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A two-phase simulation of wave impact on a horizontal deck based on SPH method

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Abstract

In this paper, a two-phase numerical model is developed to study the effect of the gas phase in problems of wave attacking deck. The model is based on weakly compressible smoothed particles hydrodynamics (WCSPH) method, and is implemented in C++ and CUDA language to running on GPUs starting from DualSPHysics. Surface tension is considered by incorporating the surface tension force into the momentum equations. Therefore, the continuum surface force (CSF) model is proposed to eliminating the interphase particle penetrations. To calculate surface tension force at interfaces, a color function is assigned to each particle from different phases. Furthermore, to enhance the robustness of this method, the assigned color function is smoothed by calculating the weighted averaging value of initial color function on its support domain. The simulation results are compared with experiment results. The point pressure from numerical results shows well agreement with experimental ones, and is more accurate than one phase simulation. The reason is lying on its satisfying on the condition of air pressure.

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Keywords: SPH; surface tension; multi-phase; wave impact

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1. Introduction

Wave impact loads cause lots of damages to coastal and offshore structures. To avoid the damage of those marine structures aroused by the wave impact forces, many laboratory experimental researches (Wang et al., Sun)

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and numerical studies (Sun et al. and Zheng et al.) have been carried out to estimate the wave impact load. Because of the complicity (strong non-linearity of wave, strong interaction between the wave and structure, instantaneous effect, strong water and gas mixing) of the impact procedure, the research in this course is not enough.

As mentioned by Sun (2011), air cushion plays an important role on the uplift force of the deck and pressure distribution under the deck. However, there is rarely research on the generation, existing, splitting situation of the air cushion for simulating wave attacking on horizontal deck. At the same time, most of the numerical studies on this problem are one-phase simulation.

With the rapid development of computers and computational fluid dynamics, it's possible to carry out huge computations on cluster with multi nodes. Especially, GPU computation becomes popular because of its inherent advantages of parallel computing (Domínguez 2013). In this paper, a two-phase numerical model, based on weakly compressible smoothed particles hydrodynamics (WCSPH) method, implemented in C++ and CUDA language to running on GPUs starting from DualSPHysics, is developed to study the effect of the gas phase in problems of wave attacking deck.

2. Two-phase SPH model

2.1. Governing equations

The mass and momentum conservation equations can be written respectively as,

(1)

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla p + \nu_0 \nabla^2 \boldsymbol{u} + \mathbf{g} + \frac{1}{\rho}\boldsymbol{f}_{(sv)} \tag{2}$$

where ρ is the density, t is the time, $\boldsymbol{u}$ is the velocity vector, p is the pressure, ν_0 is the laminar kinematic viscosity, $\mathbf{g}$ is the gravitational acceleration, and $\boldsymbol{f}_{(sv)}$ is volumetric surface tension force.

2.2. SPH formulation for two-phase flow

The SPH method is based on the interpolation theory. In SPH, the fundamental principle is to estimate any function $A(r)$ by collection of N particles interacting with each other.

$$A_i(\boldsymbol{r}) = \sum_{j=1}^{N} m_j \frac{A_j}{\rho_j} W(\boldsymbol{r}_{ij}, h) \tag{3}$$

where $\boldsymbol{r}$ is the position vector, $\boldsymbol{r}_{ij}$ is the relative vector from position i to j , and h is smooth length.

According to Colagrossi and Landriini (2003), to avoid numerical instability at the interface with a sharp density gradient, the following form of pressure divergence and gradient formula is used.

(4)

$$\nabla p_i = \sum_{j=1}^{N} \left(p_i + p_j\right) \nabla W_{ij} \frac{m_j}{\rho_j} \tag{5}$$

So, the final form of Eqs.(1) and Eqs.(2) can be written as

(6)

$$\frac{D\boldsymbol{u}_i}{Dt} = -\sum_{j=1}^{N} m_j \frac{p_i + p_j}{\rho_i \rho_j} \nabla_i W_{ij} + \sum_{j=1}^{N} m_j \frac{4\nu_0 \boldsymbol{r}_{ij}}{(\rho_i + \rho_j)\left|\boldsymbol{r}_{ij}\right|^2} \nabla_i W_{ij} + \mathbf{g} + \frac{1}{m_i} \boldsymbol{f}_{(sv)} \tag{7}$$

where m is the mass, $\boldsymbol{u}_i$, $\boldsymbol{u}_j$ are the velocity vectors of particle i and j respectively, and p is the pressure. $W\left(\boldsymbol{r}_{ij}, h\right)$ is the kernel function, $\nabla_i W(\boldsymbol{r}_{ij}, h)$ is the gradient of the kernel with respect to the position of particle i . In this paper, we use cubic spline kernel function.

The pressure is calculated according to the equation of the state as below

$$p = \mathrm{P}_0 \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right] \tag{8}$$

where ρ_0 is the reference density of fluid, P_0 is the reference pressure, and γ takes 7 and 1.4 for liquid and gas, respectively.

The surface tension force can be obtained as below

$$f_{(sv)} = \sigma \kappa \boldsymbol{n} \delta \tag{9}$$

where σ is the coefficient of surface tension, κ is the curvature of interface, $\boldsymbol{n}$ is the normal vector of interface, δ is a one-dimensional delta function.

2.3. Interface treatment

According to Zainali, Tofighi and etc.(2013), in order to distinguish among constituents of an immiscible two-phase system, and calculate relevant interface fields (i.e., the interface unit normal, curvature, and interfacial force), each particle is assigned to a color function C . The initial color function $\hat{C}$ is assigned with the phase feature, assigned when case initial, here 0 to phase A, 1 to phase B.

$$\hat{C}_i = \begin{cases} 0 & \text{in fluid A} \\ 1 & \text{in fluid B} \end{cases} \tag{10}$$

Furthermore, to enhance the robustness and calculate interface unit normal, curvature, and interfacial force, the assigned color function is smoothed as

$$C_i = \frac{\sum_{j=1}^{N} \hat{C}_j W_{ij}}{\sum_{j=1}^{N} W_{ij}} \tag{11}$$

On the contrary, we do not smooth the density and the viscosity of fluids. Because the particle size is very large than the surface thickness.

In this paper, 1D Dirac delta function is approximated by $\delta = \left|\nabla C\right|$. The unit normal vector and the curvature can be computed as,

$$\boldsymbol{n} = \frac{\nabla C}{\left|\nabla C\right|} \tag{12}$$

(13)

It is pointed out that unit normal in the vicinity of the fringes of the interface might be erroneous and in turn, when used in the computation of the curvature, may produce faulty results, by Morris(2000). Therefore, a constraint is required to choose reliable normal. Here, the constraint of $\left|\nabla C_i\right| > \varepsilon/h$ where ε is a constant used to control the thickness of the interface. Finally, substituting Eqs. (12) and (13) into Eq. (9) , the final form of volumetric surface force can be written as

(14)

Finally, it should be noted that the volumetric surface force is applied to particles within the interface zone, and we can assign a mark to the particle, when smoothing the color function.

3. Model application

In this section, the two-phase SPH model is used to simulate a green water wave impact on a horizontal deck. In coastal and offshore engineering, unexpected wave impact force is the major cause of damage to the marine structures such as open wharf and platform. Ren and Wang have done a lot of researches about the wave impact on the horizontal plate, including experimental research in the laboratory and numerical simulation research based on VOF method. In order to test our numerical model, the experimental results by Ren et al. (2003) are used for the comparison.

3.1. Introduction of the experiment

The more detailed laboratory experiment can be found in Ren (2003). Only some important parameters are listed here. The experiments were carried out in a large wave-current tank at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology. The tank is 69m long, 2m wide and 1.8m high. The deck model was a horizontal plate, 1m long, 0.65m wide and 0.02m thick, spanning one third of the width of the flume, as show in Fig. 1(a). The wave impact pressure transducers were fixed on the underside of the model, and were marked as 1 to 11, starting from seaside, as shown in Fig. 1(b).

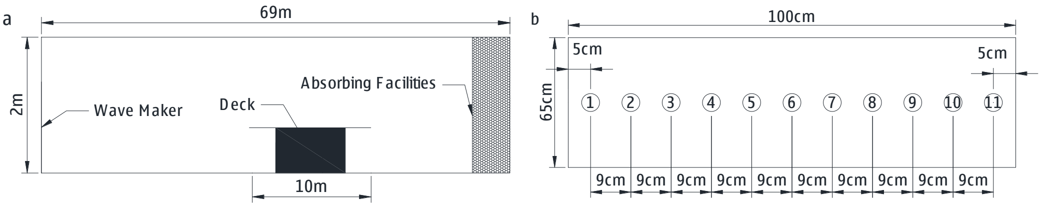


Fig. 1. (a) plane view of the experimental setup; (b) sketch of pressure transduces on the underside of the model

3.2. The numerical computational parameters

The numerical computation results of wave impact on deck for different parametric cases are verified by the experimental results. The computation region is shown in Fig. 2. The length of the numerical wave flume is 20.0 m, and the distance between the leading edge of the deck and the wave maker is 10.0m, the water depth is 0.6m, the end of the flume is a numerical absorbing area, and the length is 2 times of wave length, accordingly. The initial fluid particle spacing is dx=dy=1.0cm, the fixed particles spacing is dx=dy=0.5cm, including the solid boundary, moving paddle and the horizontal deck. Thus the total number of the particles is 206805, including 8208 boundary particles, 117351 water particles, and 81246 gas particles.

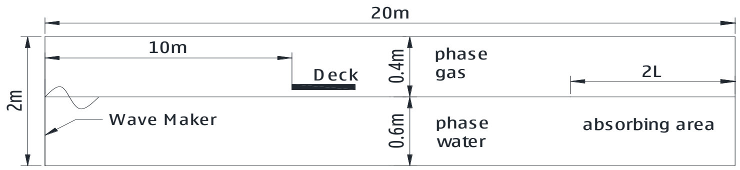
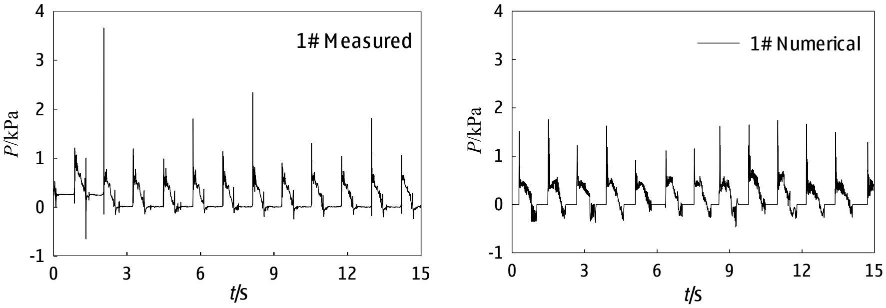


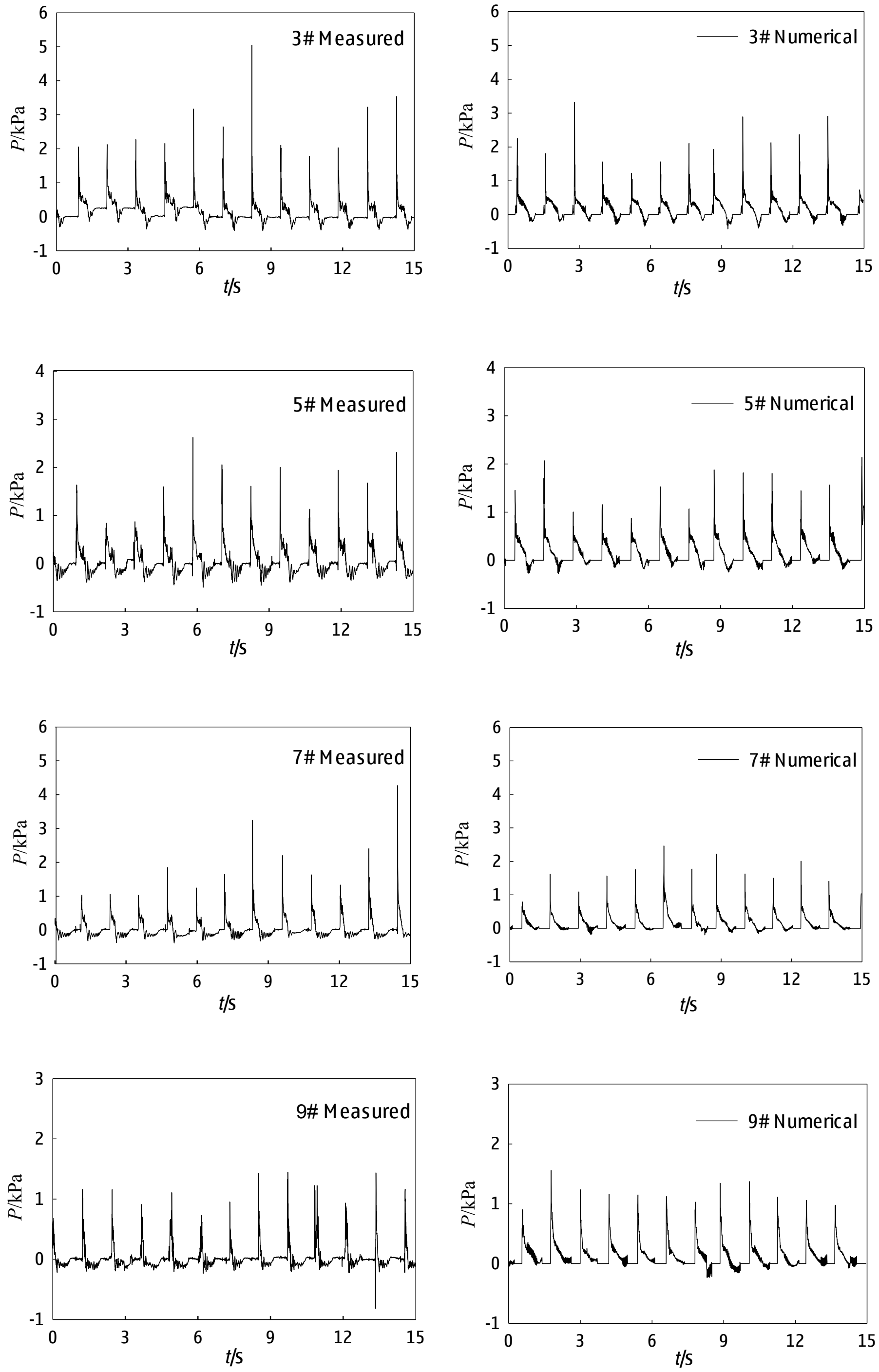
Fig. 2. Sketch of the computation domain

4. Result analyses

To compare with existing results, the same wave condition was simulated. The incoming wave is a regular wave with wave height $H = 15\text{cm}$, and wave period $T = 1.2\text{s}$. The relative clearance $\Delta h / H$ is 0.1, in which, the Δh is the distance from water green level to deck bottom. The pressure estimating method from Sun(2010) is used to get pressures at points.

Fig. 3 shows the pressure time histories of the numerical and experimental results. The left figures are the experimental results, and the right ones are results from the two-phase model. It can be seen that the pressure properties of the simulation results coincide with experimental ones at most points, and the peak pressures can be estimated by this model. But the numerical pressure results at the end of deck are different from experimental ones.




3# Measured
3# Numerical
5# Measured
5# Numerical
7# Measured
7# Numerical
9# Measured
9# Numerical
P/kPa
t/s
-1
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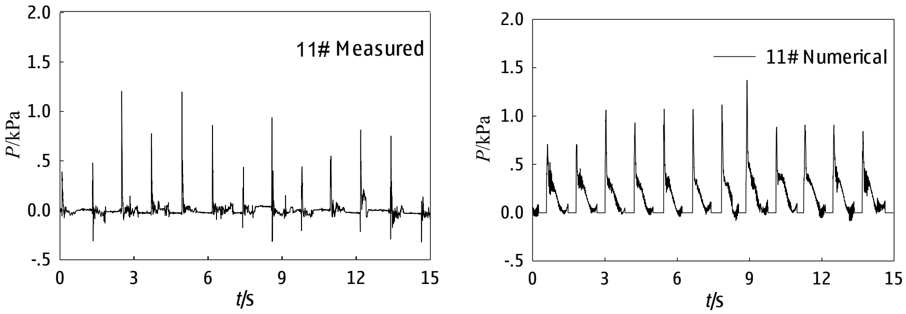
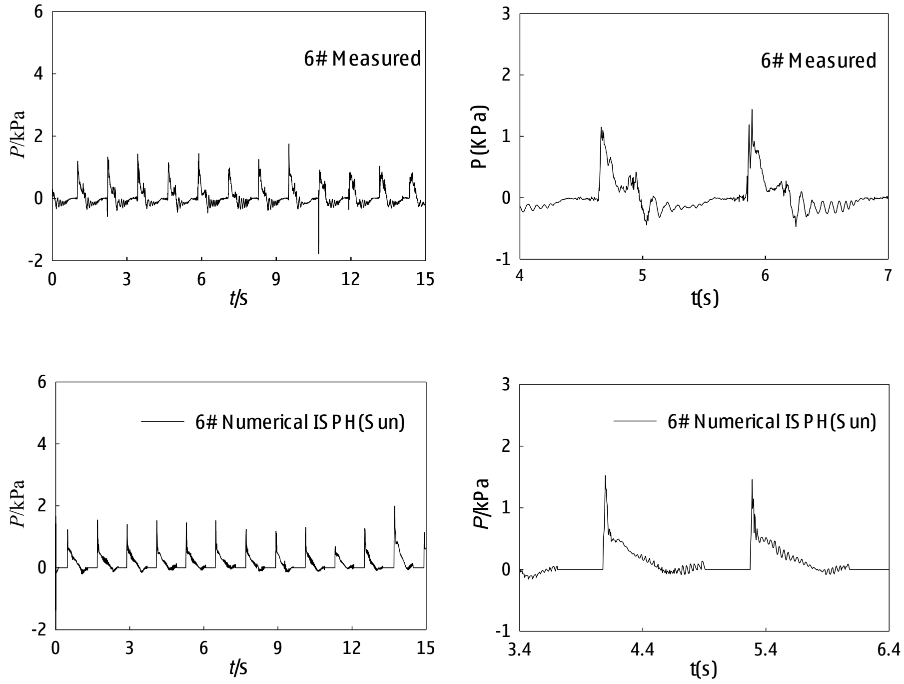


Fig. 3. Time histories of pressure of experimental and two-phase numerical model

Fig. 4 shows details of the time history of pressure at transduce 6# from two-phase model, improved SPH(Sun 2010) model, and experimental data by Ren et al.(2003). It can be seen that the results by Sun can not estimate the pre-shock pressure induced by gas phase. With the two-phase model, it is possible to predict the pressure induced by gas phase.



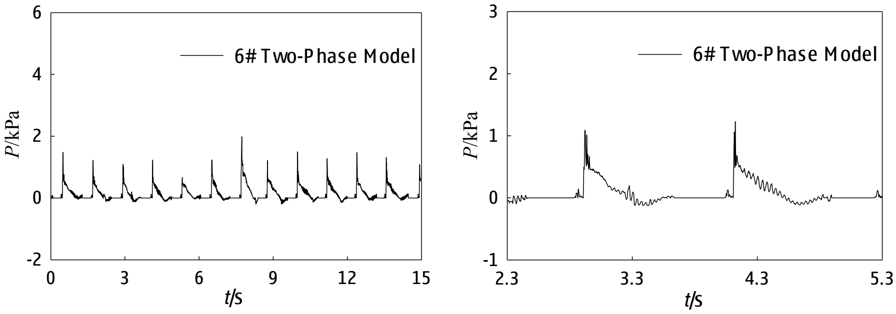


Fig. 4. Experimental result and different numerical results of pressure time history at transducer 6#

5. Conclusions

A two-phase model is carried out to study the wave impact on horizontal decks. The point pressure from numerical results shows good agreement with experimental ones, and is more accurate than one phase simulation. The reason is lying its satisfying on condition of air pressure. But this model cannot take the strong Gas-liquid mixing phase into account, which is our future work.

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