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Seismic Disaster Prevention and Mitigation Research for Long-span Cable-stayed Bridges

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ABSTRACT

With the rapid advancement of bridge engineering, the construction of long-span cable-stayed bridges has surged, with China now hosting the majority of the world's largest examples. However, issues such as cable corrosion, aging, and vulnerability to extreme events—including earthquakes—pose significant challenges. Among various natural hazards, earthquakes are particularly destructive, capable of causing widespread structural failure and triggering secondary disasters like landslides and liquefaction. In China, frequent seismic activity has repeatedly damaged vast regions, disrupted transportation networks, and hindered emergency response. As bridges serve as critical components of transportation lifelines, their seismic vulnerability can result in severe economic and humanitarian consequences. Therefore, enhancing the seismic resilience of bridge structures through targeted analysis and design measures is vital to ensuring structural safety and post-disaster accessibility.

KEYWORDS

Long-span cable-stayed bridge; Damping isolation system; Bridge orientation.

1. INTRODUCTION

China is situated between the circum-Pacific and Eurasian seismic belts, two of the most active tectonic zones in the world. This unique geographic location, combined with mountainous terrain and intense, frequent crustal movements, renders the country highly susceptible to seismic hazards. Earthquakes often cause significant damage to bridges, including failure of the superstructure, support connections, and substructure. Among these, the most severe damage tends to occur in the foundations and piers, which can lead to catastrophic collapse and are often difficult to repair post-earthquake[1].Therefore, it is imperative to investigate the seismic performance of bridge structures and implement effective seismic design measures to ensure both structural safety and the continuity of critical transportation networks during disasters.

With continuous advancements in structural analysis methods, construction technologies, anchorage systems, and material science, bridge engineering has progressively moved towards longer spans and the use of high-performance materials. Among various bridge types, cable-stayed bridges have become a dominant form for long-span crossings over the past three decades due to their aesthetic appeal, large span capability, flexible layout, and efficient use of high-tensile cable materials[2]. Although the development of cable-stayed bridges in China began relatively late, it has progressed rapidly. According to incomplete statistics, over 300 cable-stayed bridges are currently in service within the national transportation system. Notably, seven of the ten longest cable-stayed bridges worldwide are located in China, underscoring their critical role in the nation's transport infrastructure.

Unlike conventional girder bridges, long-span cable-stayed bridges—characterized by their structural flexibility—are typically designed under seismic loading with displacement control rather than force control. Given their complex configurations, high construction costs, and wide societal impacts, coupled with the absence of dedicated seismic design codes tailored to their unique characteristics, there is a clear need for focused seismic research on cable-stayed bridges to ensure their resilience under seismic events.

Structurally, cable-stayed bridges are categorized into floating, semi-floating, tower-girder consolidated, and fully fixed systems. Among these, the floating system is most commonly adopted in long-span applications due to its favorable dynamic performance, as it reduces internal force demand on pylons and minimizes secondary effects[3] such as those induced by temperature variations or concrete shrinkage and creep. Both the Guidelines for Seismic Design of Highway Bridges (2008) and the Seismic Design Code for Urban Bridges (2011) in China recommend prioritizing the floating system in regions with a seismic intensity of 8 or 9 degrees. If excessive displacements occur at beam ends, supplemental seismic control devices such as tower restraints, elastic supports, or dampers should be considered.

In recent years, seismic isolation and energy dissipation technologies have emerged as effective, economical, and practical solutions for bridge seismic protection. These systems extend the natural period of the structure and reduce the energy transferred to the main components during seismic events, all while maintaining normal service performance. The selection of appropriate, cost-effective, and reliable isolation devices is crucial in the seismic design of long-span floating cable-stayed bridges[4]. However, the application of these technologies in China is still in its early stages, and the lack of comprehensive technical guidelines and regulatory standards continues to hinder their widespread implementation.

2. COMPREHENSIVE ANALYSIS OF SEISMIC DESIGN METHODS AND MITIGATION STRATEGIES IN CABLE-STAYED BRIDGES

2.1. Design Method for Seismic Isolation of Cable-Stayed Bridges

The theory of seismic force, also referred to as seismic action theory, focuses on the dynamic effects of ground motion on structures during an earthquake. Accurate seismic analysis of bridge structures must be grounded in a realistic representation of earthquake ground motion.

Given the inherently random nature of seismic excitation, the parameters used in seismic analysis are subject to uncertainty. As a result, two principal theoretical approaches have been developed: Deterministic seismic force theory, which treats ground motion as a defined, time-dependent process; and Probabilistic seismic force theory, which models ground motion as a stochastic process.

While the probabilistic approach offers a more comprehensive representation of seismic variability, it remains under development and is not yet widely applied in engineering practice. Consequently, most international and national seismic design codes for bridges are based on deterministic seismic theory.

At present, the primary deterministic methods employed in seismic force analysis include the static method, response spectrum analysis, and dynamic time-history analysis[5]. These approaches vary in complexity and accuracy, with dynamic time-history analysis providing the most detailed representation of structural response under earthquake loading.

2.1.1. Static analysis

In the early 20th century, Japanese researchers identified the maximum horizontal acceleration as a critical factor contributing to earthquake-induced structural damage. They proposed an equivalent static analysis method to evaluate seismic effects by treating the structure as a rigid body, neglecting deformation influences as well as the time-dependent characteristics of seismic loading and its interaction with structural dynamic properties[6]. Under this approach, the maximum horizontal seismic force at each structural mass point is approximated by the product of the mass and the peak ground acceleration.

In recent decades, a widely adopted static analysis method known as the nonlinear static pushover analysis has gained prominence. Pushover analysis involves applying a predefined lateral load pattern to the structural model, gradually increasing the load intensity while monitoring the progression of cracking, yielding, plastic hinge formation, and component failures. Developed during the 1990s as an extension of capacity spectrum methods, pushover analysis is extensively used in seismic design and assessment to evaluate a structure's seismic performance under strong ground motions through nonlinear deformation. This method effectively captures the deformation behavior of structures and facilitates performance-based seismic design and evaluation tailored to varying performance objectives.

2.1.2. Response spectrum analysis

Response spectrum analysis originated from strong-motion recordings. It was first conceived by M. A. Biot in the 1940s and subsequently realized by Housner in the early 1950s. In this method, recorded ground accelerations are applied to the equation of motion for a single-degree-of-freedom (SDOF) system to compute each SDOF's peak elastic response[7]. Plotting these maxima against the system's natural periods yields a response spectrum, from which the maximum seismic demand on a structure can be inferred and its response estimated using static-equivalent procedures. Although response spectrum analysis incorporates the structure's dynamic properties, it treats inertial forces as if they were static loads, justifying its designation as a pseudo-dynamic approach.

By combining response spectrum theory with modal decomposition, engineers developed the modal response spectrum method to handle complex, multi-degree-of-freedom systems. Exploiting modal orthogonality, the global motion equations decouple into independent SDOF equations, each solved via its own spectral value. Ongoing research has extended the framework to account for nonlinear behaviour through nonlinear response spectrum techniques. Thanks to these advances, response spectrum analysis has become a cornerstone of seismic engineering and remains one of the primary methods prescribed in contemporary seismic design codes.

2.1.3. Dynamic Time-History Analysis Method

Dynamic time-history analysis involves first selecting an appropriate seismic input and then formulating the equations of motion for the structure using a finite-element dynamic model that represents it as a multi-node, multi-degree-of-freedom system[8]. These equations are solved through incremental (step-by-step) numerical integration, yielding the instantaneous displacement, velocity, and acceleration responses of the structure throughout the earthquake. By tracking these time-dependent responses, one can examine the evolution of internal forces during both the elastic and inelastic phases, as well as the progressive cracking, damage accumulation, and eventual collapse of individual components under seismic loading.

2.2. Seismic Control Strategies for Cable-Stayed Bridges

2.2.1. Assessment of Longitudinal Seismic Isolation and Damping Techniques in Cable-Stayed Bridges

In contemporary seismic mitigation schemes for the longitudinal direction of cable-stayed bridges, designers frequently introduce flexible connectors or damping devices between the towers and the deck to fulfil earthquake-resistance requirements[9]. For example, the Tatara Bridge in Japan employs large rubber bearings at the tower–deck interface; the Shantou Bay II Bridge in Guangdong Province uses longitudinally oriented elastic cables between its pylons and girders; and both the

Sutong Yangtze River Bridge and the Shanghai Yangtze River Bridge incorporate hydraulic viscous dampers in these critical regions.

China's Highway Bridge Seismic Design Specifications (2008) and Code for Seismic Design of Urban Bridges (2011) stipulate that cable-stayed bridges situated in zones of basic seismic intensity VIII or IX should, wherever feasible, adopt a floating-system solution[10]. If this approach produces excessive displacement at the girder ends, an alternative arrangement of elastic or damping restraints between tower and deck is advised. Consequently, the deployment of viscous dampers and elastic stay cables has emerged as a primary strategy for longitudinal seismic isolation in modern cable-stayed bridge design.

2.2.2. Evaluation of Lateral Seismic Isolation and Energy Dissipation Techniques in Cable-Stayed Bridges

In the seismic design of existing cable-stayed bridges, longitudinally China typically adopts a floating-support scheme. On many long-span bridges, hydraulic viscous dampers are installed between the pylon and deck, endowing the main towers with relatively high longitudinal seismic capacity.

Transversely, however, wind-resistance requirements lead to rigid connections between pylons and girders. Under this full-restraint arrangement, although the tower-base section must resist large seismic forces, its cross-section—dictated by gravity loads and construction demands—is sufficiently robust and seldom a concern[11]. The transitional piers, by contrast, are frequently overlooked. When seismic loads act laterally, the deck and piers vibrate as a single unit against the restraints, producing high force reactions. Because the transitional piers have smaller sections, their bases can yield easily and their foundations often fail to meet seismic criteria, while the bearings face excessive shear demands.

If the lateral constraints at the end piers were released, the bridge would suffer excessive seismic and residual displacements. Thus, to reconcile the conflict between force demands and allowable movement, an appropriate transverse vibration-reduction system is needed for cable-stayed bridges.

3. SEISMIC DESIGN SCHEME FOR CABLE-STAYED BRIDGES

3.1. Utilization of Viscous Dampers

Viscous dampers, which absorb and dissipate the energy generated during seismic events through viscous friction, are widely employed in seismic engineering to enhance the energy dissipation capacity of structures. These dampers function by converting the kinetic energy of the vibrating structure into thermal energy, effectively reducing structural displacements and internal forces during dynamic loading. The integration of viscous dampers into bridge and building designs provides an efficient method of controlling vibrations, thereby improving the overall seismic performance and protecting the structure from potential damage during strong ground motions.

In bridge seismic design, the strategic placement of viscous dampers can help mitigate the lateral forces induced by earthquakes, particularly in flexible structures like cable-stayed and suspension bridges. These dampers are typically installed at critical locations where they can maximize energy dissipation without compromising the functional integrity of the structure[12]. The use of viscous dampers is particularly beneficial in reducing both the amplitude and duration of structural oscillations, leading to lower peak forces and more stable performance during seismic events.

In the seismic design of cable-stayed bridges, using viscous dampers for longitudinal seismic resistance, the objective is to control displacement. From this perspective, the damping coefficient should be increased and the velocity exponent reduced. However, from the standpoint of damper design and manufacturing, the damping coefficient should not be excessively large, and the velocity exponent should not be too small.

When viscous dampers are installed between the tower and girder, the variation in damper parameters affects the base section of the bridge tower and the internal forces in the single foundation piles at the tower base more significantly than it impacts the forces in the foundation sections of the piers (auxiliary piers and transition piers) and their corresponding piles. Specifically, when the velocity exponent is fixed, the internal forces in the tower base section and corresponding single foundation pile decrease as the damping coefficient increases. Conversely, when the damping coefficient is fixed, the internal forces in the tower base section and corresponding pile increase as the velocity exponent rises.

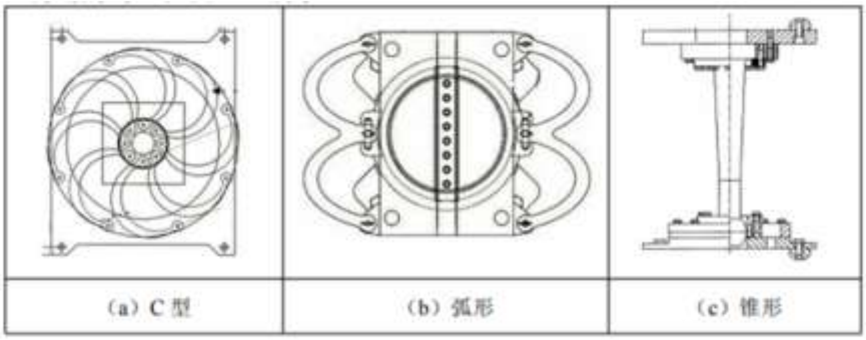

Fig 1 Metal damper

3.2. Utilization of Elastic Cables

Elastic cables are commonly employed in structural engineering to enhance the dynamic response of structures, particularly in seismic and vibration control applications. These cables, which behave elastically under load, are mainly used in cable-stayed and suspension bridges, as well as other tension-supported structures. Their key advantage lies in their ability to absorb and release elastic energy during dynamic events, such as earthquakes, thereby reducing the overall structural response.

In seismic design, elastic cables are especially useful in limiting large displacements and reducing structural damage. When integrated into the bridge design, they can work in tandem with other damping systems to form a comprehensive seismic protection strategy. By effectively dissipating energy during seismic events, elastic cables help maintain the structure's stability and prevent excessive deformation or failure.

The performance of elastic cables depends on factors like material properties, tension, and cable configuration. Proper selection of these parameters is essential for ensuring the cables' effective contribution to the structure’s dynamic behavior and seismic resistance.

The use of elastic cables in the longitudinal seismic design of cable-stayed bridges primarily serves to provide elastic stiffness, thereby altering the dynamic characteristics of the structure, rather than dissipating energy. From the perspective of controlling displacements, the stiffness of the elastic cables should be increased.[13] When elastic cables are placed between the tower and the girder, variations in the cable stiffness have a more significant impact on the internal forces in the tower base section and the single foundation pile at the tower base than on the forces in the foundation sections of the side piers (auxiliary piers and transition piers) and their corresponding piles. Additionally, the internal forces in the control section exhibit non-monotonic variations as the stiffness of the elastic cables increases.

If the elastic cables are properly selected, they can effectively modify the dynamic response of the structure. This approach, which considers both the forces at the tower base section and the longitudinal displacement requirements of the supports, also takes into account the forces in the single foundation piles.

3.3. Selection of Seismic Isolation Systems

Selecting the right seismic isolation system is essential for enhancing a structure's resilience during earthquakes. These systems work by isolating the structure from ground motion, thus reducing the seismic energy transferred to it and minimizing potential damage. Common types of seismic isolation systems include elastomeric bearings, sliding bearings, and hybrid systems, each offering unique benefits depending on the structure type, its location, and seismic risk.

Several key factors must be considered when choosing a seismic isolation system, such as the seismic hazard level, the dynamic behavior of the structure, and the specific needs of the building or bridge. For example, elastomeric bearings are frequently used in bridges and buildings due to their durability and ability to absorb seismic forces[14]. In contrast, sliding bearings are ideal for applications requiring larger displacements, as they offer low friction and enhanced flexibility.

Additionally, the selected system should account for long-term maintenance, cost efficiency, and its effect on the overall structural performance. A well-chosen seismic isolation system not only safeguards the structure from significant damage but also enhances its performance during and after seismic events, ensuring occupant safety and the continuous operation of essential functions.

The lateral performance of cable-stayed bridge side piers with full sliding and full restraining systems often fails to meet seismic requirements. In the case of the full sliding system, the displacement at the beam end and the relative displacement between the side pier and the beam are significantly large, while the forces on the substructure are minimal. Conversely, the full restraining system generates substantial seismic reactions at the base and foundation of the side piers, which may not satisfy the necessary seismic performance criteria.

To address these shortcomings, a lateral seismic isolation system for side piers has been proposed. By introducing damping devices at the side piers, this system protects the substructure from damage under strong seismic forces while fully utilizing the substructure's seismic resistance. The damping devices also contribute to energy dissipation, effectively controlling the lateral relative displacement between the pier and beam. This system offers a balanced approach to force and displacement management at the side piers and is a promising solution for improving lateral seismic resistance in cable-stayed bridges.

3.4. Use of Hydraulic Viscous Dampers

Hydraulic viscous dampers are commonly employed in structural engineering to reduce vibrations and improve seismic resilience. These dampers function by converting the kinetic energy of structural movement into thermal energy via the viscous flow of hydraulic fluid, thereby reducing vibration amplitude and protecting the structure from excessive displacements and potential damage.

In seismic applications, hydraulic dampers are integrated into buildings, bridges, and other structures to control both the intensity and duration of oscillations. Their main advantage is their ability to maintain consistent damping performance over a wide range of velocities, making them effective for structures exposed to varying seismic forces[15]. Often, these dampers are used alongside other seismic protection systems, such as base isolators or elastomeric bearings, to create a comprehensive strategy for earthquake resistance.

The performance of hydraulic viscous dampers depends on factors like the damper's size, fluid type, and system configuration. Proper design and installation are essential to ensure that they effectively minimize structural vibrations and contribute to the overall stability of the structure during seismic events.

The seismic response of the damping system utilizing hydraulic viscous dampers, when compared to the full restraining and full sliding systems, shows that the maximum displacement between the pier and beam is reduced by 70% to 80% compared to the full sliding system. Additionally, the horizontal seismic forces at the supports are reduced by 40% to 60% when compared to the full restraining system.

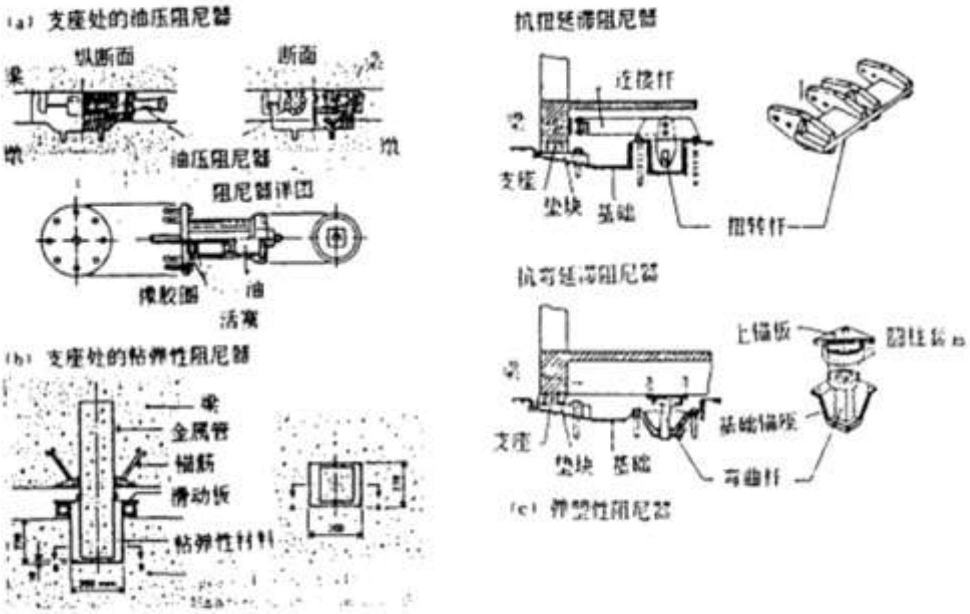

Fig 2 Place the damper at the support.

The seismic response results of the hydraulic viscous damper-based isolation system, compared to both the full restraining and full sliding systems, indicate that the maximum displacement between the pier and beam is reduced by 70% to 80% relative to the full sliding system. Additionally, the horizontal seismic forces at the supports are decreased by 40% to 60% in comparison to the full restraining system.

Table 1 Seismic response of the vibration damping system (VFD) pier damper.

	位移（m）			力（kN）			比值	
	全限位（1）	全滑动（2）	VFD（3）	全限位（4）	全滑动（5）	VFD（6）	(3)/(2)	(6)/(4)
过渡墩支座	0.000	1.409	0.271	8441	115	3083	0.19	0.37
辅助墩支座	0.000	0.943	0.259	5380	31	3306	0.27	0.61

The seismic response results of the hydraulic viscous damper-based isolation system, when compared to both the full restraining and full sliding systems, show that the seismic response at the base of the side piers is reduced by 40%, while the seismic response at the foundation of the side piers is reduced by 30%.

Table 2 Seismic internal force response at key positions of the damping system (VFD)

	剪力（kN）			弯矩（kN.m）			比值	
	全限位（1）	全滑动（2）	VFD（3）	全限位（4）	全滑动（5）	VFD（6）	（3）/（1）	（6）/（4）
过渡墩墩底	1.05E+04	8.30E+03	7.26E+03	3.77E+05	2.19E+05	2.55E+05	0.69	0.68
辅助墩墩底	1.12E+04	7.79E+03	7.17E+03	4.73E+05	2.11E+05	2.83E+05	0.64	0.60
主塔塔底	7.37E+04	7.02E+04	7.28E+04	4.93E+05	4.69E+05	4.85E+05	0.99	0.98
过渡墩单桩	3.09E+03	3.29E+03	2.39E+03	6.57E+04	7.04E+04	5.33E+04	0.77	0.81
辅助墩单桩	3.44E+03	3.17E+03	2.60E+03	7.52E+04	6.78E+04	5.47E+04	0.76	0.73
主塔单桩	3.39E+03	3.13E+03	3.25E+03	6.91E+04	6.38E+04	6.73E+04	0.96	0.97

3.5. Use of Friction Pendulum Bearings

Friction pendulum bearings are a sophisticated seismic isolation system designed to mitigate the effects of earthquake forces on structures. These bearings work by utilizing a combination of friction and pendulum motion. The system consists of a curved sliding surface and a sliding element that moves along this surface. The design enables the bearing to dissipate seismic energy efficiently while allowing minimal displacement of the structure. By combining frictional resistance and pendulum movement, these bearings offer both vertical load support and horizontal damping, effectively controlling lateral displacement during earthquakes.

These bearings are commonly applied in bridges, buildings, and other critical infrastructures, offering significant advantages over traditional isolation methods. They are especially effective in regions with high seismic activity, where large displacements are anticipated, and they perform reliably across a wide spectrum of ground motions. Furthermore, friction pendulum bearings have a self-centering feature, ensuring that the structure returns to its original position after seismic events, thereby reducing the need for extensive repairs.

The performance of these bearings is influenced by factors such as the curvature radius, friction coefficient, and material properties[16]. Proper selection and installation are crucial to ensuring the bearings function effectively, reduce seismic forces, and enhance the overall stability and resilience of the structure.

Sliding friction bearings, lacking self-centering properties, can lead to excessive relative displacement in structures. However, by modifying these bearings to include post-sliding stiffness, it is possible to achieve bearings that effectively dissipate seismic energy, such as friction pendulum bearings (FPB).

Friction pendulum bearings modify the conventional spherical sliding bearing by replacing the smooth sliding surface with a spherical one. The structure consists of an upper bearing plate with a concave spherical sliding surface, a middle bearing plate with a convex spherical surface, and a lower bearing plate with a concave rotational surface. Both the sliding and rotational surfaces are made of stainless steel and polytetrafluoroethylene (PTFE) plates. The seismic functioning of the bearing is based on its ability to dissipate energy: when the lateral force during an earthquake exceeds a threshold, shear bolts are sheared, and the lateral constraint on the bearing is released, allowing the large-radius spherical friction pair to slide freely. This process converts seismic kinetic energy into potential energy. During sliding, the frictional resistance dissipates a portion of the earthquake energy, and the potential energy generates restoring force, enabling the bearing to return to its original position.

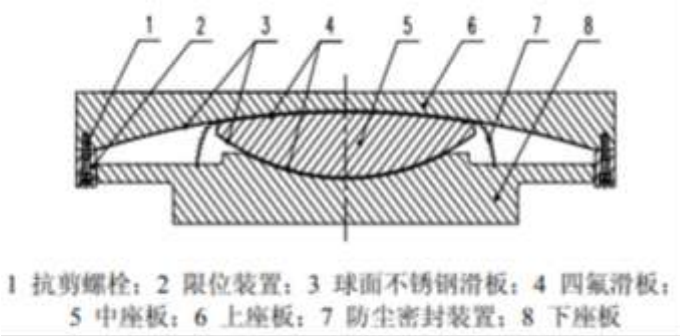

Fig 3 Friction pendulum structure

4. SUMMARY

(I) Analysis of Lateral Seismic Systems for Cable-Stayed Bridges Lateral seismic design of cable-stayed bridges commonly employs either full-sliding systems or full-restraint systems. These systems passively withstand seismic loads through structural components, lacking active energy-dissipation mechanisms, which prevents effective dissipation of seismic energy. Their seismic performance heavily relies on the load-bearing capacity of components and bearings, imposing excessive demands on the structure. Consequently, they represent non-ideal seismic solutions. In contrast, seismic mitigation systems can leverage the energy-dissipation characteristics of isolation/damping devices based on the seismic requirements of substructures, achieving coordinated control between loads and displacements at side piers.

(II) Efficacy and Limitations of Hydraulic Viscous Dampers (VFDs) Theoretical studies indicate that among lateral seismic mitigation devices, hydraulic viscous dampers (VFDs) exhibit the most pronounced efficiency in dissipating seismic energy, fully satisfying transverse seismic mitigation objectives. However, their practical engineering application requires coordination between transverse and longitudinal deformation responses, resulting in complexified structural configurations. This technical limitation hinders their widespread adoption in engineering practice.

(III) Suitability Assessment of Friction Pendulum Bearings (FPBs) The seismic mitigation efficacy of friction pendulum bearings (FPBs) primarily relies on a friction-based energy dissipation mechanism activated by vertical reactions. At side piers of cable-stayed bridges—particularly at transition piers—significantly reduced vertical reactions severely constrain their seismic energy dissipation capacity. Comparative analysis demonstrates that FPBs exhibit the least effective performance among lateral seismic mitigation devices. Thus, they are not recommended as seismic solutions for cable-stayed bridge side piers.

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