Numerical Modeling and Hydrodynamic Analysis of an Offshore Bridge Superstructure

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Abstract

This study deals with the numerical modeling and hydrodynamic analysis of an offshore bridge superstructure. A scaled numerical model is established and numerical analysis with a focus on hydrodynamics is conducted. The numerical model and methods are validated by the comparisons of the model tests in various conditions. Second-order wave loads on the superstructure of the offshore bridge in different motion directions are calculated, and they are compared with the first-order wave loads to quantify the effects of the second-order wave loads. Then, a full-scale numerical model of the offshore bridge substructure is established; the hydrodynamic analysis of the full-scale numerical model is performed. In addition, the experimental results of the full-scale model are estimated based on the model similarity law and model test results of the scaled model. The numerical results calculated based on the two methods for the full-scale model are comprehensively compared in different load cases. The results and findings of this work greatly facilitates the design and numerical analysis of offshore bridge superstructures.

1. Introduction

The coastal transport industry has been experiencing rapid development, while the marine disasters occur frequently during the past several years, such as the Hurricane Ivan and the Indian Ocean Tsunami in 2004, the Hurricane Katrina in 2005, the Tsunami in Japan in 2011 (Yeh et al. 2007; Shoji and Moriyama 2007; Motley et al. 2016). In these natural disasters, the coastal bridges suffered serious damage, which are the result of extreme storms and high-increased water lines. The situations indicate that the coastal bridges are vulnerable to the extreme wave loads caused by hurricanes and tsunamis; thus, the wave loads of the bridge structures deserve a great deal of attention. The interaction of wave loads and bridge structures is of great complexity, leading to a big challenge on assessment of structural safety. Therefore, significant efforts are required to ensure the safety of the bridge structures under extreme wave loading conditions, which could effectively enhance the development of academic research and engineering practice.

Many studies, from the aspects of the theoretical analysis, numerical methods, and model tests, have been conducted to address the wave effects on the superstructures of the coastal bridges. Denson(1980), one of the early scholars who studied the effects of wave loads on bridge structures, made a scale bridge model for a ratio of 1: 24 based on the I-90 bridge in America; in addition, effects of wave loads on the scale bridge model in different wave heights, clearances, directions of the wave propagation and angles of the bridge span were investigated. Douglass et al. (2004) proposed an improved empirical formula on a basis of the existing method to evaluate the wave load effects of the bridge structures according to the scale model tests. Bradner et al. (2011) made a concrete bridge model that consists of six AASHTO III-type rib beams and a bridge deck with a thickness of 5 cm, which was used for a wave model test that was carried out in a wave tank at the University of Oregon with a large scale ratio of 1:5; in which the wave-induced horizontal and vertical forces on the bridge model for different wave parameters were measured. Limited theoretical investigations have been conducted on the wave loads of bridges (Fang et

al. 2019). Nonetheless, numerous studies of horizontal wave loads on piers (Morison et al. 1950) and jetties (McConnell et al. 2003) have been conducted, while others have investigated vertical wave loads on cylindrical components, flat plates (French 1969), decks (Kaplan 1992), and offshore platforms. As a result, earlier theoretical approaches for calculating wave loads on other types of structures, such as exposed jetties and platforms, were extended to estimate the wave force operating on the bridge superstructure (Aguíñiga et al. 2006, Aguíñiga et al. 2008). An open-source program OpenFOAM was employed in the studies of Seiffert and Hayatdavoodi et al. (2014) for modeling of wave tanks; based on these, the load effects of the isolated waves on the upper structure of a bridge were investigated. Then, grid convergence was checked; experimental and numerical results were compared. The results showed that the numerical model can well simulate wave loads and load effects data in various conditions. Based on the numerical model, load effects with respect to upper structures of different bridges, various water depths, and different submerged depths were studied, respectively. In the study of Xu and Cai (2015), the interaction of extreme waves and T-shape bridge deck with lateral constraint stiffness was modeled by a mass-spring-damper system that was developed based on the commercial tool Fluent. In that work, the numerical model was verified by the experimental results obtained from the publicly available reference. Subsequently, numerical analysis was conducted, which showed that lowered constraint stiffness of the upper structure would render the lateral forces and the dynamic amplification coefficient increased. This implied that increasing the lateral stiffness of the upper structures of bridges is beneficial to reduce the hydrodynamic forces.

Overall, experimental tests and numerical analysis have been carried out in several public studies to analyze the hydrodynamic loads on the superstructure of coastal bridges, but only the main span is usually considered in the experimental and numerical models, while ignoring the effects of boundary conditions such as adjacent spans and substructures. Moreover, there are limited comparisons for model tests and numerical analysis; also, most experimental model tests that are used for comparisons with the numerical analysis are based on the scaled model, instead of the comparisons for full-scale models.

Motivated by this, this paper conducted the hydrodynamic analysis of the superstructures of the coastal bridges with the consideration of refined boundary conditions. Numerical models are established based on advanced simulation software. Numerical analysis and experimental tests are comprehensively compared based on a scaled model, which shows that the numerical model and methods are reasonable. Effects of the second-order wave loads on the superstructure are investigated, which provide a deeper insight into its hydrodynamic behavior. Finally, the full-scale numerical model is established and its dynamics are compared with those derived from the scaled model. The differences caused by the similarity law are discussed, which provides a basis for improving the design and dynamic analysis of coastal bridge superstructures.

2. Scaled Numerical Model And Model Tests

The scale numerical model is developed to accord well with the experimental model used in the study of Fang et al. Fang (2017). Based on this, comparisons of numerical analysis and experimental tests can be

conducted, and thus the numerical model and methods can be verified. More details about the experimental and numerical model can be found in the following sections.

2.1 Experiment model

A scale bridge structure model with a ratio of 1:10 was used for the model tests, which were carried out by Fang et al.(Fang 2017) in a laboratory equipped with a wind tunnel and wave tank in Harbin Institute of Technology, China. The basic information and test arrangement of the wave flume are shown in Figure.1. The prototype of the experimental model was selected from a general library for the T-shaped bridges with a 20-meter span, which was issued by MOT (Ministry of Transport of the People's Republic of China in 1999). The bridges mainly serve for the constructions for the expressways and the first-class highways.

The bridge was a two-column reinforced concrete bridge with a simple support system. The deck's span length and width were 20 and 10 m, respectively, and the expansion joints' gap size was 5.0 cm. The test model was created using the Froude similarity criteria and a 1:10 geometric scaling. The specimen was made up of a quarter of the neighboring segments and a complete middle segment, including the superstructure and substructure, thus the effects of those additional structural components on the wave field could be considered.

Because the lifting platform had a limited carrying capacity and there was no hoisting equipment for moving the test specimen, lightweight materials such as steel, wood, acrylonitrile butadiene styrene (ABS) plastic, and Perspex were used to fabricate the specimen to reduce the structure's self-weight. As shown in Fig. 2, the superstructures consisted of five girders, four diaphragms, and a deck. A steel keel was embedded inside the superstructure to eliminate the deformation of the specimen under the wave loads and to achieve the rigid assumption of the specimen.

To fulfill the structural configuration and hydrodynamic characteristics, as well as to monitor any possible leakage of the specimen, the bottom and lateral surfaces of the superstructure were covered with ABS plastic skin, while the top surface was sealed with transparent Perspex plates. Two bents with four piers with a clearance height of 1.0 m supported the tested superstructure. The interior steel frames were covered with Perspex plates and $D = 15$ cm circular Perspex tubes were used to construct the substructure. During the tests, the outside surface of the substructures only resisted the wave loads acting on the substructure, and the wave loads on the superstructures were directly transferred to the steel frames inside the substructure through the load cells, preventing the damage of the Perspex surface under large wave forces.

The scale ratio of 1:10 is used for the experimental model, which is determined based on the wave tank capacity for wave generation and the space of the laboratory. The scale ratios of the other variables are listed in Table 1.

Table.1 Scale ratios of physical quantity of the scale model

	Similarity ratio	Model scale
length	λ	1/10
time	$\lambda^{0.5}$	$1/10^{0.5}$
force	λ^3	1/1000
frequence	$1/\lambda^{0.5}$	$10^{0.5}/1$
velocity	$\lambda^{0.5}$	$1/10^{0.5}$
acceleration	1	1

2.2 Numerical model

2.2.1 Model specifications

The side view of the layout and specifications of the full-scale bridge model are illustrated in Fig. 3. The main parameters of bridge structure such as span, length, height are ten times that of the scale numerical model and the experiment mode. Most scholars merely consider single-span superstructure about wave force of bridge, but the boundary effects between adjacent spans and substructure of piers are less considered, which generates a negative effect on the result of accuracy to some extent.

In order to capture the dynamic characteristics of the superstructure of the bridge under the excitation of the wave loads, and thus to get more insight into its dynamic behavior, the main bridge span with boundary conditions of two side spans and a pier are considered in the numerical model. Various regular wave loads on the superstructure of the bridge numerical model are calculated, and then the characteristics of the wave loads vary with the changes of the clearance and wave propagation angle are analyzed.

The numerical model is established by means of the SESAM code, GeniE, which was developed by DNVGL. For the convenience of calculation, only the surface model of the bridge is built, and the surface is made of ordinary steel. In order to ensure its rigidity, its Young's modulus and yield strength have been greatly improved. The specific settings of the numerical model parameters are shown in Table.2. In the numerical model, the full-span girder is the main test structure, while two adjacent spans and the pier at the bottom of the bridge are not measured as they are mainly used to make the boundary conditions of the numerical model and the realistic model similar. Therefore, telescopic seams and anchors are used between the girder and adjacent spans as well as the girder and the pier, avoiding the force transmission from the adjacent spans and the pier to the girder. The wave loads sustained by the superstructure are measured at the four corners located at the girder bottom where data acquisition sensors are arranged.

The numerical model is presented in Fig.5, where the boundary conditions and the overall view of the bridge structure are illustrated.

Table.2 Detailed specifications of the scaled and full-scale numerical models

	Scaled model	Full-scale model
Test span length(m)	2	20
Test span width(m)	1	10
Expansion joint width(mm)	5	50
Surface thickness(mm)	5	50
Surface material	steel	steel
Material density(Kg/m ³)	7850	7850
Material yield strength(Pa)	2.00E+09	2.00E+09
Material Young's modulus(Pa)	2.00E+12	2.00E+12
Material Poisson's ratio	0.3	0.3
Equation solver	Direct matrix solver	Direct matrix solver
Boundary type	fixed	fixed
Logarithm-Singularity	analytical integration	analytical integration

2.2.2 Wave parameters

The significant wave height and the spectra peak period of the coastal waters lie in the range of 1.98-3.0 m and 1.19-6.0 s, respectively, which are quantified by Douglas et al. (2006) and Chen et al. (2009) according to the surveys and analyses of the disaster data for the damaged coastal bridges caused by hurricanes. Based on the Froude law, the spectral peak period ranged from 1.0 s to 3.0 s and the significant wave height ranged from 0.1 m to 0.3 m are used in the experimental tests to cover the variations of those in the realistic sea states. In the experimental tests presented in the study of (Fang 2017), influences of the hydrodynamic loads on the coastal bridge in various still water positions were studied. Five clearance heights (ZC), ZC=5.0cm, 2.5cm, 0.0cm, -8.5cm, -17.0cm, were considered, for representing the three conditions of unsubmerged, semi-submerged and fully submerged to the main bridge beam. Based on the spectral analysis of the hydrodynamic loads on the bridge for the five conditions, it was found that the quasi-static force dominates the hydrodynamic load effects while responses at the frequencies of slamming forces induced by waves are quite low under the semi-submerged and fully submerged conditions. This implies that under the semi-submerged and fully

submerged conditions, uncertainties of using potential flow theory to estimate the hydrodynamic loads on the coastal bridges are limited, thus the two conditions are used in the numerical analysis.

3. Verification Of Numerical Model

This section presents the verification of the numerical model and methods. Comparison of the numerical analysis of the scaled model and the model tests are conducted to validate the rationality of the numerical model. More specifically, horizontal forces induced by waves between the numerical and experimental models are compared. Greater details about the comparisons are presented as follows.

In the model tests presented in the study of Fang (2017), horizontal wave forces on the coastal bridge were measured and analyzed. This is because that the horizontal wave forces are closely related to the devastation of the bridges. More specifically, most coastal bridges do not equip with connections in the vertical direction; the friction between the main frame and the substructure usually plays a significant role to prevent the lateral displacement of the superstructure. However, under the conditions of the extreme storms with the high-water levels, the gravity of the superstructure is greatly offset by the buoyance, thus the friction between the superstructure and substructure is largely reduced, which makes it very possible for the superstructure to produce a large lateral displacement and even worse, to drop down. As such, the study on the horizontal wave forces could enhance the understanding of the failure mechanism of the bridges in natural disaster conditions, then aid to come up with solutions to avoid the failures.

Fig. 6 presents the variations of the horizontal wave forces on the bridge structure along with the significant wave height and spectra peak period under the conditions of semi-submerged ($ZC=-8.5\text{cm}$) and fully submerged ($ZC=-17\text{cm}$) in the model test. It shows that even though loads on the bridge are mainly induced by waves while slightly affected by slamming forces, deviations of the responses at the short period wave conditions are significant, which is due to the high uncertainty of the waves with short period, especially for the scale waves that featured with shorter wave periods. Thus, the comparisons of the numerical analysis and model tests are conducted under the wave conditions where the wave peak periods are in the range of 2.0~3.0s.

Fig. 7 demonstrates the comparisons of the numerical simulations and model tests for the horizontal wave forces on the bridge structure under the semi-submerged and fully submerged conditions. It is seen that the numerical results generally agree well with the model test results. The horizontal wave forces in both the numerical analysis and model tests increase with the significant wave height increases and a nearly linear relationship is observed. The horizontal wave forces in the fully submerged condition are slightly higher than those in the semi-submerged condition. The horizontal wave forces for given significant wave heights generally decreases as the wave peak period increases within the specified range. This is because the wave steepness of the short period waves is larger than that of the long period waves for given wave heights, and this phenomenon also leads to some uncertainties on the dynamic responses. In general, the numerical results are slightly higher than the experimental results, which is because that the potential flow theory, the basis of the numerical method, is developed based on the ideal

fluid and the formula satisfies the criterion of energy conservation. This implies that the wave energy dissipation that is existing in the experimental tests due to several reasons such as wave decay, wave interaction with structures, the friction of wave and pool wall, is not taken into account in the numerical analysis.

However, the differences between the numerical and experimental results are not of significance, which are observed from the error bars of multiple trials. Compared with the errors between multiple trials, the errors between numerical analysis and experiment are acceptable.

4. Results And Discussions

4.1 Effect of angle of incident wave

The wave propagation comes from various directions in nature, rather than the single direction. This section discusses the effects of wave incident angle on horizontal forces on the bridge structure. The definition of wave incidence angle is shown in Figure 4. The coordinate system is a right-handed coordinate system, the x-axis is along the bridge span direction, the y-axis is along the transverse bridge direction, and the wave direction angle is the angle between the wave propagation direction and the y-axis. It is defined that the wave incident angle varies from 0 deg to 75 deg with the constant interval of 15 deg. Fig.8 presents the effects of wave incident angle on horizontal force under conditions of different significant wave heights with the spectral peak period of 2s for the fully submerged case. The results indicate that under the fully submerged conditions, the wave horizontal forces generally decrease for increasing wave incident angle. The sensitivity of the load effects to the wave incident angles varies as the angle increases. More specifically, the differences in horizontal force of the bridge structure for two adjacent wave incident angles increase for increasing angles under all the environmental conditions. Therefore, it is important to focus on the conditions of small wave incident angles for the design and dynamic analysis of the bridge structures.

4.2 Effect of second-order waves

The results hereinbefore were calculated based on the linear analysis method. More specifically, the numerical analysis was carried out based on the linear potential flow theory, where the governing equation and boundary conditions that satisfy the condition of the velocity potential are linearized. Moreover, the nonlinear term was also omitted in the Lagrange integral formula for the on-field pressure calculation. In the field of ocean engineering, the linearization assumption is acceptable for academic research and engineering practice for the cases that the amplitudes of incident waves as well as ship motions are small. This is because that the forces on the floater induced by waves and floater motions oscillate in rules over certain periods and the averaged values of the wave loads and load effects are zero under the excitation of long-term regular waves. In this case, the dynamic system that is composed of waves and structures could be regarded as a linear system that accounts for steady-stated responses of the structures. The linear system can be addressed by the separation of wave loads to the parts caused

by floater motions and incident wave excitation, namely the radiation and diffraction problems, respectively.

However, the linearized method cannot well satisfy the need for the greater accuracy for the estimation of wave loads on the offshore structures and the prediction of floater motions. This is due to the limitations of the linear analysis method. More specifically, in realistic conditions, there will be certain deviations of the structural mean positions, which are the results at the condition when the wave frequency is consistent with the floater motion frequency, under the regular wave conditions. Under the irregular wave conditions, the floater will experience the drift motion with a long return period and the drift motion frequency is significantly lower than the characteristic frequency of irregular waves; in addition, the mean positions of the platform motion vary from those under the regular wave conditions. This implies that the constant or slowly varying wave drift forces on the floater exist in nature. In general, the wave drift motions in the surge, sway and yaw directions are more significant than those in the other three directions.

For the coastal bridges under the fully submerged conditions, the effects of the second-order drift forces on the motion responses of the superstructure are of great importance because of the lack of limits to the horizontal displacement, which significantly increases the risks of the girder falling down. However, in the model test, the superstructure is fixed with the loss of considering its displacement, which results in the lack of effects of second-order waves on dynamic load effects of the coastal bridges. The limitations are addressed in numerical analysis, where the second-order wave loads in surge, sway and yaw motions are modeled based on the second-order pressure integration method. The second-order wave forces in the numerical analysis are shown in Fig. 9.

In order to evaluate the influence of the second-order wave force, the second-order mean drift force was compared with the first-order force under different incident angles and wave periods, and the regular wave amplitude A was normalized. The results are shown in Table.3.

$$\chi = \text{mean drift force} / \text{exciting force} * 100\%$$

Table.3 Percentage differences for the second-order mean drift force and the first-order wave force

Component	Incident angle	Wave Period/s				
		1	1.5	2	2.5	3
Surge	0°	4.4%	3.2%	2.0%	1.3%	0.4%
	15°	6.2%	3.3%	2.0%	1.3%	0.4%
	30°	34.6%	3.5%	1.9%	1.3%	0.4%
	45°	11.0%	3.4%	1.8%	1.3%	0.5%
	60°	7.8%	3.2%	1.7%	1.3%	0.5%
	75°	11.7%	3.3%	1.6%	1.2%	0.6%
	90°	1.2%	8.0%	6.3%	0.8%	0.0%
Sway	0°	1.9%	1.2%	0.0%	0.1%	0.1%
	15°	1.6%	1.9%	1.5%	1.4%	0.7%
	30°	6.6%	1.6%	1.4%	1.4%	0.8%
	45°	4.5%	1.7%	1.4%	1.4%	0.9%
	60°	4.0%	3.1%	1.5%	1.3%	1.0%
	75°	4.8%	4.4%	1.5%	1.3%	1.1%
	90°	5.2%	4.6%	1.5%	1.2%	1.1%
yaw	0°	4.4%	3.3%	2.0%	1.3%	0.4%
	15°	5.1%	3.5%	1.8%	2.2%	0.6%
	30°	6.2%	3.1%	1.6%	2.0%	1.0%
	45°	11.1%	2.4%	1.4%	0.6%	1.4%
	60°	2.9%	1.8%	1.2%	1.4%	1.8%
	75°	1.1%	1.2%	0.4%	3.4%	1.2%
	90°	5.2%	3.2%	1.5%	1.2%	1.1%

Table.3 shows that when the wave amplitude is normalized, except for individual working conditions, the second-order average drift force has a difference in magnitude compared with the first-order force. However, it should be noted that in the three-dimensional potential flow theory, the linear force is proportional to the amplitude A , and the drift force is proportional to the square of the amplitude A^2 . Therefore, as the amplitude A increases, the proportion of the second-order average drift force is increasingly, especially in storm surge disasters caused by hurricanes, the amplitude of several meters makes the second-order drifting force a non-negligible part. Except for individual conditions, the percentage differences of the second-order drift force and the wave force decreases with the increase of

the period. For short-period waves, attention should be paid to the influence of the second-order force, especially for short-period waves with incident angles of 30°, 45°, and 75°. The influence of the second-order drift force cannot be ignored.

4.3 Comparison of dynamic responses for the full-scale model

The model test is an important measure to obtain deep insight into the hydrodynamic loads on offshore structures. However, it is unrealistic to do the model tests for the full-scale model due to the space limits of the wave pool. In addition, it is impossible to make the dynamic behavior of the scale model in the model test exactly similar to the prototype model. In the model tests for the offshore bridges, the gravity is dominating in the coupled dynamic response of the waves and bridges, thus the gravity similarity criterion is usually considered in the scale model design for model tests, but the errors in dynamic responses caused by the model size scaling is unavoidable. In order to shed light on the estimation of the discrepancies of the dynamic responses obtained from the full-scale numerical model and the upscaled results from model tests, the full-scale numerical model is established and comparisons for the dynamic load effects are conducted. The environmental and structural parameters of the full-scale numerical model, such as the structure size and wave spectral period, are backward passed by the scale ratios presented in Table.1 and Table.2. The comparison of horizontal forces from the full-scale numerical model and upscaled model tests is shown in Figure 10 where the scaled model data represents the results upscaled from the model tests based on the gravity similarity criterion. In general, the dynamic responses of the full-scale model is slightly larger than those derived from the model tests, and the trend and slope of the corresponding periodic curve are basically the same, which is in line with the basic assumptions of the potential-theory. Except for short waves with high uncertainty, the horizontal wave forces for given significant wave heights generally decreases as the wave peak period increases within the specified range. More detailed analysis for the different responses is given in the following section.

4.3.1 Error analysis

According to the wave theory, the wave length can be determined by successive approximation according to the water depth and wave period, but they will produce certain errors after the scale based on the Froude criterion. The error makes the hydrodynamic load effects different, which is illustrated in Fig. 11, where the amplitudes of the horizontal forces obtained from the derived model tests and the full-scale model in frequency domain are compared. Noted that the scale model in Fig. 11 represents the results upscaled from the model tests. It can be considered that the error is caused by improper water depth or cycle scale ratio.

In general, the amplitudes of the horizontal forces of the two numerical models have a good agreement. The amplitudes calculated by the full-scale numerical model are slightly higher than that from the scaled model tests under different frequency conditions. The trends of the two curves are basically the same. If it is considered that the error caused by the period scale ratio in the dispersion equation causes the data to shift horizontally with the period, the error can be explained well. Furthermore, the abnormality of the

short period wave in Fig. 10 can be explained well according to Fig. 11. Similarly, both figures show that the amplitude difference calculated based on the two methods increases as the wave period increases. The comparison can provide a basis for improving model tests and predicting the dynamic responses of the full-scale models.

5. Conclusion

This paper presents the numerical modeling and the hydrodynamic analysis of an offshore bridge superstructure. The numerical model of the bridge is established using Sesam package, and hydrodynamic loads and load effects of the bridge superstructure are computed based on the potential flow theory and the boundary element method. The numerical analysis is compared with model tests and the results show a good agreement, which implies that the numerical model and analysis method are reasonable.

The effects of wave incident angle on hydrodynamic responses of the scaled bridge superstructure are investigated. It is found that the wave horizontal forces generally decrease as wave incident angle increases. In addition, the second-order wave load effects on the structural response of the scaled bridge are discussed, and the results show that the second-order wave loads significantly increases the risks of the girder falling down, thus it is of great importance to take the second-order wave loads into account. Finally, the full-scale numerical model is established based on the backward pass of scale ratios of physical quantities. Then, the dynamic responses of the bridge superstructure obtained from the inversely derived experimental results and the full-scale numerical results are compared. The comparisons indicate that certain errors exist in the hydrodynamic loads and load effects calculated based on the two methods, which are caused due to the small scale of the wave period. The findings in this paper provide a solid basis for improving the engineering design and numerical analysis for the coastal bridge structures.

Declarations

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Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

References

1. Aguiñiga F, Matakis K, Estrada H, Sai J, Leelani P, Shelden J. 2006. Report Synthesis of Wave Load Design Methods for Coastal Bridges. Rep. No. FHWA/TX-08/0-5516-2, Texas A&M Univ.,Kingsville,

TX.

2. Aguiñiga F, Matakis K, Estrada H, Sai J, Leelani P, Shelden J. 2008. Wave Forces On Bridge Decks: State of the Art and State of the Practice Review. Rep. No. FHWA/TX-07/0-5516-1, Texas A&M Univ.,Kingsville, TX
3. Bradner C, Schumacher T, Cox D. 2011. Experimental Setup for a Large-Scale Bridge Superstructure Model Subjected to Waves. *Journal of Waterway, Port, Coastal and Ocean Engineering*. 137:3–11.
4. Chen Q, Wang L X, and Zhao H H. 2009. Hydrodynamic investigation of coastal bridge collapse during Hurricane Katrina. *J. Hydraul.Eng.*, 10.1061/(ASCE)0733-9429(2009)135:3(175), 175–186.
5. Denson KH. 1980. Wave forces on causeway-type coastal bridges: Effects of angle of wave incidence and cross-section shape. Rep. No.MSHD-RD-80-070, Water Resources Research Institute, Mississippi State Univ., Starkville, MS.
6. Douglass SL, Hughes SA, Rogers S, Chen J, Summary E. 2004. The Impact of Hurricane Ivan On the Coastal Roads of Florida and Alabama: A Preliminary Report. Rep. of Coastal Transportation Engineering Research & Education Center, Univ. of South Alabama, Mobile, AL.
7. Fang Q. 2017. Study On Wave Forces Acting On Superstructures of Coastal Bridges. Ph.D., Harbin Institute of Technology, Harbin, China.
8. Fang Q, Hong R, Guo A, Li H. 2019. Experimental Investigation of Wave Forces on Coastal Bridge Decks Subjected to Oblique Wave Attack. *J. Bridge Eng.* 24:4019011.
9. French JA, 1969. Wave Uplift Pressures On Horizontal Platforms. Rep. No. KH-R-19, W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Pasadena, CA.
10. JT/GQB008-96. 1999. Standard drawings of highway bridge. JT/GQB008-96, Chinese Communications Press, Beijing.
11. Hayatdavoodi M, Seiffert B, Ertekin RC. 2014. Experiments and Computations of Solitary-Wave Forces On a Coastal-Bridge Deck. Part II: Deck with Girders. *Coast Eng.* 88:210–228.
12. Kaplan P. 1992. Wave Impact Forces On Offshore Structures: Re-Examination and New Interpretations. *Proc. Offshore Technology Conf., OTC*, Houston, TX.
13. Mcconnell KJ, Allsop NWH, Cuomo G, Cruickshank IC. 2003. New Guidance for Wave Forces On Jetties in Exposed Locations. *Proc. 6th Int. Conf. on Coastal and Port Engineering in Developing Countries*, COPEDEC, Colombo, Sri Lanka
14. Morison JR, O'Brien MP, Johnson JW, Schaaf SA. 1950. The Force Exerted by Surface Waves On Piles. *J. Can. Petrol. Technol.* 2:149–154.
15. Motley MR, Wong HK, Qin X, Winter AO, Eberhard MO. 2016. Tsunami-Induced Forces On Skewed Bridges. *Journal of Waterway, Port, Coastal, and Ocean Engineering*. 142:4015025.
16. Seiffert B, Hayatdavoodi M, Ertekin RC. 2014. Experiments and Computations of Solitary-Wave Forces On a Coastal-Bridge Deck. Part I: Flat Plate. *Coast Eng.* 88:194–209.
17. Shoji G, Moriyama T. 2007. Evaluation of the Structural Fragility of a Bridge Structure Subjected to a Tsunami Wave Load. *Journal of natural disaster science*. 29:73–81.

18. Xu G, Cai CS. 2015. Numerical Simulations of Lateral Restraining Stiffness Effect On Bridge Deck–Wave Interaction Under Solitary Waves. Eng Struct. 101:337–351.
19. Yeh H, Francis M, Peterson C, Katada T, Latha G, Chadha RK, Singh JP, Raghuraman G. 2007. Effects of the 2004 Great Sumatra Tsunami: Southeast Indian Coast. Journal of Waterway, Port, Coastal and Ocean Engineering. 133:382–400.

Figures

Figure 1

Test layout in literature (Fang 2017)

Figure 2

Figure 3

Side size of scale bridge model

Figure 4

Bottom view of the bridge model

Figure 5

Numerical model

Figure 6

The horizontal wave force versus wave conditions in the literature (Fang 2017)

a) The horizontal wave force for $Z_c=-8.5\text{cm}$

b) The horizontal wave force for $Z_c=-17\text{cm}$

Figure 7

The results comparison between numerical simulation and the reference (Fang 2017)

Figure 8

Wave horizontal force at different incident angles ($Z_c=-17\text{cm}$, $T=2\text{s}$)

a) Wave drift force in the direction of surge freedom

b) Wave drift force in the direction of sway freedom

c) wave drift force in the direction of yaw freedom

Figure 9

Second-order drift force

a) Semi-submerged condition

b) Full-submerged condition

Figure 10

Comparison of horizontal force between scale model and full-scale model

Figure 11

Amplitude comparison of horizontal force in the frequency domain

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [DateandFiniteElementModel.zip](#)