DYNAMIC FLUID–STRUCTURE INTERACTION ANALYSIS OF STEEL CAISSON FOUNDATION AND BRIDGE SUPERSTRUCTURE SUBJECTED TO WAVE LOADING

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Extended Abstract

Coastal bridge foundations and superstructures are increasingly exposed to complex and extreme marine environments, including severe waves, strong currents, and combined wave–current actions. Large prefabricated steel caisson foundations are widely adopted in sea-crossing bridge construction owing to their advantages in rapid installation, high bearing capacity and adaptability to offshore conditions. Meanwhile, coastal box-girder bridges with relatively low clearance are highly vulnerable to extreme wave impacts during service. Therefore, understanding the hydrodynamic characteristics, structural responses and failure mechanisms of bridge foundations and superstructures subjected to extreme marine loading is essential for ensuring structural safety, construction stability and long-term resilience for the coastal bridge infrastructure.

The hydrodynamic interactions between ocean waves, currents, bridge foundations and superstructures are highly nonlinear and involve strong coupling between fluid motion and structural responses. During the positioning and submerging stages of large steel caisson foundations, environmental impacts may significantly influence positioning accuracy, submerging stability and construction safety. For bridge superstructures, extreme waves may induce excessive wave forces, large displacements, bearing failure and even unseating or overturning. Accordingly, evaluating both the construction-stage behavior of steel caisson foundations and the in-service performance of bridge superstructures under wave action is of great importance for the design and safety assessment of sea-crossing bridges.

This presentation focuses on the dynamic fluid–structure interaction behavior of steel caisson foundation and bridge subjected to extreme wave and current actions. A three-dimensional fluid–structure interaction numerical framework was developed using the finite element platform LS-DYNA. The numerical model incorporates the

three-dimensional numerical wave flume, surrounding fluid domain, steel caisson foundation, adjacent bridge structures and box-girder superstructure with different support configurations. The accuracy of the proposed model was validated against analytical wave solutions and available experimental results. Based on the validated model, a systematic parametric study was performed to investigate the effects of wave parameters, current velocities, submerging positions, incident wave–current directions, anchor cable arrangements, bearing details, and supplemental damping devices on the hydrodynamic loading and dynamic responses of the structure.

Figures 1 and 2 illustrate the detailed numerical model of the steel caisson foundation and the representative configuration of the bridge superstructure considered in this study, respectively. The steel caisson foundation was analyzed during the positioning and submerging construction stages under combined wave–current conditions. In parallel, the box-girder superstructure was investigated under extreme solitary wave impact considering conventional bearing systems, strengthened steel fasteners, and fluid viscous dampers. The developed numerical framework enables simultaneous evaluation of wave propagation, wave–structure interaction, force transmission, structural vibration, and progressive failure responses within the integrated bridge system under extreme marine conditions.

A unique aspect of this study is that it systematically investigates both the construction-stage stability of large offshore steel caisson foundations and the service-stage disaster resilience of coastal bridge superstructures within a unified fluid–structure interaction framework. Unlike conventional analyses focusing on either foundations or superstructures independently, the present study considers the coupled effects of varying wave and current conditions together with structural detailing measures. Particular attention is given to the influences of anchor cable systems for caisson stability enhancement and structural strengthening measures including steel fasteners and fluid viscous dampers for improving the wave resistance capacity of bridge superstructures. This integrated approach provides new insight into both temporary construction safety and long-term operational resilience of sea-crossing bridge systems.

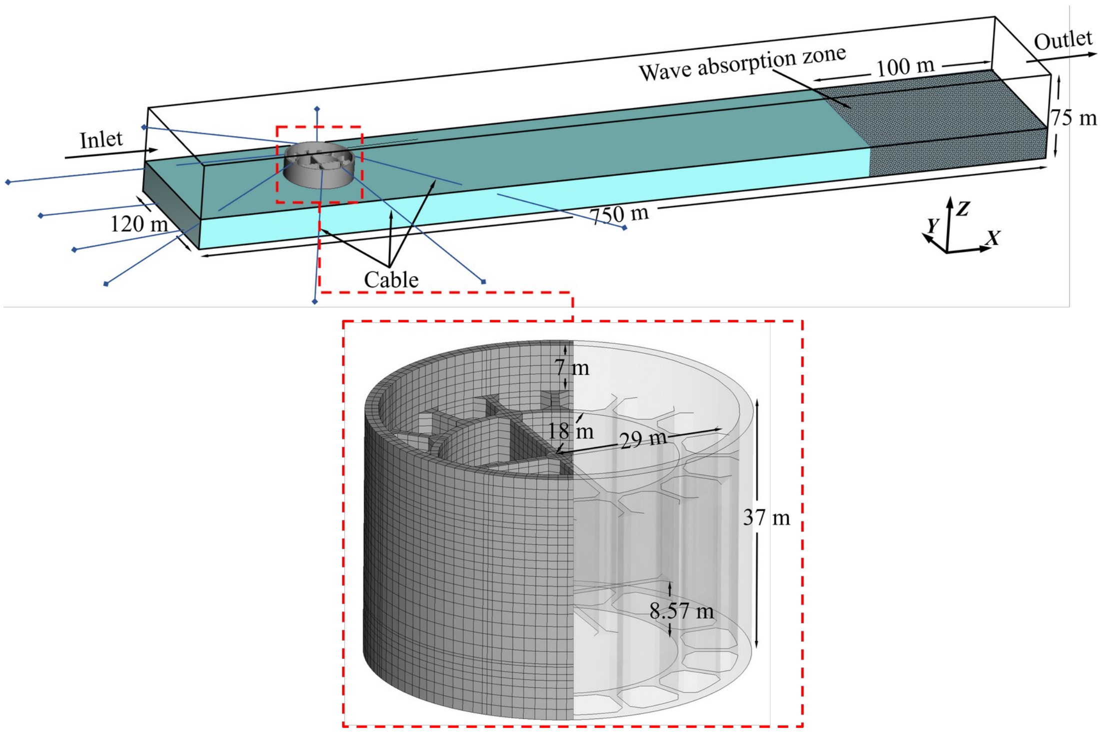

Figure 1- Details of steel caisson foundation model.

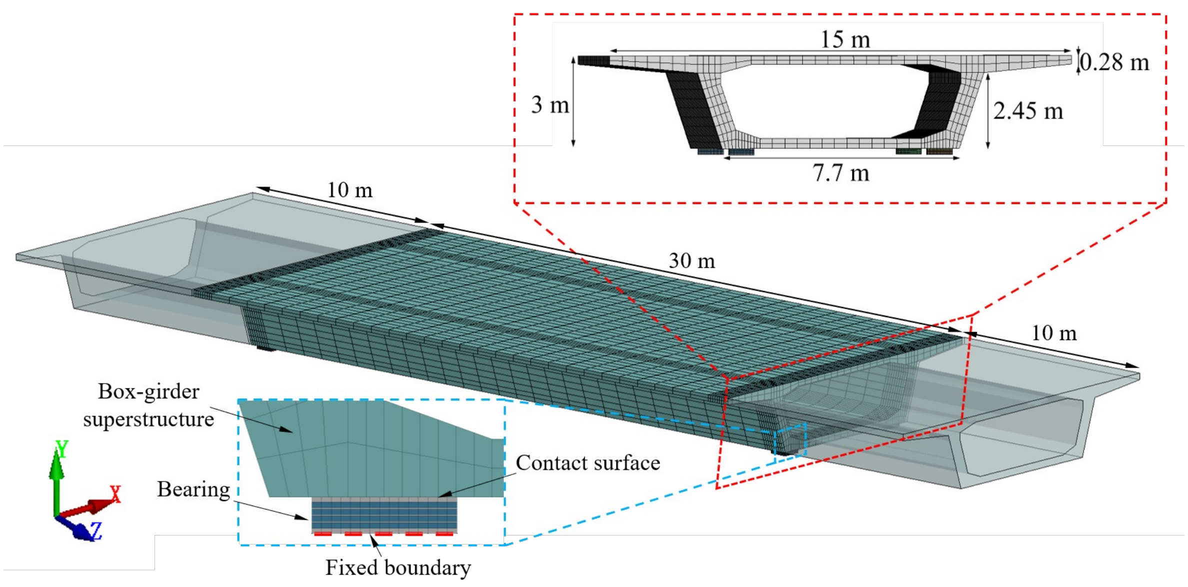

Figure 2- Details of bridge model.

The numerical results demonstrate that combined wave–current actions significantly amplify hydrodynamic loads and the structural responses compared with current-

only conditions. Variations in submerging position and wave–current incident direction strongly affect the displacement and inclination responses of steel caisson foundations during positioning and submerging operations. Proper anchor cable arrangements can effectively improve construction-stage stability under complex marine environments. For box-girder bridge superstructures, extreme wave actions may trigger sliding, unseating, overturning, and bearing failure. The introduction of steel fasteners can effectively mitigate overturning failure, while fluid viscous dampers substantially reduce maximum structural displacement and improve overall dynamic performance. The presentation will highlight the numerical modeling strategy, validation procedure, parametric investigations, response characteristics, failure mechanism. The research will provide practical mitigation measures for enhancing the safety and resilience of coastal bridge foundation–superstructure systems under extreme wave and current conditions.

Keywords*: Fluid–structure interaction; Steel caisson foundation; Coastal bridge; Stability optimization; Dynamic analysis.*