Ocean Engineering 160 (2018) 335–345

Contents lists available at ScienceDirect

Ocean Engineering

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

Assessment of random wave pressure on the construction cofferdam for sea-crossing bridges under tropical cyclone

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ARTICLE INFO

Keywords:
Wave pressure
Construction cofferdam
Sea-crossing bridge
Field measurement
Diffraction theory
Tropical cyclone

ABSTRACT

Construction cofferdams for sea-crossing bridges can be damaged or even collapsed due to extreme wave loads under tropical cyclones. To enhance a better understanding of the random wave pressure on the cofferdam, wave gauges and pressure transducers were installed on a real cofferdam for sea-crossing bridge to measure the random wave pressure during Typhoon Dujuan in 2015. The first order diffraction theory was used to calculate the wave pressure numerically. The measured and numerical results were compared in the frequency domain and discussed in terms of pressure spectrum, pressure spectral characteristics, transfer function and maximum wave pressure. The main conclusions are: (1) the wave diffraction and water depth affect the dominant frequency range, zeroth moments and peak spectral value of wave pressure spectrums on the cofferdam; (2) the maximum wave pressure on the up-wave side of the cofferdam is up to 2.2 times that on the down-wave side; (3) the secondary peaks were observed in pressure spectrums under tropical cyclone; and (4) the numerical model based on the first order diffraction theory could not capture the secondary peaks and overestimate the wave pressure energy near the primary peak frequency.

1. Introduction

Sea-crossing bridges have been built all over the world, such as the Chesapeake Bay Bridge (Meisburger, 1972), Oresund Bridge (Valeur, 2004), HongKong-Zhuhai-Macao Bridge (Yu et al., 2013). When the construction of bridge foundation takes place below the water surface, cofferdam is a common facility to create a dry and safe construction environment (Cho et al., 2008). The modern construction cofferdams for sea-crossing bridges are always made of thin-walled steel structures to withstand both hydrostatic and hydrodynamic pressure. The extreme wave induced by tropical cyclones leads to large pressure on the thin walls, which may cause severe damages or even collapse of the cofferdams. Therefore, the assessment of random wave pressure can ensure the structural safety of the construction cofferdams.

The construction cofferdam for bridge is always regarded as large-scale structure. Many researchers (Alkhalidi et al., 2015a; b; Guo et al., 2015; Houlsby et al., 2005; Wei et al., 2012) have measured the hydrodynamic loads on the large-scale offshore structures in the laboratories. However, the difference between laboratory and actual environment cannot be eliminated due to the limitation of wave maker and the effect of reduced scale. Although field measurement is the most direct way to evaluate the wave loads on structures, few literature studied wave pressure on the cofferdam by field measurement because of its huge cost.

As one of the most popular numerical approaches, diffraction theory has been widely used to calculate wave loads on the large-scale structures. MacCamy and Fuchs (1954) presented an exact mathematical approach for linearized wave based on diffraction theory to evaluate the hydrodynamics loads on the large vertical cylinder in regular waves. Many works (Ishida and Iwagaki, 1978; Raman and Rao, 1983) were then carried out using this approach to study the wave loads on cylindrical structures under regular or random waves. Since diffraction theory is derived based on the linear waves, random wave problems can be efficiently solved in frequency domain. With the development of computational fluid dynamics (CFD), many researchers investigated the wave loads on the sea-crossing bridges under regular waves by CFD approaches (Chen et al., 2016; Seiffert et al., 2015; Xu and Cai, 2014; Xu et al., 2015). But the issue relevant to the random wave pressures on the cofferdam under tropical cyclones was still seldom addressed.

This paper focuses on the assessment of random wave pressures on the wall of the construction cofferdam used for sea-crossing bridges

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https://doi.org/10.1016/j.oceaneng.2018.04.036
Received 29 November 2017; Received in revised form 7 March 2018; Accepted 10 April 2018
Available online 5 May 2018

through field measurement. The following objectives are set: (1) to conduct a field measurement program to investigate the random wave pressure on a cofferdam used in sea-crossing bridge construction; (2) to set up a three dimensional (3D) hydrodynamic numerical model of the tested cofferdam based on the first order diffraction theory to simulate the wave pressure on the cofferdam; (3) to compare the measured and numerical wave pressure in the frequency domain in terms of pressure spectrum, pressure spectral characteristics, transfer function and maximum wave pressure; and (4) to evaluate the random wave pressure on the cofferdam.

2. Setup of field measurement

2.1. Description of example cofferdam and measurement conditions

Pingtan Strait Bridge is taken as the example structure in this study. It is a 16.32 km long rail-cum-road sea-crossing bridge connecting Fuzhou City to Pingtan Island across Haitan Strait in the China East Sea. As shown in Fig. 1, the bridge site has limited wave fetches in most directions but directly open to the northeast offshore. Therefore, the waves propagating from northeast offshore caused by tropical cyclones are destructive and threaten the construction.

The steel thin-walled construction cofferdam that locates at 25.72°N, 119.61°E was taken as the example structure (Fig. 2). The dimensions of the cofferdam are 23 × 14.8 × 12.3 m. The cofferdam is supported by 13 steel-concrete composite piles, of which the diameter is 2.2 m. The piles are fully fixed on the seabed rocks. The altitudes of the top and the bottom of the cofferdam are +7.9 m and −4.4 m, respectively. The altitude of the seabed is −10 m.

The field measurement of a destructive wave event was conducted at 8:00 a.m. on September 29, 2015, when Typhoon Dujuan begun to decay. During the measurement, the storm eye located at 119.40°E, 25.00°N, 80 km south from the tested cofferdam, as shown in Fig. 3. The atmospheric pressure at storm center was 925 kPa and the maximum wind speed of the storm was 35 m/s. The measurement went on up to 17 min and captured about 100 waves. The wave surface elevation and the wave pressure data on the cofferdam were successfully measured.

2.2. Wave gauges and pressure transducers layout

Fig. 4 illustrates the layout of the field measurement system that was installed to measure the wave conditions at the site and the wave pressure on the cofferdam. The incident wave conditions were measured by a SBY 2–1 ultrasonic wave gauge, of which the measuring accuracy is ±0.2 m for wave heights and ±0.25 s for wave periods. The sampling frequency of the gauge is set to 2 Hz, which is adequate for most of the waves. The wave gauge was supported by a cantilever beam on an isolated electricity platform that is 80 m far from the cofferdam, for the convenience of power supply and little impacts from the construction activities. The seabed altitude of the platform is −9.3 m, which is approximately the same with that of the cofferdam (−10 m). The effect of wave shoaling can hence be ignored and the wave spectrum at these two locations are considered to be the same.

The hydrodynamic pressures induced by random waves were measured by fifteen CSW560 flush type pressure transducers, of which the measuring range is 0–200 kPa and the measuring error is less than 0.5%. Fig. 5 shows the installation setup of all fifteen pressure transducers. In order not to alter the roughness of the outer surface of the cofferdam, the transducers were embedded into the cofferdam at two different altitudes, -4 m and 0 m, to investigate the distribution of wave pressure along the height. Eleven transducers (#1 - #11) were installed at 0 m to capture the wave pressure around the cofferdam near Still Water Level (SWL). Four transducers (#12 - #15) were installed at −4 m. According to long-term historical wave measurements of a data buoy near the bridge site, the main wave direction was close to ENE (East-Northeast) (The Third Marine Research Institute of National Ocean Administration, 2013), as denoted in Fig. 4. Considering the possible incident wave direction is east-northeastern (ENE) at SWL, five transducers (#7 - #11) were installed on the down-wave side to capture the wave diffraction that surrounded the cofferdam.

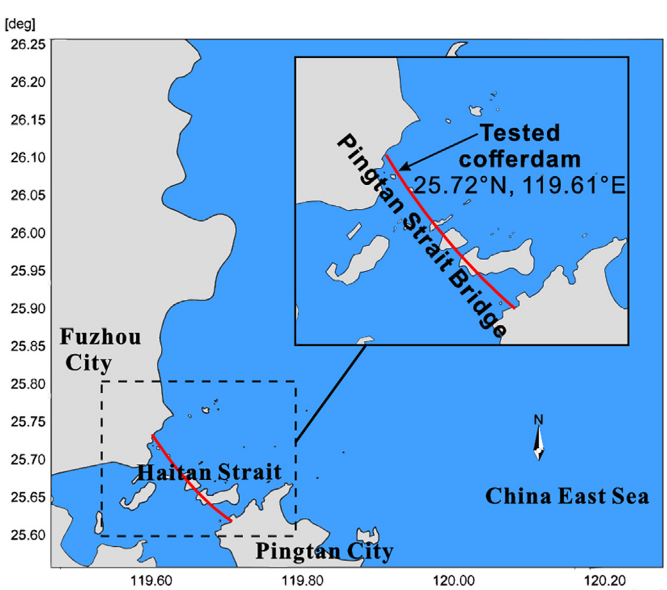

Fig. 1. Location of Pingtan Strait Bridge site and the tested cofferdam.

3. Measured data analyses

3.1. Wave height, period and spectrum

The wave conditions, such as wave height and wave period, were drawn using zero up-crossing method and listed in Table 1. The wave spectrum $S_\eta(f)$ was obtained from the measured time history of wave surface elevation by Fast-Fourier transform techniques. According to the analyses, the extreme wave height is up to 5.83 m with a period of 11.02s. The measured wave spectrum (Fig. 6) has a highly concentrated energy distribution near the peak frequency of 0.094 Hz. Because the fetches are limited and the water depth is finite at the bridge site, local winds are difficult to dominate the wave spectrum. The low peak frequency and concentrated energy distribution of the spectrum emphasized a wave condition that mainly consists of long period swells propagating from open ocean off the coast.

3.2. Still water level (SWL)

The SWL in the field was measured by SBY2-1 ultrasonic wave gauge and found to be +2.37 m at the measured time. Therefore, the water depth d of the cofferdam equals 12.37 m, and the sinking depth z for transducers installed at 0 m and −4 m equals 2.37 m and 6.37 m, respectively. The sinking depth ratio z/d is defined here to represent the ratio of sinking depth over water depth. z/d equals 0.19 for transducers installed at 0 m and 0.51 for transducers installed at −4 m.

3.3. Wave pressure spectrum

Because the measured pressure time history consists of wave pressure and hydrostatic pressure, the wave pressure history was derived by excluding the hydrostatic pressure from the measured pressure. Given time history of wave pressure, the measured wave pressure spectrum $S_p(f)_M$ can then be obtained by Fast-Fourier transformation.