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Analysis of the Influence of Deep Water on the Seismic Response of Rectangular-Section High-Pile Bridges

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Abstract: With bridge construction increasingly extending into deep-water regions, the influence of deep water on the seismic response of rectangular-section high-pier bridges has become a critical issue that cannot be ignored. Focusing on this type of bridge, this study investigates the effects of deep water based on pier–water coupled vibration theory and analyzes methods for calculating hydrodynamic pressure. The results indicate that deep water can significantly prolong the natural vibration period of the structure, alter vibration modes, and affect damping characteristics, while also exhibiting strong sensitivity to site conditions. In terms of seismic response, deep water amplifies pier-top displacement and modifies internal forces at the pier base. Moreover, the coupled effects of near-field and far-field earthquakes, as well as multi-directional ground motions, show distinct characteristics. Taking a heavy-load highway continuous rigid-frame bridge in a hydropower reservoir area as an example, this paper proposes seismic design recommendations such as cross-sectional optimization, providing both theoretical insight and practical guidance for seismic design of similar bridges.

Keywords: Deep water; rectangular-section high-pier bridge; seismic response; seismic design

Introduction

Heavy-load highway bridges in hydropower reservoir areas are often confronted with the combined challenges of deep water, high piers, and complex seismic environments. Rectangular-section high-pier bridges are widely used in reservoir-area bridge construction due to their common structural form and construction convenience. However, under deep-water conditions, the interaction between bridge piers and the surrounding water forms a pier–water coupled vibration system, in which hydrodynamic pressure can significantly alter the dynamic characteristics and seismic response of the bridge. Conventional seismic design approaches often neglect the effects of deep water or adopt overly simplified treatments, resulting in considerable discrepancies between design predictions and actual structural behavior. This paper systematically investigates the influence of deep water on the seismic response of rectangular-section high-pier bridges and, in conjunction with the engineering characteristics of hydropower reservoir areas, proposes targeted seismic design recommendations. The findings are of practical significance for improving the seismic safety and reliability of bridges in reservoir regions.

1. Theoretical Basis of the Influence of Deep Water on Seismic Response of Rectangular-Section High-Pier Bridges

1.1 Pier–Water Coupled Vibration Theory

In deep-water environments, the seismic response of rectangular-section high-pier bridges is primarily governed by pier–water coupled vibration theory. According to the *Specifications for Seismic Design of Highway Bridges* (JTG/T 2231-01-2020), which address structure–fluid interaction, this theory is based on radiation wave theory. The fluid is assumed to be incompressible and inviscid, and the dynamic equations are established by analyzing the relative motion between the structure and the surrounding water. Due to the planar upstream face of rectangular sections, vortex shedding is prone to occur during flow-around, leading to a complex distribution of hydrodynamic pressure. Along the pier height, the hydrodynamic pressure generally follows a parabolic distribution, increasing initially and then decreasing, with the maximum pressure occurring at the center of the upstream face and gradually diminishing toward both sides [1].

1.2 Hydrodynamic Pressure Calculation Method

The calculation of hydrodynamic pressure is primarily based on the added mass method, in which the inertial effect of water on the structure is equivalent to an added mass ma. The added mass can be expressed as

$$ma = k \cdot \rho \cdot A \cdot h$$

where ρ is the water density, A is the cross-sectional area of the pier, and h is the water depth. For rectangular-section bridge piers, the added mass coefficient k typically ranges from 0.5 to 1.0 and depends on the slenderness ratio (the larger the slenderness ratio, the smaller the value of k) [2]. In practical calculations, the cross section is equivalently simplified, the slenderness ratio is determined using tables or formulas, and the corresponding added mass is obtained. When the water depth reaches a certain threshold, the added mass tends to stabilize and no longer increases significantly.

2. Influence of Deep Water on the Dynamic Characteristics of Rectangular-Section High-Pier Bridges

2.1 Natural Period Prolongation Effect

Deep-water environments significantly prolong the natural vibration period of rectangular-section high-pier bridges through hydrodynamic pressure effects. The added mass induced by hydrodynamic pressure increases the equivalent mass of the structure, while the constraint provided by the surrounding water to pier vibration is relatively weak, resulting in a reduction in overall structural stiffness and an extension of the natural period. For continuous rigid-frame bridges carrying heavy highway loads in hydropower reservoir areas (with a bridge width of 10 m), the influence of deep water (e.g., water depth exceeding one-third of the pier height) on the natural period varies under different seismic intensity levels [3]. Prolongation of the natural period alters the dynamic characteristics of the structure, making it more susceptible to resonance with long-period components of seismic motions (such as low-frequency components under specific earthquakes), thereby amplifying seismic response. Consequently, seismic design should account for the added hydrodynamic mass effect and mitigate resonance risks by adjusting pier stiffness or installing energy-dissipation devices. The characteristics of natural period prolongation under different seismic levels are summarized in **Table 1**.

Table 1

Seismic Level	Peak Ground Acceleration Range	Prolongation of First-Order Transverse Period	Relationship Between Prolongation and Water Depth
E1 (minor earthquake)	Typically < 0.1 g	Relatively small (5%–10%)	Gradual increase with water depth
E2 (major earthquake)	Up to 0.2 g or higher	15%–30%	Significant increase with water depth

2.2 Alteration of Mode Shapes

Deep-water conditions have a pronounced influence on the mode shapes of rectangular-section high-pier bridges. Hydrodynamic pressure results in varying constraints along the pier height, with added mass concentrated in shallow-water zones, causing vibration modes to shift from an "overall bending" pattern (typical under onshore conditions) to a "segmented vibration" pattern. For deep-water high-pier continuous rigid-frame bridges in reservoir areas (bridge width of 10 m), the degree of mode shape alteration differs under various seismic intensities. Under E1 earthquakes, the changes are relatively moderate; under E2 earthquakes, the first-order transverse mode exhibits a composite form, while higher-order modes show downward shifts of nodal points and redistribution of participation factors. These changes affect the spatial distribution of seismic responses and may lead to stress concentration in critical components. Therefore, seismic design should incorporate targeted local strengthening measures to ensure structural safety [4].

2.3 Changes in Damping Characteristics

Deep-water environments also modify the damping characteristics of rectangular-section high-pier bridges. Coupling between hydrodynamic pressure and structural vibration induces additional energy dissipation, increasing the overall damping ratio by approximately 10%–25% compared with onshore conditions. For deep-water high-pier continuous rigid-frame bridges in hydropower reservoir areas (bridge width of 10 m), the added damping effect varies under different seismic levels. Under E1 earthquakes, it contributes to suppressing structural vibration; under E2 earthquakes, it effectively attenuates high-frequency vibrations but exhibits limited energy dissipation capacity for long-period vibrations. Changes in damping characteristics also affect dynamic decay behavior and seismic response amplitudes. Hence, seismic design should accurately evaluate added hydrodynamic damping and optimize energy dissipation capacity through appropriate devices to ensure dynamic stability [5].

2.4 Sensitivity to Site Conditions

The dynamic characteristics of rectangular-section high-pier bridges in deep water are highly sensitive to site conditions. Soft soil foundations reduce overall structural stiffness and exacerbate natural period prolongation, whereas stiff foundations constrain the effect of hydrodynamic added mass and reduce the degree of period extension. For deep-water high-pier continuous rigid-frame bridges in hydropower reservoir areas (bridge width of 10 m), the influence of site conditions varies with seismic intensity. Under E1 earthquakes, the impact on dynamic characteristics is relatively limited; under E2 earthquakes, non-uniform water depth distributions along the pier height—such as shallow water near the bank and deeper water toward the reservoir center—can result in non-uniform added mass distribution, leading to spatial variations in dynamic properties. These factors must be fully considered in seismic design.

3. Effects of Deep Water on the Seismic Response of Rectangular High-Pier Bridges

3.1 Amplification Effect on Pier-Top Displacement

The deep-water environment has a pronounced influence on the pier-top displacement response of rectangular high-pier bridges. The added mass induced by hydrodynamic pressure increases the equivalent structural mass and reduces the overall stiffness, thereby prolonging the natural vibration period of the structure. As a result, the structure becomes more susceptible to resonance with the long-period components of seismic ground motions, leading to amplified pier-top displacements. Meanwhile, the dynamic constraint imposed by hydrodynamic pressure alters the vibration mode of the pier from an "overall bending" pattern to a "segmented vibration" pattern, further intensifying displacement responses. For deep-water high-pier continuous rigid-frame bridges in hydropower reservoir areas (with a bridge width of 10 m), the amplification effect varies under different seismic intensity levels. Under E1 (minor earthquake) conditions, the displacement amplification factor is relatively small, whereas under E2 (major earthquake) conditions, the pier-top displacement may reach 1.3–1.8 times that observed under dry-land conditions, with the amplification increasing as water depth increases [6].

3.2 Characteristics of Pier-Base Internal Force Response

Deep-water conditions significantly alter the internal force response characteristics at the pier base of rectangular high-pier bridges. The added mass effect generated by hydrodynamic pressure increases the inertial forces of the pier, resulting in greater base shear forces and bending moments. The internal force distribution typically exhibits a gradient pattern characterized by smaller forces in the upper portion and larger forces in the lower portion of the pier. In addition, the coupling between hydrodynamic pressure and seismic excitation may activate higher-order vibration modes of the pier, leading to multi-peak internal force responses at the pier base and increasing the risk of localized structural damage [7]. For deep-water high-pier continuous rigid-frame bridges in hydropower reservoir areas (bridge width of 10 m), the increases in pier-base internal forces under different seismic intensity levels are summarized as follows:

Table 2

Seismic Intensity Level	Increase in Pier-Base Shear (relative to dry land)	Increase in Pier-Base Bending Moment (relative to dry land)	Internal Force Characteristics
E1 (Minor Earthquake)	5%–15%	8%–20%	Single-peak distribution, phase generally consistent with ground motion
E2 (Major Earthquake)	20%–35%	25%–40%	Multi-peak distribution, peak timing correlated with higher-order mode coupling

3.3 Differences Between Near-Field and Far-Field Seismic Responses

Rectangular-section high-pier bridges in deep-water environments exhibit pronounced differences in their responses to near-field and far-field ground motions. Near-field earthquakes contain abundant high-frequency components and long-period velocity pulses. The presence of hydrodynamic added mass amplifies the effect of long-period pulses on pier-top displacement, while high-frequency components tend to induce localized vibrations of the pier, further complicating the distribution of internal forces at the pier base. In contrast, far-field ground motions are dominated by long-period components; under such conditions, hydrodynamic effects prolong the structural natural period and intensify resonance, resulting in more pronounced pier-top displacement and pier-base internal force responses. Taking a deep-water high-pier continuous rigid-frame bridge in a hydropower reservoir area (deck width 10 m) as an example, the response differences vary with seismic intensity. Under E1 earthquakes, the differences between near-field and far-field responses are relatively small; under E2 earthquakes, the peak pier-top displacement induced by near-field ground motions may reach 1.5–2.0 times that induced by far-field motions, whereas far-field earthquakes tend to produce more sustained pier-base internal force responses [8].

3.4 Coupled Effects of Multidirectional Seismic Motions

Deep-water conditions can significantly intensify the coupled effects of multidirectional seismic motions (e.g., horizontal and vertical components) on rectangular-section high-pier bridges. During horizontal vibration, hydrodynamic pressure introduces an added-mass effect, while during vertical vibration it alters the effective stiffness of the pier, leading to horizontal–vertical coupling and increased complexity of the structural dynamic response. For deep-water high-pier continuous rigid-frame bridges in hydropower reservoir areas (deck width 10 m), the manifestation of multidirectional coupling effects varies with seismic intensity. Under E1 earthquakes, the coupling effects are relatively weak; however, under E2 earthquakes, multidirectional seismic excitation can increase peak pier-top displacement by approximately 30%–50% compared with unidirectional excitation, while also resulting in a more uneven distribution of internal forces at the pier base.

4. Seismic Design Recommendations for Heavily Loaded Highway Continuous Rigid-Frame Bridges in Hydropower Reservoir Areas

4.1 Cross-Section Optimization and Added Mass Control

For deep-water high-pier continuous rigid-frame bridges with a pier-height-to-water-depth ratio greater than 1.5, cross-section optimization and added mass control are crucial. In deep-water regions, the lower pier segments should adopt solid rectangular sections with increased dimensions to enhance stiffness and mitigate period extension caused by hydrodynamic added mass. In shallow-water regions, the upper segments may transition to hollow or thin-walled sections to reduce self-weight and limit hydrodynamic pressure effects. Hydrodynamic added mass distribution should be accurately determined through dynamic analysis and equivalently represented as concentrated masses or optimized mass matrices. Additionally, permeable structures or protective facilities may be installed in shallow-water regions to weaken hydrodynamic impact and stabilize dynamic characteristics under different seismic scenarios [9].

4.2 Enhancement of Pier-Base Shear Resistance and Transverse Stiffness

Deep-water conditions significantly increase shear forces and bending moments at the pier base, necessitating structural strengthening to improve shear capacity and transverse stiffness. The pier base should adopt solid reinforced concrete sections with enlarged stirrup diameters and reduced spacing, supplemented by transverse shear reinforcement (e.g., X-shaped diagonal bars) to form a composite shear-resistant system. To enhance transverse stiffness, transverse beams or bracing may be installed in the mid-height region of the pier, or alternative structural forms such as twin-column or hollow piers may be adopted to reduce lateral displacement and torsional effects. For tall piers (height > 30 m), metallic or viscous dampers can be installed at critical locations to dissipate seismic energy and reduce peak internal forces, ensuring safety under different seismic intensities.

4.3 Multilevel Seismic Fortification and Isolation Design

To address varying seismic intensities, multilevel seismic fortification and isolation strategies should be implemented. The design objectives should follow the principles of "no damage under minor earthquakes," "repairable damage under moderate earthquakes," and "no collapse under major earthquakes." Under minor earthquakes (E1, PGA < 0.1 g), the structure should remain elastic through appropriate detailing. Under moderate earthquakes (PGA 0.1–0.2 g), limited plastic deformation is acceptable, with energy dissipation devices absorbing seismic energy. Under major earthquakes (E2, PGA ⩾ 0.2 g), seismic isolation bearings or isolation systems should be employed to reduce seismic input. Isolation parameters must be selected in consideration of hydrodynamic effects to match the dynamic characteristics of deep-water structures, and displacement limiters should be installed to prevent excessive movement of isolation layers and ensure safety under complex seismic motions [10].

Conclusions

The influence of deep water on the seismic response of rectangular-section high-pier bridges is complex and significant. Through hydrodynamic added mass effects, deep water prolongs natural vibration periods, alters dynamic characteristics, and amplifies pier-top displacement and pier-base internal forces, particularly under long-period seismic excitation where resonance risks are heightened. This study demonstrates that rational cross-section optimization (e.g., solid sections in deep-water regions and hollow sections in shallow-water regions), enhancement of pier-base shear resistance and transverse stiffness, and adoption of multilevel seismic fortification and isolation design can effectively improve seismic performance. Future research should further integrate numerical simulations and experimental studies to refine the understanding of hydrodynamic pressure distribution and pier–water coupled vibration mechanisms, providing more precise theoretical support and technical guidance for the seismic design of deep-water high-pier bridges.

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