Study on the Mechanical Behavior of Coastal Bridges under the Oblique Incidence of Extreme Waves

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Extended Abstract

With the rapid expansion of coastal transportation infrastructure, cross-sea and offshore bridges face severe threats from extreme marine disasters during their service life. Among these hazards, earthquake-induced extreme tsunami impact loads are a primary trigger for severe structural damage or even span unseating. As tsunami waves approach offshore bridges, they induce intense fluid-structure interaction, subjecting the superstructure girders and substructure piers to massive horizontal drag, vertical lift, and overturning moments, which severely compromises overall structural safety. Therefore, deeply investigating the mechanical impact mechanisms of extreme wave loads on offshore bridges carries significant practical engineering value for enhancing disaster mitigation capabilities and formulating effective protective measures.

However, existing research on tsunami loads on offshore bridges predominantly focuses on the specific case of normal wave incidence perpendicular to the bridge axis, or simplifies the problem into a two-dimensional (2D) plane to reduce computational cost and modeling complexity. In reality, due to coastline geometry, bathymetric variations, and the randomness of wave propagation, extreme waves usually strike bridges at an oblique angle. Currently, studies on oblique tsunami incidence remain scarce. Traditional normal-incidence or 2D simplified analyses cannot effectively capture the complex effects of three-dimensional (3D) flow fields. Consequently, the 3D spatial mechanical characteristics, the disruption of load symmetry, and the load eccentricity mechanisms of box girders and pier structures under oblique tsunami impacts remain unclear.

To address the limitations of existing research, this study establishes a high-fidelity 3D numerical wave tank with dynamic-mesh wave-generation and porous-media wave-absorption capabilities using ANSYS Fluent, based on the RANS equations and the SST k-ω turbulence model. The second-order solitary wave theory, characterized by pronounced nonlinearity and concentrated energy, is adopted to simulate the tsunami environment. Dynamic-mesh wave generation is achieved by governing the wavemaker movement through User-Defined Functions (UDFs) compiled with the target free-surface equation, while wave dissipation is controlled by applying damping terms within a porous medium. The high accuracy of the numerical wave generation and wave force calculation is fully validated by comparing the time-history curves of the free-surface elevation in an empty tank with theoretical solutions, as well as the numerical vertical and horizontal wave forces on a box girder with physical experimental data.

Upon ensuring model accuracy, this paper establishes a rigid-body model of the full offshore box-girder bridge structure within the numerical wave tank. To precisely investigate the mechanical mechanisms of the bridge components at a local level, the main girder is evenly divided into 19 segments along its axis, and the pier is evenly divided into 10 segments from top to bottom. The numerical simulations maintain a strict control over the water depth while systematically combining wave heights from 4m to 8m and wave incidence angles from 0° to 60°. Using the force and moment monitoring modules in Fluent, the horizontal and vertical wave forces for each girder segment, as well as the multi-directional horizontal force components, 3D bending moments, and torques for the pier segments, are extracted and recorded across the entire impact history.

The results indicate that oblique tsunami incidence disrupts the load symmetry of the box girder, resulting in larger loads on the waveward side and inducing pronounced horizontal and vertical load eccentricities. As the incidence angle increases, although the peak overall horizontal and vertical forces on the main girder attenuate significantly due to the alleviation of fluid accumulation, the load pattern of the pier shifts completely from unidirectional to being dominated by the transverse direction. Under large-angle incidence conditions, the transverse horizontal force on the pier can reach up to 3.4 times the longitudinal force, while additionally inducing transverse bending moments and torques that peak near a 45° incidence angle.

Keywords: *Oblique incidence; Hydrodynamic force; Model experiment; Numerical simulation.*