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Seismic Reduction and Isolation Design Strategies for Bridges in High-Intensity Earthquake Areas

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Abstract: High-intensity earthquakes can cause severe damage to bridges, buildings, and ground surfaces, as well as disrupt human activities. Such earthquakes can create long-distance, high-intensity surface movements that negatively impact bridge structures. This article delves into the seismic reduction and isolation design strategies for bridges in high-intensity earthquake areas. It analyzes various seismic reduction and isolation technologies and provides case studies to help relevant units understand the design strategies of these technologies. The results of this article can be used as a guideline to effectively enhance the seismic performance of bridges in high-intensity earthquake areas.

Keywords: High-intensity earthquake areas; Rubber isolation; Seismic reinforcement technology

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1. Introduction

As an important part of China's road traffic engineering, the quality of bridge engineering directly affects transportation efficiency and the development of the national economy, especially in high-intensity earthquake areas with relatively strong earthquakes, where their special geographical environment greatly influences bridges' seismic performance. Higher requirements of bridges are necessary, such as strong earthquake resistance, shock absorption, and isolation capabilities [1]. Therefore, researching the seismic reduction and isolation design strategies of bridges in high-intensity earthquake areas is an important research activity to ensure the safety and stability of bridges in high-intensity earthquake areas as well as the safety of the public and the surrounding environment.

2. Overview of high-intensity earthquake areas

High-intensity earthquake areas are a concept in earthquake engineering. They refer to areas that are seriously damaged or have a greater threat of potential damage due to earthquakes. They are usually associated with earthquakes with a magnitude of 6 or above. The information reflected by the magnitude is the release of seismic energy size. The definition of high-intensity earthquake areas usually relies on the quantification of earthquake intensity, which is a measure of the impact or damage of an earthquake. Its main influencing factors include source energy, epicenter distance, seismic wave propagation characteristics, surface geological conditions, etc. [2].

3. Design principles for seismic reduction and isolation of bridges in high-intensity earthquake areas

(1) Principle of energy dissipation
When designing bridges at intervals, energy dissipation devices, such as isolation bearings, should be rationally applied to dissipate the energy input from the earthquake through mechanisms such as friction and deformation of the device. The setting of the energy dissipation mechanism is required to provide sufficient deformation capacity for the bridge structure while ensuring its overall stability, thereby reducing its stress level.

(2) Displacement control principle
The design of the seismic isolation system should ensure that the displacement response of the bridge during an earthquake is controlled within the acceptable range of the structure. During the design, the isolation bearings should be used to achieve relative independence between the main structure and the earthquake so that the bridge foundation and superstructure can swing within the expected displacement range to avoid damage during the earthquake [3].

(3) Multi-level protection principle
In the bridge structure's seismic reduction and isolation design, comprehensive protective measures should be taken to achieve multi-level protection. In addition to the necessary isolation supports, other isolation facilities and related isolation technologies, such as limiters, can also prevent the bridge structure from being damaged due to excessive displacement and impact problems under extreme earthquakes [4].

4. Analysis of seismic reduction and isolation technology for bridges in high-intensity earthquake areas

4.1. Shock absorption technology

4.1.1. Reduction of bridge span

The design strategy of reducing the bridge span is adopted to reduce the inertial force of the bridge structure in the transverse and longitudinal directions, thereby reducing the force impact during an earthquake. The technical key points of the bridge span design strategy include span selection, dynamic characteristic analysis, structural stiffness matching, pier design, and node characteristic optimization.

During span selection, designers must reasonably select each span based on the bridge's actual geographical location, terrain conditions, and traffic technology needs. Shorter spans can reduce the load on a single pier, and although this strategy may increase the number of piers, it helps spread the effects of seismic forces [5]. During the dynamic characteristics analysis, finite element software was mainly used to simulate the bridge structure and analyze the dynamic response under different span conditions to determine the optimal span configuration. This process must also consider whether the earthquake effects on different spans are uniform.

After determining the span of the bridge structure, the stiffness of each component of the bridge structure is matched. While reducing the span, the bridge structure maintains sufficient stiffness to support normal operations. In the pier design stage, while reducing the span, it is necessary to design the strength and toughness of the pier so that it can effectively withstand and dissipate local earthquake energy.

For node characteristic optimization, shorter spans mean the bridge will have more nodes. The design of these nodes should be able to provide appropriate deformation and energy dissipation capabilities during an earthquake [6]. In addition, when considering seismic effects and selecting the span, it is necessary to consider non-seismic effects caused by other types of loads on the bridge structure, such as wind loads, vehicle driving loads, etc.

4.1.2. Seismic reinforcement technology based on steel structures

Seismic reinforcement technology for bridge structures based on steel structures is to enhance the seismic performance of bridges by using steel with good plasticity and toughness. Steel structures can effectively absorb and dissipate seismic energy and increase the ductility of bridges during earthquakes, thereby reducing possible damage to bridges caused by earthquakes.

The key points of using steel structures to resist earthquakes in bridges include reinforced concrete composite structures, outsourcing steel plate reinforcement, steel trusses, steel support settings, and bonded steel reinforcement technology. The reinforced concrete composite structure added steel bars or reinforced concrete composite beams to the structure of the original concrete bridge to improve the transverse and longitudinal structural stiffness and ductility. The outsourcing steel plate reinforcement method is to wrap steel plates outside the key stress-bearing components of the bridge and strengthen the overall performance of the structure through welding or bolting. The principle of using steel trusses and steel supports is to enhance the lateral force-bearing capacity of the bridge structure, especially in the piers or abutments of the bridge. This strategy can effectively improve the overall seismic resistance [7]. Bonded steel reinforcement technology is used to stick external prestressed steel plates on the surfaces of bridge beams, columns, and other load-bearing components to achieve local reinforcement and improve the seismic resistance of the components.

4.1.3. Seismic design of bridge piers

The principle of bridge pier anti-seismic technology is to ensure that the pier has sufficient strength, ductility, and stiffness through effective design and can effectively resist the dynamic load during an earthquake to reduce the damage to the bridge structure under the action of an earthquake.

The first step in the seismic design of bridge piers for the seismic performance of bridge structures is to establish seismic performance targets. Designers must set clear performance targets for bridge piers based on factors such as seismic zoning, traffic importance, and expected service life, such as separation layers, maintenance ability, or non-collapse requirements. The second step, material selection and component reinforcement, aims to select appropriate materials and grades of concrete and steel bars to ensure sufficient strength and toughness. In this step, designers need to use the golden section principle as a guide to design component reinforcement and optimize component sections to increase ductility and plastic deformation capabilities. The ductile design aims to adopt appropriate design concepts to ensure that the vulnerable parts of the component can dissipate energy under inelastic deformation while avoiding brittle damage and enhancing the ductility of the component. The third step is to optimize node characteristics. The connecting parts, such as piers and beams, are called nodes. In the node design stage, sufficient ductility and appropriate mechanical properties must match the relative displacement of the beam ends and pier tops. The fourth step is to enhance the lateral bearing capacity. By setting up a sufficient number of structural transverse steel bars with a reasonable layout, the lateral bearing capacity and overall stability of the bridge pier can be enhanced [8]. At the same time, to control brittle damage, it is necessary to reduce or avoid local brittle damage through measures such as optimizing component size, improving concrete mixing quality, and selecting high-plasticity steel bars. The fifth step, bottom hinge design, aims to design hinges at the bottom of the pier so that the pier can rotate freely within a set displacement range, reducing the bending moment requirements of the superstructure on the pier body, thereby improving the overall seismic performance.

4.2. Seismic isolation technology

4.2.1. Metal vibration isolation design

Applying metal vibration isolation technology in bridge engineering reduces the resonance effect between bridge structures. It enhances their seismic resistance under earthquake action by installing metal or metal composite panels. Metal isolation bearings are generally installed on the tops of bridge piers and beam ends. As the interface between the bridge deck and the bridge piers, they absorb and disperse the energy brought by seismic waves through their elastic and plastic properties. Its design usually includes components such as thick metal plates and metal springs. The above components can undergo elastic or plastic deformation under earthquake action and absorb part of the earthquake energy while limiting the displacement of the structural system and preventing structural damage [9].

4.2.2. Rubber vibration isolation design

The rubber vibration isolation design of the bridge structure is to install rubber isolation bearings on the bridge piers to effectively isolate the transmission of seismic waves, thereby protecting the bridge structure from earthquake damage.

The design of the rubber isolation bearings focuses on its ability to absorb the input energy of the designed earthquake and exert its deformation ability. Through the composite structures of vertically stacked multi-layer rubber and internal sandwich steel plate, the high elasticity and energy dissipation characteristics of rubber are used to enable the bearing to form effective horizontal displacement under horizontal earthquake load. This feature helps reduce the transfer of shear force and bending moment from the bridge's upper structure to the lower structure, thereby avoiding damage to the bridge piers and base.

When designing rubber isolation bearings, factors such as structural, seismic, and material characteristics of the bridge must be comprehensively considered during the design stage. Firstly, the dynamic characteristics of the bridge should be determined, including the bridge's natural frequency and vibration mode, which are the basic basis for seismic isolation design. Secondly, the size of the rubber bearings needs to be optimized based on the actual load, geometric dimensions of the bridge, and the expected displacement during an earthquake. The vertical stiffness of the bearing should meet the requirements of the vehicle load under normal use, and the horizontal stiffness also needs to meet seismic isolation requirements.

To improve the seismic isolation effect, it is necessary to conduct an in-depth analysis of the energy dissipation performance of the bearing. The energy dissipation capacity is directly related to the performance of the seismic isolation system during an earthquake [10]. In addition, due to factors such as ambient temperature and aging, the performance of rubber bearings will degrade over time. Therefore, the long-term performance guarantee should be considered in the design. Limestones or other auxiliary facilities should be installed if necessary to prevent excessive displacement.

5. Case studies on seismic reduction and isolation design of bridges in high-intensity earthquake areas

To objectively understand the application of seismic reduction and isolation design strategies for bridges in high-intensity earthquake areas, this article takes a continuous girder bridge in a high-intensity earthquake area in Xichang City, Sichuan Province, as the research object to discuss the specific application of seismic reduction and isolation technology in this continuous girder bridge.

5.1. Project overview

The 5 × 20 m continuous girder bridge in a high-intensity earthquake area in Xichang City, Sichuan Province adopts the design method of simply supported continuous small box girders (**Figure 1**). Its lower structure is a reinforced concrete circular double-column pier with a pier height of 3–6 m.

In this case, the seismic fortification intensity of the continuous beam bridge was IX degree, the basic earthquake acceleration was 0.4 g, and it was a Category III site. Records show that the largest earthquake in the area was a 7.5-magnitude earthquake in 1536.

5.2. Shock absorption and isolation design

The bridge in the case study has taken the following technical measures in terms of earthquake reduction and isolation:

(1) Use seismic isolation bearings: install HDR d370x177 circular high-damping rubber isolation bearings are installed on continuous piers 1#~4#; the 0# abutment and the 5# bridge are equipped with LNR (H) d270x109 circular sliding horizontal force dispersing rubber bearings to meet the large displacement of the abutment and expansion joint areas under the action of earthquakes.

(2) A cable limiter is set at each box girder to limit the longitudinal deformation of the bridge. The cable limiter on one side of each box girder is designed to be 17 MN/m and consists of 6 cables.

(3) Anti-seismic blocks are installed on both sides of each box girder to limit the lateral deformation of the bridge.

(4) The short piers and columns of the bridge belong to the category of short piers in earthquake-resistant structures; the bridge piers and pile foundations use HRB500 φ 28 main bars and HPB300 φ 10 stirrups.

(5) The whole area of the bridge piers and columns and the 10 m range below the ground of the bridge pier pile foundation shall be designed with dense stirrups and two-legged parallel winding (**Figure 2**).

(6) The support length of the bridge abutment and expansion joint cover beam is designed to be 1.3 m, which is greater than the length required in the specification.

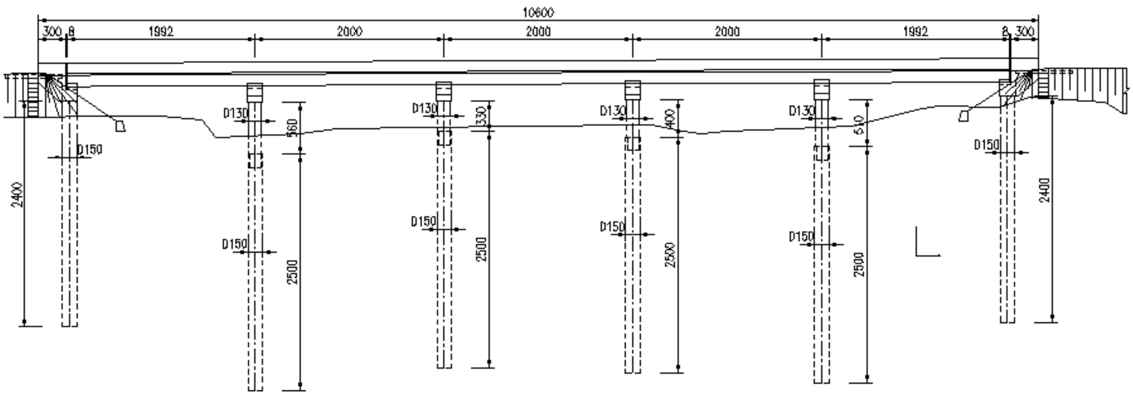

Figure 1. Bridge layout (Unit: mm)

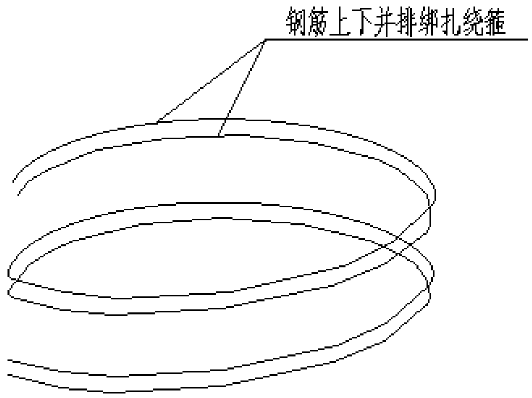

Figure 2. Bridge pier stirrup reinforcement design drawing (mm) (Translation: Steel bars are tied up and down side by side with hoops)

5.3. Calculation results

After establishing the full-bridge seismic response analysis model and damping simulation through midas Civil software, the seismic verification of E1 and E2 effects was carried out by the "Seismic Design Code for Highway Bridges" (JTGT 2231-01-2020). Under the E1 earthquake effect, the bridge structure meets the relevant requirements of the code; without considering the isolation bearing, the strength of some bridge piers under the rarely occurred earthquake E2 does not meet the specification requirements. Considering seismic reduction and isolation measures, time history analysis was used, and the strength and deformation of the bridge piers met the specification requirements.

6. Conclusion

In summary, after a detailed analysis of the seismic reduction and isolation technology of bridges in high-intensity earthquake areas, this article takes a continuous girder bridge in a high-intensity earthquake area in Xichang City, Sichuan Province as an example to analyze the seismic reduction and isolation design of the bridge. After adopting the design scheme proposed in this article, the bridge structure was calculated to meet the performance objectives. Therefore, relevant units can learn from case design methods to improve the seismic performance of bridges in high-intensity earthquake areas based on fully mastering the seismic reduction and isolation technology.

Disclosure statement

The author declares no conflict of interest.

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