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Analysis of innovative structural design of Liyutuo Lounge Bridge in Dujiangyan

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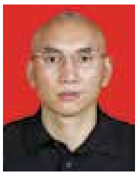

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Professional paper

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Analysis of innovative structural design of Liyutuo Lounge Bridge in Dujiangyan

According to its design, the Liyutuo Lounge Bridge combines a multilayer frame structure with a large bridge structure, offering a solution involving a unique dual-use structure. The transport layer of the superstructure is a prestressed concrete rigid frame, and the pier, girder, and cross girder, are rigidly connected, and have typical characteristics of a prestressed concrete bridge structure and frame structure. For the structural design of pier foundations, the post-grouting and a combination of longitudinal tie beams are used to solve the challenges associated with a small pile diameter and large loads.

Key words:
Liyutuo Lounge Bridge, integration, structural design, optimization, innovation

Stručni rad

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Analiza inovativnog projekta mosta Liyutuo Lounge u Dujiangyanu

U projektu mosta Liyutuo Lounge višekatna okvirna konstrukcija kombinirana je s masivnom konstrukcijom mosta, te je tako projektirana jedinstvena građevina dvostruke namjene. Prometni dio rasponske konstrukcije mosta je prednapeti kruti betonski okvir, kruto spojen sa stupom, nosačem i poprečnim nosačem koji se odlikuju tipičnim značajkama prednapete betonske konstrukcije i okvirne konstrukcije. Pri projektiranju temelja stupa, primjenjeno je naknadno injektiranje te kombinacija uzdužnih veznih greda kako bi se riješili problemi malog promjera pilota i velikog opterećenja.

Ključne riječi:
most Liyutuo Lounge, integracija, projekt konstrukcije, optimizacija, inovacija

Fachbericht

Xianbin Huang, Chenyang Liu, Yongding Tian, Chunyang Chen, Jialin Xu, Jian Wu

Analyse des innovativen Brückenprojektes Liyutuo Lounge in Dujiangyan

Im Brückenprojekt Liyutuo Lounge wird die mehrstöckige Rahmenkonstruktion mit der massiven Brückenkonstruktion kombiniert, wodurch ein einzigartiges Gebäude mit doppeltem Verwendungszweck entsteht. Der Verkehrsteil der Spannweitenkonstruktion der Brücke ist ein vorgespannter starrer Betonrahmen, starr verbunden mit dem Pfeiler, dem Träger und dem Querträger, die sich durch typische Merkmale der vorgespannten Betonkonstruktion und der Rahmenkonstruktion auszeichnen. Bei der Planung des Pfeilerfundaments wurden nachfolgende Vergussarbeiten sowie eine Kombination der Längsverbindungsbalken angewendet, um die Probleme des kleinen Pfeilerdurchmessers und der großen Belastung zu lösen.

Schlüsselwörter:
Brücke Liyutuo Lounge, Integration, Konstruktionsprojekt, Optimierung, Innovation

1. Introduction

The structural design of the Liyutuo Lounge Bridge features unique innovations. The overall bridge is an integrated structure consisting of a multilayer frame structure and a large bridge. A combination of a rigid frame structure and a prestressed bridge structure is used in the transport layer of the superstructure. The high-strength profile steel, high-strength steel rebar, and high-strength concrete, are combined in the pier column of the substructure. In addition, post-grouting piles and longitudinal girders are used to strengthen pier foundations. This design scheme solves the challenges associated with large loads, long span and small column pile [1-5]. The roadway slab and girders meet bridge and building codes [6-9], and the seismic design of the frame column and main girder meet the building code, and were verified based on the bridge code. The effects of the design drift limit, gravity load, and the effect of earthquakes on the design strength of the frame structure, should be considered during the design process [10-12]. This unique dual-use structure was selected for the following reasons. First, this structure is a development goal of the city of Dujiangyan, which is a famous tourist resort in China, renowned historical and cultural city, and a tourist city. Second, according to flood discharge requirements, the longitudinal spacing distance of piers is 30 m, and the width of the positive side of the pier should not exceed 1.5 m. Third, in addition to considering the structural forces in the structural design [13], frequent and severe earthquake conditions must also be considered. The risk of strong earthquakes should be taken into account because the Liyutuo Lounge Bridge is located 20 km from the epicentre of the Wenchuan "5/12" earthquake. The high erosion risk should also be considered because the bridge site is 8.2 km from the Zipingpu Reservoir Dam.

1.1. Bridge description

The Liyutuo Lounge Bridge is located 1200 m upstream of the Qingcheng Bridge, which carries the national road G213 to Dujiangyan. The first floor of the bridge is used as a roadway and sidewalk, i.e., as the transport layer. The second to fourth floors are designed following the form of antique landscape architecture with a viewing terrace [14-16]. A rendering of the bridge is shown in Figure 1.

The bridge subsoil is composed of Quaternary Holocene deposits (Q4me) and a Quaternary Holocene river transported diluvial deposits (Q4al+pl). The geotechnical engineering character index, pile tip resistance, and pile side resistance, are presented in Table 1. The soil profile is shown in Figure 2.

Figure 1. Rendering of Liyutuo Lounge Bridge

The peak flow of the hundred-year design flood for Liyutuo Lounge Bridge is 3748 m^3/s. The corresponding flood water level is 722.11 m with a backwater height of 0.28 m. The lowest elevation of the bottom of the main bridge is 723.20 m, which complies with the hundred-year flood discharge requirements. The mathematical model results indicate that, after bridge construction, the hundred-year flow area decreased by 5.0 %, the maximum backwater height is 0.28 m, and the maximum backwater length is 460 m. Thus, the backwater amplitude of this project is small and has only a small effect on the river water level for flood control.

The sediment of the bed load and suspended load in the Jinma River amounts to approximately 9 million tons per year. Most of this sediment comes from the Minjiang mainstream flood. The construction of the Zipingpu Water Conservation Project

Table 1. Measurement results

Number	Geotechnical name	Layer thickness [m]	Gravity [kN/m³]	Internal friction angle [°]	Allowable bearing capacity [kPa]	Standard value of ultimate pile side resistance [kPa]	Standard value of ultimate pile tip resistance [kPa]
	Fill soil	1.0-5.6	17.5	/	/	/	/
②	Fine-grained sand	0.4-1.2	18.5	20	110	40	/
③-1	Pebbles mixed with soil	1.5-10.0	20.0	28	180	100	/
③-2	Pebbles	1.2-15.3	20.5	35	320	140	/
③-3	Boulders mixed with soil	1.5-13.9	21.0	40	550	200	3000
③-4	Boulders	5.7-32.0	22.5	45	800	300	4000

greatly reduced the sediment concentration in the river, but the riverbed erosion could be increased by flooding.

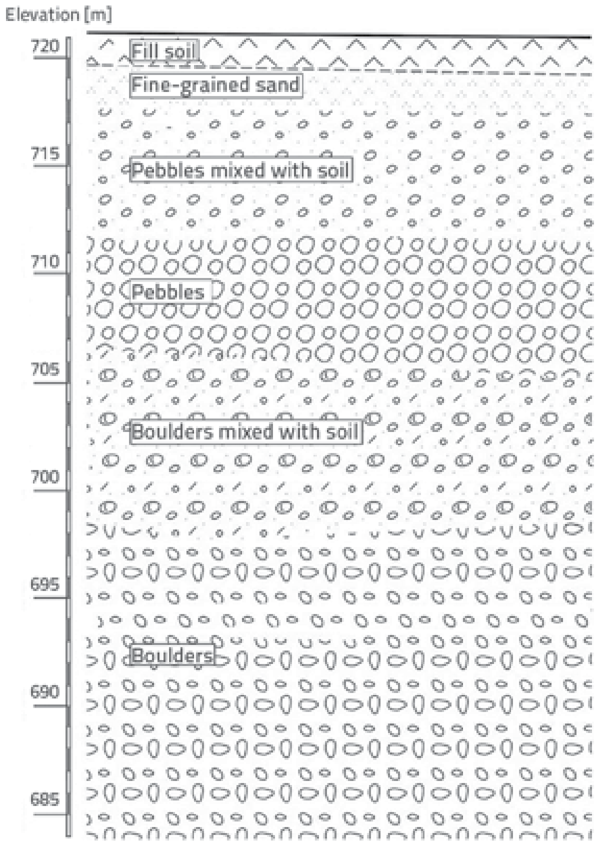

Figure 2. Map of geological cross section

1.2. Span arrangement

The span arrangement of the Liyutuo Lounge Bridge is 13×30 m, and the overall length is 579.5 m. The main bridge is 391.5 m long and it consists of three structural units: one central unit and two side units. The central unit is 5×30 m, out of which the central 3×30 m segment is the consolidated pile and girder structure. On the two sides of this central segment, one end contains the rigid connection, and the other end contains the hinged connection. The side unit is 4×30 m, where the 3×30 m segment is the consolidated pile and girder structure, and the remainder is consolidated at one end and hinged at the other, see figures 3 and 4. The central unit is investigated in this paper. The structural model of the central unit is shown in figures 5 and 6. The structural system of this bridge is a prestressed concrete rigid frame, and the main girder is a rectangular beam with a solid cross-section made of prestressed concrete. The bridge piers are generally 8.5 m high except for the boundary pier 5.4 m in height. The pier cross section is rounded, and features profile steel. The foundation of the bridge is formed of the bearing platform and a group of piles. Tie beams are installed on the longitudinal and lateral sides of pile caps.

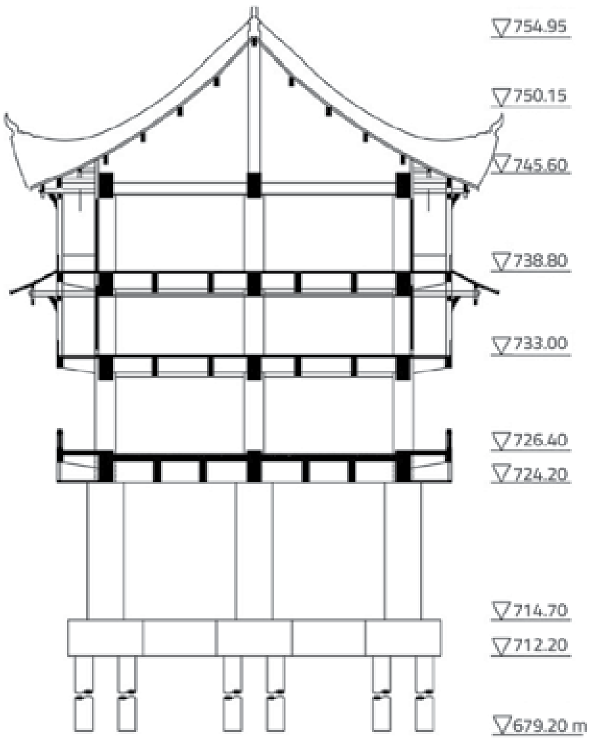

Figure 4. the cross-sectional view of 1-1

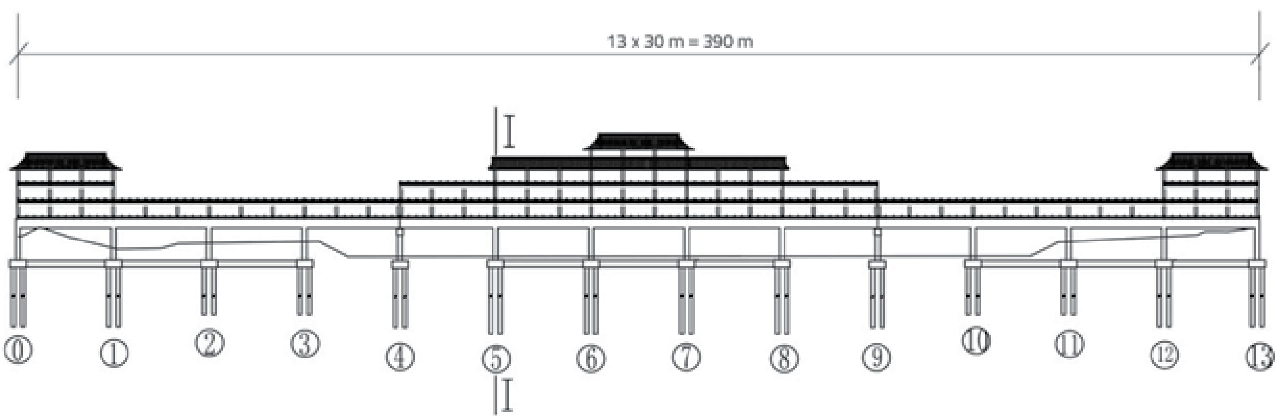

Figure 3. The Longitudinal profile of the main bridge

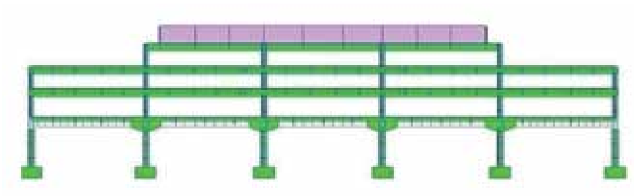

Figure 5. Front view of structural model for central unit

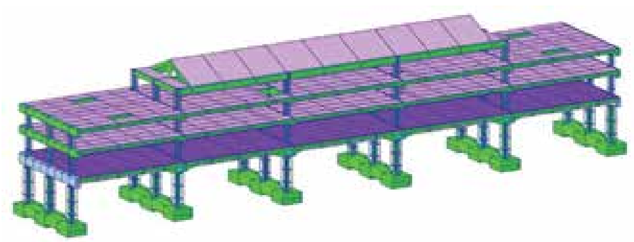

Figure 6. Side view of structural model for central unit

1.3. Superstructure design

The central unit of the main bridge makes use the local seismic isolation system of cantilever beams, which can effectively release temperature-induced stress and resist horizontal forces. The transport layer in the main bridge superstructure is a 4 × 30 m + 5 × 30 m + 4 × 30 m prestressed concrete rigid frame. The arrangement and configuration of the main girder is presented in figures 7, 11, and 12. There are three girders in the transverse direction of the bridge, and longitudinal beams of the roadway are installed between adjacent girders. The main beam is consolidated with the bridge pier, and the main transverse beam is arranged at the connection joint between the main girder and the bridge pier (Figure 7).

The longitudinal beam of the roadway and main girders use a prestressed structure with the high-strength low-relaxation steel, and GQJZ17500ZX-e60 seismic isolation bearing steel bearings are used as the side span bearings. They are marked with red dots in Figure 7.

2. Innovative analysis of substructure design

The main frame of the Liyutuo Lounge Bridge is a composite structure made of profile steel and reinforced concrete. The main girder of the superstructure is supported by single-row, three-column reinforced concrete bridge piers of circular cross section, and the top of the rigid connection pier is rigidly consolidated with the main girder and the main transverse beam of the superstructure (as shown in figures 10 and 12). This project is located on the Jinma River, which is near the main flood-draining channel of the Mingjiang River. The span arrangement of the Liyutuo Lounge Bridge is controlled by the P=1 % flood level of the Jinma River. According to the flood passage requirements examined and approved by the Yangtze River Conservation Committee, the longitudinal span of piers is 30 m, and the pier column width on the positive side cannot exceed 1.5 m [17].

2.1. Pile foundation design

Pile foundations are 33 m in depth, 1.2 m in diameter, and are made of C40 underwater concrete. The expected vertical and horizontal bearing capacities of each pile are 33,000 kN and 2200 kN, respectively. The post-grouting technology is used at the side and bottom of all piles. To verify the bearing capacity of pile foundations, static load balancing tests in vertical direction

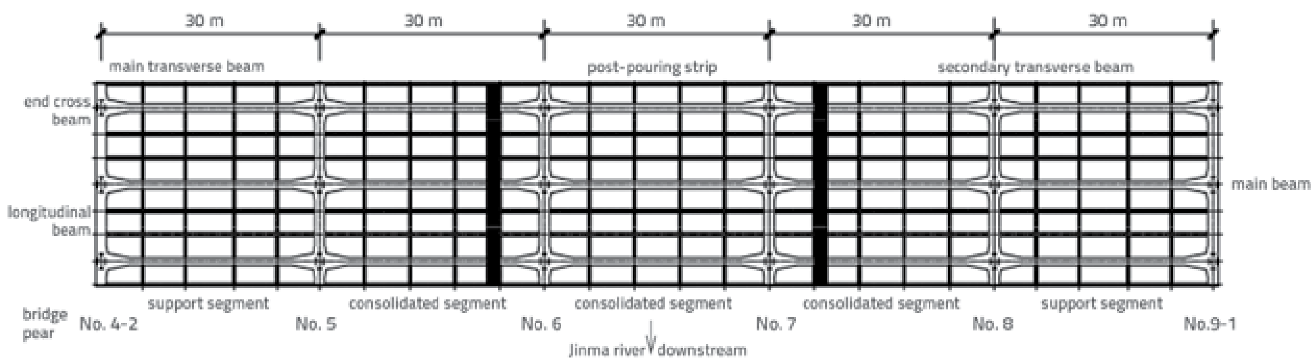

Figure 7. Beam layout in transport layer

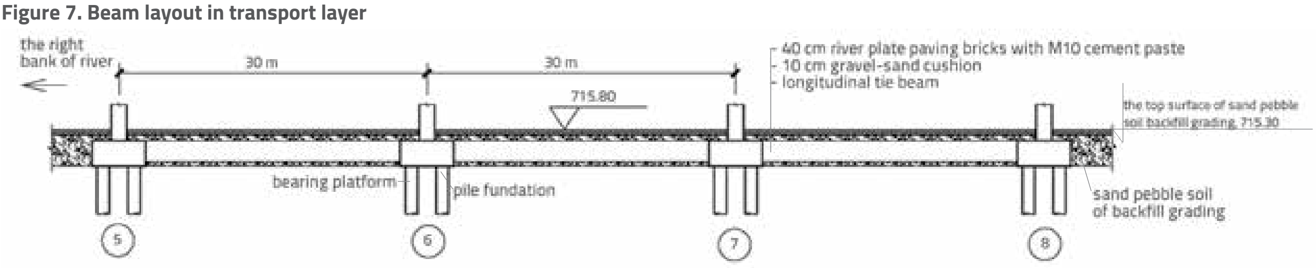

Figure 8. Longitudinal backfill of pier foundation pit (5 to 8)

were conducted on piles 3c2 and 3c4 at the right bank of the river, while horizontal loading tests were performed on piles s1, s2, 3c2, and 3c4, [18, 19].

Longitudinal and transverse tie beams are installed at each bearing platform in both the longitudinal and lateral directions, and the longitudinal beam of the bearing platform has a rectangular cross section measuring 0.85 m × 2.0 m (Figure 8). The method of using post-grouting and installing collar beams to increase bearing capacity of the bridge structure is one of innovative features of the substructure design of the Liyutuo Lounge Bridge.

Figure 9. Diagram of profile steel and steel bar arrangement for pier

2.2. Structural design of the pier

Expected vertical and horizontal loads are 4 × 33,000 kN and 4 × 2200 kN, respectively. The rigid connection pier is 8.5 m in height, and rounded solid bent frame RC piers are used in pier design. Pier dimensions are 1.5 m × 2.5 m. The width of the water-retaining surface is 1.5 m. The horizontal section and reinforcement of the 2.5 m long piers are shown in Figures 9 and 10, respectively.

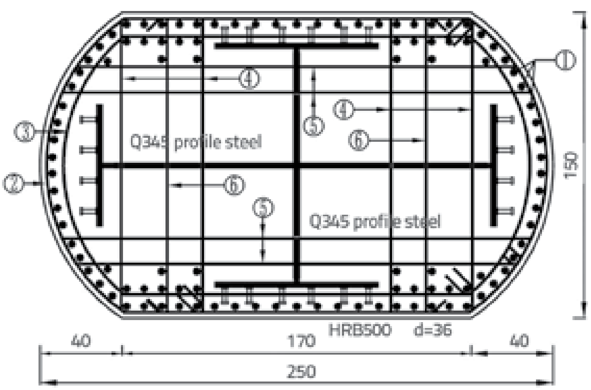

Figure 10. Bridge pier reinforcement (Q345 profile steel)

Appropriate incorporation of profile steel and numerous reinforcing steel bars into a limited cross section is a challenging problem for designers. Among other challenges, this problem includes determination of appropriate locations for steel bars and concrete cover, and appropriate allocation of profile steel and vertical steel bars at the rigid connection pier. To solve these problems, Q345 profile steel and 40 mm steel plates are bi-directionally placed in the horizontal section of piers 6 and 7. Each 8.5 m high pier requires the following materials: 24,987 kg of profile steel, 11,653 kg of HRB500 vertical main steel bars 36 mm in diameter, 4916 kg of HRB400 reinforcement stirrups 14 mm in diameter, and 28.8 m^3 of C50 concrete. The bridge piers are consolidated at the junction of the main transverse girder and main girder using Q345 profile steel, HRB500 main reinforcement steel, and C50 concrete to improve the bearing capacity. The combination design involving profile steel, reinforced concrete column and 6 direction nodes (piers, main transverse beam, and main girder) is an obvious innovation of this project.

3. Innovative analysis of the main bridge superstructure design

The force transfer at superstructure level in the central unit of the main bridge is operated as follows: upper frame beams, upper frame column, haunched frame joints of the main transverse beam end, and pier columns. For the transport segment of the main beam, the force is transferred in the following order: roadway deck, secondary transverse beam, longitudinal beam of the roadway deck, main transverse beam, haunched frame joints of the main transverse beam end, and pier columns of the bottom frame.

Structural design must simultaneously meet requirements for building standards and bridge standards. To satisfy seismic requirements and to ensure good integrity of the structure, a prestressed structure based on bridge design codes and a prestressed concrete frame based on building design codes are used in this project. The superstructure uses neither a beam-bridge structure, which includes a simply supported beam, a continuous beam and a continuous rigid frame, according to the design concept of bridge codes, nor the reinforced concrete frame structure according to the design concept of building codes.

3.1. Main beam design

The central unit includes main longitudinal beams and other longitudinal beams. In total, three main longitudinal girders rest directly on the main transverse beam, and main longitudinal beams, piers, and main transverse beam are consolidated. Six longitudinal beams rest directly on the main transverse beam. The main beam has a variable rectangular section and consists of a prestressed concrete structure with eight bundles, each of which consists of seven low-relaxation prestressed steel strands (Figure 11). Each steel strand is longitudinally curved according to stress characteristics, and the plane arrangement is also curved to stagger the layout of the Q345 profile steel in the piers and the end section. Considering the continuous temperature stress and the concrete shrinkage stress of the framework and bridge deck, two post-cast strips are designed with improved shrinkage-compensating concrete; these strips are 150 cm wide and are arranged in the central unit. The strands of all main beams are connected by ML15-7 surrounding suspension squeeze connectors at the position of the post-cast

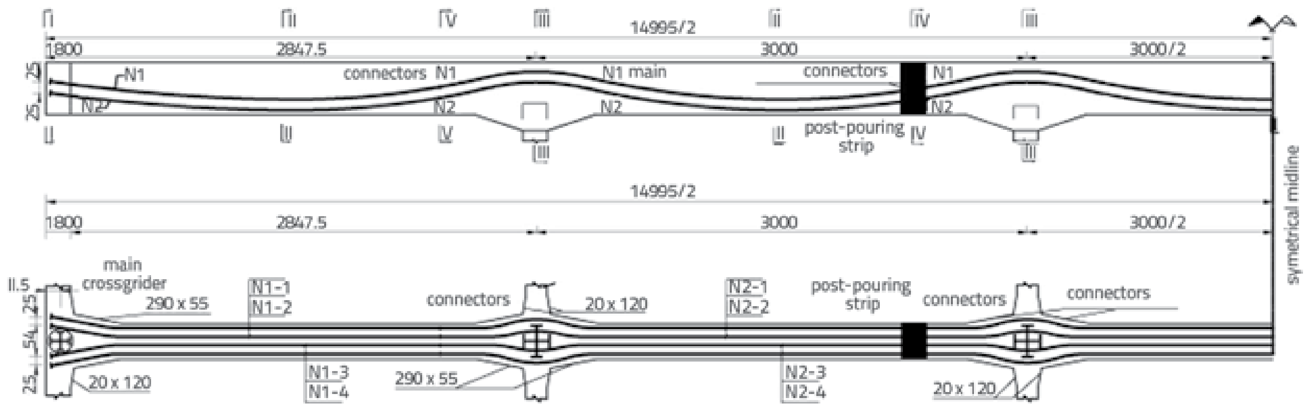

Figure 11. Arrangement of prestressed tendons in the main beam

strips, and 32 sets of connectors are arranged along a beam. Two longitudinal beams with prestressed concrete are parallel to the main beams of the Liyutuo Lounge Bridge.

There are many innovative features in the main beam design. The main innovation is combining the frame structure and the prestressed concrete structure of the bridge. Main beams solidify the pier and cross-beam connection, i.e., the framework. In the prestressed concrete structure, the longitudinal steel strands of the main beam have a bidirectional curve. To resist the positive moment at the mid-span and the negative moment at the support, the steel strands are bent downward and upward, respectively. The main beams have connectors to link the longitudinal prestressed tendons at the post-cast strip. A part of the prestressed tendons pass through the Q345 profile steel (Figure 11). Therefore, the longitudinal beam and the rigid connection of the steel strand of the main girder are highly challenging to design and construct.

Figure 12. Bridge pier, main girder and main cross-girder

3.2. Construction design for central unit of the main bridge

Longitudinal steel strands of main beams bend in both plane and elevation directions and are forcibly separated at the post-cast strips (connectors are used to connect them). The longitudinal steel strands pass through piers and are cramped with the vertical Q345 profile steel and vertical HRB500 main reinforcement. The installation of the longitudinal steel wire of the main beams is challenging. Therefore, the construction process plan must be developed during the design phase. The construction process of the central unit of the main bridge has 5 stages:

<u>Stage one:</u> Construct the pile, bearing platform and main piers; erect the scaffold; and determine the elevation of the formwork. Then, erect the formwork and arrange welding points or prestressed reinforcement (e.g., main bars and stirrups). Install the bellows and the corresponding strand. Finally, pour C50 shrinkage-compensating concrete at the beam.

<u>Stage two:</u> Conserve concrete to reach the 100 % design strength at a curing time longer than the minimum of 14 days. Then, apply tension to the first segment of the steel strand and grout-reserved hole in the strand with the M50 chlorine-free compensation shrink cement slurry. Finally, connect the steel strands with ML15-7 surrounding the suspension squeeze connector at the anchor end and the corresponding M15-7-type anchor at the beam end.

<u>Stage three:</u> Continually conserve concrete on both sides of the post-cast strip for at least 42 days. Chisel the marginal concrete of the first post-cast strip. Pour the first post-cast strip with the C55 shrinkage-compensating concrete, and cure each post-cast strip for at least 28 days [20].

<u>Stage four:</u> After the curing time of the first post-cast strip exceeds 14 days and the concrete attains the 100 % design strength, apply tension to the second segment of the prestressed steel cable and grout-reserved hole in the strand with the M50 chlorine-free shrinkage-compensating concrete slurry. Then, connect the strand with the ML15-7 surrounding suspension squeeze connector at the anchor end and continue conserving the first post-cast strip for at least 28 days. Finally, chisel the marginal concrete of the second post-cast strip, and pour the second back strip with C55 shrinkage-compensating concrete. The curing time of the post-cast strip should be at least 28 days.

<u>Stage five:</u> After the second back strip has been cured for more than 14 days and the concrete has attained 100 % of the design

strength, apply tension to the third section of the prestressed steel cable and the grout-reserved hole in the strand with the M50 chlorine-free shrinkage-compensating concrete slurry. Use the ML15-7-type anchor at the end of the beam to anchor the steel strands, and seal the connection with the M50 chlorine-free shrinkage-compensating concrete slurry.

In this construction process, a contradictory handling mechanism of the continuous strand and post-cast strip in the central unit is proposed, i.e., using a steel strand connector and hierarchically pouring the main beams and post-cast strip concrete. This mechanism ensures continuous force characteristics of the strands and reduces the temperature stress and shrinkage stress of the concrete after setting the back strip design.

4. Discussion

The innovative features in the design of the Liyutuo Lounge Bridge are remarkable; in particular, the multilayer frame structure is applied for the first time to a large bridge. In addition, the structural design scheme involves multi-model and multi-software techniques for conducting an elastic and elastoplastic analysis of the box support conversion and multi-span continuous prestressed–steel reinforced concrete (SRC) under frequent earthquake and rare earthquake conditions.

Pile foundations involve a small pile diameter and large load; post-grouting is conducted after formation of piles. Moreover, longitudinal tie beams are innovatively arranged in a bearing platform. Because the pier span and longitudinal cross-sectional dimensions are limited by the flood requirement of the Yangtze River Water Conservation Commission, the cross section has an "arc + rectangle + arc" shape with a rigid skeleton made of Q345 profile steel and HRB500-grade steel 36 mm in diameter.

The entire structural system designed to withstand vehicle load is a unique prestressed concrete rigid frame. Three structural units of the main bridge have different characteristics. The central unit has five prestressed spans, three of which are pier-beam rigid connection segments, while the other two spans are edge spans, which are consolidated at one end and hinged at the other.

In summary, the structural scheme of the Liyutuo Lounge Bridge is full of innovations, challenges, and success.

Due to some complex limitations, certain shortcomings have nevertheless been revealed in structural design of the Liyutuo Lounge Bridge. First, the overall design appears top heavy, as expressed in the superstructure with a prestressed concrete frame composite system. The light bottom is expressed in small diameter and short piles to withstand the large vertical and lateral loads. Due to the flood discharge requirements, the width of the positive side is at most 1.5 m; thus, the bearing capacity of the pier is highly deficient [17]. The pile and pier design of the Liyutuo Lounge Bridge is governed by horizontal earthquake action. The foundation design is controlled by the vertical bearing capacity and settlement indicators. In addition to the large equivalent gravity load of the superstructure, the serious local erosion of the riverbed where the base is located, the weaker resistance to horizontal forces for the pile foundation, the horizontal displacement of the pile, and the horizontal bearing capacity of the pile, must be strictly controlled during the design process [21]. Although measures including longitudinal tie beams and post-grouting have been taken to improve the intensity of piles and piers are reinforced with Q345 profile steel and Φ36 HRB500IV grade steel, these measures are non-conventional, expensive and challenging for construction.

How should these issues be reasonably resolved? The authors hypothesize that mathematical model results and practical experience can be used to solve these problems. We can learn from the experience gained with the Qingcheng Bridge that is located downstream of the Liyutuo Lounge Bridge and has been in use for 22 years. The combination of the following two aspects can accommodate the constraints to resolve any contradictions.

4.1. Improving bearing capacity of piles by increasing pile diameter and length

The piles below ground are not completely flood resistant. The diameter and length of piles of the Liyutuo Lounge Bridge are 1.2 m and 33 m, respectively. To improve the bearing capacity of the piles, we can improve the concrete grade to C40 and use the longitudinal tie beam and post-grouting. A lengthy time period after bridge completion is required to test whether the measures are effective.

The post-grouting effect of experimental pile foundations makes it challenging for the engineering piles to meet design requirements. Therefore, the post-grouting effect is not ideal.

The design shows that foundations of piers 0-3 and 11-13 are backfilled with undisturbed sand to the original ground level. Piers 4-10 in the Jinma riverbed have reached sedimentation equilibrium and stabilized over the years, but the sedimentation exhibits certain annual changes. The riverbed is paved with 40 cm M10 mortar rubble within 15 m upstream and downstream of the bridge axis (as shown in Figure 8 and Table 2). This rubble ensures structural safety of bridges so that the cover depth of bridge foundations can resist possible erosion. In fact, after Zipingpu Dam was constructed, the sedimentation equilibrium was completely broken, causing only erosion without deposition, which inevitably causes erosion of the Jinma Reach downstream of the Zipingpu Reservoir. The backfill thickness of piers 5-8 at the centre of the riverbed is 1.10 m. Even if the riverbed surface is simply paved, it is challenging to resist erosion caused by the Minjiang River Basin in summer and during periods of heavy rain.

The Minjiang River Bridge No. 3 is located 15 km downstream of the Liyutuo Lounge Bridge. The traction load is intercepted, and suspended sediment is precipitated by the Zipingpu Reservoir so that the river sediment concentration is reduced significantly via the Jinma River. The erosion of the Jinma

Table 2. Thickness of the pit backfill of the Liyutuo Lounge Bridge

Pier no.	**Thickness of the bearing platform** [m]	**Bottom elevation of the bearing platform** [m]	**Top elevation of the backfill or paving** [m]	**Thickness of the backfill** [m]	Note
0-3	2.0	712.70	720.00	5.30	River embankment
4, 9	2.0	712.19	715.80	1.61	
5-8	2.0	712.70	715.80	1.10	
10-13	2.0	712.70	721.00	6.30	River embankment

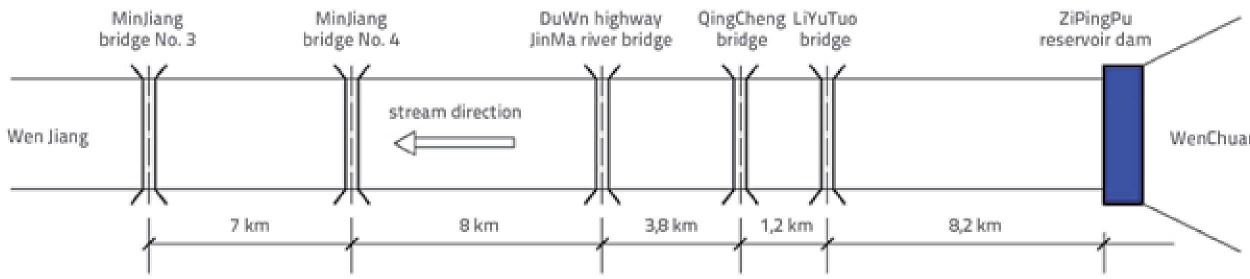

Figure 13. Schematic of relative location of nearby projects

riverbed may be exacerbated under flood conditions, and illegal mining also exacerbates the pile exposure. The pile erosion depth of the Minjiang Bridge No. 3 in the main river is 4.5-9.2 m, and the average and maximum erosion depths are 6.9 m and 9.2 m, respectively [22]. Research has shown that the maximum erosion depth of the Qingcheng Bridge, which is 1.2 km downstream of the Liyutuo Lounge Bridge, is more than 2.0 m. In addition, the maximum erosion depth of the Jinma River Bridge, which is 5.4 km downstream of the Liyutuo Lounge Bridge, is more than 2 m. The backfill thickness of the longitudinal tie beams is 1.61 m for piers 4 and 9 and 1.10 m for piers 5- 8. According to the erosion survey made for downstream bridges, the exposure risk of the longitudinal tie beams is high because of flood erosion. If longitudinal tie beams are exposed after erosion, the flood, traction load and suspended load will directly scour longitudinal tie beams under flood erosion in summer. Negative effects of additional horizontal force caused by erosion are substantial. After the bridge is built, the effect of the erosion depth and erosion on the longitudinal tie beams will require further observation and research.

Clearly, the piles of the Liyutuo Lounge Bridge that are scoured by flood are subject to uncertain effects. Increasing the pile diameter to 1.5-2.0 m or appropriately increasing the pile length would significantly improve the overall carrying capacity of the piles.

4.2. Shorten span and increase positive side size of piers to improve bearing capacity

The Qingcheng Bridge, rebuilt in 1994, lies 1.2 km downstream of the Liyutuo Lounge Bridge. It has a span of 22.2 m, gravity foundations, and a gravity pier 3 m in diameter (see Table 3 and Figure 13). Based on the 21-year use of the Qingcheng Bridge, it was established that its flood carrying capacity complies with the requirements.

Table 3. Important project overview of Liyutuo Lounge Bridge

Project name	Location	**Distance** [km]	**Single span** [m]	**Bridge pier diameter** [m]	**Pile diameter** [m]	Year of completion
ZiPingPu Reservoir Dam	Upstream	8.2	/	/	/	2003
Liyutuo Bridge	Studied bridge	0	30	Width of water-retaining surface 1.5 m	Pile groups 1.5 m	2014
Qingcheng Bridge	Downstream	1.2	22.2	Gravity type 3.0 m	Spread foundation	1994
Duwen Highway JinMaHe Bridge	Downstream	5	20	1.2	Single pile 1.5 m	2009
No. 3 MingJiang bridge	Downstream	20	25	1.6	Single pile 1.8 m	2009
No. 4 MingJiang bridge	Downstream	13	20	1.3	Single pile 1.5 m	2005

According to the flood discharge requirements approved by the Yangtze River Water Conservation Commission, the longitudinal spacing of piers is 30 m, and the positive side width of the pier cannot exceed 1.5 m. Table 3 shows that the spans of several bridges downstream of the Liyutuo Lounge Bridge are all less than 30 m in span. The Liyutuo Lounge Bridge connects the architecture and bridges into a harmonious single structure. If the span of the piers decreases from 30 m to 20 m, the width of the positive side must increase or the column diameter must increase from 1.5 m to 2.0 m. These adjustments offer several advantages:

- the overall structural design is simplified
- due to the decrease in the vertical and horizontal load of the pile foundation, the two complex projects of the post-grouting and capping the longitudinal beam can be eliminated
- because of the smaller horizontal and vertical load, Q345 profile steel can be eliminated
- the connection between the pier and the main beam and rigid joints of the main beams is favoured
- the arrangement and construction of the longitudinal steel strands in the main beam are favoured
- the cost and time spent in the design and construction stages are significantly reduced.

5. Conclusions

By analysing structural design of the Liyutuo Lounge Bridge, the following conclusions can be reached:

- This design combines the multilayer frame structure and large bridge design for the first time and successfully solves the problem of integrating architecture and bridge structures. Moreover, this design innovatively uses a two-terminal cantilever support with a local vibration isolation system.
- A prestressed concrete frame with a rigid frame structure is applied as the transport layer of the bridge superstructure. The pier, main beam and main transverse beam are rigidly connected, providing the characteristics of both a prestressed bridge structure and a frame structure. (
- The span of the pier column and the positive side width are limited by the Yangtze River Water Conservation Commission. The bearing capacity of the bridge is maintained by the composite structural design involving the high-strength Q345 profile steel, high-strength HRB500 steel bars, and high-strength concrete C50.
- Due to small pile diameter of 1.2 m and large load on pile foundations, the Liyutuo Lounge Bridge uses C40 concrete, post-grouting, and the composite structural design of longitudinal tie beams. A vertical bearing capacity self-balancing test, single pile horizontal load test, and horizontal load test, were conducted for the bearing platform with double horizontal piles. The design, experiment and construction impart considerable benefits.
- By analysing the downstream Qingcheng Bridge and several other bridges, it was established that the Liyutuo Lounge Bridge can be additionally optimized by reducing pier span, by increasing pile diameter, and by reducing the design and construction challenges.

The overall design, superstructure design, pier design, and pile design of the Liyutuo Lounge Bridge present numerous innovative features. Thus, this bridge design is worth examining as an important reference for structural designs that integrate architecture and bridges.

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