Design of Beipanjiang First Bridge

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ABSTRACT
The Beipanjiang First Bridge is situated above a river and gorge of depth 575m in Beipanjiang in the border of Yunnan and Guizhou Provinces in the south-west of China with a total length 1341.4m. The bridge main span length 720m is currently the second longest span steel truss girder cable stayed bridge in the world. After the completion of Beipanjiang First Bridge, the journey time from one side to another substantially reduces from the original 5 hours to slightly over 1 hour. This paper describes the design of this cable stayed bridge.

KEYWORDS: gorge, steel truss girder, karst landform, longitudinal shifting, cantilever assembling

1 INTRODUCTION
The Beipanjiang First Bridge has a total length 1341.4m and is spanning the Beipanjiang Gorge in the border of Yunnan and Guizhou Provinces of China. The bridge construction started in March 2013, and it opened to traffic in December 2016. The overall project cost is about US$158 million.
The cable stayed bridge has two towers and seven-span continuous deck structure in steel truss girder with a span arrangement 80m+88m+88m+720m+88m+88m+80m. The approach spans on Yunnan side comprise 3 nos. 34m continuous prestressed concrete girders. The abutments on Guizhou side and Yunnan sides have lengths 2.4m and 5m respectively. The overall structure length is 1341.4m.
construction, it has attracted the major medias’ attention all over the world. Dozens of world-wide medias have given a high appraisal to the Beipanjiang First Bridge; some well-known examples are People’s Daily, XNA, CCTV, Washington Post, The Wall Street journal, Daily Mail, The Mirror, BBC, and Asahi Shimbun. Washington Post commended it “the completion of The Beipanjiang Bridge marks yet another infrastructure record in China”; and BBC acclaimed it is “China’s impossible engineering feat”.

2 BACKGROUND

The site is in the west slope of the Yunnan-Guizhou plateau and upstream of Beipanjiang basin. The gorge at the bridge location has a width 400m and a depth 565m from the deck level. The terrains are steep on both sides with slopes at angles 20-30 degrees. The site geology is dominated by Devonian-Jurassic strata and the bedrock is soluble carbonate formation. The outcrops are light grey thick-bedded to massive limestones. The main adverse engineering geology included karst, fracturation zone, unloading fractures and landslip along strata.

Since ancient times, the inconvenient transportation on Yunnan-Guizhou Plateau has restricted the development of various regions in this area, especially the economic and social development in Guizhou province. A proverb “No three feet of flat land, no three days without rain, and no families with three grams of silver” has been for a long time the best description for the rough living condition of people in Guizhou. The Wumeng mountain area on the Yunnan-Guizhou Plateau is a well-known Karst geomorphic development zone, with high mountains, deep valleys, narrow ravines and terrible climate. The Beipan River cuts the mountains into a grand gorge which separates Yunnan and Guizhou. Figure 5 shows the typical gorge that the bridge needs to cross.

![Figure 4: The Karst Landform with Mountains That the Bridge Crosses and Valleys](image)

The gorge that the bridge crosses features a great cutting depth. Years of cutting has created cliffs of 400 meters to 700 meters high along the gorge, making the gorge unprecedentedly deep and spectacular which other known gorges cannot match. The bridge is built over a deep U-shaped gorge with an altitude difference of more than 600 meters. Precipitous cliffs on both sides and complicated geological conditions have brought unprecedented challenges to the selection of bridge type and span.

Barren mountains and deep valleys have made the bridge site conditions poor. Since the construction site is narrow, water and power supplies are scarce, temporary haul roads are very steep with many sharp turns, and the river under the bridge is not open to navigation, it is rather inconvenient for heavy-cargo transportation. The bridge is built on higher ground which is one of severely frozen areas in western China. In 2008, freeze lasted for 34 days in this area. Ice accretion on power lines was up to over 80mm. Therefore, for operation safety of the bridge, it is necessary to monitor undesirable risks of the valley such as wind, fog and freeze, so that preventive measures can be taken proactively. In order to break through the above restrictions, constructors have made great efforts in aspects of structural system and theories, efficient and safe construction technologies, new health monitoring system, etc., and developed ingenious and unique solutions.

Because of the difficult traffic conditions in Guizhou, the local economy and society development have not entered the national mainstream development circle. Since the establishment of People’s Republic of China, the economic and social development level of Guizhou remains falling behind at the very end. It was not until 2015 that Guizhou for the first time entered “the trillion RMB club” with the total economic of 1,050.256 billion RMB, but was only ranked twenty-fifth out of 32 provinces and municipalities in the country. At present, Guizhou is still the most poverty-stricken
province in the country, with the largest poverty-stricken population and area, facing the most challenging task of poverty reduction.

The transportation infrastructure construction has become a strategic choice for the economic and social development of Guizhou. Road and bridge construction has become a great historical mission for engineers.

3 BRIDGE TYPE SELECTION AND ENVIRONMENTAL PROTECTION

From the very beginning of bridge type selection, designers were facing a series of challenges. The Beipanjiang First Bridge would be designed to span over a world-class gorge, which is a U-shaped grand gorge with both sides standing straight and steep as if cut by sword. Moreover, because of the fragile local ecological vegetation, it has a high demand for environmental protection, which brings great challenges to the design and construction.

If the arch bridge scheme is selected instead, abutment excavation must be performed on the cliffs. However, abutment excavation will cause serious ecological damage to the cliffs on both sides. In addition, before the construction, a temporary haul road is needed to be built on the cliff, and it will also cause serious damage to the ecological environment. The excavated earth and stone will fall into the river down below and have the river polluted. If a steel truss girder suspension bridge is chosen otherwise, it means two big anchorages are bound to be excavated on both sides. Adopting this bridge type will also cause damage to the mountain ecological environment. The serious influence of ecological environment will even directly impact on the stability of the mountain.

The steel truss cable-stayed bridge finally turned out to be the best choice for Beipanjiang First Bridge because it would minimize the impact of the bridge construction on the ecological environment. With the design philosophy of green environmental protection, human, bridge, society, and natural ecological environment are harmoniously integrated as one.

4 DESIGN AND FUNCTIONAL REQUIREMENTS

Road grade: dual carriageways two traffic lanes in each direction
Design speed: 80km/h
Design loading: Highway grade I to Chinese Standards
Bridge maximum longitudinal gradient: 1.1%, bridge deck cross fall: 2.0%
Design basic wind speed: $V_{10}=26.03\text{m/s}$ (100-year return period)
Seismic peak ground acceleration: 0.083g (475-year return period)

5 BRIDGE STRUCTURAL SYSTEM

5.1 Main Deck Girder

The cable stayed bridge deck girder is divided into either 12m or 16m long segments at main span or side spans respectively. The deck structure can be accomplished by either steel box girder or truss girder. However, considering the transportation difficulty in the site mountainous area, the steel truss girder was adopted in which each segment is split into 18 structural steel components (excluding orthotropic deck) with a maximum weight 20t for a single component. All the steel structural components were fabricated off site and they were bolt connected after delivered in bulk to site. This can avoid the use of heavy lifting machineries which are not accessible to the site.
5.2 Steel Orthotropic Deck

Orthotropic deck was used instead of concrete top slab in order to reduce the structural self weight. The weight of each orthotropic deck is 31t. They were fabricated off site and connected to the top chords of truss girder by site welding.

5.3 Bridge Bearings

Spherical bearings are used for resistance of vertical loadings at the towers and side span piers. Although the structural analysis did not reveal any tension in bearings, the bearings adopted in side span piers have an uplift capacity 1000kN as an extra safety margin. In addition, for the resistance of wind loading, horizontal bearings are set in the bridge towers.

5.4 Dampers

Four dampers are adopted between the truss girder and tower cross beam. The function of them is to reduce the displacements in tower top and deck mid span displacements as well as minimizing the moment at the tower base. When damper velocity index $\alpha =0.2$ in the dampers, the reduction in tower top and deck mid span displacements become the maximum. Therefore, the damping device parameters were determined as: velocity index $\alpha =0.2$, linear damping coefficient $=600[kN/(cm/s)0.2]$, maximum stroke 500mm and specified damping force 2300kN.

5.5 Side Span Counterweight

In order to balance the dead and live loads in the main and side spans, concrete maintenance access, infill concrete in truss members and precast concrete counterweight on pier top were employed.
to increase the self-weight. A total concrete weight of 7214t was imposed in the side spans for the counterweight purpose.

### 5.6 Stayed Cable

Two planes of fan-shaped stayed cables were adopted. Top of stayed cables are anchored to the tower top by means of steel anchor beams whereas the bottom of stayed cables are anchored to the truss girder by steel anchor boxes. Parallel strands stayed cables were used for the ease of future maintenance and replacement. There are total 112 pairs of stays in the bridge.

### 5.7 Towers

Several tower shapes were considered and compared during the conceptual design stage and H-shaped concrete tower was eventually adopted considering the aesthetic effects and structural behavior. The tower heights are 269m and 248m at the Guizhou and Yunnan sides respectively. Concrete grade C50 was used in the tower and its cross beam.

![Figure 7: Tower Arrangement](image1)

![Figure 8: Artist’s Impression of Tower](image2)

### 5.8 Foundation

For the foundation, 28 nos. of 2.8m diameter bored piles were adopted to support each tower. The piles are end bearing on the slightly weathered lime rock. The tower pile cap has a plan dimension 38.2m x 21.4m with a thickness 6m.

### 6 INNOVATIONS

Although the design and construction technology of the steel truss cable-stayed bridge have been well developed, when engineering professionals are facing a really steep gorge surrounded by giant mountains and try to build the tallest bridge in the world, they encounter many headaches such as material transportation, narrow construction site, etc. Also, without high quality rive sand as fine aggregate, how to vertically pump the concrete to the top of the 269m high tower? Furthermore, for the steel truss girder with a main span length of 720m, how to symmetrically assemble it from two sides to the middle and still ensure precise closure? Facing those problems and challenges, engineering professionals have carried out a series of innovative research and studies.

### 6.1 Design Concept Innovation

In the design of conventional steel truss girder cable-stayed bridge deck system, the structure supporting system normally adopts multi-longitudinal girder + secondary transverse girder + upper
transverse girder. High usage of steel is one shortcoming of this structure support system. Therefore, Beipanjiang First Bridge, for the first time in China, adopted "middle longitudinal girder + secondary transverse girder" as structure support system.

Based on the steel truss girder plate and truss composite system, Beipanjiang First Bridge adopted "middle longitudinal girder + secondary transverse girder" as structure support system. The bridge is designed with a middle longitudinal girder at the center line of the bridge as the support of the cross girder of orthotropic steel deck, so as to avoid longitudinal girders set below the cableway, thus avoiding longitudinal girders being repeatedly rolled, and effectively improving the fatigue resistance of the deck system from the structural and load bearing perspectives. Compared with conventional supporting system, it has reduced the amount of steel, decreased the peak value of hot spot stress of the orthotropic steel bridge deck, and increased fatigue resistance of main girder structure. In terms of structure construction, in order to reduce the overhead welding work, reduce the influence of rain and fog on the welding of steel structure, and avoid secondary stress resulting from welding shrinkage, the block-building approach is adopted, which means the steel truss girder and the bridge deck are to be divided into individual small members for factory manufacturing, and then be transported in bulk to the site. The horizontal orthotropic steel bridge deck and upper chords of the steel truss are connected with high-strength bolts. Through these structural decomposing and assembling techniques, the problem of main girder transportation and installation are solved.

Figure 9: “Middle Longitudinal Girder + Secondary Transverse Girder” Supporting System of Bridge

6.2 Construction Innovation

During the construction of Beipanjiang First Bridge, engineering professionals for the first time proposed and implemented the Construction technology of “steel truss girder whole segment longitudinal shifting and cantilever assembling under the girder bottom rail”. The whole steel girder is made up of 46 segments. Each segment of the main span truss is 8m in depth and 12m in width.

Are there any more convenient, efficient, effective and safer construction methods to overcome the limitations of cost, schedule and safety? Engineering professionals began theoretical research and full-scale model test. Through hard work, the construction technology of “longitudinal shifting and cantilever assembling under the girder bottom rail” was finally improved. Meanwhile, engineers and technicians also developed a segment launching gantry system. The construction technology of “Longitudinal shifting and cantilever assembling under the girder bottom rail” means erecting a steel truss girder segment production platform in the pier area under the main tower, vertically lifting the whole segment to the longitudinal shifting machine, then through the longitudinal shifting machine transporting the girder segment to an independently invented launching gantry system, lifting the whole segment to the corresponding design position, splicing after precise fine tuning in X, Y and Z directions, longitudinally shifting erecting machine, tensioning stay cables, and finally completing one hoisting cycle. The major characteristic of this technology is that segments are spliced in the air, instead of individual spare parts splicing, which greatly reduces the safety risk of air splicing, and also speeds up the splicing progress. Under the scheme of “steel truss girder longitudinal shifting and cantilever assembling under the girder bottom rail”, the construction period is shortened by one half to 4 days for each segment, compared with the scheme adopting a conventional full swing derrick crane.
The construction technology of "longitudinal shifting and cantilever assembling under the girder bottom rail" is a domestic initiative. This innovative technology is of great significance to the construction of similar bridges in the gorge areas in China and abroad.

Figure 10: Longitudinal Shifting and Cantilever Assembling and Full-scale Model Test for the Bridge

6.3 Material Innovation

River sand is scarce in Guizhou province. How to deal with construction sand in the bridge construction has become another big problem. However, the usage of machine-made sand has effectively solved this problem. The machine-made sand, as the name implies, is the sand manufactured by the machine. During the construction, engineering professionals developed the batching technology of machine-made sand self-consolidating concrete, which can achieve the required flow and compaction of machine made sand concrete under the action of gravity without vibration. This guaranteed the construction quality, substantially minimized the numbers of workers, and eventually reduced the cost to the maximum extent. The bridge piling foundation, pile cap, tower and other structural components of the bridge all adopted the machine-made sand self-compacting concrete, and successfully reached the maximum pumping lift of 269m.

6.4 Operation and Management Innovation

The bridge site is situated in the extremely harsh climate, often with freezing, hail, low freezing weather, and other natural disasters especially the icing phenomenon occurred in the winter, which not only bring difficulties to the construction of the bridge, but also bring challenges to the management and maintenance of the bridge. For this reason, the engineering professionals developed a set of freezing monitoring technology. This set of monitoring system for freezing monitoring is developed in two aspects. One is that the system designed a set of freezing monitoring and early warning system based on micro environmental monitoring, image recognition, and dynamic-static characteristics identification of cable freezing. Another one is that, according to the freezing image captured by the camera, the system automatically carried out a series of precise calculation, and compared before and after freezing thickness and boundary, then carry out early warning and propose a plan to deal with the hazard may cause by the freezing.

7 STRUCTURAL ANALYSIS MODEL

7.1 Global Analysis Model

Figure below indicates the global analysis model for the whole bridge. The software MIDAS/Civil was used for the structural analysis. Non-linear effects including stayed cable sagging and P-Δ were also taken into account. The bridge is divided into 5193 elements (including the virtual elements for traffic lanes) and 2087 nodes.
7.2 Live Load Displacement

Due to the effect of traffic live load, the maximum mid span deflection is 790mm which is equivalent to 1/911.4 of mid span length.

![Bridge Deck Displacement due to Live Load](image)

7.3 Structural Dynamics

Structural dynamic analysis was performed for the bridge completion status. The frequencies for various bridge vibration modes are summarized in below table.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Bridge Vibration Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1114</td>
<td>Main Deck Longitudinal Vibration</td>
</tr>
<tr>
<td>2</td>
<td>0.2073</td>
<td>Main Deck Symmetric Transverse Vibration</td>
</tr>
<tr>
<td>3</td>
<td>0.2413</td>
<td>Main Tower Asymmetric Transverse Vibration</td>
</tr>
<tr>
<td>4</td>
<td>0.2516</td>
<td>Main Tower Symmetric Transverse Vibration</td>
</tr>
<tr>
<td>5</td>
<td>0.3102</td>
<td>Main Deck Symmetric Vertical Vibration</td>
</tr>
</tbody>
</table>

7.4 Construction Stage Stability Analysis

Stability analyses for cases of longest cantilevers and self standing tower were also conducted. For the former case, the factor of safety is 25.9. For the latter case, the factor of safety is 12.1.
8 BRIDGE DECK ERECTION METHOD

Counterweights are needed in the side spans as described above. For better control of side span deck construction, the side spans were erected prior to the main span. The side spans can be erected by either incremental launching method or supported on temporary scaffolding. Considering the side span deck level is about 90m from ground, the temporary scaffolding would be substantial and thus the incremental launching method was adopted for side span erection.

For the main span deck structure, rotatable lifting crane on deck level was employed for the erection. The crane maximum lifting weight is 180t. The truss components were delivered to the lifting crane position by truck. The stayed cables were installed in parallel with the main deck erection.

9 SPECIAL ENGINEERING STUDIES AND DESIGN OPTIMIZATION

9.1 Wind Loading

The wind loading on the bridge becomes complex due to the deep gorge, high deck level and tall towers. It is difficult to obtain accurate wind design parameters using the conventional approaches. In connection with the complicated topographic condition and the aerodynamic properties of steel truss girder, special engineering studies including wind tunnel test and on-site measurement of truss girder vibrations and other structural behaviours due to wind in similar mountainous terrain were carried out. All these results were used for establishing the wind loading design parameters for the bridge.

9.2 Orthotropic Deck Design Optimization

In the conventional orthotropic deck design, at least 1-2 nos. of longitudinal beams are adopted located directly below the wheel positions of large trucks. Under repeated wheel loading, the top plate above the longitudinal beam may become a weak point leading to fatigue issue. In our design, we have minimized the longitudinal beam with only one in the middle and used larger secondary transverse
beams for supporting. This can avoid the longitudinal beam directly under the truck wheels and hence reduce the possible fatigue hazard.

![Figure 15: Longitudinal and Transverse Beams Arrangement in Orthotropic Deck](image)

9.3 Analysis of Fatigue Sensitive Zone in Orthotropic Deck

In this project, three-dimensional solid modeling was employed to identify the fatigue sensitive zone in orthotropic deck. The results indicated the weld between U rib and top steel plate has large stress concentration. When the traffic wheel loadings imposed above two adjacent U ribs, the tensile stress becomes very large in the welds between U ribs and top steel plate and this is the major reason of occurrence of fatigue crack in this position.

![Figure 16: Fatigue Analysis for the Weld between U-ribs and Steel Top Plate](image)

10 ECONOMIC AND SOCIAL BENEFIT

After the completion of the Beipanjiang First Bridge, it signifies the full operation of Hang Rui Expressway (G56) that is 3404 km long in total and connect seven provinces in China including Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Guizhou and Yunnan. After the bridge opened to traffic, the travel time from Xuanwei to Liupanshui is substantially reduced from original 5 hours to slightly over 1 hour.

Shuicheng County located in the Guizhou side of Beipanjiang First Bridge, which is not only abundant with coal resources, but also famous of it’s good quality walnut and kiwifruit. Xuanwei City located in the Guizhou side of Beipanjiang First Bridge, which is the place of manufacture of Chinese famous brand “Xuanwei ham”. After Beipanjiang First Bridge opened to the traffic, the products and resources near the site will be conveniently transported through the Hang Rui Expressway to Centre and East regions of China. Yunnan and Guizhou provinces are the regions where Chinese minorities live in compact communities, with strong ethnic minorities atmosphere and a beautiful natural environment. Moreover, in Shuicheng County, there are famous scenic spots, such as Yuhe National
Forest Park; folk festivals, such as the torch festival of Yi nationality; and other cultural products, such as the farmer painting. Xuanwei City has scenic spots, such as Nizhu River Canyon that is in the upstream tributary of Beipanjiang River. The bridge is joined together with Yejiping tourist spot and Beipanjiang gorge, so the bridge and the miraculous and magnificent natural scenery constitute the ingenious combination of the humanities and the nature. At the highland of the grand rift valley, the Beipanjiang First Bridge viewing platform is established for sightseeing purpose, available for free climbing, cloud road, aerial ladder, and hiking trail, which therefore formed a new mode of tourism, so called "bridge tourism". The traffic situation of Guizhou and Yunnan province and even other western regions will be further improved. Traffic improvements will further stimulate and push forward the economical development of the two provinces to a higher level.

Figure 17: Glass tread surface partially set on the skywalk and campsite at the Gorge bottom

11 CONCLUSION

The bridge is located in the plateau mountainous area with precipitous topography. Barren mountains and deep valleys have made the bridge construction rather difficult. Meanwhile, the bridge is in harmony with the magnificent natural landscape of the Beipanjiang grand gorge. The structural system of “middle longitudinal girder + secondary transverse girder” applicable for the steel truss has greatly reduced the amount of steel usage, decreased the peak value of hot spot stress of the orthotropic steel bridge deck and increased fatigue resistance of main girder structure. The construction technology of “longitudinal shifting and cantilever assembling” has saved about half of the construction time compared to conventional full swing derrick cranes, increased work efficiency, shortened construction period, reduced safety risks and enhanced assembly accuracy. The technology can be generally applied to other cable-supported bridges over valleys. The usage of machine-made sand self-compacting concrete has not only ensured construction quality, but also facilitated the construction and greatly reduced the workload and work time. As the Beipanjiang First Bridge is open to traffic, people can travel more conveniently and faster. The journey time from Xuanwei downtown, Yunnan to Liupanshui, Guizhou can be shortened to slightly over 1 hour from about 5 hours before.

12 REFERENCES

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