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Seismic fragility analyses of sea-crossing cable-stayed bridges subjected to multi-support ground motions on offshore sites

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ABSTRACT

As key components in the transportation networks at coastal areas, sea-crossing cable-stayed bridges play a very important role in the development of regional economy. These bridges may be subjected to severe earthquakes during their life-cycles. Owing to the lack of actual seafloor earthquake recordings and approaches in synthesizing offshore seismic motions, the onshore seismic motions are commonly utilized as inputs in the seismic design of sea-crossing cable-stayed bridges. However, this approach may lead to erroneous structural response predictions since the characteristics of onshore and offshore seismic motions are different. In this paper, the seismic performance of a sea-crossing cable-stayed bridge is comprehensively evaluated based on the fragility function methodology. A novel approach is presented to theoretically calculate the ground motion transfer function at any location within an offshore site and stochastically synthesize the offshore multi-support ground motions at different depths (MGMDDs). The OpenSees analysis platform is employed to develop the three-dimensional finite element model of the example bridge, in which the p-y, t-z and q-z elements are installed at the pile nodes to simulate the interaction between the bridge piles and surrounding soils. Moreover, the effect of seawater on the bridge seismic responses is modeled using the hydrodynamic added mass method. The seismic fragility curves of the example bridge are generated by using the synthesized MGMDDs as inputs. The influences of spatial and depth varying offshore seismic motions, soil-structure interaction (SSI) and seawater added mass on the bridge component and system fragilities are investigated and discussed. Numerical results show that the seismic fragility of the example sea-crossing cable-stayed bridge is affected by the above mentioned influencing factors with different extents. The proposed approach can rationally and effectively assess the seismic fragilities of sea-crossing cable-stayed bridges.

1. Introduction

To optimize the transportation network and promote the economic development in the coastal areas, a certain number of large-span sea-crossing bridges have been constructed around the world in the last few decades. Among the various structural types of bridges, the cable-stayed bridges are commonly adopted in the design of sea-crossing bridges due to their elegant appearance, large spanning capacity and high economic efficiency [1,2]. The seismic risk in coastal areas is usually very high owing to the movements and collisions between the continental and oceanic plate margins [3]. More recently, some severe earthquakes occurred in the coastal areas e.g., the 2011 Tohoku-Oki, Japan Mw 9.0 earthquake and the 2015 Illapel, Chile Mw 8.3 earthquake. Sea-crossing cable-stayed bridges possess the characteristics of long designed service life and high investment costs; their damage under earthquakes may not only cause huge losses of lives and property, but also lead to profound and far-reaching social and economic impacts. Therefore, the seismic performance of these bridges should be properly evaluated to ensure their safety and serviceability.

The seismic fragility function, which defines the conditional probability of reaching or exceeding a specified structural damage state as a function of ground motion intensity measure, has become a practical and effective tool for the seismic performance assessments of bridge structures [4–6]. The seismic fragility curves can be generated

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empirically using the bridge damage data in past earthquake events [7,8] or analytically using the numerical simulation of bridge structural seismic responses [9–12]. The application of empirical seismic fragility analysis method is limited owing to the insufficiency of recorded bridge seismic damage data. By considering the uncertainties regarding the structural parameters and input seismic motions, many researchers developed the analytical fragility curves through the numerical modeling of bridge structures and corresponding seismic response analyses [13–17]. However, most previous studies focused on the seismic fragilities of bridges constructed on onshore sites, a comprehensive study on the seismic fragilities of sea-crossing cable-stayed bridge structures subjected to offshore seismic motions has not been reported in the literature.

In the seismic analyses and design of offshore engineering structures, the seismic ground motions at onshore sites are commonly used as inputs due to the scarcity of offshore earthquake recordings from seafloor stations and the lack of techniques for the simulation of seafloor seismic motions [18]. However, this approach may lead to erroneous structural response predictions because the characteristics of seafloor seismic motions may be very different from those of the onshore motions. Based on the statistical analyses of recorded seafloor seismic motions, Boore and Smith [18] and Chen et al. [19] revealed that the propagation of seismic P-waves on the offshore sites can be significantly affected by the overlaying seawater. The vertical-to-horizontal PGA and response spectral ratios of seafloor seismic records are much lower than those of the onshore records. In engineering practice, the seawater is commonly regarded as an ideal fluid, in which seismic S-wave cannot propagate. Under this assumption, Crouse and Quilter [20] and Li et al. [21] theoretically investigated the effect of seawater layer on the ground motion transfer functions of offshore sites. It was reported that the vertical component of seafloor seismic motions can be intensively suppressed near the resonant frequencies of the overlaying seawater, owing to the destructive interference effect of P-wave motions at the water-seafloor interface. Moreover, the seawater can indirectly influence the seafloor seismic motions by introducing the low-velocity sedimentary soft clay and by increasing the degree of saturation and Poisson's ratio of subsea soils. The ground motion transfer functions of a layered soil site can be significantly affected by the water saturation of porous soil layers [22,23]. Therefore, the frequency contents and amplifications of seismic motions on an offshore site can be very different from those of onshore motions. To achieve reliable seismic response and fragility predictions of sea-crossing cable-stayed bridges, the offshore seismic motions should be employed as inputs.

Spatial variation of seismic ground motions is another significant factor affecting the seismic fragilities of sea-crossing cable-stayed bridges. During an earthquake, the seismic motions at different supports of long-span bridges may vary significantly from each other due to the wave passage, coherency loss and local site effect [24–27]. In the past few decades, the seismic responses of bridge structures under spatially varying ground motions have been studied by many researchers using the stochastic methods in the frequency domain [28–30] or the nonlinear time history analyses in the time domain [31–33]. It was revealed that the seismic responses of long-span bridges could be significantly impacted by the ground motion spatial variation effect. With the popularization of the seismic fragility analysis method, some researchers placed special attention on the seismic fragilities of bridge structures under spatial ground motions. Saxena [34] and Deodatis et al. [35] firstly developed the bridge fragility curves with the consideration of ground motion spatial variation. Kim and Feng [36] demonstrated that the bridge seismic fragilities under spatial ground motions could be much higher than those under identical earthquake excitations. Lupoi et al. [37] systematically examined the effects of wave passage, coherence and local site on the seismic fragility curves of bridge structures. Li et al. [38] analyzed the lifetime seismic fragilities of deteriorating reinforced concrete bridges subjected to spatially varying seismic motions. Zhong et al. [39] studied the impact of ground motion spatial variability on the seismic fragility of a cable-stayed bridge. However, the seismic fragilities of sea-crossing cable-stayed bridges have not been investigated owing to the difficulties in modeling the spatially varying ground motions at multiple offshore sites.

Sea-crossing cable-stayed bridges are commonly constructed on large-dimensional pile foundations passing through soft subsea soil layers. Therefore it is important to consider the effect of soil-structure interaction (SSI) on the bridge seismic analyses. The effect of SSI on the seismic performances of bridges has been studied by many researchers using various approaches [40]. Among others, the dynamic beam on nonlinear Winkler foundation (BNWF), i.e., p-y method [41–44], which utilizes continuously distributed hysteretic springs and dashpots along the length of bridge piles to model the pile-soil interaction, is recognized to be a versatile approach that can achieve balances between the acceptable precision and computational efficiency in the seismic response analyses of bridge structures considering SSI [45–47]. Most recently, Li and Conte [48] and Xie et al. [49] developed a p-y modeling approach by considering the site amplification effect of seismic motions, in which the depth-varying ground motions simulated using SHAKE 91 [50] were used as inputs at the free ends of the p-y elements along each pile. This approach can more precisely simulate the effect of SSI on the bridge seismic responses as compared to those using uniform input ground motions. However, only the vertically propagating seismic shear waves in the site was taken into account in their studies, the inclined wave propagation in the site and ground motion spatial variation effects were neglected. Moreover, SHAKE 91 is incapable of simulating spatially varying ground motions at multiple offshore sites, therefore the calculated ground motions at different depths of the site are not necessarily accurate for representing those at offshore sites.

This paper proposes a seismic fragility analysis method for the sea-crossing cable-stayed bridges by using the simulated multi-support ground motions at different depths (MGMDDs) of offshore sites as inputs. In Section 2, an example sea-crossing cable-stayed bridge is introduced and the finite element model is developed by using the OpenSees analysis platform [51]. In particular, the interaction between the bridge pile foundations and surrounding soils is simulated by the p-y approach and the influence of seawater on the structural dynamic responses is modeled by the added mass method [52–54]. Section 3 presents a novel simulation approach of spatially varying offshore seismic motions at different depths, in which the depth-varying property of input motions is considered through the ground motion transfer function at each free end of the distributed p-y elements along a pile. Section 4 introduces the component and system fragility analysis method of the example bridge subjected to the synthesized MGMDDs. In Section 5, the effects of offshore seismic motion input, ground motion spatial variations, SSI and added mass of seawater on the seismic fragility of the example sea-crossing cable-stayed bridge are discussed in detail. The final section provides a brief summary with conclusions of the present study.

2. Bridge description and numerical modeling

2.1. Overview of the example sea-crossing cable-stayed bridge

A double-pylon sea-crossing cable-stayed bridge located in the southeast coastal areas of China is adopted as an example in this study. The elevation view and component cross sections of the bridge are illustrated in Fig. 1. The bridge is designed according to the Chinese seismic design code [55] with a service life of 120 years. As shown in Fig. 1, the bridge has a length of 75 + 164 + 320 + 164 + 75 = 798 m. It consists of two reinforced concrete pylons, four reinforced concrete piers, a steel box girder bridge deck with uniform cross section and two sets of double plane cables arranged in semi-fan configurations. The heights of pylons and piers are 125 m and 40 m, respectively. The superstructure of the cable-stayed bridge is supported on eight large pile group foundations. The heights