Investigation on a damaged ship model sinking into water based on three dimensional SPH method

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Damaged ship at sea will be a direct threat to lives and property, and it has a great significance of studying ship's remaining buoyancy, stability, sinking time and other important parameters. The process of a damaged ship sinking into water is a complex motion involving ship hull, inner and outer fluid coupled with waves and many other factors. It is featured by high nonlinearity and hard to establish a precise theoretical model to study. Yet SPH (smoothed particle hydrodynamics) as a meshfree method has a great advantage in solving such problems because of the nature of self-adaptive and Lagrangian. Firstly, the experiments of two scaled ship models with different openings sinking into water are carried out, through the sinking processes of broadside opening and bottom opening models, the conclusion is drawn that although the serious loss of stability of broadside opening model, the sinking time and other parameters are more conducive to rescue after maritime distress. Secondly, the parallel program of three dimensional SPH is developed to simulate the above more complex model, broadside opening model. The coupled process of sloshing is compared with that of experiment, and the results show good agreement with each other which verify the accuracy and feasibility of three dimensional parallel program.

1. Introduction

Ships at sea are often damaged due to many factors including collision, grounding, etc. The influenced will change the floating condition and stability of a damaged ship, and thus it will cause a great threat to the safety of the ship and persons on board. Therefore, it is badly needed to evaluate the ship floating condition, remaining buoyancy, remaining strength and sinking time after ship damaged immediately, and make a rescue schedule to rescue. Consequently, the studies on motion of a damaged ship are significant. However, the coupled motion is too complex involving influential, ship hull, and other external loads, which are numerous nonlinear. Moreover, the flip and splash will occur when the fluid sloshing against the side of bulkhead, which will cause great difficulties to numerical simulation. Therefore, there are few scholars to study the floating condition and the influences of influential on the performance of damaged ships in theory. Palazzi and De Kat [1] and Lee et al. [2] studied the process of a damaged ship sinking with the traditional hydrodynamic model, ignoring the coupling between fluid in cabin and ship model. Vassalos et al. [3] studied the process of a damaged Ro–Ro ship overturning in reality sea conditions in time domain, considering roll, heave and sway in random waves. The most cited literatures on the damaged cabin influential problems regard the movement of fluid synchronization with the motion of ship hull, and free surface parallel with average water surface. Chang [4] separated the analysis of influential from ship hull when simulating the coupled motion of damaged ships, according to the conversion relation and related experimental coefficient, the influential was linked with the movement of entire ship so as to evaluate the effect of influential on the ship motion. Papanikolau et al. [5] proposed an improved model on the movement of water in cabin. Gao et al. [6] simulated the influential process of a Ro–Ro ship by VOF (volume of fluid) method. Valanto [7] and Santos and Guedes Soares [8] solved the liquid flow in cabin with the shallow water wave equations, yet restricted to the description of complex free surface. Smoothed particle hydrodynamics (SPH) is a Lagrangian mesh free particle method, due to self-adaptability of the method, the construction of SPH formula is not subjected to the influence of particle distribution; the track of free surface does not require specialized method and therefore it particularly suits the simulation of free surface flow problems which are characterized by large deformation, splash, etc. In the recent years, with the accuracy and stability improvement of SPH method, it is widely used in various fields. González lez et al. [9] predicted the movement of a damaged Ro–Ro ship with a flood deck with SPH method. Skaar et al. [10] simulated influential problems of a simple damaged ship model under the condition of roll and heave respectively with SPH method. Shen and Vassalos [11] simulated the influential and sloshing process of a 2D and 3D rectangular box. Le Touzé [12] predicted the wave height above deck when ship moves in waves and the transient height of water in cabin after two ship collision. To sum up, SPH method is a good choice to simulate the complex free surface flow...
problems of a damaged ship. The above literatures mostly focus on the static cabin and water influent process, and the coupled nonlinear motion of ship hull with internal liquid is rarely mentioned.

The influential process of scaled ship models with broadside and bottom opening will be studied by experiments in this paper, and the complex movements of ship hull and internal fluid of the above two models will be compared. And then to ensure the feasibility, efficiency and accuracy, the continuity of kernel function which is improved by moving least square (MLS) will be verified, moreover, the efficiency of parallel program is also tested. On the basis of the above researches, the broadside opening ship model sinking into water, the coupling motion of heaving and rolling as well as the sloshing of inner water, will be simulated with the three dimensional SPH parallel program, and the results will be compared with those of experiment.

2. Theoretical background

2.1. SPH model

SPH method is based on interpolation theory, and the problem domain is discretized into particles with mass, density, velocity and other physical quantities reflecting true material properties. The increment of physical quantities of every particle is drawn from particles in support domain by weighting summation, and the solution of fluid dynamics problems will be realized by time integration. As for a particle, the differential equation [13] can be expressed as follows:

\[
\frac{dP}{dt} = \frac{\sum_{j=1}^{N} m_j \left( \frac{\rho_i}{\rho_j} \right) \left( P_i + \frac{\rho_i v_{ij}^2}{\rho_j} + \Pi_{ij} \right) \frac{\partial W_{ij}}{\partial x_{ij}} + g(0)}{1} \tag{1}
\]

where \( P, m, \rho, v, x, g, N \) denote pressure, mass, density, velocity, coordinates, acceleration of gravity, and total number of particles. Besides, \( v_{ij} = v_i - v_j \); \( W \) is kernel function; \( \Pi_{ij} \) is artificial viscosity; the superscript \( a \) indicates direction of axis; the subscripts \( i \) and \( j \) represent a pair of interacting particles.

In the standard SPH model, fluid is regarded as weakly compressible, and thus the pressure can be obtained by equation of state. In the view of Monaghan [14], the relationship between pressure and density of fluid can be written as:

\[
P = B \left[ (\rho/\rho_0)^\gamma - 1 \right] \tag{2}
\]

where \( \gamma = 7; \rho_0 = 1000 \text{ kg m}^{-3}; B = c_s^2 \rho_0 / \gamma; c_0 \) is reference sound speed, and \( c = \sqrt{\gamma P/\rho} \); the rate of density change can be approximated by the expression \( \delta \rho / \rho = [\rho_{\text{max}}^2 / c_0^2] \), \( \rho_{\text{max}} \) denotes the estimated maximum fluid velocity in actual condition, and \( c_0 \) is usually selected more than 10\( \rho_{\text{max}} \) so as to guarantee the rate of density change does not exceed 1%. The selection of \( c_0 \) not only affects the time step size but also the compressibility of the flow field, and further the efficiency, accuracy, and stability of numerical simulation. Therefore, \( c_0 = 14.0 \rho_{\text{max}} \) is selected in this paper.

In the treatment of weak compressible fluid, a correction of particle velocity is required [15], and the modified form of equation of motion is:

\[
\frac{dx_i}{dt} = v_i + \epsilon \sum_j \frac{m_j v_{ij} W_{ij}}{\Pi_{ij}} \tag{3}
\]

where \( \Pi_{ij} = (\rho_i + \rho_j) / 2; 0 \leq \epsilon \leq 1.0 \), \( \epsilon = 0.5 \) is selected to ensure the regularity of particle movement and avoid particle penetrate when velocity is too large.

2.2. Continuity correction

When solving the fluid dynamics problems with the above SPH continuous equation, the consistency of mass and density cannot be
guaranteed, and acute pressure fluctuations will generate with the accumulation of errors. In order to overcome the problem, the improved moving least square (MLS) [16] is introduced to correct density. The interval of 20 time steps is selected to reinitialized density, the corrected formula is:

\[ \rho_i = \sum_j \rho_j W_{ij}^{\text{MLS}} m_j^{\text{MLS}} / \rho_j = \sum_j m_j W_{ij}^{\text{MLS}} \]

(4)

where MLS kernel function is expressed as:

\[ W_{ij}^{\text{MLS}} = \left[ \beta_0 + \beta_{1x} x_{ij} + \beta_{1y} y_{ij} + \beta_{1z} z_{ij} \right] W_{ij} \]

(5)

and should satisfy:

\[ \sum_j m_j W_{ij}^{\text{MLS}} \left[ \begin{array}{ccc} 1 & x_{ij} & y_{ij} & z_{ij} \end{array} \right]^T = \left[ \begin{array}{cccc} 1 & 0 & 0 & 0 \end{array} \right]^T \]

(6)

substitute (5) into (6):

\[ \sum_j m_j W_{ij}^{\text{MLS}} \left[ \begin{array}{ccc} 1 & x_{ij} & y_{ij} & z_{ij} \end{array} \right] \left[ \begin{array}{cccc} \beta_0 & \beta_{1x} & \beta_{1y} & \beta_{1z} \end{array} \right] = \left[ \begin{array}{cccc} 1 & 0 & 0 & 0 \end{array} \right] \]

(7)

namely:

\[ \sum_j m_j W_{ij}^{\text{MLS}} \left[ \begin{array}{cccc} 1 & x_{ij} & y_{ij} & z_{ij} \end{array} \right] \left[ \begin{array}{cccc} \beta_0 & \beta_{1x} & \beta_{1y} & \beta_{1z} \end{array} \right] = \left[ \begin{array}{cccc} 1 & 0 & 0 & 0 \end{array} \right] \]

(8)

solving (8), then

\[ \beta = [ \beta_0 \ \beta_{1x} \ \beta_{1y} \ \beta_{1z} ]^T \]

(9)

and thus \( W_{ij}^{\text{MLS}} \) is obtained.

The accurate regeneration function by SPH approximation should satisfy some conditions, for example, if the continuity of order 0, the following equation exists:

\[ M_0 = \int W(x - x', h) \, dx' = 1 \]

(10)
The comparison of \( M_0 \) for cubic spline kernel function and MLS function is shown in Fig. 1. The problem domain is a cube, as can be seen from Fig. 1(a), the cubic kernel function cannot always satisfy the continuity, and \( M_0 \) is equal to 1 in the inner problem domain but significantly smaller than 1 at the boundary. However, the function constructed by MLS function satisfies the continuity condition in the entire domain, as shown in Fig. 1(b), which can improve the calculation accuracy and stability greatly.

In order to validate the influence of MLS correction on continuity, a simple case of dam-break flow is established. The dimensionless pressure is presented in Fig. 2. From the comparison of the above two results, it is obvious that the pressure distribution with MLS correction is more uniform, and the non-physical fluctuations of local pressure are eliminated, as shown in Fig. 2(b). However, there are some noises near free surface and wall without MLS correction, as shown in Fig. 2(a). To sum up, the reasonable results are obtained with the MLS correction. Although the MLS correction makes the calculation slightly expensive, the first order completeness [17] is realized which is critical to numerical simulation.

### 2.3. Treatment of floating bodies

According to the principle of buoyancy loss, the influential region is no longer a part of floating body after floating body damaged, that is, the buoyancy has been lost and the loss of buoyancy is compensated by displacement. As for a damaged floating body, the barycenter is unchanged but with the volume of displacement change, the position of buoyant center will change continuously. Regarding the floating body as a rigid body and discretized into particles in the simulation, the resultant reaction force of all particles will act on the floating body, as shown in Fig. 3. \( G \) represents the barycenter; \( B \) is the center of buoyancy; \( \theta \) is the heeling angle.

The force of unit mass acting on every boundary particle of floating body can be written as:

\[
f_j = \sum_{i \in \text{PBPs}} f_{ij}
\]  

(11)

The movement of any point on the floating body can be decomposed into translation of centroid and rotation about centroid. Therefore, the motion equation of floating body can be described as:

\[
u_j = \mathbf{V} + \Omega \times r_{j0}
\]  

(12)

where \( \mathbf{V} \) is the average velocity of centroid, \( \Omega \) is the angular velocity and \( r_{j0} \) is the vector of displacement of particle \( j \).

The discretized equation of translational velocity and rotational angular velocity of floating body can be written as:

\[
\begin{align*}
\frac{d\mathbf{V}}{dt} &= \sum_{j \in \text{PBPs}} m_j \mathbf{f}_j \\
\frac{d\Omega}{dt} &= \sum_{j \in \text{PBPs}} m_j r_{j0} \times \mathbf{f}_j
\end{align*}
\]  

(13)

where \( M \) is the mass of floating body; \( I \) is the rotational inertia; \( \text{PBPs} \) denotes fluid particles; \( \text{BPBPs} \) denotes boundary particles.

### 2.4. SPH program parallelization

The serial program can be paralleled by the ways [18] of data parallel (HPF, etc.), message passing (MPI, PVM, etc.), shared variables (OPENMP, etc.), etc. The program in this paper is paralleled by OPENMP command language, that is, the shared variable mode is adopted. The OPENMP programming interface can easy parallel program in different system configurations, besides, the less modification on original serial program is required. Only the specific compiler command statement should be inserted before the parallel region.

Taking the linked-list search program for example, the pseudo code of parallelization can be:

```c
! Set the number of threads in the parallel code, num_threads is the number of threads
! OPENMP parallel command statement, the following section begin to parallel; dx, dy, dz are specified as private variables
! To do parallelization
! N is the total number of particles
! To determine upper bound of the searching grid of particle i
! To determine upper bound of the searching grid of particle i
! To do loop parallelization
! To do parallel

call omp_set_num_threads(num_threads)
!omp parallel private(dx, dy, dz ...
!
!omp do private(i, j ...)
do i from 1 to N
Xcell_min = max(low_xcell, 1)
Xcell_max = min(up_xcell, nxgrid)

... Search particles in adjacent grids ...
... j = grid(xcell, ycell, zcell)
if dr - kh then

W and DWDX
end if
j = celldata(i)
end do i
!omp end do
!omp end parallel
```

**Fig. 12. Comparison of vertical velocity for experiment models.**

### Table 1

<table>
<thead>
<tr>
<th>Thread q</th>
<th>CPU time-consuming ( t (\text{s}) )</th>
<th>Theoretical speedup ratio ( S_{p} )</th>
<th>Speedup ratio ( S_{p} )</th>
<th>Efficiency ( E_{p} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.986</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3.976</td>
<td>1.818</td>
<td>1.757</td>
<td>0.753</td>
</tr>
<tr>
<td>4</td>
<td>2.300</td>
<td>3.077</td>
<td>3.037</td>
<td>0.660</td>
</tr>
<tr>
<td>6</td>
<td>1.765</td>
<td>4.000</td>
<td>3.957</td>
<td>0.532</td>
</tr>
<tr>
<td>8</td>
<td>1.640</td>
<td>4.706</td>
<td>4.259</td>
<td>0.400</td>
</tr>
<tr>
<td>12</td>
<td>1.455</td>
<td>5.714</td>
<td>4.801</td>
<td>0.344</td>
</tr>
<tr>
<td>16</td>
<td>1.271</td>
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<td>0.306</td>
</tr>
<tr>
<td>20</td>
<td>1.143</td>
<td>6.897</td>
<td>6.111</td>
<td></td>
</tr>
</tbody>
</table>

In order to test the efficiency of the parallel program, the example in Section 4.1 is selected. The total number of particles is about 900,000. The hardware environment is dawn W5801 workstation, CPU is double Xeon(R) X5650, 2.67GHz, and 24 threads in all. The compiler is Intel Fortran ifort v11.0.061. The average CPU time-consuming of different threads of each timestep is shown in Table 1, where speedup ratio \( S_{p} \) and efficiency \( E_{p} \) can be defined as:

\[
S_{p} = t_{1}/t_{q}
\]

(14)

\[
E_{p} = S_{p}/q
\]

(15)

where \( q \) is the number of threads; \( t_{1} \) is the time-consuming of serial program; \( t_{q} \) is the time-consuming of \( q \) threads.

The speedup ratio \( S_{p} \) in theory of the parallel program on multiple processors, according to Amdahl’s law, is defined as:

\[
S_{p} = 1/(a + (1-a)/q)
\]

(16)
where \( a \) is the proportion of the serial program, here \( a \approx 0.1 \).

The relationship of different threads and average CPU time-consuming is shown in Fig. 4. It is obviously that when the thread number is less than 6, about account 50% cores of the single CPU, the time-consuming is exponential attenuation with the increase of thread number and linear attenuation after 6 threads. The time-consuming attenuation is slowed down after 6 threads, and thus the parallel efficiency is reduced.

3. Experimental study

3.1. Experiment set-up

The experiment devices mainly include high-speed motion analysis system (high-speed camera and relevant post-processing software), U-shaped plexiglass floating bodies, pulley system and cube transparent tank, as shown in Fig. 6. The type of high-speed camera is Phantom V12.1, and shooting frequency is set to be 1000 frames per second in this experiment. The size of tank is 0.5 m \( \times \) 0.5 m \( \times \) 0.5 m, filled with water of height 0.4 m. The size of floating bodies are 0.35 m \( \times \) 0.17 m \( \times \) 0.13 m, with the wall thickness 0.01 m, and a hole with a diameter of 0.09 m at the broadside or at the bottom, the detailed parameters are shown in Fig. 5. All the devices are arranged as Fig. 7.

The preparation of the experiment is mainly to balance the floating body model. As shown in Fig. 5, there are six holes at the top center line, used to hanging floating body and reduce the influence of air. When the experiment is carried out, the floating body hangs above still water surface by the cord pass through the pulley, and thus the position of model can be adjusted by the length of cord and the position of pulley so as to keep the bottom of the model in contact with the water surface and guarantee the floating body sinking into water vertically. At the beginning of the experiment, the cord is sheared quickly, as shown in Fig. 8; the cord is thin enough so the influence of cord in the experiment can be ignored (Fig. 8).

3.2. Experimental results analysis

The main reason leading ship to sink at sea is damaged at broadside or bottom. Therefore, the models of broadside opening (model a) and bottom opening (model b) are selected in the experiment research. The mass of the models is same, \( M_a = M_b = 2.15 \) kg. The sinking process of 3D damaged model is strongly nonlinear, and the experimental results are random and probabilistic. Therefore, the experiments of each model have been repeated for many times. Three results have been extracted from relatively successful experiments. The changes of heel angle and vertical velocity for the two models during the whole sinking process are shown in Figs. 9–11. The upward direction is assumed to be positive.

It is obvious that the variation tendency of heel angle and vertical velocity of model a are similar. The heaving motion of broadside opening model is more regular in the sinking process. The curves of heel angle for model a are slightly different in Fig. 10. The first four periods are mainly the process of instantaneous influent, where the vibration frequency is high. At about \( t = 2.60 \) s, the water level in the model almost parallels with the outer water level and the sloshing
is small, so the differences are little. At $t = 3.00$ s, the influent increases continuously. At $t = 7.00$ s, the influent begins to be steady. The sinking process of model a is similar to the actual ship.

The sinking process of model b is only accompanied with heaving motion; the curves of vertical velocity are shown in Fig. 11. After 2.5 periods of heaving motion, the model is sunk completely. The comparison of vertical velocity for the above two models within 2 s is shown in Fig. 12, which indicates the heave motion of model a is fiercer and has a higher vibration frequency.

A series of typical diagrams are shown in Figs. 13 and 14. The sinking process of ship model a: when the port of the model damaged, the barycenter moves to the starboard. At initial time, the buoyant center locates between barycenter and port which will produce a tilting moment toward starboard. When the hole on the broadside is below water surface, water flows into the model, and the tilting angle increased. With the increase of displacement, the buoyancy increases, this will generate upward acceleration. When the downward velocity decreased to zero, the model starts to move upward. Following, displacement decreases and the upward velocity slows down. Water in the model starts sloshing with the rolling of the model, flipping after a collision with the wall which will produce a moment to the port of the model. The location of buoyant center is changed to starboard again. Under the action of both restoring moment, the heeling angle is reduced. With the repeat of such movement, the rolling period becomes longer and the amplitude of heave motion decreases. The inflow quantity increases in the sinking process ($t = 2.67$ s), and reduces in the lifting process ($t = 2.90$ s). After about eight times of
obvious heaving movement, about at $t = 7.00$ s, the model movement tends to be stable until $t_0 = 9.00$ s, the model fully filled with water.

The sinking process of ship model b: the model generates downward acceleration due to gravity and water flows into the model vertically. When the water surface was over the hole at the bottom, a mushroom shaped pillar formed. With the increase of displacement, the buoyancy increases and the sinking velocity decreases. The velocity decreases to zero after $t = 0.30$ s, and the model begins to lift. The inflow quantity keeps increasing until the model is lifted to the highest point at $t = 0.60$ s. At that moment, the inner water volume is about half of that of the model. The model repeats such heaving movement. The second heaving begins at about $t = 0.85$ s. The model fully filled with water when the third heaving begins. The inflow quantity is large and the rate is fast and the total sinking time is about $t_0 = 2.00$ s.

According to the above analysis, the influent process is a complex non-linear movement because of the left-right asymmetry for the broadside opening model. The movement of heaving and rolling is coupled with inner water sloshing. The vibration frequency is high and the total sinking time is long with periodic influent. It is easy to cause the ship capsized in this process. Compared with the bottom opening model, the stability is critical to survive for the broadside opening ship. However, the bottom opening model is characterized by fast influx, large inflow, and short sinking time. Although there is only heaving movement, the floating ability is fatal for surviving. In practice, design of double bottoms and compartments would be essential to enhance the stability and anti-sink ability of ships.
4. Numerical study

4.1. Numerical model

Through the analysis of the above experimental results, the broadside opening model is utilized in the numerical simulation. The parameters of model in numerical simulation including dimensions of floating body and tank are exactly same with the experimental model. The numerical model is shown in Fig. 15. The effect of air is not considered in the simulation. The total number of particles is 909,318. Among them, 784,080 are water particles, which are in a uniform distribution and particle spacing \( dx = 0.005 \text{ m} \). The remaining 117,384 particles are boundary particles and the distribution is shown in Fig. 16. The number of floating body particles is 7854. The initial acceleration \( g = [ 0 \ 0 \ -9.81 ] \). A constant time step \( dt = 5 \times 10^{-6} \text{ s} \) is used (Figs. 15 and 16).

4.2. Comparison of numerical and experimental results

The model sinks into water after several oscillations. As is shown in Fig. 17, the typical sinking process of ship model is studied. At \( t = 0.15 \text{ s} \), floating body sinks and the water begins to flow into model when the liquid level exceeds the height of the hole. With the model going downward, it tilts at the same time. At \( t = 0.25 \text{ s} \), the intense leads the model unbalance and the side of opening begins to lift. With the heel angle increasing, at \( t = 0.55 \text{ s} \), the opening is above the outer liquid level and at the same time internal water rolls after collision with starboard. The inflow reduces gradually. At \( t = 0.70 \text{ s} \), the second period begins. Heel angle decreases due to changes of the center of buoyancy. At \( t = 0.85 \text{ s} \), the downward velocity of the model reduces to zero. Obviously inflow increases which will cause heel angle increasing again. At \( t = 1.05 \text{ s} \), after the second inflow, it repeats the motion process of \( t = 0.55 \text{ s} \). Compared with \( t = 2.00 \text{ s} \) and \( t = 3.20 \text{ s} \), because of the violent oscillation of the model, the inflow is less. Through the above comparison, the numerical results agree well with experiment.

Regarding the floating body as a rigid body, considering the symmetry of front and rear, the movement during the sinking progress is mainly rolling and heaving. Comparison of numerical and experimental results of the vertical velocity and changes of heel angle are shown in Figs. 18 and 19 respectively. The motion tendency of the numerical and experimental results agrees well with each other. Due to the ignorance of coarseness of the experimental model, some asymmetrical factors and the accumulation of calculation error, some errors are brought in numerical simulation. Due to the influence of various nonlinear factors, the later periods of numerical and experimental results are misaligned compared with the selected three groups of experimental results.

5. Conclusions

Through the theoretical study of SPH method, considering the continuity and efficiency problems at the same time, the three-dimensional parallel SPH code is programed. The efficiency and accuracy are verified by the model in this paper. Based on the above studies, two U-shaped ship models of broadside opening and bottom opening are set up respectively. The coupled sinking process of ship hull, influent and outer water are studied. Comparisons of experimental and numerical results are made. The following conclusions can be obtained:

(1) When parallel program is executed, the efficiency decreases with the increase of the number of threads. In the hardware environment of this paper, computational efficiency achieves a balance when the number of threads accounts for 50% of a single CPU core.

(2) The sinking progress of broadside opening model is accompanied with rolling and heaving of ship hull and with the coupled sloshing of water in tank. The vibration frequency is high and sinking time is long along with periodic influence. However, the sinking progress of bottom opening model is a kind of coupled heaving movement between water and ship model. Vibration frequency is low, yet the inflow is large so that sinking time is short. It tends to be more dangerous for the ship model.

(3) The numerical results are in good agreement with those of the experiment. Efficiency, feasibility and accuracy of the parallel three-dimensional program are verified which lays a good foundation for further prediction for the entire ship sinking and rescuing.

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