Study on coastal bridge under the action of extreme wave

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Abstract In order to research the catastrophic damage problem of coastal bridge under the action of extreme wave, combine the numerical simulation with tank experiment and based on RANS and $k-\varepsilon$ equation, a bridge-wave interaction model is established. The free surface locations in the model are represented by the Volume of Fluid method. Confirmed the wave parameters and the cross-section form of the girder bridge of tank experiment reference the Pingtan Straits Rail-cum-Road Bridge and the Hong Kong-Zhuhai-Macau Bridge. The tank experiment was conducted for verification of the calculations of numerical simulation. The simulation results show that the constraint conditions between the box girder and pier has an important influence in horizontal translocation damage of the box girder under the extreme wave. With increasing the submerged coefficient, the buoyancy force increases first and the decreases. With increasing the submerged coefficient, the horizontal force decreases.

1 Introduction

With the development of economy and society, the bay bridge has become an indispensable part of rapid coastal transportation network. Since the last decade, several large-scale tsunamis, hurricanes and typhoons occurred around the world, especially Hurricanes Ivan and Katrina in the U.S. had caused a great deal of coastal bridge destruction [1, 2]. Now, the world-class bridge engineering in china is Hangzhou bay sea-crossing bridge and zhoushan cross-sea bridge, the hongkong-zhuhai-macao bridge and across the Taiwan straits pingtan channel bridge are under construction. Most of these bridges in the eastern and southern part of china, vulnerable to the typhoon attack, which causes great damage on the construction of sea-crossing bridge and bridge construction. Studying the coastal bridge's behaviour in action of extreme wave have significant meanings in design, construction and protection of it

In the past decades, many important results on the research of under the extreme wave sea-crossing bridge damage were obtained. Ghamry's [3] deck wave lift experimental study points out that the variation in lifting force of horizontal plate are depend on the wave period and plate clearance. Robertson [4] used the exiting data and method to calculate the hydrodynamic lift and hydrostatic lift of damage to hurricane Katrina bridge, show that the destroy bridge's lift is greater than its own gravity. Xiao [5, 6] used the Volume of Fluid (VOF) and a numerical wave-load model based on the incompressible Reynolds averaged Navier-Stokes equation and $k-\varepsilon$ equations has been used to investigate dynamic wave force exerted on the bridge deck. Different bridge deck elevations submerged at different water depths were investigated. But until now, they didn't do the numerically simulating and flume experiment research to the bridge structure under the same wave environment, use the flume experiment to test the numerical model.

In this paper, a numerical wave-load model based on the incompressible Reynolds averaged Navier-Stokes equation and $k-\varepsilon$ equations has been used to investigate dynamic wave force exerted on the bridge deck and the Volume of Fluid (VOF) is adopted in the model to describe dynamic free surface. Choosing the actual cross section form and wave parameters based on the hongkong-zhuhai-macao bridge and across the Taiwan straits pingtan channel bridge. Studying the coastal bridge's behaviour in action of different bridge deck elevations submerged and wave environment through the numerical simulation and flume experiment.

2 Governing Equations

2.1 Governing Equations

For the wave-structure-interaction, the RANS equations are used to solve the mean flow velocity and the second=order $k-\varepsilon$ turbulent model is used for the closure of RANS equations.
RANS equation:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+g_i+\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

$k-\varepsilon$ model:

$$\frac{\partial k}{\partial t}+u_j\frac{\partial k}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\frac{v_t}{\sigma_k}+v\right)\frac{\partial k}{\partial x_j}\right]+G-\varepsilon \tag{3}$$

$$\frac{\partial \varepsilon}{\partial t}+u_j\frac{\partial \varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\frac{v_t}{\sigma_k}+v\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G-C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{4}$$

Where:

$$\tau_{ij}=2\left(v+C_d\frac{k^2}{\varepsilon}\right)\sigma_{ij}-\frac{2}{3}k\delta_{ij},\sigma_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right),\ \ v_t=C_d\frac{k^2}{\varepsilon},G=2v_t\sigma_{ij}\frac{\partial u_i}{\partial x_j}$$

k is turbulent kinetic energy, v_t is eddy viscosity, u_i is velocity vector of the men flow, ε is turbulent dissipation rate, $C_d=0.09,\ C_{2\varepsilon}=1.44,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.3,\ \sigma_{ij}$ is rate of strain tensor, p is pressure of the mean flow, g_i is ith component of the gravitational acceleration.

2.2 Numerical Method

In the numerical model, used the two-step projection method [7] to solve the RANS equations (1) -

(2).First, introduce an intermediate velocity $\hat{u}_i^{n+1}$, its can carries the correct vorticity, there has:

$$\frac{\hat{u}_i^{n+1} - u_i^n}{\Delta t} = -u_j^n \frac{\partial u_j^n}{\partial x_j} + g_i + \frac{\partial \tau_{ij}^n}{\partial x_j} \quad (5)$$

Where the Δt is time step, the equation (5) didn't have the pressure gradient term and the intermediate velocity didn't satisfy the continuity equation.

The second step is to project the intermediate velocity field onto a divergence free plane to obtain the final velocity:

$$\frac{u_i^{n+1} - \hat{u}_i^{n+1}}{\Delta t} = -\frac{1}{\rho^n} \frac{\partial p^{n+1}}{\partial x_i} \quad (6)$$

$$\frac{\partial u_i^{n+1}}{\partial x_i} = 0 \quad (7)$$

Consider the pressure gradients at the n+1-time step, combine the equation (6) and (7), the RANS almost satisfied.

3 Numerical Simulation

3.1 Numerical model

Based on the actual box section of the hongkong-zhuhai-macao bridge structure, using the established mathematical model of box section to simulate the wave force and wave of torque. Box section size as shown in figure 1.

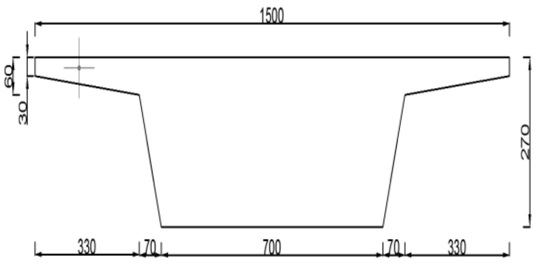


Fig.1 Box section size

The wave parameters of the box section references the measurement of wave parameters on the the Taiwan straits pingtan channel bridge site location. Calculation for different water depths, different submerged depth and different wave heights, a total of 70 kinds of box section under the condition of wave force and moment. Using the second order stokes wave theory to generation wave, and the Volume of Fluid (VOF) is adopted in the model to describe dynamic free surface, which is capable of simulating complex discontinuous free surface during wave-deck interaction. Horizontal direction with non-uniform grid partitioning and in dense mesh size near the structure. In order to make the wave actioned on the bridge fully developed, placed the center of the structure at least three wavelengths away from the boundary location. A sponge layer is set in front of the outflow boundary wave area to absorb the wave energy. Computational domain arrangement is shown in figure 2.

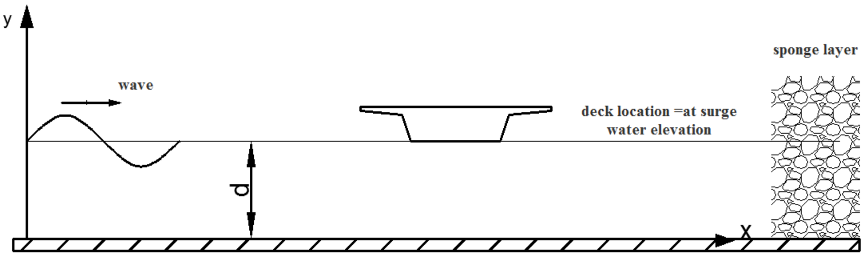


Fig.2 Computational domain arrangement

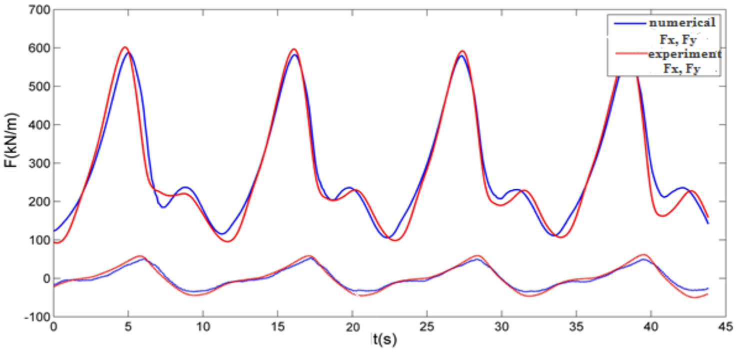
3.2 Numerical model Validation

According to the gravity similarity criterion and the requirements of wave model test procedures, in harbor engineering institute of Tianjin hydraulic research institute, a 1:30 scale model test in no reflection wave machine to verify the above the accuracy of the numerical model. The length, width and height of the water tank are 68m, 1m,1.6m, respectively. According to figure 1 box section size to make the box girder model, model geometry size error of the dimensions and elevation must be controlled at + / - 1.0 mm. In order to ensure the rigidity of test model, box girder structure made of organic glass, hollow inside and outside closed. In the central section of beams, use 3-component dynamometer to measure the total force. Considering the demands of test depth and wave cycle, breakwater model set up on the horizontal section at the bottom of the tank directly. Model was settled six time the size of the wavelength away from the wave machine, the distance from the rear wave sponger slope must greater than 2 times the wavelength.

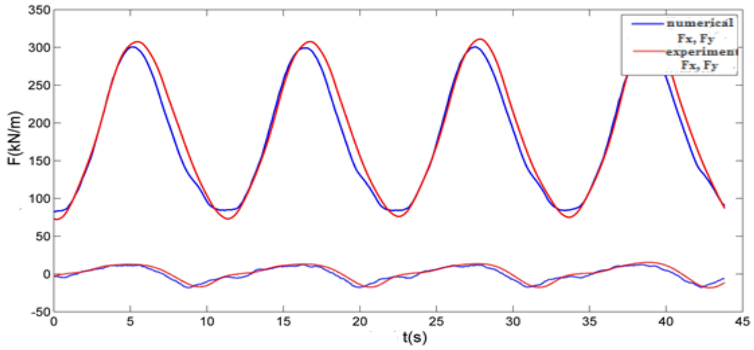
Physical model and test installation is shown in figure 3:

Fig.3 Test model installation plan

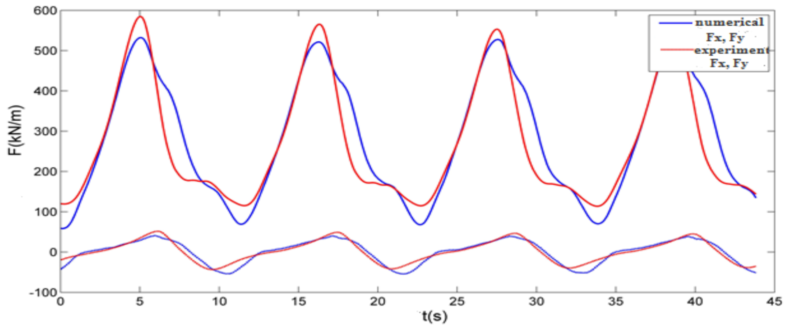
Figure 4 shows the model of submerged coefficient of 2.0, bottom elevation of 11.94 m, wave height is 6 m; the bottom elevation of 15.99 m, wave height is 2 m; the bottom elevation of 15.99 m, wave height is 6 m, comparison of the buoyancy of box girder in these three working conditions. Numerical results are in good agreement with experiment results, show that the results of numerical simulation can well reflect the real stress distribution of box girder under wave load.



Y=11.94，H=6



Y=15.99，H=2



Y=15.99，H=6

Fig.4 The time curve of buoyancy

3.3 Wave Force Calculation of Box Girder

With the box girder section as the research object, numerical model for wave forces acting on the box girder section were simulated. Calculation for different water depths, different submerged depth and different wave heights, a total of 70 kinds of box girder cross section under the condition of wave force. The working condition of wave elements shown in the table:

Table.1 Wave elements of numerical simulation

NO	The heights of model bottom Y (m)	Water depth d		Wave height H (m)	Period T (s)
		Submerged coefficient	model (m)		
				2	11.2
1		0.0	7.89	3	11.2
				4	11.2
2	7.89	0.5	9.24	Ditto	
3		1.0	10.59	Ditto	
4		1.5	11.94	Ditto	
5		2.0	13.29	Ditto	
				2	11.2
				3	11.2
6		0.0	11.94	4	11.2
				5	11.2
	11.94			6	11.2
7		0.5	13.29	Ditto	
8		1.0	14.64	Ditto	
9		1.5	15.99	Ditto	
10		2.0	17.34	Ditto	
				2	11.2
				3	11.2
				4	11.2
11		0.0	15.99	5	11.2
				6	11.2
	15.99			7	11.2
12		0.5	17.34	Ditto	
13		1.0	18.69	Ditto	
14		1.5	20.04	Ditto	
15		2.0	21.39	Ditto	

Figure 5 shows the curve of box girder per linear meter of peak buoyancy the ratio of its own gravity per linear meter change with submerged coefficient at the 15 kinds of working condition. Figure 6 shows the curve of box girder per linear meter of peak horizontal force the ratio of its own gravity per linear meter change with submerged coefficient at the same working condition.

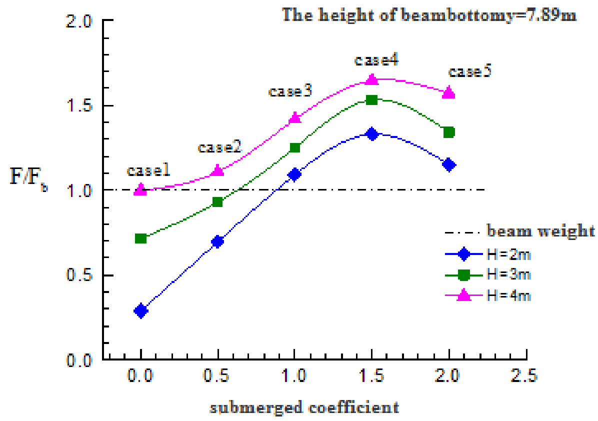


Fig.5 The curve of buoyancy and the gravity ratio changes with the submerged coefficient

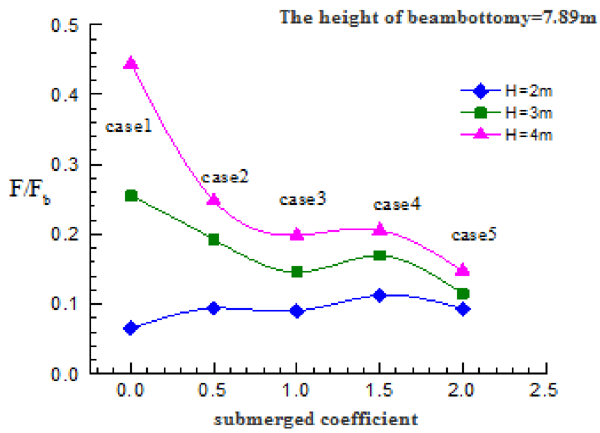


Fig.6 The curve of horizontal force and the gravity ratio changes with the submerged coefficient

As the figure 5 shows, the box girder per linear meter of peak buoyancy the ratio of its own gravity per linear meter will increase first and then decrease as the submerged coefficient increase, because when the submerged coefficient is less than 1.0, with the box girder gradually sinking, causing drainage volume increased, then buoyancy increased. When submerged coefficient greater than 1.0 and less than 1.5, the box girder is fully immersed in water, but because of the influence of the wave, buoyancy at this time continue to increase, gradually increase to the maximum value. As the submerged coefficient continues to increase, the influence of the waves to the box girder will gradually weaken, the buoyancy is decreased.

As the figure 6 shows, with the increase of submerged coefficient, box girder is gradually sinking, wave effect on box girder section gradually weaken, then the horizontal forces are present decreasing trend.

According to document [9], the friction coefficient between bridge abutment and box girder was $\mu = 0.3$, the bridge beam body will damage because the horizontal displacement under the extreme wave load. By the damage formula of horizontal displacement (8):

$$\mu(G - F) \leq N \tag{8}$$

Where: $\mu = 0.3$, G is weight of box girder, F is buoyancy, N is horizontal force.

Can be concluded: when submerged coefficient is greater than 0.5, the box girder damage of horizontal displacement will easy happen.

4 Conclusion

In this paper, using the incompressible Reynolds averaged Navier-Stokes equation and $k-\varepsilon$ equations to establish wave-bridge interaction numerical model, and verified the accuracy of the numerical model by tank test. Through numerical simulation of 70 kinds of working conditions, obtained the following conclusion:

(1) The numerical model established in this paper, through the scale tank test under the condition of same contrast, proved to be accurate. The established numerical model can better simulate the actual engineering of the bridge problem under the extreme wave action, it can provide effective numerical simulation tools on design and construction of sea-cross bridge.

(2) When submerged coefficient is greater than 0.5, the box girder damage of horizontal displacement will easy happen. It has the guiding role on the sea-crossing bridge elevation design, especially in low elevation design.

(3) The type of bearing between box girder and pier plays a decisive role in the damage of sea-crossing bridge under the extreme wave action. Strengthen vertical and lateral constraint between box girder and pier can effectively avoid the damage of beam horizontal displacement.

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