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Simulation of Wave Impact on Inclined Deck Based on VOF Method

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Abstract: The increasing importance of the sustainability challenge in ocean engineering has led to the development of floating structure of various configurations. In this study, a numerical wave tank based on the Navier-Stokes equations has been established. The turbulence model, namely standard k-ε is incorporated to the numerical tank to broaden applicability of simulation. The VOF method has been widely used in the free-surface hydrodynamic flows with good accuracy. The wave impact phenomenon is extremely complicated and restriction of experimental condition. To better understand the mechanisms and rules of wave slamming on the floating structure, in the first instance, this study simplifies the problem and assumes 5 key gestures for floating structure with inclined angles (10°, 5°, 0°, -5° and -10°) and secondly, a periodic motion deck model has been established. The computation result is in good agreement with the experimental data. The numerical method can predict the impact peak pressure and the distribution of wave impact along underside of the inclined deck. It is also significant to research the wave impact force of the inclined deck and has great scientific value and practical significance.

Keywords: Inclined deck, periodic motion, regular wave, wave impact

INTRODUCTION

As mining technology has a development, offshore oil exploration and development have been proposed requirements into the deep sea around the world. Fixed and floating platform is very important and necessary in oil and gas exploration fields and its security gets more extensive industry's attention. Superstructures of breakwaters, decks of jetties or platforms, elements of balustrades, etc., are typical elements of maritime structures supported above still water level. The elements of maritime structures are often subject to wave attacks despite of precautions at the design stage. The potential deck impact, of ocean structures under waves get generally of considerable interest. It is particularly complicated in the case of floaters because of their large volume and the resulting effects of wave diffraction and radiation. Green water damage to offshore structures results from high pressures and dynamic loads that occur when wave crests inundate the structure far above the waterline in areas not designed to withstand such pressures.

Computational Fluid Dynamics (CFD) methods are increasingly used for analyzing problems related to gravity wave interaction with structures. Early numerical studies are mostly based on the potential flow theory (Longuethiggins and Cokelet, 1976; Grilli *et al*., 1997) and the shallow water equations (Li and Raichlen 2001) in which the fluid viscosity is not taken into account. However, for a real fluid, viscous effect plays an important role in balancing the fluid inertia and dissipating the energy. With the development in computer technology and CFD methods, it is possible to solve directly the Navier-Stokes equation. Several methods have been developed and applied to tackle the simulation of the free surface, such as the Marker and Cell (MAC) method (Kaplan and Silber, 1976; Ching-Jer *et al*., 1998; Bai *et al*., 2001), level set method (Iafrati *et al*., 2001) and smoothed particle hydrodynamics (SPH) method (Gotoh *et al*., 2004). The volume of Fluid (VOF) method was introduced by Hirt and Nichols (1981) through the SOLAVOF algorithm. It is a promising tool to predict extreme wave loads on fixed and floating offshore structures and it is widely used for its simplicity as well as effectiveness. The Navier-Stokes equations are solved in air and water with respect to the real density ratio between the two fluids. The interface tracking is achieved by the well known concepts of VOF, which is intended for two-dimensional time-dependent viscous free-surface flow, features the distinct use of a volume of fluid function to model the displacement of the free surface. The VOF technique however is not the only existing method for treating arbitrary free surfaces. Over the past few years, a number of publications related to wave lamming on horizontal cylinder or horizontal plate have been published. Kaplan and Silbert (1976) developed a solution for vertical force on a horizontal cylinder from the instant of impact to full immersion (Kaplan and Silbert, 1976).

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Koo and Kim (2007) studied the wave body interactions for stationary floating single and double bodies using a potential-theory-based fully nonlinear 2-D numerical wave tank. Wang and Ren (1999), Ren and Wang (2004) and Xuelin *et al*. (2009) investigated a numerical wave tank based on improved VOF method to study the wave slamming on a horizontal deck in the splash zone.

In recent years, more attentions have been paid to the wave impact by many researchers all over the world. But most of studies are focus on the fixed structures, especially the horizontal deck. For floating structures, there are rarely researches mentioned. The wave impact phenomenon is extremely complicated and restriction of experimental condition. To better understand the mechanisms and rules of wave slamming on the floating structure, this study simplify the problem and assume 5 key gestures for floating structure with inclined angles (10°, 5°, 0°, -5° and -10°). The study describes the method of generating transient wave groups in a CFD analysis of wave in deck impact. The typical approach is to use a regular wave at the inflow condition and time step the wave field for a few wave periods. The study presents the numerical simulation of the wave slamming on the deck of different inclined angles and the contrastive analysis by the experimental investigation.

NUMERICAL MODEL

Governing equations: The numerical model VOF, VOF-algorithm for breaking waves on structure is based on the original SOLA-VOF code (Nichols *et al*., 1980) capable of treating low-speed flows involving arbitrary free surface configurations. For turbulent flow, the velocity field and the pressure field can be decomposed into two parts: the mean velocity and pressure, $\overline{u_i}$ and $\overline{p_i}$ and the corresponding fluctuating components, u_i' and p_i'.
Thus:

$$u_i = \overline{u_i} + u'_i$$

$$p_i = \overline{p_i} + p'_i \tag{1}$$

The mean flow field is governed by the Reynolds Averaged Navier-Stokes (RANS) equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \overline{u}_i) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \overline{u}_i) + \frac{\partial}{\partial x_i}(\rho \overline{u}_i \overline{u}_j) = -\frac{\partial \overline{p}}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j}(\mu \frac{\partial \overline{u}_i}{\partial x_i} - \rho \overline{u'_i u'_j}) + S_i \tag{3}$$

where, ρ = fluid density; i, j = 1, 2 for two dimensional flows; u_i = *ith* component of the velocity vector; p = pressure; g_i = *ith* component of the gravitational acceleration; μ is coefficient of viscosity; and S_i = momentum source function.

To appropriately model the Reynolds stress, the k-ε models are employed. For the standard k-ε model (Launder and Spalding, 1972), the turbulence kinetic energy k and its rate of dissipation ε are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{5}$$

where, μ_t is turbulent viscosity, G_k represents the generation of turbulent kinetic energy due to the mean velocity gradients and:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

$$G_k = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial \mu_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{7}$$

The model constants have the following values:

C_μ= 0.09, $C_{1\varepsilon}$= 1.44, $C_{2\varepsilon}$= 1.92, σ_k= 1.0, σ_ε= 1.3

The VOF method: The VOF method is known for its capacity to simulate free-surface flow. The free surface is capture by the VOF method. This is made possible by means of a fluid fraction function F (x, y, t), which has a value between unity and zero, representing the volume fraction of a cell being occupied by a fluid. Thus, a cell full of fluid is reflected by F = 1, while an empty cell will have F = 0. A cell that is either intersected by a free surface or contains voids will be partially filled with fluid and has a value of F between zero and unity. Furthermore, a free surface cell can be indentified being a cell with a non-zero F and have at least one neighboring cell where F = 0. The time variation of this function is governed by:

$$\frac{\partial F}{\partial t} + \frac{\partial (uF)}{\partial x} + \frac{\partial (wF)}{\partial w} = 0 \tag{8}$$

Fig. 1: Photograph of the experiment platform

MODEL APPLICATIONS

Wave impact on a inclined deck: In this section, the incompressible VOF model is used to simulate a green water wave impact on a inclined deck with different angle. In deepwater engineering, unexpected wave impact force is the major cause of damage to the marine structures such as floating platform. The author has done some of researches about the wave impact on the inclined deck, including experimental research in the laboratory. In order to test our numerical model, the experimental results are used for the comparison.

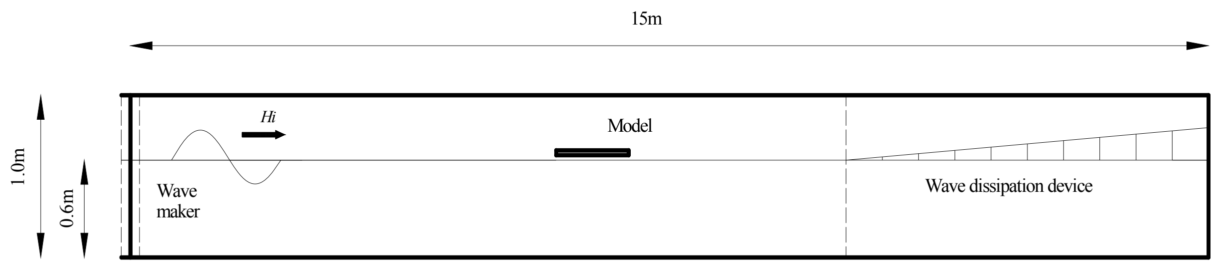

Fig. 2: Sketch of the numerical wave tank

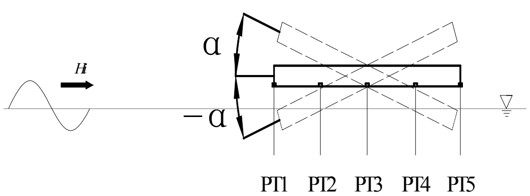

Fig. 3: Sketch of the inclined angle α and pressure transducers location

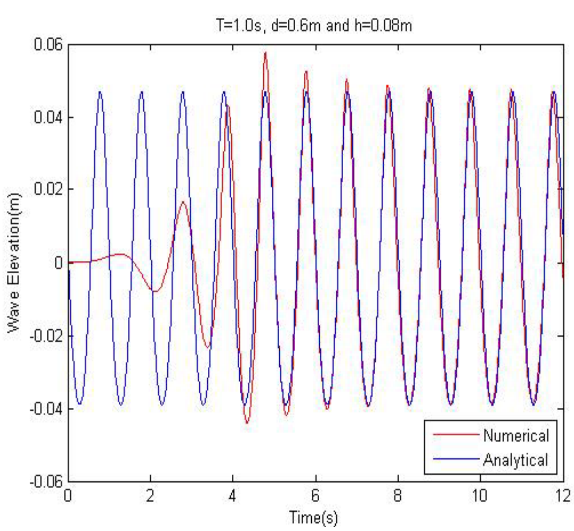

Fig. 4: Comparison of wave elevation for stokes wave at x=7m

Introduction of experiment: The laboratory tests were conducted in a 50m long, 1m wide and 0.6m deep wave-current tank in the Research Institute of Ocean Engineering, Dalian University of Technology. The deck model was a inclined deck, 0.5m long, 0.5m wide and 0.01m thick, as shown in Fig. 1. The wave impact pressures on the underside of the model were measured using a multi-point pressure measuring system.

The numerical computational parameters: It can be seen from Fig. 2 that the length of the numerical wave tank is 15m and distance between the leading edge of the deck and the wave maker is 7m, the water depth is 0.6m, the end of the tank is the wave dissipation device. The inclined angle α and pressure transducers location are shown in Fig. 3. The Quadratic Upwind Interpolation of Convective Kinematics (QUICK) algorithm is used for the momentum and the Pressure Implicit with Splitting of Operators (PISO) algorithm is used for the pressure-velocity coupling. The QUICK algorithm is a second order upwind scheme for quadrilateral and hexagonal meshes.

A second order Stokes wave with wave height H from 0.08 m to 0.14 m and wave period T from 1.0 to 2.0 on a constant depth d = 0.6 m are simulated with the turbulent model. A fine vertical mesh is used in the vicinity of the free surface with the minimum mesh size Δx = 0.01m and Δy = 0.005 m. The computed wave elevation and analytical solution are show in Fig. 4 at x = 7 m. It can be observed that the numerical profiles

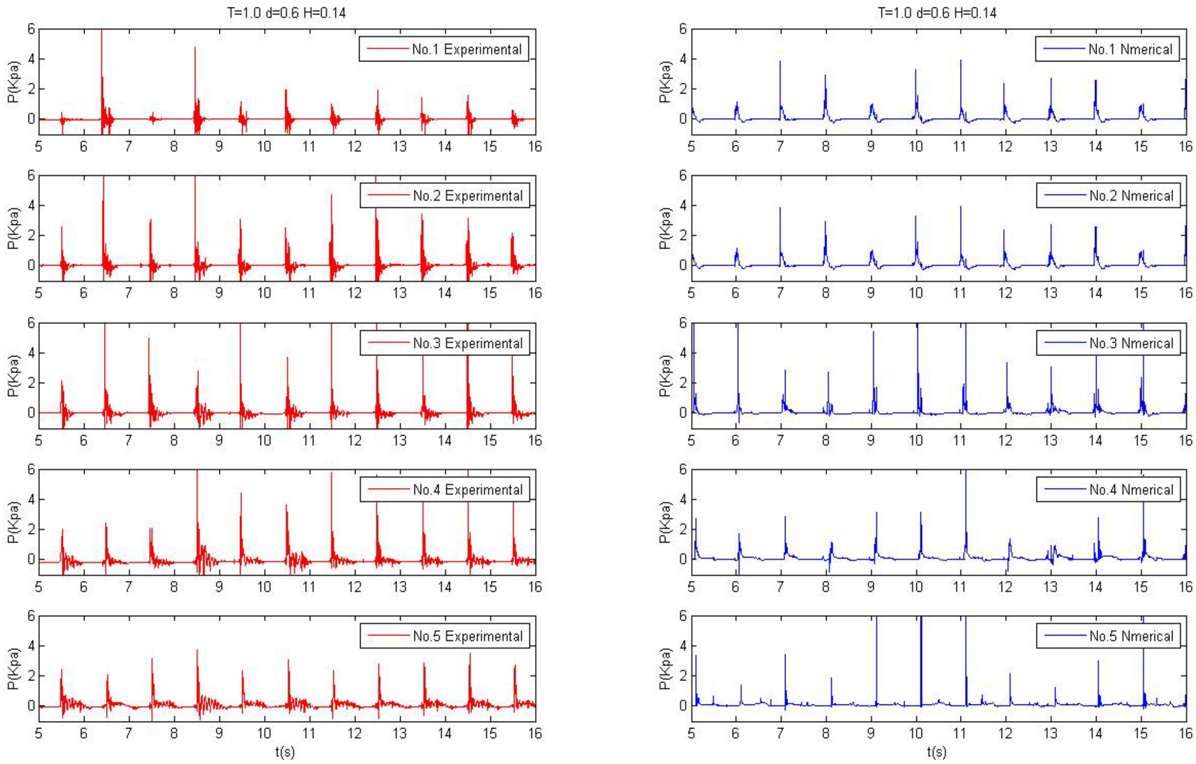

Fig. 5: Experimental results and numerical results of time history of pressure at transducers 1#-5#, α = 10º T = 1.0s d = 0.6m H = 0.14

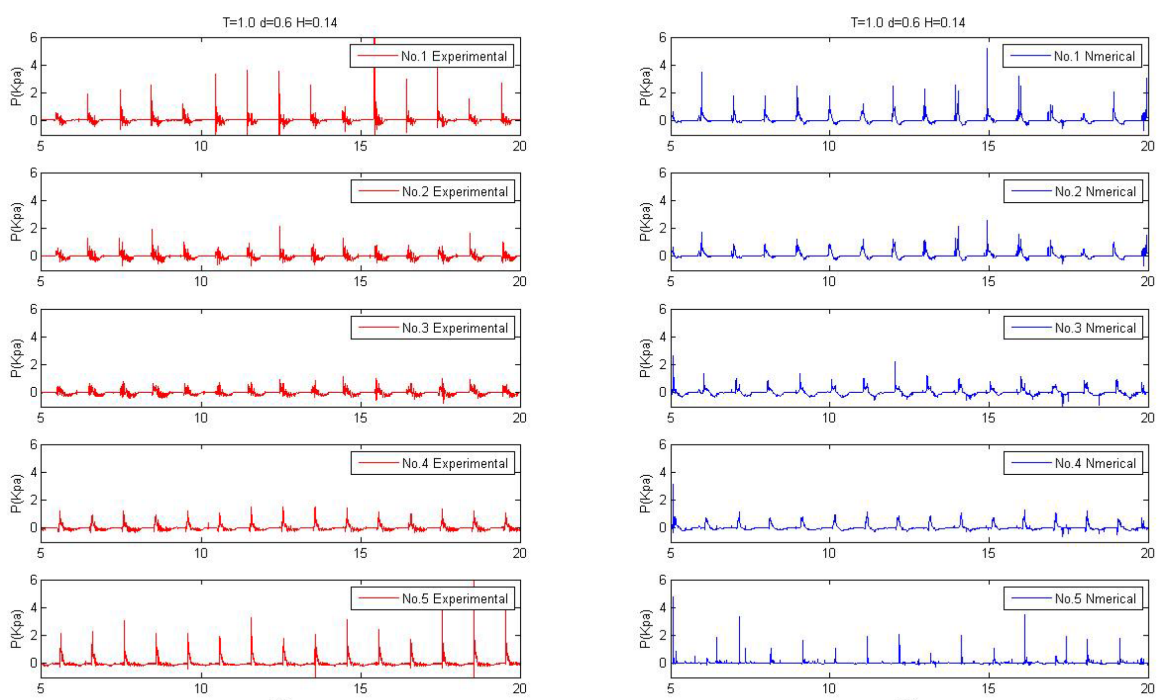

Fig. 6: Experimental results and numerical results of time history of pressure at transducers 1 # -5 #, α = 5º T = 1.0s d = 0.6m H = 0.14

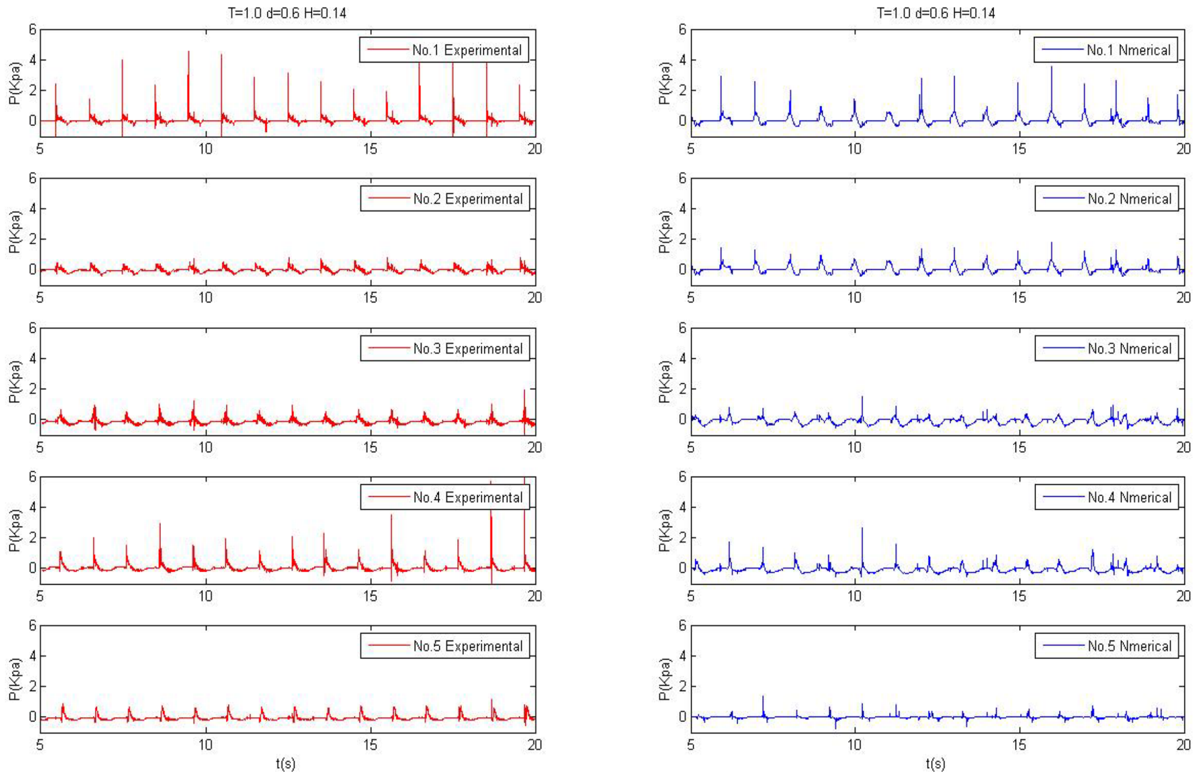

Fig. 7: Experimental results and numerical results of time history of pressure at transducers 1 # -5 #, α = 0º T = 1.0s d = 0.6m H = 0.14

from the two cases are nearly the same and both agree well.

RESULT ANALYSES

The time history of pressure: Figure 5 to 9 shows the numerical and experimental results of the time history of impact pressure on the deck in different inclined angle (10°, 5°, 0°, -5° and -10°). The left figures are the experimental results and the right ones are the simulated results based on the VOF numerical model. The incoming wave is regular wave with wave height H = 0.14m and wave period T = 1.0s and the relative clearance $\Delta h/H = 0.2$, in which Δh is the distance between the deck and the water surface. The abscissa designates the time and the ordinate designates the impact pressure on the deck. It is seen that the impact pressure properties of the computation results coincide with those of the experimental results at most points, the numerical result can predict the magnitude of the peak pressure.

The distributions of the impact pressure: We use the average value of the largest one-third peak pressure as the significant peak pressure. Figure 10 show the distributions of impact pressure along the underside of the deck at the relative clearance $\Delta h/H = 0.2$. The abscissa represents the number of pressure transducer along the underside of the deck in different inclined angles. The ordinate represents the measured result and numerical result of the wave impact pressure in different wave periods. It is learnt from Figure 10 that the wave impact pressures are sensitive to inclined angle change. When the inclined angles are negative, 2# point is the dangerous area, the maximal impact peak value reaches 8kp. On the contrary, when the inclined angles are positive, the total pressure level is higher and we can find the impact peak value emerges in turn at 1#-5#. It is obvious that the numerical results are in good agreement with experimental results at most measure points.

The wave impact pressure of a periodic motion deck: In order to further study the wave impact on the inclined deck, a periodic motion deck model has been established. The rotating period is the same with wave period. Figure 11 show the peak value comparison of the wave impact on the Rotating and fixed deck. The abscissa represents the number of pressure transducer along the underside of the deck. The ordinate

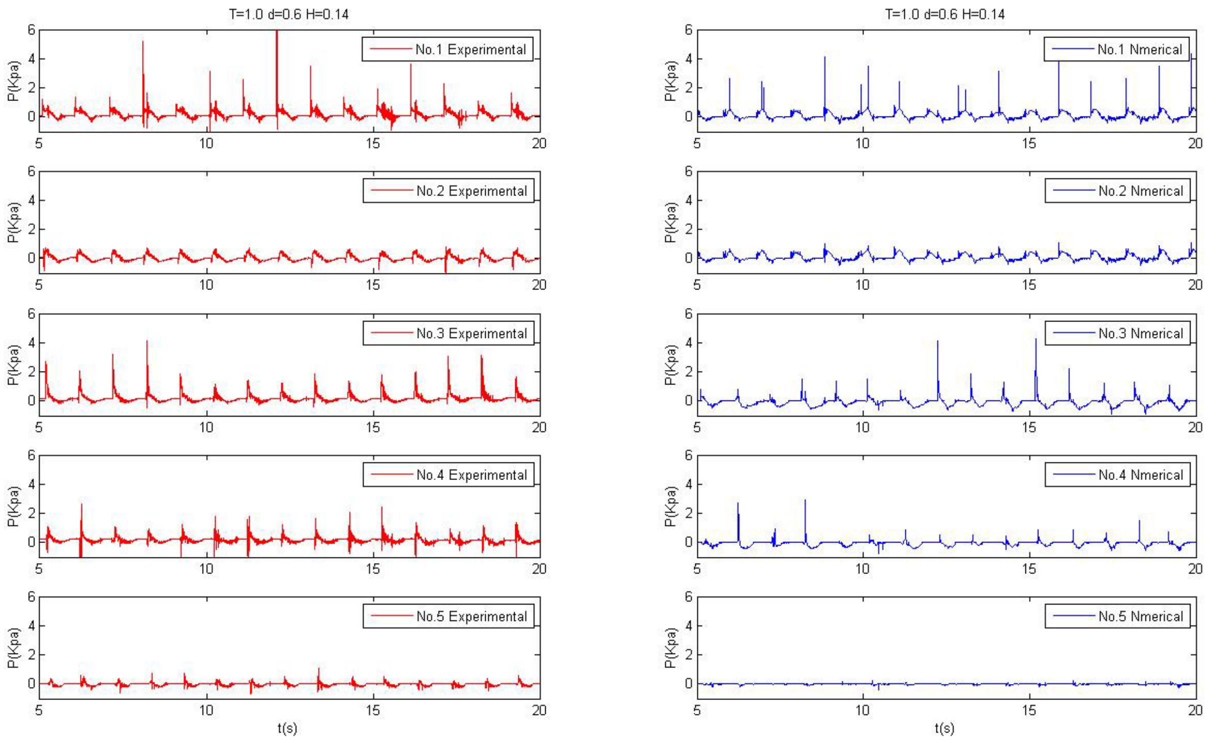

Fig. 8: Experimental results and numerical results of time history of pressure at transducers 1 #-5 #, α = -5º T = 1.0s d = 0.6 m H = 0.14

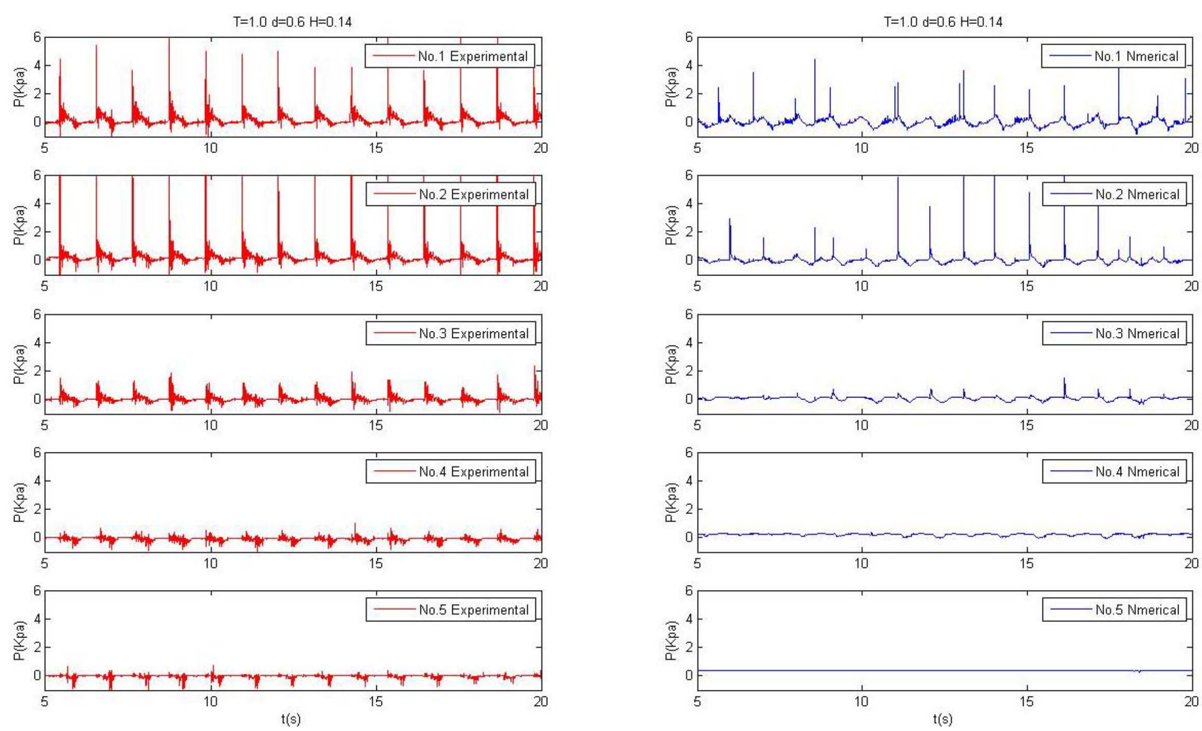

Fig. 9: Experimental results and numerical results of time history of pressure at transducers 1 #-5 #, α = -10º T = 1.0s d = 0.6m H = 0.14

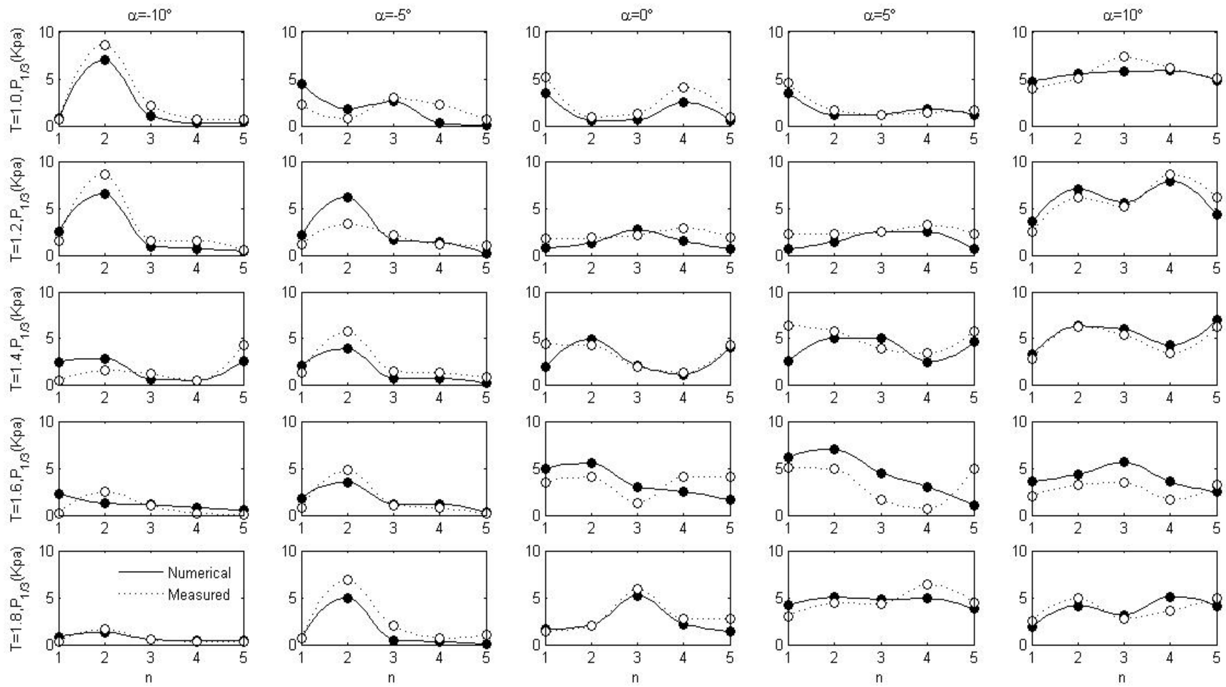

Fig. 10: The wave impact pressure along the underside of the deck in different inclined angle

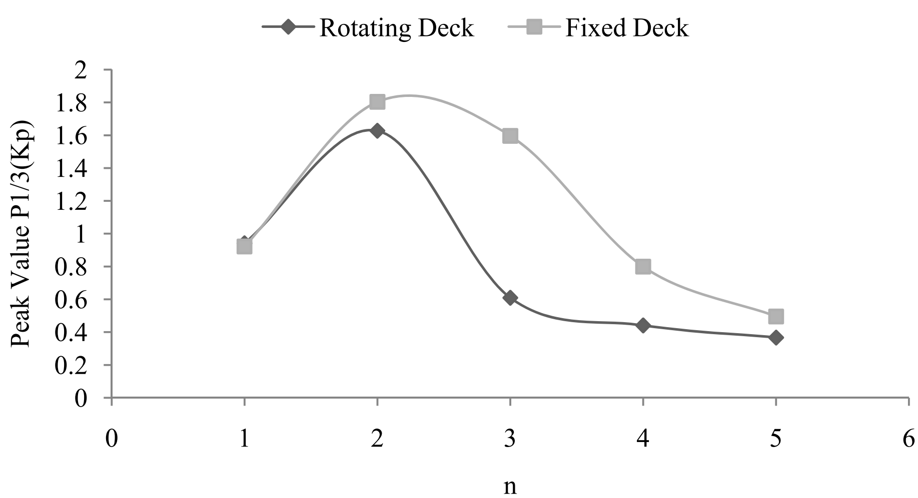

Fig. 11: The peak value comparison of the wave impact on the Rotating and fixed deck, (T = 1.0s, H = 0.1m, d = 0.6m)

represented result of the wave impact pressure on the deck. In the case of fixed deck, the maximum value has been selected in different inclined angles as the nth pressure transducer's result. Form Fig. 11, it is found that the 2# transducer give a max value and 3#, 4# and 5# transducer have a safe value relatively, cause the energy of wave dissipation at the front of the rotating deck. According to the comparison, there are better agreement results in 1# and 2# transducer and the results of fixed deck are more conservative in other transducers.

Plots of the pressure distribution in the water due to a marginal deck impact are shown in Fig. 12 at T = 1.0s, H = 0.1m and T' = 1.0s (period of motion deck). The positive pressure peak is narrow and follows the front of the wave and a significant negative pressure area rapidly develops behind the front. The latter is associated with the downwards acceleration of the fluid

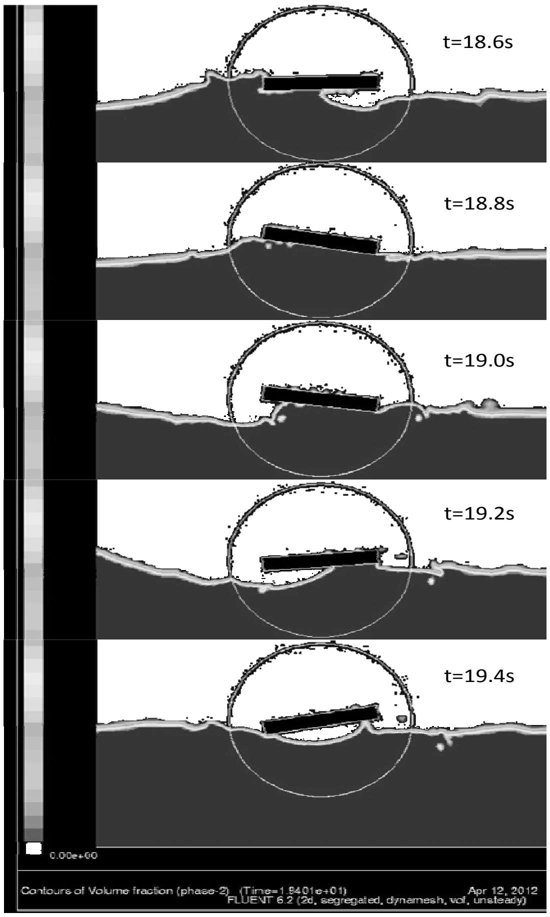

Fig. 12: The wave impact pressure of a periodic motion deck

and causes a significant deformation of the wave profile.

CONCLUSION

A numerical wave tank based on the Navier-Stokes equations and the VOF method have been established. The turbulence model, namely standard k-ε is incorporated to the numerical tank to broaden applicability of simulation. A number of inclined placement scenarios are presented and discussed in the previous sections to investigate the influence of inclined angle to the wave impact of the deck model. The computation result is in good agreement with the experimental results. The numerical method can predict the impact peak pressure and the distribution of wave impact along underside of the inclined deck. Some discrepancy between the calculations and experiments for several tilted severely cases in the transmitted waves suggests that a more refined turbulence model may be needed for the simulation of complex wave motions such as wave breaking.

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REFERENCES

Bai, Y., C. Jiang and H. Shen 2001. Large eddy simulation for wave breaking in the surf zone [J]. China Ocean Eng., 15(4): 541-552.

Ching-Jer, H., Z. En-Cheng and L. Jaw-Fang, 1998. Numerical simulation of nonlinear viscous wavefields generated by piston-type wavemaker. J. Eng. Mech., 124(10): 1110-1120.

Gotoh, H., S.D. Shao and T. Memita, 2004. SPH-LES model for numerical investigation of wave interaction with partially immersed breakwater. Coast. Eng. J., 46(1): 39-63.

Grilli, S.T., I.A. Svendsen and R. Subramanya, 1997. Breaking criterion and characteristics for solitary waves on slopes. J. Waterw. Port C-ASCE, 123(3): 102-112.

Hirt, C.W. and B.D. Nichols, 1981. Volume of Fluid (VOF) method for the dynamics of free boundaries. J. Comput. Phys., 39(1): 201-225.

Iafrati, A., A. Di Mascio and E.F. Campana, 2001. A level set technique applied to unsteady free surface flows. Int. J. Numer. Meth. Fl., 35(3): 281-297.

Kaplan, P. and M.N. Silber, 1976. Impact forces on platform horizontal members in the splash zone. Offshore Technology Conference, Texas, USA, 2498: 2749-2758.

Koo, W.C. and M.H. Kim, 2007. Fully nonlinear wave-body interactions with surface-piercing bodies. Ocean Eng., 34(7): 1000-1012.

Launder, B.E. and D.B. Spalding, 1972. Lectures in Mathematical Models of Turbulence. Academic Press, London, England.

Li, Y. and F. Raichlen, 2001. Solitary wave run up on plane slopes. J. Waterw. Port C., 127(1): 33-44.

Longuethiggins, M.S. and E.D. Cokelet, 1976. Deformation of steep surface-waves on water 1: A numerical-method of computation. Proc. R. Soc. Lond. A, 350(1660): 1-26.

Nichols, B.D., C.W. Hirt and R.S. Hotchkiss, 1980. SOLA-VOF: A Solution Algorithm for Transient Fluid Flow with Multiple Free Boundaries. Los Alamos, CA, USA, LA-8355.

Ren, B. and Y. Wang, 2004. Numerical simulation of random wave slamming on structures in the splash zone. Ocean Eng., 31(5-6): 547-560.

Wang, Y.X. and B. Ren, 1999. Study on wave slamming by turbulent model. J. Hydrodyn. Ser. A, 14(4): 409-417.

Xuelin, L., R. Bing and W. Yongxue, 2009. Numerical study of the irregular wave impacting. Proceedings of the 19th International Offshore and Polar Engineering Conference, Osaka, Japan, pp: 510-517.