Numerical Simulation of the Influence of Large-scale Structures on Wave Force of Adjacent Small-scale Bars in Composite Structures

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Abstract. In order to calculate the wave loads on the small and medium scale bars of composite structures accurately, not only the action of incident wave but also the wave diffraction caused by near large-scale structure and the effect of radiation on wave load of small scale bars should be considered. In this paper, based on the VOF method, the three-dimensional wave numerical flume of the wave acting on the composite structure is constructed in Fluent. The incident wave force, diffraction wave force and total force acting on the composite structure are obtained by numerical calculation. Compared with the results obtained by using the Morison formula alone, the effectiveness of the wave loads calculated by the model is verified. The results show that under certain wave conditions, the wave diffraction caused by large-scale structures can not be ignored. In addition, the influence of the incident wave number, the diameter of the pile and the position of the pile on the wave load of the small-scale pile is also studied. The results can provide a scientific reference for the accurate calculation of wave loads on small-scale piles in marine engineering with composite structures.

1. Introduction
Pile structure of various scales is a common structural form in marine engineering. Scholars at home and abroad have done a great deal of researches on wave loads on pile structures. MacCamy et al. [1] gave an analytical solution to the problem of diffraction of vertical cylinders in finite water depth. Linton et al. [2] studied the interaction of waves on vertical pile groups. Yilmaz et al. [3] studied the diffraction of truncated cylinders. Existing researches on Truss Spar platform and TLP platform ignore the diffraction and radiation due to the existence of large scale main structure usually when using Morison formula to solve the stress of small-scale members or tension legs of the platform. Geng B L et al. [4] calculated the wave loads of small and medium diameter cylinders in diffracted wave field by using Morison formula. On the assumption of linear theory, Jiang S C et al. [5] established an analytical solution of vertical cylindrical wave diffraction under finite water depth. Wu and Chwang et al. [6] studied the diffraction problem of submerged two-dimensional porous horizontal thin plates. Yu and Chwang et al. [7] studied the wave distribution when the wave passed through the submerged disk. Sakar et al. [8] studied the scattering velocity potential and the radiation velocity potential of the truncated cylinder. Techet et al. [9] gave the boundary conditions of wave radiation problem of large diameter cylinder and the wave force calculation formula. Y.Drobyshchevski et al. [10] obtained the analytical solution of hydrodynamic characteristics of truncated cylindrical platform by means of asymptotic matching method, Hu J M et al. [11] numerically simulated the diffraction problem of a
Considering the deficiency of the research on wave loads of small and medium scale piles in composite structures at present, this paper takes the composite structures composed of large-scale cylinder and small-scale pile as the research object, and considers the effect of diffraction. In this paper, the wave loads on composite structures are studied. In this paper, based on Fluent software, N-S equation is used as control equation, VOF method is used to control free surface, UDF secondary development function is used to realize physical wave generation, and PISO velocity coupling mode is adopted. The method of adding additional source term to the momentum equation is used to reduce the reflection of distant walls, and a three-dimensional numerical wave flume which can produce stable linear regular waves is established. The wave force acting on a small scale member is obtained by numerical calculation, and the influence of the incident wave number, the diameter of the upper cylinder and the position of the pile on the diffraction is also analyzed. The research results in this paper will provide a good scientific basis for the parameter design of composite marine structures.

2. Mathematical Model
In this paper, the fluid in the numerical wave tank is set up as incompressible viscous fluid. The governing equations include continuity equation and Navier-Stokes equation.

Continuity equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0
\]  

(1)

Momentum conservation equation:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + g_x
\]  

(2)

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + g_y
\]  

(3)

\[
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + g_z
\]  

(4)

In the formula, \( u, v, \) and \( w \) are the velocities in \( x, y \) and \( z \) directions respectively; \( g_x, g_y, \) and \( g_z \) are volume accelerations in \( x, y \) and \( z \) directions respectively; \( p \) is fluid pressure, \( \rho \) is fluid density, \( \nu \) is the viscosity coefficient of fluid motion.

3. Numerical simulation

3.1. Geometric Model.
The geometric diagram of the three-dimensional numerical wave flume is shown in Figure 1. The overall size of the tank is 20m long, 4m high and 4m wide. The initial water depth of the flume is 2m, above the water surface is air, and the wave absorption area is 16~20m at the end of the flume. The radius of the upper large-scale cylinder of the composite structure is 0.4m and the draught of the cylinder is 1m. The superstructure is supported by a small scale pile with a radius of 0.1m and a pile length of 1m. The pile is in the same axis as the upper cylinder. The left wall of the three dimensional flume is used to simulate the wave-making plate. The coordinate system of the 3D model is arranged as shown in Figure 2, and the wave propagates in a positive direction along the \( x \) axis.
3.2. Parameter Setting.

The structure grid is divided in ICEM, and the motion law of the plate in the numerical wave tank and the wave elimination source terms in the wave absorption area are compiled by UDF. The left wall of the tank is equivalent to the wave-making plate. The moving mesh model is used to realize the motion of the wall. The pressure inlet boundary is set at the top of the flume to define the pressure condition and other scalar properties of the inlet, and the other boundary is wall boundary. The free water surface is obtained by VOF method, the pressure and velocity terms are calculated by Piso algorithm, the grid updating method of Layering is used to realize the wave-making of push plate. The time step is 0.01s and the simulated time is 20s.

3.3. Model verification.

In order to verify the validity of the model, the numerical results are compared with the theoretical results. The incident regular wave height is 0.15m and the period is 1.6s. It can be seen from the diagram that the simulated value is in good agreement with the calculated value of Morison formula. It can be preliminarily concluded that FLUENT has considerable accuracy in numerical simulation of wave interaction with small-scale vertical column structures.
4. Result and analysis

4.1. Influence of incident wave number on wave force of pile.

The regular incident wave with different incident wave number \( k_a \) is considered. Figure 4 is comparisons of incident wave force, diffraction wave force and total force \( e \) of the pile with different incident wave number \( k_a \).

It can be seen from the diagram that the amplitude of the total force is larger than that of the incident wave force when the \( k_a \) values are different, because the phase of the diffraction force is basically the same as the incident force. When \( k_a < 1.0 \), the diffraction wave force is smaller than the total force, and the total wave force is mainly dependent on the incident wave force, and the diffraction wave force can be neglected. When \( k_a > 1.0 \), the effect of diffraction wave becomes more and more obvious and cannot be ignored. At \( k_a = 2.5 \), the diffraction wave force is about equal to the incident wave force, and the amplitude of the total force is about twice that of the incident wave force. When \( k_a > 2.5 \), the diffraction wave force is larger than the incident wave force, which dominates the total force.

4.2. Influence of upper cylinder size on wave force of pile.

When the radius of the upper cylinder is different multiple of a, let the radius of the different cylinder be \( R = n a \), and \( n \) be equal to 1, 2, 3, 4 respectively. The influence of diffraction field on the wave load of a small pile with different radius is investigated. Consider the regular wave incidence of the wave number \( k_a = 0.8 \) with a wave amplitude of 0.75. Figure 5 shows comparisons of incident wave force,
diffraction wave force and total force amplitude of the pile with different radius R of the upper cylinder.

Figure 5. Comparisons of incident, diffraction and total waves forces with different upper cylindrical radius

Since the incident wave field is invariant, the incident wave force is the same, and its amplitude is 8.8N. It can be seen from the diagram that the diffraction field becomes stronger with the increase of the radius of the upper large-scale cylinder. The diffraction wave force on the bottom pile also increases, but the amplitude of the increase in wave force gradually slowed down. At the same time, due to the difference between the phase of diffraction force and the incident force, the amplitude of total force is smaller than the incident wave force most of the time.

4.3 Influence of upper cylinder size on wave force of pile.
For ease of representation, the projection of the composite structure on the XOZ plane is represented by polar coordinates (r, θ), as shown in Figure 6. In the calculation, the incident condition is invariant, the radius of the large scale cylinder is a, and the other dimensions of the structure are the same as before. Because the incident wave goes in the positive direction of x, according to symmetry, the wave load on the pile at the symmetrical position on the left and right sides of the x axis is the same, so only the force of the pile at different positions \( \theta \in [0^\circ, 180^\circ] \) is studied here. Figure 7 shows comparisons of the diffraction wave force and the total wave force at different values of r and θ.

Figure 6. Projection of the pile at XOZ plane
Figure 7. Comparisons of diffraction and total wave forces with different $r$ and $\theta$

Because the incident wave condition is invariant, the amplitude of incident wave force is still constant, its value is $8.8N$. It can be seen from Figure 7 that the amplitude of force and diffraction wave force are smaller than the incident wave force. For the total force, the amplitude of the total force increases with the increase of the distance $r$. The amplitude of the total force is larger than that of the diffraction wave force when $r$ is 0.5$a$ and 0.75$a$, and the diffraction wave force is larger than the total force at the back side of $\theta\in[135^\circ, 180^\circ]$ when $r$ is 0.25$a$. At the front side of $\theta\in[0^\circ, 90^\circ]$, the amplitude of total force is larger than that of diffraction wave force. The amplitude of total force reaches maximum at $\theta=0^\circ$ and minimum at $\theta=135^\circ$. On the contrary, the diffraction force reaches the maximum at $\theta=135^\circ$ and the minimum at $\theta=0^\circ$. The diffraction wave force decreases with the increase of the distance $r$. When $r$ is 0.25$a$, the diffraction wave force is almost equal to the total force due to the phase difference.

5. Conclusion

In this paper, based on the VOF method, the numerical wave environment of wave action on composite structures is constructed in Fluent. The wave loads on small and medium scale bars in diffraction field are analyzed by a series of numerical examples, the conclusions are as follows: (1)
under the action of regular wave, when $ka > 2.5$. The diffraction wave action is greater than the incident wave action, which dominates the total force, and the magnitude of the total force is about twice of the incident wave force. (2) the size of the upper part directly changes the shape of the diffraction field in the wave field. The wave force of the diffraction field on the pile increases with the increase of the upper cylinder size. (3) the wave force of the small-scale pile will be greatly affected by the different positions of the small-scale pile in the diffraction field, and for the total force, the wave force will be greatly affected by the different positions of the small-scale piles in the diffraction field. The amplitude of the resultant force increases with the increase of distance $r$. The diffraction wave force decreases with the increase of distance $r$.

6. Reference

[1] MacCamy R C, Fuchs R A 1954 US Army Coastal Engineering Research Center. P 69
[2] Linton C M, Evans D V 1990 J.Fluid Mech. (215):549-569.
[3] Yilmaz O, Incecik A 1998 Ocean Engineering. 25(6): 385-394.
[4] Geng B L, Teng B, Ning D Z and Gou Y 2009 Journal of Dalian Maritime University. 35(3):5-8.
[5] Jiang S C, Teng B, and Ning D Z 2010 Ocean Engineering. 28(3):68-75
[6] Wu J H, Chwang A T 1994 Proc. of the Fourth Int. offshore and Polar Engineering Conference. pp 154-159.
[7] Yu X P, Chwang 1993 Journal of Engineering Mechanics. 119(9):1804-1817
[8] Sarkar A, Eatock Taylor R 2001 Journal of Fluids and Structures. (15):133-150
[9] Techet A.H. 2005 Design Principles for Ocean Vehicles pp125-256
[10] Y.Drobyshevski 2004 Ocean Engineering. (31):269-304
[11] Hu J M Numerical Simulation of Wave Radiation and Diffraction Problems based on Fluent. Harbin: Harbin Engineering University.