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Spatial failure mechanism of coastal bridges under extreme waves using high-efficient pseudo-fluid-structure interaction solution scheme

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Abstract: Coastal bridges serve as lifelines in evacuation and rescue after coastal natural hazards. It is thus vital to reveal the spatial failure mechanism for coastal bridges under extreme waves. In this study, a high-efficient pseudo-fluid-structure interaction (PFSI) solution scheme is proposed to investigate the spatial failure mechanism of coastal bridges under extreme waves. A series of laboratory experiments and numerical simulations are conducted to verify the proposed solution scheme. The results solved by the proposed solution scheme are acceptable and reliable under the small rotation of the deck, which could be used to efficiently assess the deck failure, and the calculation process is high-efficient. The spatial failure mechanism of the typical coastal bridge is investigated by using the proposed solution scheme in this study. The properties of wave forces on the deck are discussed based on numerous experimental measurements considering various wave parameter combinations and inundation conditions firstly. Subsequently, the failure thresholds of bearing vertical and horizontal reaction forces are obtained by parametric analysis considering various wave parameter combinations using the proposed solution scheme. Additionally, two typical failure modes (i.e., fall-beam failure and overturning failure) are analyzed by considering time-varying restraining stiffnesses in vertical and horizontal directions. The obtained results can be served as a robust reference for the design and management of coastal bridges under extreme waves.

Keywords: Coastal bridge; Spatial failure modes; Fluid-structure interaction; Extreme waves; Combined effects; Restraining stiffness.

1 Introduction

Coastal bridges connect different coastal areas and communities and serve as important lifelines in evacuation and rescue after natural hazards (e.g., storms and tsunamis) [1]–[3]. However, they are susceptible to damage from extreme waves, e.g., 81 coastal bridges connected Banda Aceh and Malabon were entirely or partly removed from their initial positions in the 2004 Indian Ocean Tsunami [4]. 103 bridges, 437 bridges, and 300 bridges were damaged in 2004 Hurricane Ivan [5], 2005 Hurricane Katrina [6], and 2011 Tohoku Tsunami [1], respectively. Due to the severe damage to coastal bridges, the first responder cannot reach certain communities after natural disasters [7], and would further cause huge life and financial cost [8][9]. Therefore, it is of vital importance to improve our understanding of the spatial failure mechanism of coastal bridges under extreme waves.

Post-disaster surveys on damaged coastal bridges [5][10][11] shown that the main type of bridges damaged in Hurricanes Ivan and Katrina was the simply supported bridge with I-shaped girders, which was extensively used in the coastal zones of North America due to the superior anti-overturning property compared with a box-shaped girder [12]–[15]. The experimental investigation conducted by Buddenbrooks et al. [16] indicated that when the deck-pier connection was rigid (i.e., bearings can withstand tensile forces), this type of bridge was less likely to fail in a steady river flow, and its deck was washed away prior to the pier collapse. However, this type of bridge either failed or sustained significant damage when the deck-pier connection was weak [17]. The study from Stearns and Padgett [18] shown that the deck-pier connection was the weakest joint of a bridge under extreme waves. Therefore, the wave forces on the deck [19][20] and deck-pier connection stiffness (i.e., bearing stiffness) are the two key factors for the spatial failure of coastal bridges under extreme waves.

The Computational Fluid Dynamics (CFD) method is widely used to calculate wave forces on bridge models by considering rigid constraints or fixing a deck in the fluid domain [21]–[25], while the deck failure is determined based on the fixed constraints and obtained wave forces. This procedure is quite effective when parametric analysis, which requires numerous repetitive simulations, is involved [26]–[30]. However, practical bearings are sensitive to the displacement of the deck, only limited displacement is allowed before bearings fail [31]–[33], and the large deck displacement, including vertical and horizontal movements and rotations, would be observed once the wave force on the deck surpasses the structural capacity [26]. Therefore, the deck rigid constraint is inappropriate to study deck failure under waves, and it is crucial to develop a high-efficient solution scheme to calculate the deck dynamic responses considering varying restraining stiffnesses and could be used to quantify the deck failure criterion.

Little previous research has been conducted to study the spatial failure of the deck by considering varying restraining stiffnesses in vertical and horizontal directions. Literature [24][25][34] investigated the effect of total lateral restraining stiffness on the bridge deck-wave interaction by ignoring vertical movements of the deck, but this assumption is invalid when the wave force surpasses the structural capacity. Ataei and Padgett [35] simulated the bearing using the Coulomb friction, but only the horizontal constraints were considered in the study and practical constraints were more complicated than Coulomb friction. In addition, the restraining stiffness of bearings is time varying. Specifically, to prevent unseating failure of the coastal bridge and reduce damage to the substructure and superstructure [36], different types of constraints, such as bearing types, shear keys, restraining cables, and shape memory alloys [31]–[33], are used to flexibly restrain the deck displacement. Also, the restraining stiffness gradually decreases or even fails with the corrosion of bearings under the ocean chloride environment and the aging of rubber bearings. However, little research focuses on the influence of time-varying bearing stiffnesses on deck failure. Therefore, a sophisticated 3D model considering time-varying restraining stiffnesses in the vertical and horizontal directions should be established and be used to investigate various failure modes of coastal bridges.

To address all the issues mentioned above, a high-efficient pseudo-fluid-structure interaction (PFSI) solution scheme is proposed in this study to explore the spatial failure mechanism of the coastal bridge under the extreme wave forces considering time-varying vertical and horizontal restraining stiffnesses. A series of laboratory experiments and numerical simulations are conducted to verify the proposed solution scheme, and its reliability and applicability are confirmed by comparative analysis. The remainder of this paper is organized as follows: Section 2, a typical coastal bridge (i.e., the extensively used simply supported bridge with I-shaped girders) is introduced, and the corresponding hydrodynamics experiment is designed and conducted. Section 3, the pseudo-fluid-structure-interaction solution scheme is formulated and verified based on the experimental measurements and numerical results, and its reliability and applicability are examined. To explore the spatial failure mechanism of the typical coastal bridge, the characteristics of wave forces on the deck are first investigated considering various wave parameter combinations and inundation situations in Section 4. Subsequently, failure thresholds of bearing reaction forces are studied by considering the combined effect of the self-weight and wave forces in Section 5. Additionally, two main failure modes of the deck are discussed taking into account time-varying vertical and horizontal restraining stiffnesses in Section 6. Finally, the conclusions are summarized in Section 7.

2 Hydrodynamics Experiment of a typical coastal bridge

2.1 *Typical coastal bridge*

Due to the superior anti-overturning property, construction and maintenance convenience, and low cost [12][13], the simply supported bridge with I-shaped girders is widely used in the coastal region. However, coastal bridges often suffer from wave-induced vertical upward forces, which are quite different from the traditional downward traffic loads. Furthermore, the deck surface suffered from wave force is large, so the wave forces are inconsistent at different bridge surfaces and directions. Also, it is not easy to design the bearing, which can reduce the damage of superstructure and substructure and resist vertical upward forces simultaneously. Therefore, due to the wave forces and constraint deficiency against the non-traditional loads, i.e., wave forces [37]–[40], two movement modes (see Fig. 1) of the deck are recognized when the pier-deck connection fails [41]. Note that the entire collapse is not discussed in this study when the pier fails [42][43].