be achieved by that time). The major merit of this method is that there is minimal disturbance for the area beneath the bridge deck hence it could be used when the bridge is crossing major roads, water ways, forests or difficult topographies. However, bridges constructed using such method should be designed carefully taking into consideration the different cantilever load cases (Blank, Blank, & Luberas, 2003).

Figure 1: Construction of the Pierre Pflimlin bridge using the balanced cantilever method (Leonard, 2007).

2.2.3 Unidirectional Cantilever Method

This method (also called progressive placing construction method) is similar to the balanced cantilever method but instead of moving in both directions from a pier with cantilevering segments, the segments are instead added to the pier in a unidirectional manner (in one direction). In this method since the casting is done in one direction only, the moment is significantly high on the segment at the pier which should be taken into consideration on designing the deck, the pier and the pier-deck connection. Additionally, a temporary support system is typically used at the mid-span to reduce this moment (Barker, 1981).

This construction process is less complicated than the balanced cantilever method since work is done in one direction only as shown in Figure 2. Also, completing one span of the bridge gives better accessibility to construct subsequent spans; this is not possible when the construction is done in both directions from the pier. Accordingly, this method needs temporary supports; it is slower and could be applied for shorter spans when compared to the balanced cantilever method (Barker, 1981).

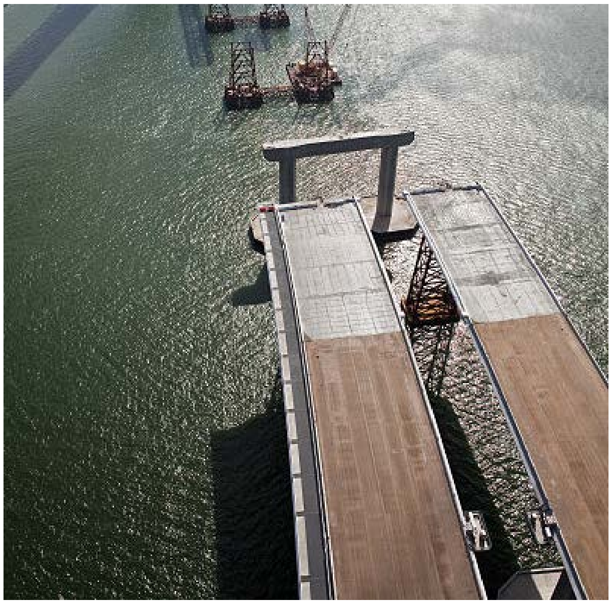

Figure 2: The construction of the new SF-Oakland Bay Bridge using the unidirectional cantilever construction method (Katz, 2011).

In both cantilever construction methods the cantilevering segments from each pier will reach to a point where they meet at mid-span between the two piers and these segments need to be joined. Joining the segments is either done using a hinged connection which is a simple connection but could lower the loadbearing of the bridge structure or the segments could be kept suspended and allowed to rest on bearings between the cantilevers. This might be more structurally complex, but is more structurally sound. Due to all of that, both cantilever methods could be used for various lengths of bridge spans ranging from short spans to long spans although the balanced cantilever method is capable for constructing longer spans than the unidirectional cantilever method (BBR, 2014).

2.2.4 Incremental Launch Method

This method involves the casting of continuous segments at a specific location of the site, then pushing this continuous chain using hydraulic rams to be placed in position. Casting beds in this method have formwork that is adjustable and movable. After constructing the piers the segments (which are usually pre-stressed concrete) are cast in continuous chains on site. Typically, on constructing bridges using this method, three types of pre-stressing are usually utilized: the central, the eccentric and the transverse pre-stressing each increasing the section strength in a certain direction. After that, the chains are pushed into position using hydraulic jacks that act in both vertical and horizontal directions, these lift and push the segments into place. The segments are supported with temporary supports as they advance from the casting yard to the pier (if the chains of segments are of long spans). The first segment is attached to a launching nose (usually steel) as shown in Figure 3. This nose will rest on the temporary supports (in longer spans) and then rest on the permanent supports providing more stability which is the main difference between this method and the unidirectional cantilever method (VSL Inc., 1977).

This method is very suitable when the site below needs to remain unobstructed. Due to its higher stability, temporary supports are not needed for short spans. It is economically sound as the transportation of the segments for long distances is avoided and the use of large amount of formwork is reduced. However, this method could only be used if the bridge has a constant cross section and a straight alignment (Barker, 1981). Due to the need to launch a significant weight using a set of jacks this method is limited to bridge spans less than 60 m (BBR, 2014).

Figure 3: A launching nose of the bridge over the Itz in Germany. Photo by (Storfix, 2005).

3 ARCH BRIDGE CONSTRUCTION.

In addition to having a good aesthetical appearance, the shape of an arch bridge determines how the bridge behaves structurally. The vertical (gravity) loads are transformed horizontally to the supports at each of the sides, also known as abutments. Abutments then form reaction forces to these thrusts. As it was the case for segmentally constructed bridges, arch bridges are either cast-in-place or precast. Each of these two alternatives is discussed in the following subsections. Span distance and height clearance are the major factors of choosing arch bridges. If the span distance is short, it is reasonable to choose an arch bridge design.

3.1 Cast-in-place

This method could be applied using either wooden formwork supported by false work or by using inflated forms. If wooden or steel formwork and false work are used the dismantling of these temporary structures should start from the middle of the arch (the crown) not from the supports sides (FHWA, 2003). Inflatable forms are typically made of polymer materials that are inflated by pressurized air to take the required arch shape. If the inflated forms are used, the closed-end cylindrical balloon is inflated and the shape is controlled by placing steel strapping. Then divider forms are placed at intervals to produce short segments that can be handled by a crane on site. After that the reinforcements are placed and concrete is poured by layers of shot-creting with each layer having a thickness of 150 mm to 250 mm. Then the forms are removed when concrete starts to set. These inflatable forms are inexpensive and can be used 40-50 times. Each form can be used to build many sizes of bridge arches. However, wooden forms and wooden or metal false work are more known to engineers and contractors, could cover larger spans and do not require concreting in layers (Ruhl, 1997).

3.2 Precast Construction

Within this alternative precast concrete sections are placed in position after transportation to site and the joints between the sections are connected either using grouts (wet joints) or using dry joints. If one is choosing which type of arch bridge to construct (forms vs. precast), then the span distances and heights will not be the critical factor however the segment size comes into the picture as the larger and/or heavier segments could not be easily transported and assembled on site. Additionally, one will need to consider availability of precast plants near the site and transportation costs. However, the major merit of this alternative is the accelerated construction speed (Khan, 2015).

4 STEEL BRIDGE CONSTRUCTION.

Steel bridges have an advantage over concrete bridges as for the same span a lighter steel bridge could carry the load, however from a material cost perspective concrete is more cost-saving. Typically, the designer is the one who decides on the method of construction as this must be accounted for in the design of steelwork. Also, it is up to the designer to indicate the sequence assumed in the design both for erection of the steelwork and for the decking system. The alternatives of the bridge erection are either erection by crane, launching, sliding, rolling or lifting large preassembled sections (Durkee, 2003).

4.1 On-site Assembly by Cranes

The higher ability of steel bridges to cover large spans with lighter dead loads makes it easier to transport and assemble a steel section than to transport and assemble a prefabricated concrete section. Due to that, the most common method of erection for short-span steel bridges is by assembly using mobile cranes. Typically for short span bridges, girders or trusses are erected on the side or in workshops and lifted by two mobile cranes (one from each side) and placed directly on the piers/columns either singly or braced in pairs spanning the full length between two supports. As for multiple spans, the girders are erected either singly or braced in pairs in a span and cantilever sequence involving erecting members that cantilever over the supports to the point of contra-flexure in the next span. After placing the main girders or truss in locations, the secondary beams and the bracing members are mechanically connected to the main girder/truss placed (Alberta Transportation, 2013).

4.2 Segmental Erection Alternatives

The erection methods described within section 2.2 could be used to erect steel bridges in a manner very similar to erecting pre-cast concrete bridges. However, the difference in the material properties affects the application of such methods in terms of several issues. First of all, a typical steel member would be able to carry the same load that a heavier concrete member could carry. This fact reduces the overturning moments at the deck – pier connection hence reducing the moment loads on the pier itself hence reducing the dimensions of the piers and reducing the material cost. Also, the capacities of the lifting equipment needed to perform the job is reduced which will reflect in a reduction in the equipment cost (Durkee, 2003). Secondly, the nature of the connections between the successively erected members (whether truss members of girders) will be different as due to the higher strength of steel when compared to concrete the need for using post-tensioning technologies at the connections on site is reduced reflecting a significant reduction in the equipment, labor and material costs. On the other hand the connections between the erected members are usually bolted or riveted as welded connections are not preferred due to structural design considerations (related to their fatigue strength) and quality control concerns as the quality of welding is highly dependent on the qualifications of the welder while the quality of bolted and riveted connections is less dependent on the level of skill of the labors (CISC, 2008).

5 CONSTRUCTION METHODS SELECTION CRITERIA.

Based on the discussion of the different methods presented in the previous sections, a selection criteria could be developed to aid the decision making process concerning the short-span bridge construction methods. Typically, the conventional methods whether involving simple installation of steel or precast concrete girders or involving cast-in-place concrete using conventional false work carrying formwork is more economical than erection methods however, if the bridge is planned to pass over a busy road, a river or a valley that could not allow false work to be placed the segmental erection methods are the only remaining alternative. The bridge length and location are the most important factors governing the choice between the different methods. The need for special design considerations, temporary mid-span supports, level of risk, time frame, resources (especially equipment), costs and constructability also affect the method selection. A summary of the selection criteria between different segmental erection methods could be found in Table 1.

Table 1: Selection criteria for short-span bridge segmental erection methods.

	Span-by-Span	Balanced Cantilever	Unidirectional Cantilever	Incremental Launching
Need for mid-span temporary supports	Not needed	Sometimes needed for moderate-long spans	Needed	Needed for moderate-long spans
Material	Precast concrete or steel	Concrete or steel	Concrete or steel	Concrete or steel
Level of mechanization	High	Moderate	Moderate	High
Need for special design consideration	Not needed	Should account for additional number of load cases		Additional load cases and limited for decks of constant sections and slopes
Construction Speed	Fast	Fast	Moderate	Fastest
Cost	Cost saving for large number of spans	Cost saving for short-medium spans	Cost saving for shorter spans	Cost saving for short-moderate spans
Risk	Low	Moderate	Highest	Low

6 CASE STUDIES.

6.1 Ravensbosch Viaduct, Netherlands

The Ravensbosch Viaduct is a part of the highway connecting Maastricht and Heerlen in Netherlands. It spans the valley of the Strabekervloedgraaf near Valkenburg at an approximate height of 25 m. The bridge superstructure is composed of two parallel box girders on which a 37.77 m wide common deck slab rests. The total bridge length is 420 m and divided into eight spans. The two outer spans are of a length of 42 m while each of the six inner spans had a length of 56 m (VSL Inc., 1977).

6.1.1 Applied Method

Three different design alternatives were prepared for tender. The first was the basic design with eight spans of 42, 6 x 56 and 42 m to be constructed using the Incremental Launching technique. The second option was to have seven spans of 45, 5 x 66 and 45 m to be carried out with prefabricated segments. The third was having nine spans of 35, 7 x 50 and 35 m to be constructed of conventionally poured reinforced concrete. The joint venture of Internationale Gewapend Betonbouw (IGB) and Societe Belge des Betons (SBB) offered the lowest bid with its price using the first design. Consequently this joint venture was awarded the job which was within the order of 7.5 million Dutch Florins. The time frame for the viaduct construction which was the first incrementally launched Dutch bridge was only 26 months (VSL Inc., 1977).

The depth of the section was specifically suited in order to accommodate the use of the Incremental Launching Method as the depth of the box girder was sized to be about 1/17th of the main spans while for other boxed bridges this ratio is typically 1/20th. That was done to decrease the quantity of post-tensioning cables to be placed by increasing the moment of inertia of the superstructure. As it is the case for any incrementally launched bridge, the section dimensions were kept constant along the length of the bridge.

The construction yard of the bridge was chosen to be behind the eastern abutment as this side had a higher elevation than the western side hence the launching process would be easier if done downgrade. Consequently, the friction beneath the bridge deck was counter-effected by the downslope motion. The construction yard was 75 m long and 25 m wide that included two areas, a storage area for reinforcing and post-tensioning steel and a runway having a tower crane and a concrete batch plant. Each increment was about 19 m long and constructed in three stages. Initially, the bottom slab was constructed. Secondly, the webs were cast and succeeded with the deck slab. Hence, the bottom slab was capable of carrying the inner formwork and the concrete top slab weight as by the time the top slab was constructed the bottom slab was one week old. Special consideration had to be set to the precision of the shuttering as it was important to place the shuttering with a precision of 0.1 mm which was a very difficult task but it was necessary in order to not accumulate errors along the bridge length. The central post-tensioning consisted of tendons having an ultimate capacity of 828 kN; eight cables were placed in the bottom slab and eighteen in the webs and upper slab. The use of temporary mid-span supports helped to reduce the bending moments during launching and keep the central pre-tension small. Concerning continuity cables connecting different spans, within each web six cables were placed such that above the supports cables from two adjacent spans overlap. Consequently, above each pier six cables were anchored in block-outs at the top of the webs. The cables were tensioned into the ducts only after the launching is complete and then fully tensioned (VSL Inc., 1977).

The launching nose in front of the structure was a 15 m long steel truss weighing 20 tonnes. Two jacks were fit to steel girders located in front of the eastern abutment. Each jack pulled a cable anchored to two steel girders specially placed at the end of every increment. The launching process over the segment length (about 19 m) took around six hours. During the construction stage all permanent and temporary piers had concrete bearings having a compressive strength of 60 MPa covered with a stressed sheet of chrome steel. In order to minimize friction, plates made of steel/neoprene/teflon were placed between the launched box girder and these bearings. The friction was monitored at each jacking process, it was initially high at the beginning but it reached only 5 % of the value assumed at the design phase (VSL Inc., 1977).

6.1.2 Construction Method Evaluation

The decision of using a conventional method would have been wrong as constructing the false work for a height of 25 m would have been costly and time consuming. On the other hand, installing precast segments would have been extremely difficult and hence expensive as transporting such large segments to the site would have been extremely difficult and needs extremely large cranes and trucks to place the sections in their locations. Hence, the only alternative left was to use a segmental erection method. As transporting precast segments in the middle of the valley is really difficult, using the span-by-span would have been really difficult. Also, as time was of the essence, and according to the selection criteria presented in section 5, the incremental launching method was the best choice as it was the fastest method of all the segmental erection methods.

6.2 King Fahd Causeway, Saudi Arabia – Bahrain

This four-lane road is 25 km in length and had a width of approximately 23 m, and constructed of 350,000 m^3 of concrete and 47,000 tonnes of reinforcing steel. The project cost was approximately US$ 800 million. The causeway was constructed in three segments. The first segment was from Al-Aziziyyah, south of Khobar, to the Border Station on Passport Island. The second segment was from the Border Station to Nasan Island in Bahrain. The third segment was from Nasan island to the Al-Jasra, on the main island of Bahrain. The causeway was composed of seven embankments (12570 m long) and five bridges (12430 m long) crossing the strait between Saudi Arabia and Bahrain in the Arabian Gulf. This project started in 1981 and the time was considered to be of the essence finishing this megaproject by 1986 (KFCA, 2013).

6.2.1 Applied Method

Two of the five bridges are long-spanned (which are not within the scope of this paper) to allow for the passage of ships beneath the causeway. The other three bridges where composed of a series of short spans. These short spans where composed of prefabricated concrete box sections. Each span included two box sections (one for each traffic direction) located side by side. Each boxed span was fabricated as one segment in a casting plant on the shore, lifted by cranes and placed over barges. The barges transport each segment to its location where two cranes resting on boats carry each segment and place it in position. After that, the post-tensioning of the continuity cables connecting the different spans took place and a common slab was poured above the two box girders. This process was repeated for all of the spans for the three short-spanned bridges (KFCA, 2013).

6.2.2 Construction Method Evaluation

Due to the difficulty of using false work in the middle of the Arabian Gulf, using conventional cast-in-place construction would have been nearly impossible. The significantly large vertical curvature of several spans within the bridges crossing the strait negated the ability to use the incremental launching method (which is the fastest available method) as it couldn’t be applied in cases of large vertical curvatures. As the project time was of the essence, the two cantilever methods would be time consuming in comparison to the span-by-span construction that would install smaller prefabricated segments and connect them together or by simply installing the prefabricated span in one piece. On the other hand, it was possible to construct these spans using the span-by-span method. If this option was used, smaller segments would have needed smaller barges and smaller cranes to install and hence the cost would have been lower. However, installing the larger prefabricated box girder in one piece would need large barges and large cranes which would incur a high cost but the rate of installation of each span would be faster as the time of connecting smaller segments together would be saved. Accordingly, and as the owners had high preference to finish the project on time and were willing to pay for the additional costs, the method used in this project was the most appropriate in such a case.

7 CONCLUSIONS AND RECOMMENDATIONS.

When examining the methods applied in the two cases discussed in section 6 of this paper against the selection criteria developed in section 5, the selection criteria proved that it covered the different aspects governing the selection of the most suitable methods for different short-span bridge construction cases. The most governing factors of choice are the bridge length and location. The need for special design considerations, temporary mid-span supports, level of risk, time frame, resources (especially equipment), costs and constructability also affect the method selection. Hence, it is highly recommended when using the selection criteria matrix to take all the factors governing the method selection into account as neglecting some of them could cause serious problems that are difficult in fixing.

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