Design and Construction

Innovative Design of Continuous Rigid Frame Bridges with High Piers and Large Spans in Mountainous Areas

Zhenyu Liu

Sichuan Highway Planning Survey and Design Institute Co., Ltd., Chengdu 610041, Sichuan Province, China
Correspondence: 438011823@qq.com

Abstract: High-pier large-span continuous rigid frame bridges in mountainous areas with high-intensity earthquakes are characterized by large variations in pier height, heavy weight of the upper structure, and large seismic forces. Therefore, seismic performance is a key design consideration for these bridges. To improve the seismic performance of large-span continuous rigid frame bridges, this paper studies seismic reduction techniques from the aspects of pier type optimization and pier stiffness matching. The results show that (1) the robust framed reinforced concrete pier structure adopted for the main pier can reduce the weight of the lower structure, reduce the stiffness of the pier, and reduce the seismic force on the pier and (2) optimizing the section sizes of the high and low piers and adjusting the pier stiffness can match the bearing capacity of each pier with the seismic force it receives.

Keywords: mountainous bridges; steel-tube concrete piers; high piers; continuous rigid frame bridges; seismic design

1 Introduction

In the western mountainous areas, the mountains are high, the valleys are deep, and the earthquake intensity is high. When roads cross valleys, high-pier large-span bridges are generally used. Among them, large-span continuous rigid frame bridges are often used because they have the characteristics of good driving comfort, low construction costs, mature construction technology, good overall bridge integrity, and convenient later management and maintenance [1]. In complex terrain with deep valleys, the upper structure of large-span continuous rigid frame bridges is heavy, and the seismic force is large. The height of each pier varies greatly, and the uniformity of the seismic force on the piers under seismic action is poor. It is difficult to perform seismic calculations in conventional design, so bridge seismic reduction is a key design consideration. Chinese scholars have studied the type selection of piers, dynamic characteristics, and ductile seismic resistance of high-pier large-span continuous rigid frame bridges, but there are few studies on bridge seismic reduction using new materials, new structures, and new technologies. Lightweight high-strength high-performance concrete has good development prospects, but it is rarely used in continuous rigid frame bridge box girders, and its influence on bridge seismic performance needs to be studied. Steel-tube concrete structures have been widely used in arch bridges, cable-stayed bridges, and suspension bridges. Their main technical characteristics are high bearing capacity, good plasticity and toughness, excellent seismic performance, and convenient construction [2]. Although lattice columns composed of steel-tube concrete as the main component have good ductility and high ultimate bearing capacity [3], their seismic performance in high-pier large-span continuous rigid frame bridges in high-intensity earthquake zones needs to be further studied.

Citation: Liu, Z. Innovative Design of Continuous Rigid Frame Bridges with High Piers and Large Spans in Mountainous Areas. *Prestress Technology* **2024**, *2*, 58-69. https://doi.org/10.59238/j.pt.2024.02.005

Received: 23/04/2024
Accepted: 14/06/2024
Published: 30/06/2024

The Jinyang River Bridge in Jinyang County is a large-span high-pier bridge built in a high-altitude, high-intensity earthquake zone with mountainous canyon topography. The bridge spans over the Jinyang River valley, where the valley cross-section is V-shaped, with a width of about 700 m. The bridge deck has a maximum height difference of 256 m from the valley bottom, and the terrain on both sides is steep (see Figure 1). The route compared to the original mountain road saves about 3.5 km of road distance, reducing travel time between the new and old urban areas by 1 hour.

Figure 1 Jinyang River Bridge in Jinyang County

The bridge is located in the Anning River fault zone, where seismic activity is frequent. Following the design concept of "economic rationality and low carbon development", the Jinyang River Bridge conducted a scheme comparison for continuous rigid frame bridges, reinforced concrete arch bridges, and double tower cable-stayed bridges (refer to Table 1). The prestressed concrete continuous rigid frame bridge scheme is more economical, with a simple structural system, the ability for simultaneous construction on multiple surfaces, and the advantage of having a small amount of maintenance work in the later stage. It can adapt well to the terrain, geology, and other construction conditions of the high mountain canyon of the Jinyang River, making it the recommended implementation plan for the project. The total investment of the project is 301 million yuan, and the construction lasted for 32 months. It was completed and opened to traffic in July 2022.

The Jinyang River Bridge has a total length of 758 m, a deck width of 16 m, two lanes in both directions, and nonmotorized lanes and sidewalks on both sides. The main bridge is a 106 + 2×200 + 115 + 40 m continuous rigid frame, the upper main girder is a single-box single-cell C60 prestressed concrete continuous box girder, and the pier top girder is 13.2 m high. The mid-span beam height is 4.1 m, and the beam height is gradually changed by a 1.6-degree parabola. The heights of the 5th, 6th, and 7th main piers are 113 m, 196 m, and 182 m, respectively, all of which are reinforced concrete box piers. The main pier is 11.9 m wide in the transverse direction, the #5 pier is 9.4 m wide in the longitudinal direction, and the #6 and #7 piers are 11.0 m wide; The full height of #5 pier shall be designed as per equal section, the transverse slope of #6 and #7 piers shall be 60:1, and the longitudinal dimension of the bridge shall remain unchanged. Its 196-meter-high pier has been certified by the professional world record organization of the United States as holding a flag-carrying world record. The diagram of the bridge layout is shown in Figure 2.

Table 1 Comparison of bridge design schemes (Unit: CNY)

Scheme	Renderings	Features	Duration (months)	Cost (Million Yuan)
PC Continuous Rigid Frame Bridge		The structural system is mature, the design and construction of the super-high pier control the construction period, and the cost is low.	32	301
RC Arch Bridge		The construction process is complicated, the technology and management are difficult, and the cost is moderate.	36	349
PC Cable-Stayed Bridge		The construction difficulty is moderate, the workload of later management and maintenance is large, and the cost is the highest.	48	404

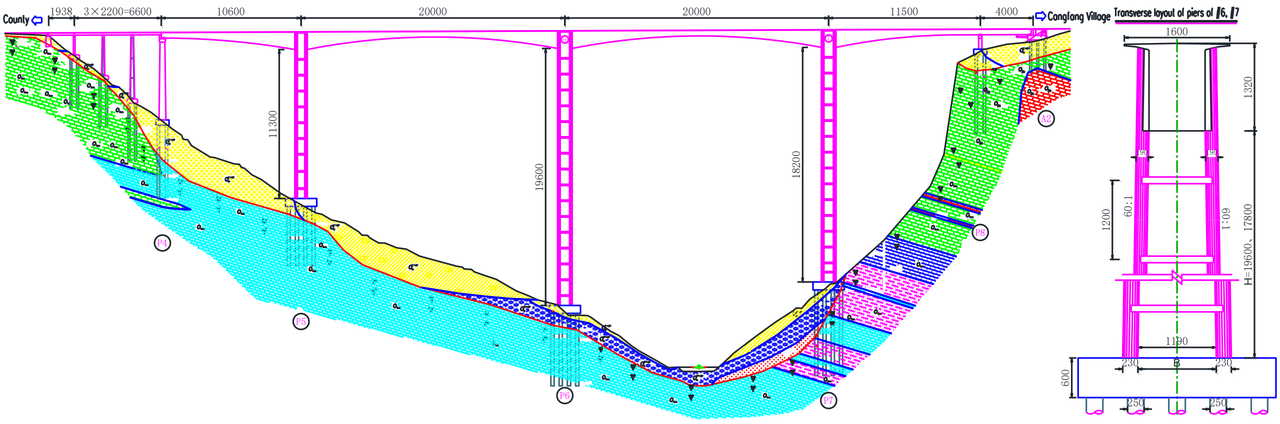


Figure 2 Bridge layout elevation (Unit: cm)

2 Seismic Design Challenges

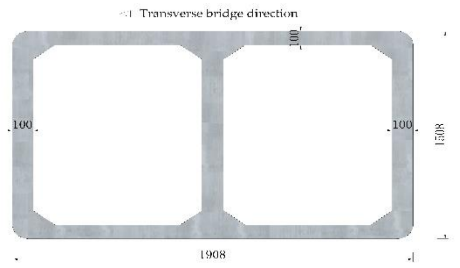
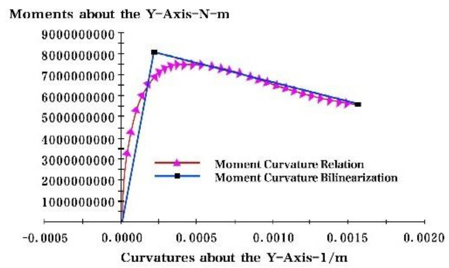
The Jinyang River Bridge is located in the Anning River Fault Zone, an area with frequent seismic activity. The seismic intensity of the site is 7.7 degrees, with a horizontal seismic acceleration of 0.15 g on the bedrock, and the site horizontal seismic acceleration is 0.201 g (with a 10% exceedance probability over 50 years). The peak value of the site horizontal acceleration corresponding to the E2 seismic motion (with a 50-year exceedance probability of 2%) is 0.365 g. To meet the crossing capacity and construction conditions, a concrete-filled steel tube combined with a high-pier prestressed concrete continuous rigid frame bridge with a main span of 2×200 m is adopted, which adapts well to the terrain and construction conditions of the Jinyang River alpine canyon and has excellent economic performance. Piers #6 and #7 of the

Jinyang River Bridge reach heights of 196 m and 182 m, respectively, and the seismic intensity of 0.201 g in the bridge site area is a major controlling factor for the design and construction of high-pier bridges, presenting significant engineering challenges and difficulties. To achieve this vision, the project must focus on solving the following two technical problems.

2.1 Poor Seismic Performance of High Concrete Bridge Piers

The study of ordinary reinforced concrete piers revealed that the self-weight of the reinforced concrete pier is large, and the corresponding axial force and bending moment of the pier section are relatively large. At the same time, the stirrups of the concrete thin-walled hollow pier body impose a relatively weak restraint effect on the section, the ductility performance of the section is poor, and the seismic performance of the structure is relatively weak. Comparing ordinary concrete piers with robust frame concrete piers, the bottom axial force of ordinary concrete piers is 105% greater, and the corresponding transverse bottom moment is 30% greater. The fundamental frequency of ordinary reinforced concrete piers is comparable to that of robust frame concrete piers. However, the seismic displacement ductility coefficient of ordinary reinforced concrete piers is only 1.15 (refer to Table 2), which is far below the reasonable range of $1.5 < \mu\Delta < 3.0$. A lower displacement ductility coefficient implies poor energy dissipation and deformation capacity of the bridge piers, severe cracking of the structure during strong earthquakes, and difficulties in repair after damage. Therefore, there is an objective need to improve the structural form of the pier columns.

Table 2 Seismic response of an ordinary RC continuous rigid frame bridge with high piers

<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Section size of the bottom of Pier #6</td><td>M-ϕ curve at the E2 seismic motion</td></tr>
<tr><td colspan="2">Pier fundamental frequency: 0.198 Hz; Displacement ductility coefficient: 1.15;
Initial yield bending moment of the pier bottom: 6730 MN·m;
Equivalent yield bending moment of the pier bottom: 7750 MN·m;
Conclusion: The seismic performance of the pier is poor.</td></tr>
</table>

2.2 Seismic System Challenges of High-Pier Long-Span Bridges

The seismic design of high-pier long-span bridges has always been a core technical challenge in the engineering field. To overcome the adverse effects of pier stability and seismic forces, superhigh pier bridges generally adopt variable slope designs along the longitudinal and transverse directions to increase the size of the bottom section of the piers. For traditional left and right double continuous rigid-frame bridges, the transverse seismic response can be mitigated by connecting the left and right pier columns with transverse frames to form a lateral mutual support system.

The Jinyang River Bridge is a multi-span continuous rigid frame bridge with tall piers. Due to the high piers and significant differences in pier height, the longitudinal seismic response of the piers is significant and the seismic response of each pier varies greatly. The bridge's width-to-span ratio B/L = 1/12.5, placing it in the category of narrow bridges in beam bridges. The fundamental vibration mode and subsequent multiple vibration modes of the bridge are all related to the lateral bending and twisting of the main pier (refer to Table 3), indicating that the transverse seismic issues of this bridge are also prominent. This makes the seismic design of the bridge a critical control factor.

Table 3 Dynamic characteristics of the bridge

Modes	Frequency (Hz)	Mode shape description
1st order	0.165	Symmetrical lateral bending of main piers
2nd order	0.196	Longitudinal drift longitudinal bending of main piers
3rd order	0.268	1st-order antisymmetric lateral bending of pier #5 and pier #7, 3rd-order torsion of pier #6
4th order	0.400	Second-order antisymmetric lateral bending of pier #5 and pier #7, 3rd-order torsion of pier #6

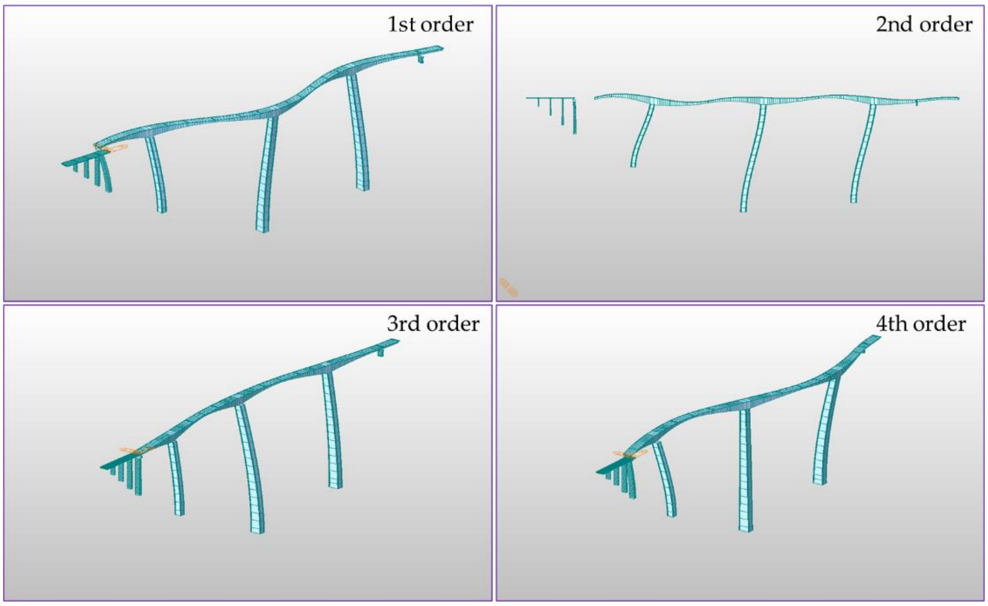


Figure 3 Mode shapes of the 1st to 4th order of the main bridge

3 Key Technologies of Seismic Design

3.1 Structure of Robust Frame Reinforced Concrete Piers

For long-span continuous rigid-frame bridges, hollow thin-walled piers or double thin-walled piers are generally used as the main piers. Double thin-walled piers have low shear resistance and long bridge vibration periods and are suitable for situations where the pier height is not large [5]. However, for superhigh piers with heights exceeding 100 m, due to their slightly poorer stability, greater construction difficulty, and greater risks, double thin-walled piers are less commonly used [6]. According to the classification based on pier materials and structural types, hollow thin-walled piers include ordinary reinforced concrete hollow thin-walled piers and concrete-filled steel tube lattice-type hollow thin-walled piers. Research has shown that changes in the pier stiffness have a significant impact on lateral bending and longitudinal bending frequencies, and optimizing the pier type can adjust the dynamic response of bridge structures [7].

When the pier height is in the range of 60 m to 100 m, ordinary reinforced concrete hollow thin-walled piers exhibit good load-bearing performance. The section size and wall thickness of the pier body increase with increasing pier height. Concrete-filled steel tube lattice-type hollow thin-walled piers have the characteristics of cost savings, low stiffness, light weight, good seismic performance, and convenient construction [2]. They can achieve good economic benefits when the pier height exceeds 100 m and have been successfully applied in western mountainous areas, such as the Labeijin Special Large Bridge on the Yaxi Expressway in Sichuan Province (with the maximum main pier height reaching 183 m) [2].

In response to the challenge posed by the 196m super-high piers of the Jinyang River Bridge and the high-intensity seismic forces, the design team innovatively proposed a new structure for robust frame reinforced concrete bridge piers. The robust frame reinforced concrete bridge piers consist of ultra-high-strength steel tube concrete columns and reinforced concrete diaphragms as the frame, enveloped by reinforced concrete abutments forming a box-shaped concrete pier. Taking advantage of the high strength and high toughness characteristics of steel tube concrete materials, the robust frame serves as the main load-bearing component of the pier, with the concrete diaphragms cooperating with the frame to bear the load and providing bending stiffness for the pier, forming a composite structural system (refer to Figure 4). Under the occasional seismic loads of E2, the reinforced concrete diaphragms are allowed to crack, with the robust frame bearing the main load, providing structural support, and ensuring the overall safety of the structure. This design concept complies with the seismic fortification requirements of both levels [8].

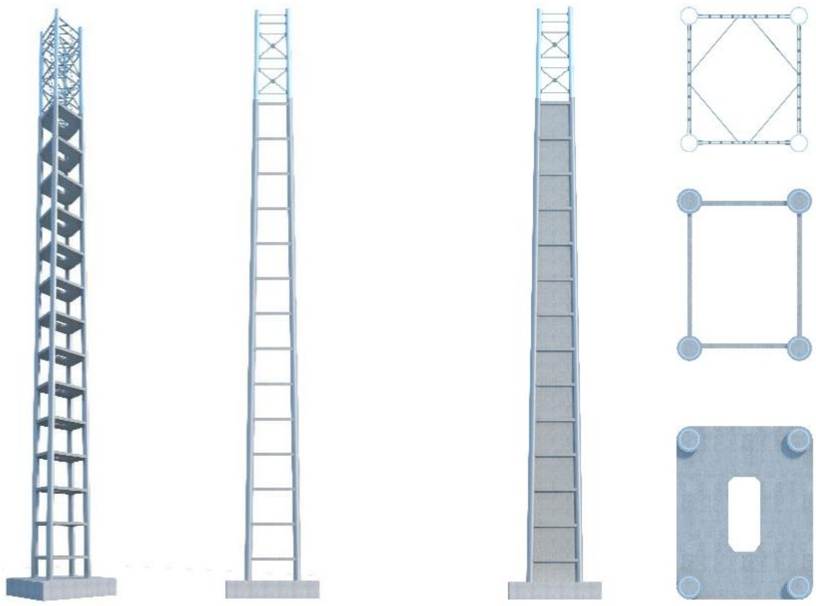


Figure 4 Principle of robust frame reinforced concrete bridge pier construction

Based on the aforementioned design concept, the robust frames of piers #5, #6, and #7 of the Jinyang River Bridge consist of four-limb steel tube concrete columns (with a spacing of approximately 10 m) and reinforced concrete transverse diaphragms (spaced at 12 m intervals). The process involves pre-assembly of the empty steel tube-I-beam frame in 12 m length segments, followed by pouring of C80 self-compacting shrinkage-compensating concrete into the steel tubes. Subsequently, 1.0 m thick transverse diaphragm concrete is cast in place, and longitudinal and transverse prestressing tendons are tensioned to form the robust frame. Reinforcing bars are then wrapped around the exterior of the steel tube frame, enveloped by 20 cm thick C30 steel fiber concrete. Simultaneously, 50 cm thick C30 concrete diaphragms are poured to form the integral box-shaped cross-section of the pier body (refer to Figure 5). For the tallest pier, Pier #6, the robust frame comprises steel tubes with diameters of 1.5 m (top of pier, thickness = 18 mm), 1.7 m (middle of pier, thickness = 26 mm), and 1.9 m (bottom of pier, thickness = 34 mm).

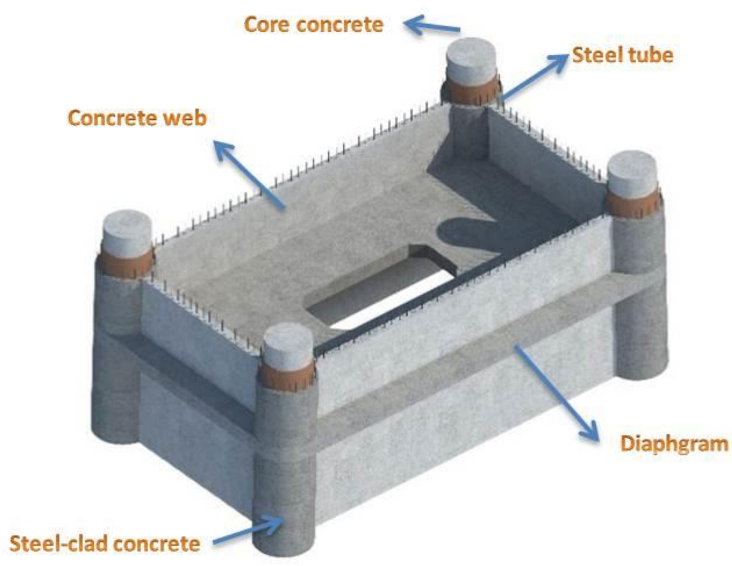


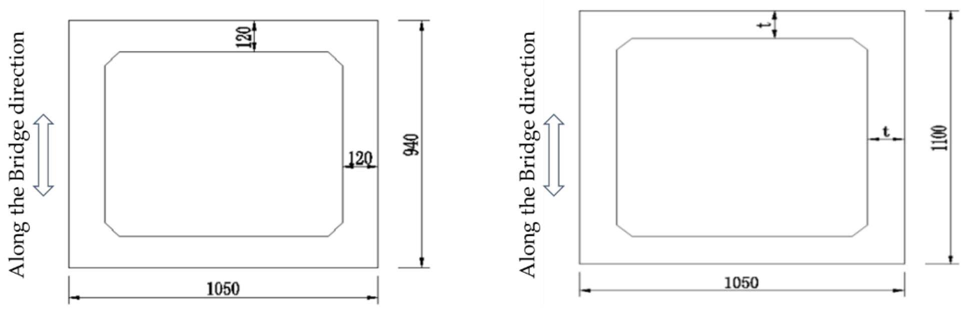
Figure 5 Schematic of the segmental structure of the robust frame pier

3.2 *Seismic Calculation Comparison of Different Pier Types*

Liu et al. [5] calculated and compared robust frame reinforced concrete bridge piers and traditional reinforced concrete bridge piers with a calculation model adopting fixed-bottom constraints for the piers. Elastic supports were used to simulate movable bearings, and general connections were used to simulate viscous dampers [9,10]. According to the paper, the calculation comparison schemes for Piers #5 to #7 of the bridge are as follows:

(1) Scheme 1: Ordinary reinforced concrete hollow thin-walled piers

For Pier #5, the longitudinal width is 9.4 m, and the transverse width is 10.5 m, with a wall thickness of 1.2 m. For Piers #6 and #7, the longitudinal width is 11 m, and the transverse width is 10.5 m. The wall thickness is divided into three sections: 1.0 m, 1.2 m, and 1.5 m, as shown in Figure 5. The concrete strength grade is C50, with a vertical interval of 15 m and one diaphragm plate.

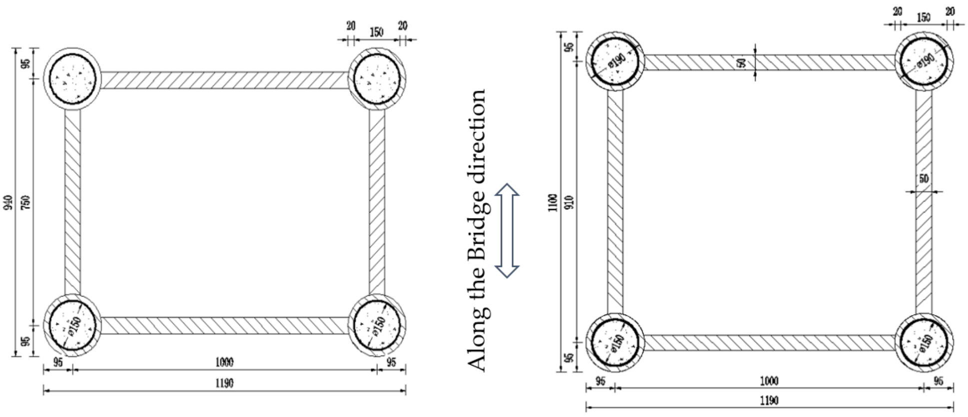


(a) Pier #5 (b) Piers #6 and #7

Figure 6 Section of ordinary reinforced concrete hollow thin-walled piers (Unit: cm)

(2) Scheme 2: Concrete-filled steel tube lattice hollow thin-walled piers

The width of these piers is 11.9 m in the transverse direction, and the top width for Pier #5 is 9.4 m, while for Piers #6 and #7, it is 11.0 m. The concrete-filled steel tube lattice hollow thin-walled piers have a single-box single-room section formed by lattice columns and concrete rib plates between the columns. The lattice columns are composed of 1.5 m diameter steel tubes wrapped with 20 cm thick concrete. The wall thickness of the concrete rib plates is 50 cm, as shown in Figure 6. A 1.0 m thick diaphragm plate is set every 12 m vertically inside the piers. The steel tube strength is Q370, with a wall thickness of 34 mm. The steel tubes are filled with C80 self-compacting concrete, and C50 concrete is used for the external concrete and rib plates. The piers are mainly composed of three different materials (excluding support frames and reinforcement effects). When conducting seismic analysis, they need to be converted to a unified material, considering the increase in stiffness and strength due to the concrete-filled steel tube sleeve effect. The diaphragm plates are simulated using concentrated masses.



(a) Pier #5 (b) Piers #6 and #7

Figure 7 Section of concrete-filled steel tube lattice hollow thin-walled piers (Unit: cm)

The elastic modulus, area, moment of inertia, and bending stiffness of the pier sections for Schemes 1 and 2 are compared in Table 4.

Table 4 Section design parameter table of different schemes

Pire schemes	Pier No.	E MPa	A m^2	Iy m^4	Iz m^4	EA ($\times 10^6$ MN)	EIy ($\times 10^7$ MN·m^2)	EIz ($\times 10^7$ MN·m^2)
Scheme 1	#5	34,500	42.56	501.03	605.25	1.47	1.73	2.09
	#6, #7 (upper)	34,500	39.50	657.65	608.91	1.36	2.27	2.10
	#6, #7 (middle)	34,500	46.34	743.84	687.84	1.60	2.57	2.37
	#6, #7 (lower)	34,500	56.00	851.98	786.33	1.93	2.94	2.71
Scheme 2	#5	42,865	25.04	303.42	501.53	1.07	1.30	2.15
	#6, #7	42,363	26.64	458.39	540.08	1.13	1.94	2.29

From Table 4, it can be observed that compared to ordinary reinforced hollow thin-walled piers, concrete-filled steel tube lattice hollow thin-walled piers have the following characteristics: (1) a significant reduction in the section area, with a decrease of 41.2% for Pier #5 and 32.6% to 52.4% for Piers #6 and 7; (2) a significant decrease in the section bending stiffness in the longitudinal direction, with a reduction of 24.9% for Pier #5 and 14.5% to 34.0% for Piers #6 and #7; and (3) mixed changes in the section bending stiffness in the transverse direction, with a decrease of approximately 15.5% for the bottoms of Piers #6 and #7.

The E1 seismic moment responses at the bottom of the piers for the two different pier types are shown in Table 5.

Table 5 Bending moment response of the pier bottom under different pier schemes under E1 seismic action

Pier schemes	Bending moment of the pier bottom in the longitudinal direction My (×10^5 kN·m)			Bending moment of the pier bottom in the transverse direction Mz (×10^5 kN·m)		
	Pier #5	Pier #6	Pier #7	Pier #5	Pier #6	Pier #7
Scheme 1	14.4	12.0	12.7	8.23	11.5	7.11
Scheme 2	11.6	8.47	9.02	7.34	8.78	5.72

From Table 5, it can be observed that under E1 seismic action, compared to ordinary reinforced concrete hollow thin-walled piers, concrete-filled steel tube lattice hollow thin-walled piers exhibit a decrease in longitudinal bending moments of 19.4% to 29.4% and a decrease in transverse bending moments of 10.8% to 23.7%. The main reasons are as follows: (1) a decrease in the bending stiffness leads to a slight extension of the vibration period, resulting in a reduction in the corresponding acceleration response spectrum values and (2) a reduction in the pier section area reduces the mass, resulting in a smaller contribution of pier self-vibration to the internal forces at the bottom of the piers.

3.3 Pier Stiffness Matching

In mountainous regions, bridges are influenced by changes in terrain, and there is a large difference in pier height. When piers with the same section size are used, the linear stiffness of a short pier is high and the pier bears more seismic forces, exhibiting uneven force distributions. Therefore, the stiffness of the piers is usually adjusted to ensure that the seismic forces received by different piers match their bearing capacity.

Table 5 shows that the longitudinal bending moment under E1 seismic action for Pier #5 is greater than that for Piers #6 and #7. This is due to the significant difference in height between Pier #5 and Piers #6 and #7, with the lateral stiffness inversely proportional to the cube of the pier height, resulting in Pier #5 having a significantly greater lateral stiffness than Piers #6 and #7, thus bearing more longitudinal seismic forces.

The seismic design of the Jinyang River Bridge still faces the challenge of mismatch between the longitudinal and transverse seismic responses of the ultra-high bridge piers and the section dimensions. The design team has optimized and innovated the seismic-resistant system (refer to Figure 8) as follows: (1) Addressing the prominent transverse seismic response and large differences in pier height, a 60:1 slope protection measure was implemented on both sides of the transversely higher piers #6 and #7. This measure increases the transverse section dimensions to match the transverse seismic response of the bridge piers. (2) Longitudinally, traditional slope protection designs for bridge piers have been eliminated. Instead, energy dissipation and damping are achieved through viscous damping installed at the beam ends on Abutment A2 and junction pier #4 [4]. Simultaneously, damping parameters are optimized to achieve the optimal proportion of seismic response control for the longitudinal sections of each main pier. This approach maintains constant longitudinal dimensions of the piers to facilitate construction.

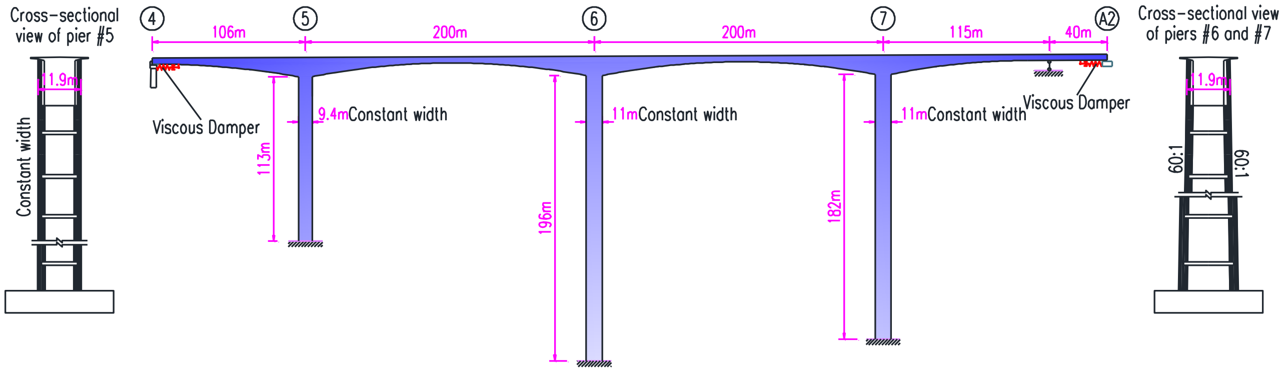


Figure 8 Diagram layout of seismic-resistant system (Unit: m)

After optimizing the seismic-resistant system, the transverse bending moment at the base of the main piers is essentially proportional to the pier height (refer to Figure 9). The increased transverse section dimensions at the base of the piers, achieved through transverse slope protection, match the transverse seismic response, meeting the requirements of seismic design. Longitudinally, the maximum longitudinal seismic response at the base of the piers is reduced by 40% after damping is installed (refer to Figure 10). Additionally, the longitudinal bending moments at the bases of Piers #5, #6, and #7 remain relatively consistent, indicating that the decision to eliminate longitudinal slope protection for the piers and to optimize damping configurations is effective and reasonable.

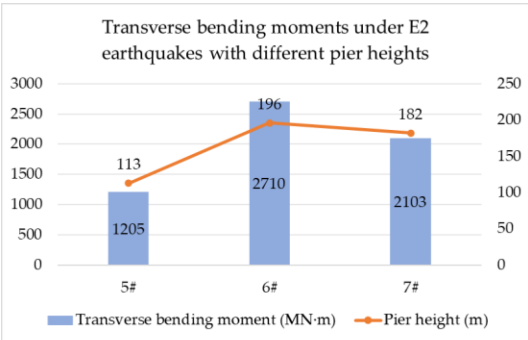


Figure 9 Transverse bending moment under E2 earthquake with different pier heights

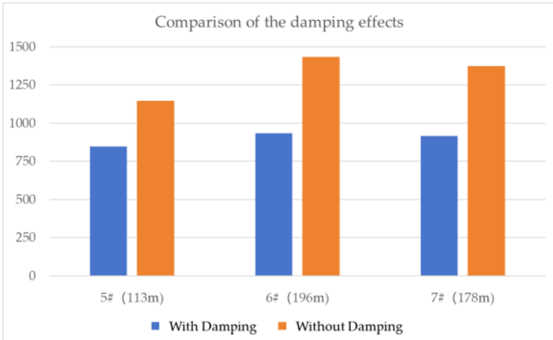


Figure 10 Longitudinal moment at piers bottom before and after increased damping

***3.4** Robust Frame Pier Connection Scheme*

The connection between the steel tubes and the main girders, as well as between the steel tubes and the bearing platform, in the robust frame reinforced concrete bridge piers, is a critical node construction. To ensure the reliability of the pier-girder connection, this bridge adopts widened transverse dimensions for the piers, placing the steel tube columns outside the main girder web, allowing smooth passage for the main girder reinforcement and prestressing tendons. The shear forces from the main girder are then transmitted to the steel tube concrete columns through PBL shear keys located on the steel tube columns. Horizontal prestressing tendons are tensioned on the transverse diaphragm at block 0# to transfer transverse moments (refer to Figure 11), thereby ensuring reliable pier-girder connection. The connection structure between the steel tube concrete columns and the bearing platform adopts a configuration of bearing plates + PBL shear keys (refer to Figure 12). The bearing plates are utilized to distribute the axial compressive stress at the base of the steel tube concrete columns, and the PBL shear keys are used to anchor the column foot into the concrete of the bearing platform.

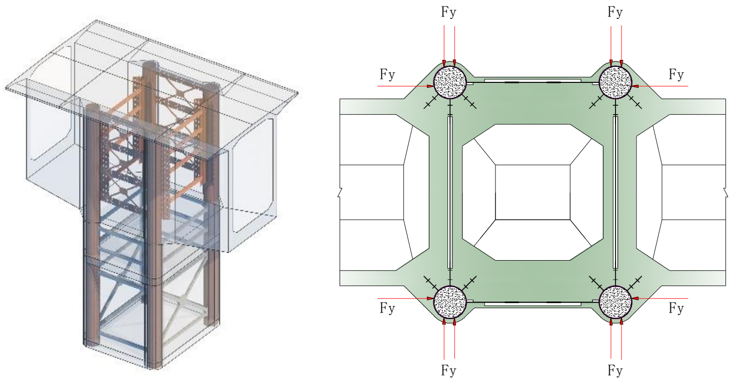


Figure 11 External shear connection structure of pier top web

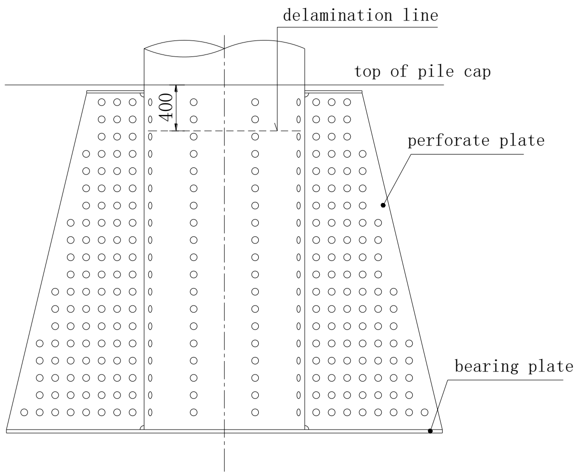


Figure 12 Pier bottom bearing plates + PBL shear keys (Unit: mm)

4 Conclusions

For high-intensity seismic areas with high piers and large-span continuous rigid frame bridges in mountainous regions, the following seismic reduction technologies can effectively improve the seismic performance of bridges:

(1) The use of robust frame reinforced concrete pier structures for the main piers can reduce concrete usage, decrease pier self-weight, and decrease pier stiffness, thereby significantly reducing the seismic response of piers.

(2) Considering the significant differences in pier heights in mountainous bridge construction, optimizing the pier cross-sectional size by sloping from top to bottom can rationalize the distribution of internal forces at the base of each pier under seismic action. In large-span continuous rigid frame bridges with high piers, where the lateral stiffness is low, the displacements are large, and the seismic forces on the piers are high, appropriate pier stiffness matching measures can effectively increase lateral stiffness, reduce lateral displacements, and ensure that the bearing capacity of each pier matches the seismic forces.

The Jinyang River Bridge in Jinyang County has accumulated experience in the seismic system of high piers and large-span bridges, as well as in the structural design of superhigh concrete-filled steel tube composite piers. These technological innovations have greatly promoted the advancement of concrete-filled steel tube composite pier technology.

https://doi.org/10.59238/j.pt.2024.02.005

Conflict of Interest: All authors disclosed no relevant relationships.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Liu, upon reasonable request.

References

1. Ma, B. *Continuous Rigid Frame Bridge with High Pier and Long Span* China Communications Press Co., Ltd.: Beijing, 2001.
2. Mou, T.; Fan, B.; Zhao, Y.; Li, S. Application and Development of Steel Pipe Concrete Bridges in China. *Highway* **2017**, *62*, 161-165.
3. Chen, B.; Ou, Z. Experimental Study on the Ultimate Load Carrying Capacity of Four-tube Concrete Filled Steel Tubular Laced Columns. *China Civil Engineering Journal* **2007**, *40*, 32-41, doi:10.3321/j.issn:1000-131X.2007.06.006.
4. Li, H.; Geng, B.; Feng, L. Parameter Analysis of Viscous Damper for Zhongxian County Yangtze River Bridge on Chongqing Zhongxian Expressway. *Technology of Highway and Transport* **2007**, 81-85, doi:10.3969/j.issn.1009-6477.2007.03.023.
5. Liu, H.; Zheng, G. Seismic Analysis and Seismic Performance Evaluation for Large-span Continuous Rigid Frame Bridges. *Technology of Highway and Transport* **2009**, 81-84, doi:10.3969/j.issn.1009-6477.2009.06.020.
6. Ning, X.; Li, R.; Yang, C.; An, X. Design Study on Supertall Pier. *Technology of Highway and Transport* **2008**, 87-90, doi:10.3969/j.issn.1009-6477.2008.01.026.
7. Li, H.; Chen, S. Analysis for Spatial Dynamic Characteristics of High-pier Large-span Continuous Steel Structure Bridges. *Technology of Highway and Transport* **2013**, 58-60,66, doi:10.3969/j.issn.1009-6477.2013.05.015.
8. Huang, Z.; Qiang, S.; Cui, S.a. Probabilistic Seismic Capacity Model for High Pier of CFST Composite Column. *Journal of Southwest Jiaotong University* **2015**, *50*, 852-857, doi:10.3969/j.issn.0258-2724.2015.05.013.
9. Guo, J.; Deng, X.; Pang, M.; Zhuo, W.; Liu, Z. Experimental Study on Seismic Performance of Prestressed Precast Pier of Ningju Intercity Rail Transit. *Structural Engineers* **2023**, *39*, 116-126, doi:10.15935/j.cnki.jggcs.2023.02.009.
10. Sun, Z.; Ruan, H.; Liu, W. Experimental Study on Seismic Behavior of Profiled Steel Reinforced Concrete Composite Columns. *Structural Engineers* **2022**, *38*, 106-112, doi:10.3969/j.issn.1005-0159.2022.02.014.

AUTHOR BIOGRAPHIES

Zhenyu Liu
D.Eng, Professor Engineer, Working at Sichuan Highway Planning Survey and Design Institute Co., Ltd.
Research Direction: Design of Large-span Bridges in Mountainous Areas and Bridges Across Rivers.
Email: 438011823@qq.com