# Constructability Analysis of the Bridge Superstructure Rotation Construction Method in China

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**Abstract:** Constructability analysis can provide valuable input to optimizing urban bridge construction in terms of reducing impacts on traffic, safety, and overall project budget and duration. This paper presents a constructability analysis of the superstructure rotation method for bridge construction. The method includes building the bridge parallel to the obstacle being overpassed (a river or a highway) and then rotating the superstructure into place. The method has been used successfully in over one-hundred bridges (mostly in China). The paper documents two case studies of bridges that used this method and provides an analysis of the constructability of the method. This includes identification of the factors influencing the constructability of the methods and lists of design and construction objectives/strategies that support the constructability of bridges using this method.

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## Introduction

A substantial number of urban bridges are undergoing (or are due for) rehabilitation. The implications of rebuilding such bridges could have significant influence on local communities, traffic flows, and business activities. Innovative construction methods and constructability analyses can support optimum implementation of such projects. Constructability is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives (CII 1993).

This paper presents a constructability analysis of what is referred to herein as the bridge superstructure rotation construction method (SRM). This method is also known as the central bearing rotation method or the rotating deck construction method. The technique has been used mainly and extensively in China. The paper documents two case studies for the SRM in China; it presents a system to support constructability analysis of the SRM, and draws some lessons learned about SRM applicability for urban bridge construction.

## Background

The SRM is mainly applicable to any bridge that spans a major obstacle with challenging traffic or access conditions, such as a navigational water body or a highway with heavy traffic. The main bridge span (be it a girder, a truss, or an arch) is divided into two main parts. Each part is built at one side of the obstacle—normally at a 90° angle to its final position, depending on the bridge layout and surrounding landform. Each part is then rotated into its final position. The major steps of the SRM are (see Fig. 1):

1. Build the piers at each side of the obstacle;
2. Install the rotating mechanism on the top of each pier. The rotating mechanism is normally a spherical hinge. In larger sized bridges, additional circular rotational rollers are needed. The design of the mechanism depends on the weight of each span, its configuration (mainly weight distribution), and the site characteristics;
3. Build the two half-spans. To make each half-span self-balanced, a counterweight is normally placed at the outer side of the half-span. In the case of longer spans, the weight of side spans is used as the counterweight. In some cases, temporary supports may be needed to keep the structure in balance;
4. Use the rotating mechanism to rotate each half-span into its final position (normally using hydraulic jacks); and
5. Lock the rotating mechanism in place (normally by concrete sealing).

The first bridge to use the SRM was the Danube Canal Bridge in Vienna (a cable-stayed bridge). It was built in 1976 with a span distribution of 55.7 m–119 m–55.7 m. The middle span was divided into two sections each approximately 59.5 m long. The total weight of each side was 4,400 t (Chen et al., 2001). The SRM has since been used extensively in China—especially to span rivers. The first implementation of the SRM in China was the Suining Bridge (span of 70 m) in 1977.

In the late 1980s, the SRM became quite popular in China. Given the importance of waterway transportation in China, the fact that the SRM reduces the impact on waterway traffic was one of the significant reasons for its popularity. Table 1 lists some of the major SRM projects over the last 10 years in China. The table illustrates the growing confidence in the method, the growth in

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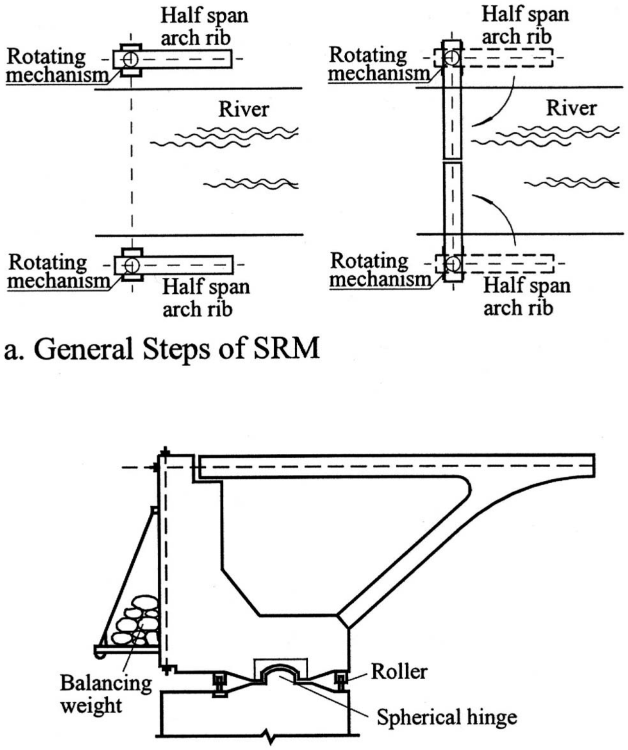


a. General Steps of SRM

b. Balancing the half-spans

**Fig. 1.** Illustration for the use of SRM to span a river: (a) General steps of SRM and (b) balancing the half-spans

bridge span (peaked at 360 m), and the applicability of the method to different structural systems. Among these, the Yajisha Bridge and the Shijingshan Station Bridge encapsulate several aspects of the SRM—they are discussed below in detail.

## Case of the Yajisha Bridge

With a main span of 360 m and a total horizontal rotating weight of 13,685 t, the Yajisha Bridge is the longest and the third heaviest bridge built by the SRM method in the world. The heaviest was the Ben-Ahin Bridge built in 1991 in Belgium (cable-stayed, span distribution of 42 m–168 m–42 m, total horizontal rotating weight of 19,500 t). Prior to the Yajisha Bridge, most of the SRM applications in China were in bridges with a main span of 70–200 m, with the longest being 236 m (Beipanjiang River Bridge, Guizhou, China).

The Yajisha Bridge crosses the Zhujiang River as a part of the Ring Freeway around Guangzhou City, Guangdong. It was designed by the Professional Design Institute of China's Railway Ministry and constructed by Guizhou Provincial General Highway and Bridge Construction Corporation. The construction lasted 19 months (finished in June 2000).

The Yajisha Bridge is a cable-suspended arch bridge with a main span of 360 m. Each arch rib is composed of three steel trusses; the upper and lower chord of each truss are made of concrete-filled tubular steel (diameter=750 mm). Two side spans (each 76 m long) were designed to balance the horizontal thrusting force from the main span. The bridge has a width of 36.5 m and a maximum clearance of 76.45 m. Fig. 2 shows the bridge elevation and the built bridge.

In normal circumstances, one-half of the main span (about 180 m) would be built as a half-arch at each side of the river. Due to the considerable length and height of each span, the tubular trusses (of each half-span) were fabricated as a two-hinge arch on the ground along the river banks, and then were tilted (upward) to the designated profile before they were rotated (transversely) to the final position.

## Construction Alternatives

Construction-management-at-risk was selected as the project delivery system. Several erection methods were proposed for the bridge. Two representative alternatives for construction are discussed in this section.

### *Alternative 1: Sectional Lifting with Two Towers*

Fig. 3 shows an outline of the erection method that calls for dividing the main arch (360 m) into three arch sections (75 m–210 m–75 m). The erection steps are:

1. Prefabricate (on site) the two concrete side spans (half arches, each 76 m long);
2. Build two temporary towers in the river (204 m apart);
3. Float the two 75 m sections by barge and lift them into place using the towers (effectively, these measured 78 m each due to the design of the towers as shown in sections 1 and 3 in Fig. 3); and
4. Prefabricate (in plant) and transport the 210 m arch (section

**Table 1.** Major Bridges Built with SRM in China

| Bridge | Location | Main span (m) | Type | Rotating weight (kN) | Completed in |
|---|---|---|---|---|---|
| Wenfenglu Bridge | Anyang | 135 | Arch bridge | 58,500 | 1995 |
| Daliying Bridge | Shandong | 110 | Cable-stayed | 80,400 | 1997 |
| Waiheba Bridge | Chongqing | 60 | Concrete truss | 10,100 | 1997 |
| Yajisha Bridge | Guangzhou | 360 | Arch bridge | 136,850 | 2000 |
| Beipanjiang Bridge | Liupanshui | 236 | Arch bridge | 106,000 | 2001 |
| Shijingshan Bridge | Beijing | 166.7 | Cable-stayed | 140,000 | 2003 |
| Diaozhongyan Bridge | Longyan | 140 | Arch bridge | 30,120 | 2003 |
| Chumi Bridge | Guizhou | 110 | T-Beam | 33,000 | 2004 |
| Tiaoyukan Bridge | Hefeng | 125 | Arch bridge | 65,000 | 2004 |



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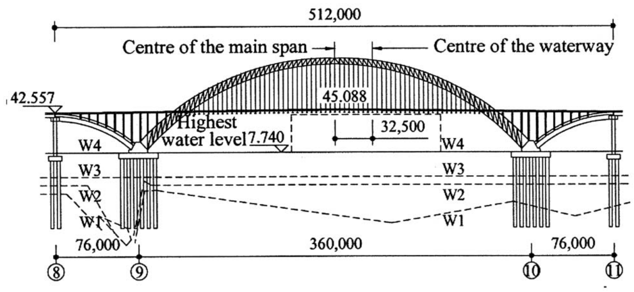


a. Bridge elevation (Yin, 2000, with permission)

b. View of the actual bridge

**Fig. 2.** Yajisha Bridge: (a) bridge elevation (Yin 2000, with permission) and (b) view of the actual bridge

2) by two barges to the construction site, lift into place (using the two towers), and join with sections 1 and 3. During the transport of this section, install a tie cable (to handle transverse thrust), remove the cable once in final position.

The major advantage of this method is that it uses very familiar/mature techniques, reducing the overall risks. However, significant concerns were raised regarding the cost and impact on marine traffic. The Zhujiang River is a very important transportation route in southern China. The Guangdong Ministry of Transportation was quite sensitive to the impacts on marine traffic. The Zhujiang River is the second busiest river in China, with 0.2 billion t of shipment in 2002. This amounts to approximately 20% of the total volume of river shipment in China ("Shipping" 2003).

In fact, this alternative called for dividing the main span into 75 m–210 m–75 m sections (instead of three 120 m-length sections), to allow for adequate river width (between the two towers) for marine transit during construction. Still, during the period of floating and lifting of the 210 m section, the waterway has to be totally closed for at least 1 day. Additional disruption to traffic will also occur during the erection of the towers and the installation of the two 75 m sections.

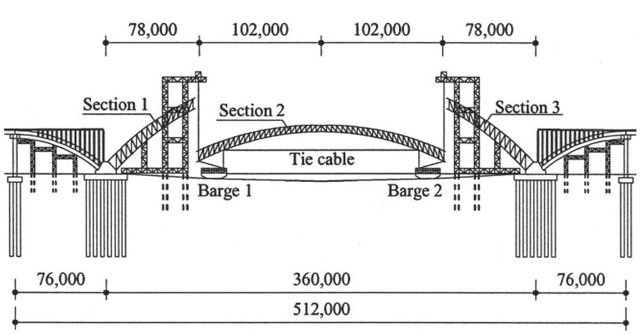


**Fig. 3.** Alternative 1—sectional lifting method (He and Yi 2000, with permission)

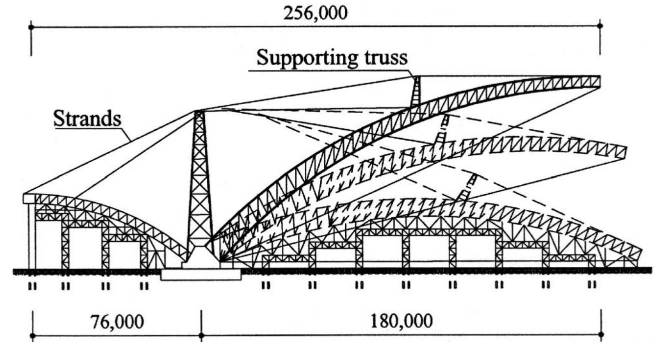


**Fig. 4.** Alternative 2—superstructure rotation method (He and Yi 2000, with permission)

Technically, to avoid the distortion of 210 m-length section during floating, two barges (supporting both ends) have to be synchronized in speed and direction. Therefore the floating has to be executed in good weather conditions without too much wind. However, the construction site is located at the sea gate of the Zhujiang River, which is normally windy. As such, the stress and distortion during floating could not be accurately forecasted. Finally, the construction and final demolition of two temporary towers was an extra cost for the owner that required closing the river again.

### *Alternative 2: Superstructure Rotation*

The previous alternative was developed by the design firm. The proposal was rejected by the owner due to the anticipated penalties for the shipping industry and other stakeholders (estimated at US \$0.55 to \$0.65 million/day) and the fact that part of the construction would take place during the hurricane season. The owner hired a construction manager, who proposed using the SRM. The design team worked with the contractor to design the SRM erection, and in the mean time, several special workshops were held by the owner to understand the risk and develop risk mitigation strategies. The estimates of direct cost for both alternatives were very close (around US \$30 million each).

Fig. 4 illustrates the use of SRM on this project. The proposal called for dividing each arch rib into two half-span sections (about 180 m each) and to fabricate each section alongside both river banks (parallel to the river). Each side would be built as a two-hinge arch. Later, they would be tilted (vertically) to the required elevation to assume their final profiles (as two half arches). The process was as follows:

1. Build the piers of the two main arches;
2. Set up the rotating mechanism on the top of each pier [see Fig. 4(a)]. This mechanism is composed of an arch abutment, a spherical hinge (1 m radius), and rollers (resting on circular track of 33 m diameter);
3. Build the side spans (76 m long) parallel to the river banks (using falsework);
4. Construct a steel tower on top of the arch abutments (required height=64 m);



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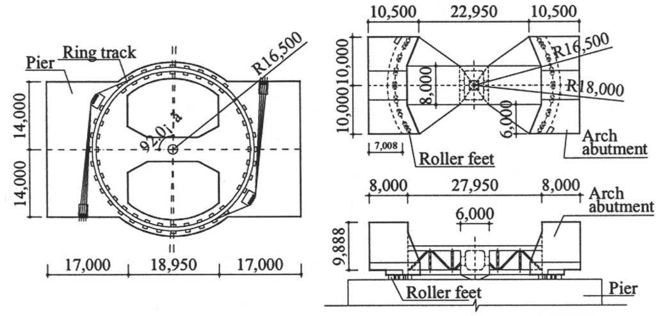
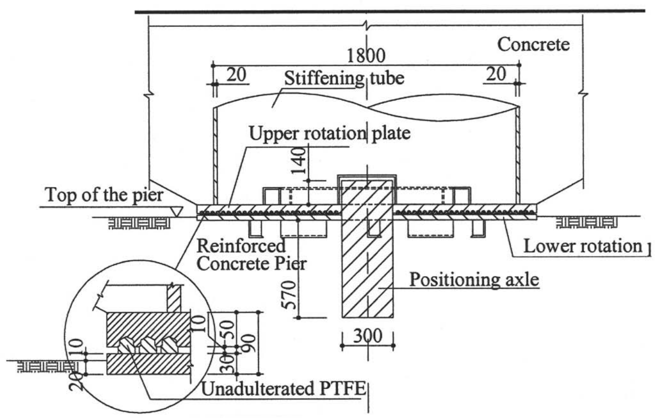



a: Layout (Yin, 2000, with permission)




b: Rotation plates and positioning axle (Hu, 2001, with permission)

**Fig. 5.** Horizontal rotation mechanism: (a) Layout (Yin 2000, with permission) and (b) Rotation plates and positioning axle (Hu 2001, with permission)

5. Build the half-spans (each 180 m long) using falsework. Use steel strands (supported by the towers) to rotate the half-spans into final profile. Use strands to support the side spans [see Fig. 4(a)]. Lock the steel strands. The whole structure should be self-balanced on top of the rotating mechanism;
6. Rotate the self-balanced structure horizontally on both sides of the river to their designated axis by hydraulic jacks. Close the gap at the crown of the arch; and
7. Seal the rotating mechanism with concrete and release the steel strands.

The major advantage of this alternative is that it has minimal impact on marine traffic. Because the major fabrication work is performed on the ground, the cost of equipment and materials will be significantly lower than conventional erection methods. The SRM also reduces most high-rise operations and, therefore, is safer than most conventional erections.

## Major Constructability Issues

The following sections discuss some of the major issues related to the constructability of the Yajisha bridge.

### *Horizontal Rotation Mechanism*

The key success of the SRM erection is a well-designed rotating mechanism. Typically, the bearing system is a spherical hinge. To assure stability during rotation, a set of rollers (resting on circular track) are installed (see Fig. 5). Normally, these rollers do not touch the tracks (typically, the clearance between track and rollers is 2–20 mm). If the structure becomes unbalanced during rotation, one of the rollers touches the track thereby providing a second support (in addition to the hinge). In most cases, spherical hinges are made of steel or reinforced concrete. Unadulterated PTFE (polytetrafluoroethylene) flakes are normally used to reduce the friction.

Due to its weight and span, the Yajisha Bridge needed a hinge 8 m in diameter. The accuracy and smoothness of such a large sphere could not be guaranteed. A new bearing system was proposed. The new system uses three points of support (instead of the traditional single point). First, a spherical hinge (2 m in diameter) was to be placed on top of the pier. The rollers were to be set to fully rest on the circular tracks (with a 33 m diameter). The only problem is that this three-point support system (one spherical hinge and two sets of rollers) was statically indeterminate—causing variable load distribution on the three points during the rotation. This means that the forces in the trusses (of each half-span) could not be verified at all times.

To assure the structural integrity of the half-spans, the three-point system was replaced by a two-point system. The two arch abutments were connected by a (relatively flexible) steel truss, instead of a rigid connection. As such, the load of the structure is transferred directly to two sets of rollers. Each set of rollers was



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composed of 16 concrete-filled steel tubes. The circular track has a width of 1.1 m, which ensures sufficient stability. The central spherical hinge was replaced with a 300 mm diameter positioning axle [see Fig. 5(b)] to ensure alignment of the vertical axis (as such, it bears a negligible load). This was surrounded by two plates (1,800 mm in width). The upper plate was tied to the truss. The lower rotation plate was embedded in the pier [see Fig. 5(b)]. To reduce friction, PTFE flakes were used between the upper and lower rotation plates and on the top of the track. The coefficient of friction was recorded as 0.0414 in one side and 0.022 in the other (Hu 2001). The starting driving force was approximately 5,000 kN, and the total rotation time was 8 h (S. Xu, Chief Project Engineer for Yajisha Bridge and Shijingshan South Station Bridge, Professional Design Institute, Railway Ministry, China, personal Communication, January 7, 2005).

After rotation, the horizontal rotating mechanism was sealed by concrete. Before casting the concrete, the upper and lower rotation plates were welded together. The PTFE flakes were removed and the track was welded to the rollers. The embedded reinforcement on the abutments and the pier top were also welded.

### Vertical Rotating Mechanism

Vertical rotation (or tilting) of bridge decks was first implemented in the Domus Bridge, Rome, Italy in the 1950s (Chen et al. 2001). However, the implementation of such a technique has been limited, at least in China. Normally, vertical rotation systems use only one set of cables to lift the half-span structure, which limits the size of such a span. Because the structure rotates vertically, the magnitude of the force in the tension cables is always changing. Using more than one set of cables requires a synchronized system of cables to assure that all of them are at proper tension at all times (otherwise, the structure could fail).

Obviously, one set of cables was not sufficient to lift the Yajisha Bridge vertically. As shown in Fig. 4, two sets of cables were connected to each side. To reduce the height of the tower, a supporting truss was erected on top of each half-span to support one set of cables. To balance the horizontal force at the top of the tower, a third set of balancing cables was employed by connecting the tower and the side span.

The synchronization of tensions in all cables was realized by adjusting the tension forces in cables. Data from angle sensors, oil pressure sensors, and elevation difference sensors were sent to a central computer. Operators could compare and adjust the required pressure of the hydraulic jacks (and in turn synchronize the tensions in cables). The vertical rotation of each side took 12 h. Each half span was lifted 79 m to its designated elevation (S. Xu, Chief Project Engineer for Yajisha Bridge and Shijingshan South Station Bridge, Professional Design Institute, Railway Ministry, China, personal communication, February 7, 2005).

### Crown Closing

At the final position, the gap between the two half-spans was 1,000 mm. The crown closing included two phases: a temporary closing and a permanent closing. The temporary closing uses a turnbuckle to close the gap between the two half-spans. This is needed to support the two arches during the permanent closing. Temporary closing can also reduce the impact of increased temperature during welding (see Fig. 6).

A temperature-elevation curve was developed (through observation) after the vertical rotation had been done. This was used to accurately define the length of the temporary closing turnbuckle. After adjusting the elevation to the correct position, the turnbuckle connection was installed. The turnbuckle connection was fastened after the shape and stress were adjusted to the designated status.

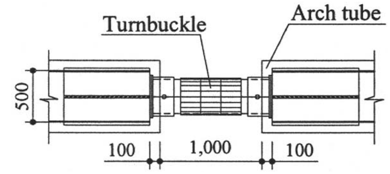


**Fig. 6.** Turnbuckle connection in temporary closing (Hu 2001, with permission)

The permanent closing was performed by welding steel tubes in the upper chord, the lower chord, and web members in each of the six trusses. The exact length of each steel tube was determined through an in situ survey and the closing follows the order of "lower chord—web members—upper chord." All welding seams were inspected using ultrasonic equipment.

After the permanent closing phase, both the upper and lower chords were welded to the abutments (of the rotation mechanism). The final step is to loosen the cables gradually and alternately until the tension in all cables is zero.

## Case of the Shijingshan South Station Bridge

The Shijingshan South Station Bridge (in Beijing) used the SRM for erecting the main girder. The bridge is a cable-stayed reinforced concrete bridge with a total rotation weight of 14,000 t (this is the heaviest cable-stayed bridge in China that used the SRM). The bridge crosses seven railway tracks (see Fig. 7). As is the case with other railways in China, these railways are heavily used, with an average rate of 1 train per 3 min. The estimate of direct loss due to railway closure is US $1,728 per min on average (MOC 2003). Furthermore, three of these seven railways are the only railway connections between Beijing and northern China. Conventional erection methods were deemed impractical as they significantly increased user costs.

The estimated direct cost for constructing this segment of the bridge using SRM was approximately US $5million. The direct cost for using traditional construction methods was about US $5.8 million. It was estimated that the owner would have to compensate the Railway Bureau for a total of US $2 million due to traffic interruptions. Moreover, the Railway Bureau would not allow the railway system to be closed for more than 3 h at a time.

The bridge construction plan for the Shijingshan South Station Bridge included rotating a span with a total length of 166.7 m (80 m on one side and 86.7 m on the other side). Twelve cables were used to hold the cantilever structure during the rotation (see Fig. 8). The rotating structure was fabricated along the railway (at a 49° angle with the central axis of the final bridge). The central rotating mechanism used a spherical hinge (3.2 m in diameter). More than 500 PTFE flakes were placed between the upper rotation plate and the lower rotation plate to reduce friction. To assure structural stability during rotation, 6 sets of arm braces were placed around the spherical hinge (with a diameter of 10 m). The distance between the bottom of the arm brace and the top of the pier is 3–5 mm.



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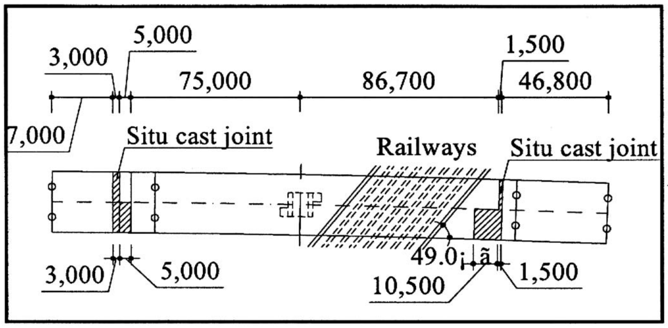


a: Bridge plan (rotating part)

b: View of the actual bridge

**Fig. 7.** Shijingshan South Station Bridge: (a) bridge plan (rotating part) and (b) view of the actual bridge

The rotation process took 68 min. Including the preparation before rotation and the clean up after rotation, the railway was closed for 95 min in total. The average rotating speed was 0.72° per min (automatically controlled by a computer). In the last stages of rotation, the driving force was controlled manually (0.1° at a time), to prevent over-rotation due to inertia.

## Analysis of SRM

Some of the benefits and drawbacks of applying SRM in bridge construction are presented below.

### *User Cost (Impact on Traffic)*

The most significant benefit of the SRM method is the minimal impact on traffic. In the case of the Yajisha Bridge, with the construction period of the Yajisha Bridge being close to over 19 months, a conventional erection method could result in large losses to the shipping industry (and all other industries depending on it). The sectional lifting method (alternative 1) was expected to block 38% of the waterway over the entire construction period due to the erection of the two towers. In addition, the waterway between the fabrication plant and the construction site would be completely closed during the floatation of the 210 m arch section.

In the case of the Shijingshan South Station Bridge, the railway was closed for 95 min during rotation. Any other conventional erection method would obviously have imposed a closure time far greater than the above mentioned 95 min (usually days or even weeks).

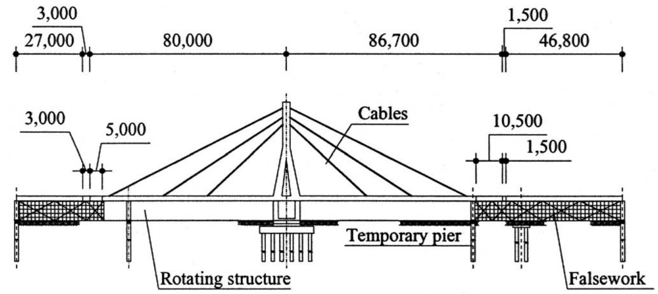


**Fig. 8.** Bridge elevation (rotating part)

### *Construction Cost*

Applying the SRM method can reduce the direct and indirect costs of bridge construction—mainly through savings in the following categories:

1. Falsework cost: The SRM significantly reduces the size of bridge falsework (especially if vertical rotation is included) and the associated labor, equipment, and material costs;
2. Equipment cost: The SRM reduces the need for large lifting equipment;
3. Labor cost: The SRM method reduces the need for working at elevated levels leading to enhanced safety and productivity. This also reduces the extra premiums for working at higher elevations; and
4. Indirect cost: The SRM reduces overhead costs due to the normally shorter construction period. In addition, the SRM reduces the need for frequent traffic control and detours.

The SRM method, however, adds the costs of building and operating the rotation mechanism to the overall project budget (including the relatively large hinges, hydraulic jacks, and labor training). However, in many large bridges (especially those that cross traffic) the savings in falsework and traffic operation outweigh the costs of the rotation mechanism. In fact, the saving on falsework itself and falsework-related labor cost is the most significant contribution of the SRM. As such, more savings are realized in bridges with higher elevations. Observation in the Qianjiang area, in Chongqing City, China, provides anecdotal evidence that when the rise of the bridge is less than 10 m, the cost of traditional construction and the SRM are similar (He 2002).

In terms of overall cost comparison, one study compared two (almost) similar bridges (Guan 1996): the Beijin Bridge and the Xingxian Bridge. Table 2 illustrates the attributes of both bridges, which were built by the same contractor in 1994, and had similar site conditions. The Beijin Bridge was built using the SRM, while the Xingxian Bridge was built using conventional full scale falsework. The cost of the Beijin Bridge was 25% less.

**Table 2.** Comparison between the Beijin Bridge and the Xingxian Bridge (Guan, 1996)

| Attribute | Beijin Bridge | Xingxian Bridge |
|---|---|---|
| Load | Car-20, Truck-100 | Car-20, Truck-100 |
| Width | 10 m | 10 m |
| Main span | 40 m–65 m–40 m | 42 m–60 m–42 m |
| Side span | 80 m–79 m | 60 m–60 m |
| Type | Concrete contentious beam | Concrete contentious beam |
| Major obstacle | Sunan Canal | Sunan Canal |
| Construction cost | US $835,000 | US $1,103,000 |



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Field data (in China) shows that for concrete arch bridges (crossing rivers), the most expensive construction method is the suspension and lifting method without falsework. The second most expensive method is the wood/steel falsework supporting method, and the most economical method is the SRM. The average construction cost is US $400–430, US $330–370, US $300–340 per square meter in China, respectively (He 2002).

### *Shorter Construction Period*

The SRM erection method normally shortens construction duration for the following reasons:
1. Major fabrication is performed on the ground, allowing for easier access for crews and more working surfaces than when using other methods;
2. The SRM reduces the size of falsework and in turn reduces the overall project duration;
3. The SRM reduces traffic disruption and traffic control activities; and
4. The SRM enhances productivity due to the fact that laborers are working at lower levels and away from traffic, which provides better and safer work zones. It also allows for easier access to different parts of the bridge before it is rotated.

The Beijin Bridge, which applied the SRM, was built within 5 months. The Xingxian Bridge needed 10 months with conventional falsework. Generally, the SRM erection method will save 3–7 months on small/medium span bridges and 7–15 months on large scale bridges (He 2002).

### *Safety*

Constructing a bridge over a waterway or highway always bears certain safety risks. The SRM almost eliminates the risks associated with construction while over traffic. However, the rotation process bears considerable risks. In fact, the SRM was perceived as too hazardous when it was first proposed due to the unusual nature of the rotation process. However, risks associated with the SRM have three positive characteristics, which should be carefully considered before dismissing the SRM (more than 100 bridges were built using the SRM in China, Germany, Italy, Japan, France, Canada, and Austria, without any failure).
1. Risks are clearly identified: The inherent risks of the SRM exist mainly during the rotation process. This process has very systematic procedures. The almost mechanical repetitiveness of the process means that if best practices are applied and if experienced workers are included, we can assure that these risks are adequately addressed.
2. Risks can be mitigated at the design stage. The main risk of the rotation process is that the bridge can fail due to unbalance, unsynchronized rotation, and/or inadequate support at the rotation base. These risks can be adequately addressed at the design stage by installing a variety of overlapping and redundant measures.
3. Reduced risk window. The most important feature of the SRM is that the risk window is reduced to the duration of the rotation process, which is fairly short compared to traditional methods.

### *Environmental Impacts*

One major disadvantage of using the SRM (especially in crossing rivers) is the fact that most of the construction activities would normally take place alongside the river (which is usually environmentally sensitive). This could have negative impacts on the environment (such as increased disturbance to local habitat on the river bank) and could also increase the owner risks and costs due to the additional environmental assessment that could be needed. In fact, this was the major reason for unsuccessful bids for the SRM implementation in Canada (F. Zhang, Project Engineer, Peto MacCallum Consultants Ltd., Toronto, personal communication, February 10, 2005). One of the best means to address such concerns is to use prefabricated elements. In contrast, the SRM could be a feasible alternative for bridges crossing roadways (especially in urban settings) as demonstrated by the case of the Sarcee Trail pedestrian overpass project in Calgary.

## Constructability of SRM

Through observing and documenting several cases of bridges that used the SRM, the research team developed a web-based system to support the analysis of the SRM constructability. This included the following elements.
- An influence diagram: This diagram portrays the factors that have bearing on the constructability of the SRM and their interrelationships. To assure constructability, design and construction teams have to understand, analyze, and plan for controlling/addressing the impacts of these factors;
- A hierarchy of objectives technique (HOT) diagram: this diagram helps design and construction teams identify and structure a unified set of objectives for the bridge design and construction plans. The hierarchy of objectives help communicate project objectives to all stakeholders and documents strategies that should be used to address the limitations of the influencing factors; and
- A database of best practice/lessons learned.

A web portal was developed to link a lessons learned database, influencing factors, and the HOT diagram to CII formal constructability concepts. Through navigating through CII formal constructability concepts, system users can find relevant lessons learned; access information about the influencing factors; and learn about relevant techniques and strategies to enhance the SRM constructability through accessing the HOT diagram.

### *Lessons Learned*

The research developed a list of lessons learned to enhance the constructability of SRM. The following section provides a sample set of lessons learned that were documented for the Yajisha Bridge:

#### Alignment between Abutment and Rollers

The innovative horizontal rotation mechanism used in the Yajisha Bridge project has several advantages, including a higher overturning resistance index. Due to the design of the sheet piles supporting the bridge pier, the diameter of the circular tracks cannot exceed 33 m, while the shorter width of the rectangular pier is 28 m, leading to a cantilevered section of the tracks of about 2.5 m. Moreover, the required distance between the two abutments of the rotation mechanism is 35.95 m [see Fig. 5(a)]. During its passage over the cantilevered portion of the tracks, the abutment could produce excessive moments at the tying truss. To alleviate this, prestressed steel strands were used to build the upper chord. However, the prestressing force could cause vertical distortion of the loads, and in turn would change the load distribution on the positioning axle and the circular track (Yin 2000).



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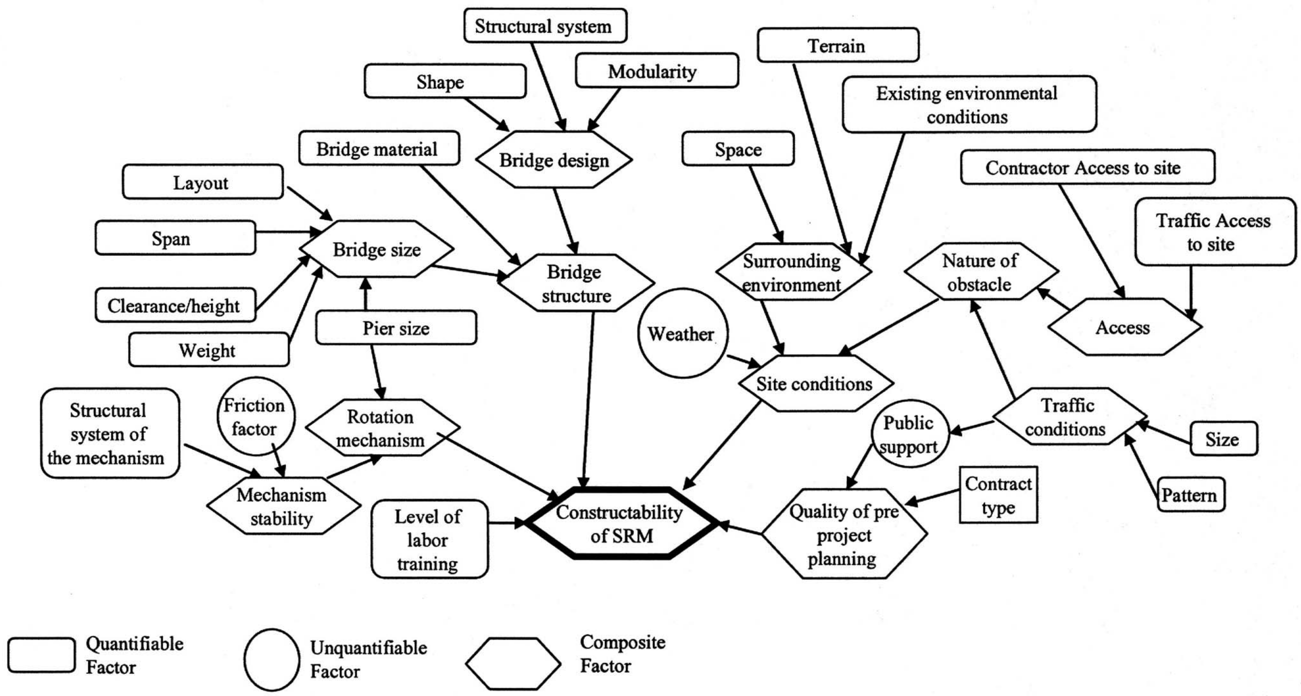


**Fig. 9.** Top level influence diagram

During rotation, this distortion has to be balanced by the eccentric moment (caused by the lack of alignment between the abutment and the rollers). This was taken into consideration in setting the dimension of the abutments. Had there been a formal constructability analysis, it would have been much cheaper to align the abutment and the rollers. This could have improved the safety factor and facilitated the rotation.

### Design of Tracks

The circular track was made using short 25-mm-thick steel plates, standing 3 mm apart to account for expansion due to the higher temperature during rotation. The plates were covered by 3-mm-thick stainless steel plates. During rotation, it was noticed that some of the stainless plates were twisted. One suggestion for overcoming this problem is to weld the vertical plates together at proper spacing (Yin 2000).

### Estimate of Friction Coefficient

PTFE flakes are usually used to reduce friction between rollers and the track. PTFE flakes have the property that its friction coefficient is inversely proportional with direct stress and proportional with movement velocity. As such, the friction coefficient is not constant during rotation. Due to the lack of theoretical analysis, most projects, including the Yajisha Bridge, adopts a conservative value of 0.1 as the friction coefficient when calculating the required driving force. The real friction coefficient measured in the Yajisha Bridge project was in the range of 0.022–0.0414 (Yin 2000). It is far less than the value assumed during the design stage. Therefore certain driving equipment was redundant. If the friction coefficient could be correctly estimated, then some savings could have been realized in equipment cost.

### Balancing Weight

Appropriate balancing weight is another important element in the SRM. Normally, the balancing weight is provided by side spans. If side spans are not heavy enough, or there are no side spans, there is then a need to add more weight (normally through concrete blocks). This only applies to lighter bridges. In heavier bridges, an additional structure could be built to provide the required balance (using cables).

## *Influence Diagram*

Understanding the factors that have bearing on the constructability of a construction method is a very important step to address their impacts and enhance site operations. The research team identified a set of generic factors that have influence on the constructability of the SRM. Fig. 9 shows the major factors considered in the influence diagram and their interrelationships. These factors have been linked to the HOT diagram and the lessons learned to allow designers and planner to understand the factors and the best means to deal with them. The major influence factors considered include:

- Level of training of labor: This could be the most important factor in assuring constructability of the SRM. The rotation of the superstructure requires following meticulous steps and a great deal of coordination. The lack of experienced crews was a major source of risk to the owners who considered the SRM in Canada (F. Zhang, Project Engineer, Peto MacCallum Consultants Ltd., Toronto, personal communication, February 10, 2005).
- Site conditions: The SRM has no specific requirements for waterways or highways/railways, but it does require an open field along both sides of a river or highway/railway. In addition, it requires a clear space in the rotation area. The availability of adequate space for building and rotating the superstructure is a fundamental factor in enhancing the construction of bridges using the SRM.
- Bridge design: The weight, layout, and dimension of the bridge have a major influence on all construction procedures.



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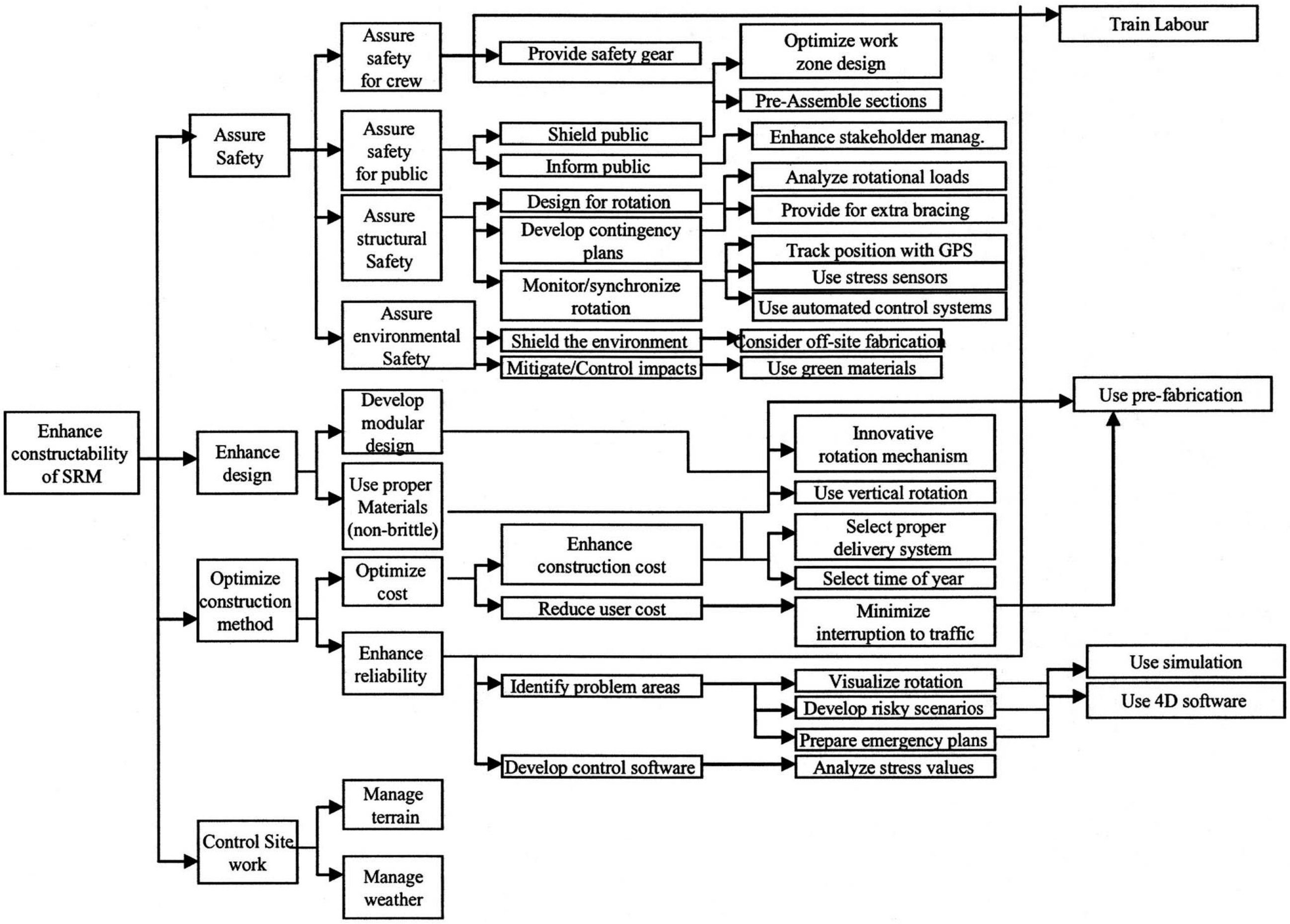


**Fig. 10.** Top level of HOT diagram

Careful analysis of the impacts of the dimensions and the need to support the structure during rotation are key for any successful implementation.

- Preproject planning: The SRM is a relatively new technique (especially outside of China). Successful implementation requires the collaboration of all partners. There is a need to adopt a less-rigid project delivery system to allow for a better environment for partnering and for conducting constructability analysis.

### HOT Diagram

Along with understanding the factors that have influence on the constructability of a construction method, there is a need to set the design and construction strategy in a manner that would put constructability in the forefront of project activities. The research documented some of the most effective strategies for enhancing the constructability of the SRM bridges. A design team can use these strategies to guide their work during the selection of design features. Moreover, through the web portal, they can link these strategies to CII formal constructability concepts. Fig. 10 shows the top level strategies in the HOT diagram, which are summarized below.

- Assure safety: This encompasses safety for crews, the public, and the surrounding environment. In this regard, careful planning, training of crews, and adequate communication with all stakeholders are some of the most important strategies to implement. To assure structural safety, designers and project managers have to work together to design the whole structure for rotation, monitor stresses during rotation (using sensors and other means), and develop proper contingency plans.
- Enhance the design: The designers of bridges using the SRM have to select proper materials that are flexible and tolerant of construction-induced loads. Modularity of the design will also help in assuring a better learning curve for crews, a unified design of the rotation mechanism, and the ability to prefabricate some elements off site. The design should investigate the use of vertical rotation as it makes for easier construction.
- Optimize construction method: This can be achieved through controlling the overall project costs and enhancing the SRM reliability (to address any risks). The project direct costs can be enhanced through the use of vertical rotation, innovative rotation mechanisms, coordination of design and planning, and selection of the proper time of year for construction (to address the impacts of wind and temperature variations). Costs to users can be enhanced through better management of traffic and effective communications with local communities. Finally, to enhance the reliability of the process and assure the proper understanding of all risks associated, project teams have to train crews, develop and address the various risky situations/



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scenarios, and use simulation (or four-dimensional visualization) to analyze construction steps.
- Control site: Project teams have to carefully manage the terrain and address any limitations that the terrain may impose on the build-up of section or their rotation. They also have to address the possible impacts of wind and temperature on the structure during rotation and final positioning.

## Conclusion

Through these two case studies, namely the Yajisha Bridge and the Shijingshan South Station Bridge, this paper presents an analysis of the SRM erection method in bridge construction. The main advantage of the method is the reduction of associated user/traffic cost. This is achieved through transferring most of the construction work (of the superstructure) to the side of the roadway or river. This enhances the overall safety of the project and could reduce direct and indirect project costs.

A web-based system was developed to support constructability analysis of SRM. The system includes clear identification and analysis of site and design factors that could have an effect on the constructability of SRM. These factors are linked to CII formal constructability concepts to help designers address relevant factors during their consideration of CII concepts. Similarly, the CII concepts were linked to a hierarchy of objectives (and strategies) for enhancing the constructability of a typical bridge. Finally, the web-based system includes access to a set of best practices and lessons learned to support future implementations.

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