Marine Structures 58 (2018) 301–320

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

Underwater shaking table tests on bridge pier under combined earthquake and wave-current action

Yang Ding, Rui Ma, Yun-Dong Shi*, Zhong-Xian Li

School of Civil Engineering, Tianjin University/Key Laboratory of Coast Civil Structure Safety (Tianjin University), Ministry of Education, Tianjin 300072, China

A R T I C L E I N F O

Keywords:
Bridge pier
Earthquake
Wave-current
Combined action
Distribution of hydrodynamic pressure

A B S T R A C T

The cross-sea bridges that located in earthquake-prone areas have the potential to be subjected to earthquake and wave-current action simultaneously during their construction and service period. In order to investigate the dynamic response of the pier under combined earthquake and wave-current action, a series of model tests of scale 50:1 was carried out using the Earthquake, Wave and Current Joint Simulation System. Four main tests were conducted under various water levels, including white noise tests, independent earthquake tests, independent wave-current tests and combined earthquake and wave-current tests. The effect of wave-current action on the seismic responses of the pier and the distribution law of hydrodynamic pressure along the height of the pier under various load conditions are determined. The test results show that the existence of water decreases the natural frequencies of the pier. The peak dynamic responses of the pier in water under independent earthquake action are mostly larger than those without water. When the earthquake excitation is moderate and the wave-current action is relatively severe, the dynamic responses of the pier under independent wave-current action are comparable to those under independent earthquake action, and the effect of wave-current action on the seismic responses of the pier under combined earthquake and wave-current action is great and can not be ignored. Therefore, it is necessary to consider the combined action of earthquake and wave-current in bridge design under this circumstance, and the effect of long-period earthquake on bridges should be considered.

1. Introduction

In order to meet the needs of transportation and economic development, several cross-sea bridges have been built or are under construction in recent years all around the world. Among them, the bridges that located in earthquake-prone areas may be subjected to not only earthquake action but also wave-current action during their construction and service period. At present, the combined action of earthquake and wave-current is generally not taken into consideration in the design of bridges, because the probability of a strong earthquake occurring simultaneously with a severe wave-current condition is relatively low. However, studies show that some previous strong earthquakes have happened in spring or winter, the season in which wave-current conditions are usually moderate or even severe. This suggests that a significant earthquake is possible to coincide with a moderate wave-current condition. In addition, the bridges have the potential to be struck by both the main earthquake triggered tsunami and aftershocks [1]. Therefore, to guarantee the safety of bridge structures which are the important parts of lifeline engineering, it is necessary to study the dynamic response of bridge piers under combined earthquake and wave-current action.

* Corresponding author.
E-mail address: yundong@tju.edu.cn (Y.-D. Shi).

https://doi.org/10.1016/j.marstruc.2017.12.004
Received 9 March 2017; Received in revised form 23 September 2017; Accepted 12 December 2017
0951-8339/

Currently, the combined action of earthquake and wave-current on offshore structures is studied mainly by the Morison equation [2]. For example, Yamada et al. [3] adopted the frequency-domain random vibration approach to analyze the dynamic response of offshore structures under random earthquake and wave action simultaneously considering the effect of soil-structure interaction, and found that the seismic response was reduced by sea waves. Karadeniz [4] made a spectral analysis of steel offshore structures subjected to combined earthquake and wave action by applying a different linearization process to the Morison equation, and demonstrated that the earthquake and wave forces were dominant at the natural frequencies of the structure and the peak wave frequency, respectively. He and Li [5] investigated the effects of seismic intensity, wave condition and site soil condition on the dynamic responses of an offshore platform under combined earthquake and wave action, and the equations of motion were solved by the Newmark's method. Jia [6] studied the dynamic response of piers subjected to earthquake, wave and ice action, and employed an iterative method to solve nonlinear coupling equations. Bai et al. [7] explored the effect of wave and current action on the seismic responses of bridge piers considering the soil-structure interaction. However, the Morison equation usually only applies to small-scale structures which are assumed to have no effect on wave-current motion. For large-scale structures, Li and Huang [8] respectively employed radiation wave theory and diffraction wave theory to consider hydrodynamic pressure and wave action, and established dynamic equations of bridge structures under combined earthquake and wave action. It can be seen that the above research introduces some assumptions to solve the complicated interaction between water and structures under combined action, but the accuracy lacks test verification. In order to simulate actual situation and provide verification for theoretical research, the experimental research method is employed to investigate the dynamic response of bridge piers under combined earthquake and wave-current action in this study.

So far, lots of experimental research on offshore structures under independent earthquake action and under independent wave-current action has been conducted, while the tests under combined earthquake and wave-current action are relatively rare. In the respect of independent wave-current action, Akyildiz [9] carried out an experimental research on the wave pressure distribution at different locations around a large vertical cylinder. Taking two group pile foundations of the East Sea Bridge as research objects, Liu et al. [10] systematically studied the wave-current forces on single piles and pile groups. Qi and Gao [11] conducted a series of tests to investigate the local scour response around a large-diameter monopile subjected to wave-current action considering the pore pressure. In the respect of independent earthquake action, Wei et al. [12] focused on the fluid-structure interaction impact on the modal dynamic responses of three bridge pile foundations under different water levels by experimental and numerical methods. Huang [13], Li [14] and Song et al. [15] carried out shaking table tests to investigate the effect of hydrodynamic pressure on the dynamic responses of bridge piers under sinusoidal and earthquake excitations, in which a water tank was used to simulate water area. Wang et al. [16] and Liu et al. [17] conducted underwater shaking table tests to analyze the seismic response of bridge piers in deep water. In the respect of combined earthquake and wave-current action, Zheng et al. [1] made an experimental study on the dynamic response of a monopile wind turbine foundation under joint earthquake and wave action. Zhu et al. [18] made a research on the dynamic response of spanning submarine pipelines under combined action of earthquake, wave and current. Chen [19] studied the independent and combined action of sinusoidal excitations, waves and currents on the bridge model, respectively. At present, there is limited experimental research that systemically investigates the effect of wave-current action on the seismic responses of bridge piers and the distribution law of hydrodynamic pressure along the height of the pier under various load conditions, especially for large-scale bridge piers.

In this study, a series of 50:1 scale underwater shaking table tests on a large-scale bridge pier under combined earthquake and wave-current action was conducted. The effect of wave-current action on the seismic responses of the pier and the distribution law of hydrodynamic pressure along the height of the pier under various load conditions are determined. The results of this study can provide a useful reference for the design of cross-sea bridges.

2. Test equipment and model design

The tests were conducted using the Earthquake, Wave and Current Joint Simulation System of Dalian University of Technology, which can simulate earthquake, wave and current action separately or simultaneously in the same flume [1]. As shown in Fig. 1, the dimensions of wave-current flume are $21.6 \times 5 \times 1$ m, and the maximum water depth can reach 0.8 m. An energy dissipation slope is set up at the downstream end of the flume, which can greatly absorb waves and eliminate reflection, preventing the wave reflection from affecting test

Fig. 1. View of the Earthquake, Wave and Current Joint Simulation System.