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Numerical simulations of lateral restraining stiffness effect on bridge deck–wave interaction under solitary waves

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ABSTRACT

A computational fluid dynamics (CFD) based numerical methodology using a dynamic mesh updating technique is developed in the present study in order to investigate the lateral restraining stiffness effect on the bridge deck–wave interaction under solitary waves. Firstly, a mass–spring–damper system is implemented with a commercial CFD computer program in order to numerically simulate the complicated bridge deck–wave interaction. Then, the methodology is verified with experimental measurements in the literature, which assures its valid applications in the following parametric study. Finally, the general dynamic characteristics of the structural vibration and the wave forces in the bridge deck–wave interaction under solitary waves are discussed in the parametric study. The numerical results illustrate that increasing the structural flexibilities by reducing the lateral restraining stiffness in the transverse/horizontal direction results in larger horizontal forces on the interface between the bridge deck/superstructure and the substructure and larger dynamic amplification factors for the horizontal forces on the bridge deck. Therefore, rigidifying the superstructure by increasing the lateral restraining stiffness is generally beneficial to reducing the hydrodynamic wave forces. This methodology may also be adopted for other near shore and offshore structures when the dynamic effect is expected to be significant.

1. Introduction

Tsunamis, especially in the last decade, have devastated many coastal communities, including many low-lying coastal bridges [1–6]. Post-disaster reports show that these coastal bridge decks under wave actions during these extreme natural disasters were subjected to huge wave loads that are acknowledged as the main reason for these bridges' failures.

Similar to mitigating aerodynamic effects in long span bridges [7], there are a few commonly used practices for mitigating hydraulic forces, such as by changing a solid railing system into an open one or cutting slots or venting holes on a bridge deck to release the trapped air [8–10]. Additional mitigation ideas may be learnt from earthquake engineering where base isolations, cable restraints, shear keys, and shape memory alloys are commonly used to adjust the interface stiffness between the superstructures and substructures to reduce the damage to structures. For example, when the restraining force reaches to some extent, the shear key will be sheared off as intended so that the substructures will be protected from damage. A good mitigation strategy would be to balance both the superstructure and substructure performance. While a weak connection/restraining system may not be good enough in protecting the superstructure, a too strong one would put too much force on the substructure that tends to be very expensive for repair. Therefore, before developing a good mitigation strategy, the dynamic analysis regarding the general lateral restraining stiffness (representing the substructures and interface connections such as restraining cables as discussed later) effects on the bridge deck–wave interaction needs to be fully understood.

Many studies for the solitary wave (representing the incident waves in tsunamis [11]) forces on coastal bridge decks were conducted in order to predict the wave forces on the rigidly supported bridge decks (rigid setups) [12,13,9,10]. However, very few studies focused on the dynamic characteristics of the bridge deck–wave interaction problems considering the flexibility of the bridge deck supports (flexible setups) [1]. There were some discussions that using flexible connections between the superstructure and substructure (similar to the base isolation for seismic loading) may reduce the interaction forces [14], which was based on the assumption that a larger displacement of the superstructure in the horizontal direction would dissipate more energy in the bridge deck–wave interaction process. However, a comparison of experimental results between the rigid and flexible setups by Bradner et al. [15] did not support this assumption and a general consensus

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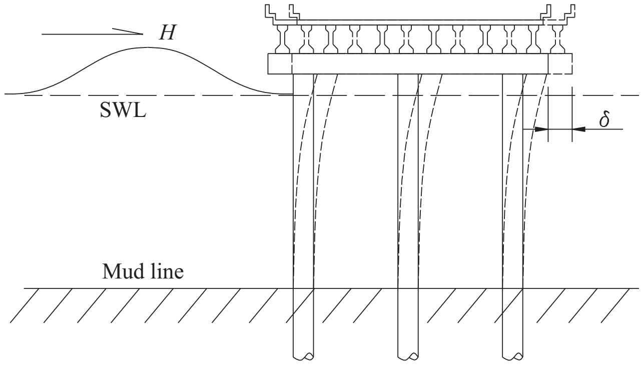

Fig. 1. Schematic diagram for the bridge deck–wave interaction under solitary waves. H refers to the wave height; δ is the structural displacement for the bridge deck; and SWL refers to the still water level.

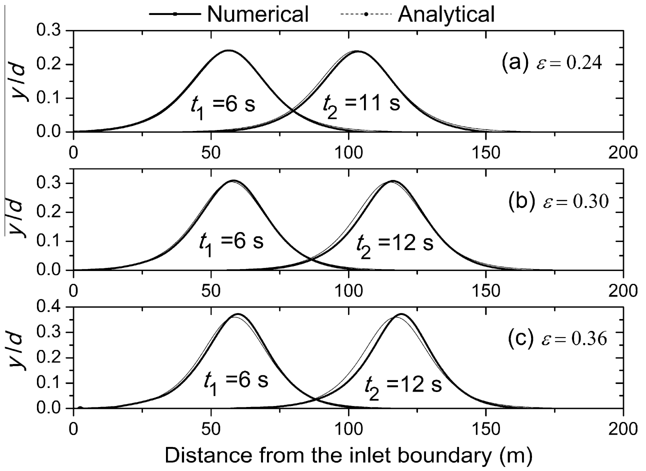

Fig. 3. Comparisons of the free surface profiles for solitary waves at two different simulation times. (a) $\varepsilon = 0.24$; (b) $\varepsilon = 0.30$; and (c) $\varepsilon = 0.36$.

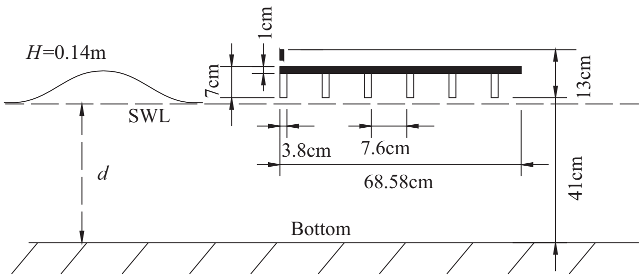

Fig. 4. Schematic diagram for the bridge model adopted by McPherson [12].

has not been reached. As a matter of fact, a complete dynamic analysis is essential for the design of coastal bridges, similar to the requirements for other nearshore and offshore structures [16,17].

The dynamic analysis for the bridge deck–wave interaction is recognized as an extremely complex problem not only because of the limitations for adequately describing the bridge deck/superstructure system but also because of the difficulties of realizing the procedure for the bridge deck–wave interaction with sufficient accuracy, experimentally or numerically. A schematic diagram for the bridge deck–wave interaction under solitary waves is demonstrated in Fig. 1, where the interface between the superstructure and the substructure is not shown for clarity. It is noted that the lateral restraining stiffness of the superstructure represents the combined effects of the substructure stiffness and the interface stiffness between the substructure and superstructure. The substructure stiffness depends on the soil condition, the structural stiffness of the piers/piles, etc. The interface stiffness depends on the connections between the superstructure and substructure, such as bearing types, shear keys, restraining cables, and shape memory alloys [18,19]. In the present study, only the total lateral restraining stiffness of the bridge deck is concerned, without distinguishing the stiffness from the interface or substructure, similar to that adopted in the study by Bradner et al. [15]. While a very large restraining stiffness represents a case that the bridge deck is almost not moving under wave loading, a very small restraining stiffness (such as cases with very slender piers or weak connections between the super and substructures) will result in a large movement of the bridge deck, which, in turn, results in hydrodynamic interaction between the bridge deck and wave.

Numerical modeling and simulation is undergoing fast development and is widely adopted in the efforts to study the effects of tsunami or hurricane impacts on coastal bridge decks [20–24,8,10]. The advantages of numerical simulations are that full scale models can be easily realized; model geometries and positions can be adjusted conveniently; and experimental cost and time can be saved. In order to achieve an appropriate balance between the computational cost, model sophistication, and physical realities, 2D numerical simulations that are usually used in the literature for this topic are adopted here and the bridge deck is considered as a single degree of freedom system (SDOF) to accommodate the comparison with the experimental study by Bradner et al. [15]. Similar to the base isolation for the seismic loading, the horizontal displacement may be more prominent than the vertical and rotational displacement. Hence, the vertical and rotational displacements were not considered at the current stage.

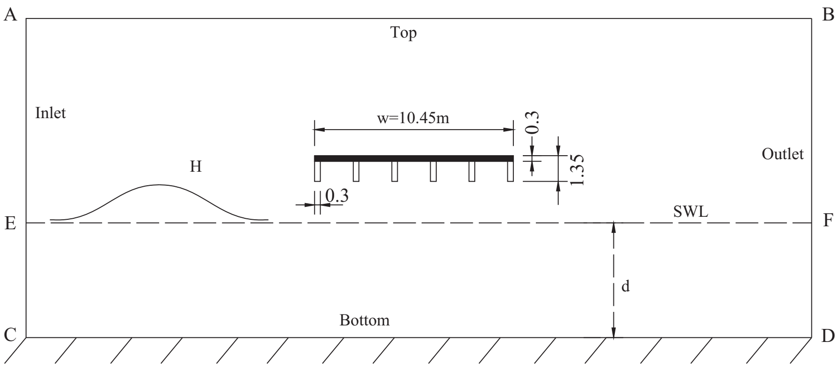

Fig. 2. Schematic diagram for the computational domain and bridge deck model.