Article

Numerical study on underwater explosion simulation surrounded by an iron wall using smoothed particle hydrodynamics

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Abstract

The Smoothed Particle Hydrodynamics (SPH) method is used to simulate the dynamics of the underwater explosion within the two-dimensional square metal vessel. The SPH particles well represent detonation gas of an explosive charge, water confined in the vessel, or metal surrounding water as the vessel. The shock wave propagating in water impacts the metal wall and deforms the vessel. Finally, the vessel is ruptured at the corner by the impact of the underwater explosion. Furthermore, the impact passing through the metal wall is simulated and eventually causes the shock propagation in the next room within the vessel. The present simulations clearly demonstrate the advantage of SPH method reproducing the damage of the explosion accident including the coupled fluid-structure interaction.

Keywords: Smoothed particle hydrodynamics, Particle method, Underwater explosion, Underwater shock wave, Structural analysis, Coupled problem

1. Introduction

The SPH, as meshfree, Lagrangian and particle method, was originally invented for modeling astrophysical phenomena[1]. These features allow us to easily treat heterogeneous state which includes gas, liquid and solid simultaneously. The SPH method has been used for a simulation[2] of underwater explosion (UNDEX), which mainly focused on the interaction between the detonation gas and the surrounding water, or the high velocity impact (HVI)[3]. Once UNDEX occurs in the closed space like a vessel, the strong shock wave propagates in water and ruptures the surrounding walls of the vessel. Such coupled problem consisting of gas, liquid and solid is one of the important topics to predict the hazards by the explosion accident. Especially, it is desirable to predict the rupture of the building or solid structure by means of the impact of the explosion, using the simple and light-loaded simulations. In the present study, it is investigated that the possibility of the SPH method reproducing the damage of the explosion with coupled fluid-structure problems. The subject of simulations is UNDEX, which is exploded by TNT explosive and surrounded by the iron walls as the two-dimensional square vessel.

2. Numerical setup

2.1 Governign equations

Following inviscid compressible equations simulate UNDEX phenomenon.

$$\frac{D\rho}{Dt}=-\rho\nabla\cdot v\,,\ \frac{Dv}{Dt}=\frac{1}{\rho}\nabla\sigma\,,\ \frac{De}{Dt}=\frac{1}{\rho}\sigma{:}\nabla\otimes v,\ P=P(\rho,e) \tag{1}$$

ρ, e, σ, v and t represent density, internal energy, stress tensor, velocity and time, respectively. The stress tensor appearing in Eqs. (1) is defined in terms of an isotropic part which is the pressure P and the deviatoric stress S ($\sigma=-PI+S$). I represents an unit tensor. The following equation is a constitutive equation of elastic material.

$$\frac{DS}{Dt} = 2\mu\left(\dot{\varepsilon} - \frac{1}{3}Tr(\dot{\varepsilon})I\right) + w\cdot S - S\cdot w \tag{2}$$

S, $\dot{\varepsilon}$, w, and μ represent deviatoric stress tensor, strain rate tensor, rotation tensor and share module respectively. The plastic flow regime is determined by the von Mieses criterion.

2.2 Equation of state

Each equation of states for detonation gas, water and iron are the JWL equation[4], the polynomial equation for water[5] and the Mie-Gruneisen equation for solid[3], respectively. See references for each parameter of these equations.
The JWL equation:

$$P = A\left(1 - \frac{\omega\eta}{R_1}\right)e^{-\frac{R_1}{\eta}} + B\left(1 - \frac{\omega\eta}{R_2}\right)e^{-\frac{R_2}{\eta}} + \omega\eta\rho_0 e \tag{3}$$

The polynomial equation for water:

$$\begin{cases} P = a_1\mu + a_2\mu^2 + a_3\mu^3 + (b_0 + b_1\mu + b_1\mu^2)\,\rho_0 e, & \mu > 0 \\ P = a_1\mu + (b_0 + b_1\mu)\,\rho_0 e, & \mu < 0 \end{cases} \tag{4}$$

The Mie-Gruneisen equation for solid:

$$P = \left(1 - \frac{1}{2}\Gamma\mu\right)P_H(\rho) + \Gamma\rho e\,,$$

$$P_H = \begin{cases} a_0\mu + b_0\mu^2 + c_0\mu^3, & \mu > 0 \\ a_0\mu, & \mu < 0 \end{cases} \tag{5}$$

$$\mu = \rho / \rho_0 - 1 \tag{6}$$

3. Results and discussions

The SPH method is applied to UNDEX simulations in two-dimensional space, which is exploded by TNT explosive and surrounded by metal walls as a square vessel. Two kinds of square vessels are simulated, one has single room, and the other does two rooms, where one room is charged with TNT explosive.

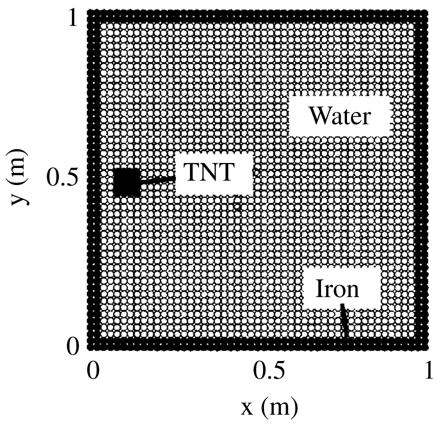


Fig. 1 Initial distribution.

3.1 Dynamics of UNDEX simulation in square vessel

A square shaped TNT charge (0.1 m ×0.1 m) explodes as a high-density gas in a metal vessel, filled with water in two-dimensional space, as shown in Fig. 1. Initially, 10201 particles located as 101 in each direction are distributed at equal intervals. The outer 5 or 10 particles represent the 0.05 m or 0.1 m thickness of the walls of vessel respectively and the other particles are used for water and TNT charge. 121 particles represent the TNT charge and are placed on center near the left wall of the vessel. The initial conditions are listed in Table 1.

Figures 2 show the pressure contour plots in water, the TNT gas bubble as the black region and the deformation of the vessel walls by the black particles at 0.29 ms. The gas bubble expands in the surrounding water. The initial shock wave propagating outwards and the reflected waves on the metal walls are clearly observed as the round shape in the pressure distribution. The shock wave impacts the left wall intensively and deforms the vessel shape. The thickness of the iron walls causes different features on the deformation of the metal wall as shown in Figs. 2.

Figures 3 show the features at 0.9 ms. The left wall is ruptured by UNDEX and separated form the other walls in both cases because the TNT is charged near left wall.
There is less deformation in the case of the thick walls. The simulations demonstrate the dynamics of UNDEX, such as shock wave propagation, gas bubble expansion and metal deformation including the metal thickness.

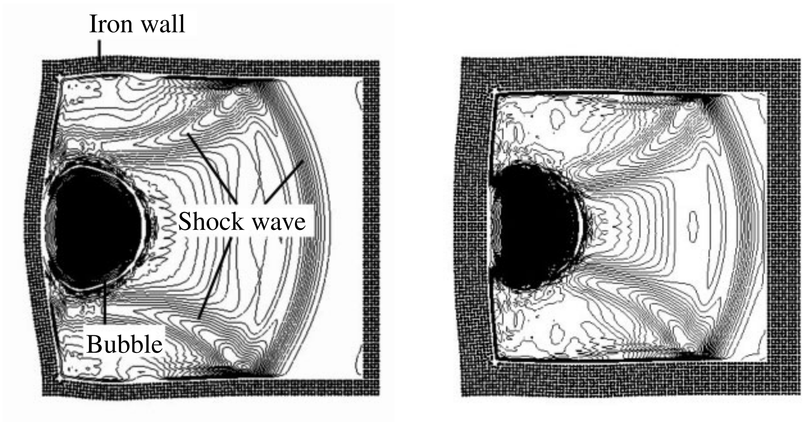
3.2 Dynamics of UNDEX simulation in vessel divided into two rooms

The vessel divided into two rooms by an iron wall is utilized to observe the feature of impact passing through the metal wall. A square-shaped TNT charge (0.1 m ×0.1 m) explodes as a high-density gas in the right room as shown in Fig. 4.

Figure 5 shows the pressure contour plots in water, the TNT gas bubble as the black region and the deformation of the vessel walls by the black particles at 0.14 ms. As observed in Figs. 2, the gas bubble expands in water. The shock wave roundly propagates in water in both rooms although the shock wave in the left room obviously weak-

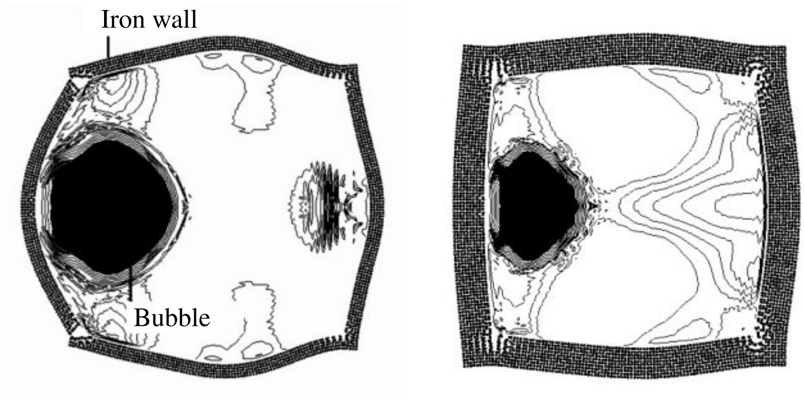
Table 1 Initial condition.

	TNT (gas)	Iron (solid)	Water (liquid)
ρ_0 (kg m^{-3})	1630	7850	1000
P_0 (GPa)	8.38	1×10^{-4}	1×10^{-4}
E_0 (MJ kg^{-1})	4.29	0.25	0.25



(a) Thin wall (b) Thick wall

Fig. 2 Pressure distribution and deformation of the vessel walls at 0.29 ms.



(a) Thin wall (b) Thick wall

Fig. 3 Pressure distribution and rupture of the vessel walls at 0.9 ms.

er than that in the right room. It can be said that the shock wave in the left room is caused by the impact passing through the iron metal wall. See the center wall, it is deformed by the impact as observed in Figs. 2.

Figure 6 shows the features at 1.5 ms. The right wall in the right room is almost ruptured by UNDEX although the TNT is charged near left wall. This simulation clarifies the dynamics of shock wave passing through the metal wall from water to water by UNDEX. We can say that the present simulation results indicate a potential of the SPH method for a prediction of the UNDEX damage.

4. Conclusions

A series of simulations was carried out to clarify a potential of the SPH method for reproducing the damage of the explosion accident including the coupled fluid-structure interaction. The SPH method was applied to UNDEX simulations in two-dimensional space, which was exploded by TNT explosive and surrounded by metal walls as a square vessel. The simulations were performed using two kinds of vessels. The dynamics of UNDEX, such as shock wave

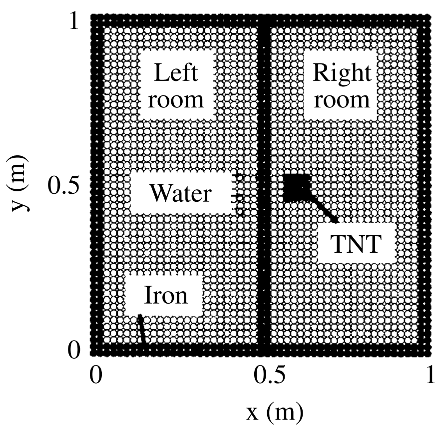


Fig. 4 Initial distribution.

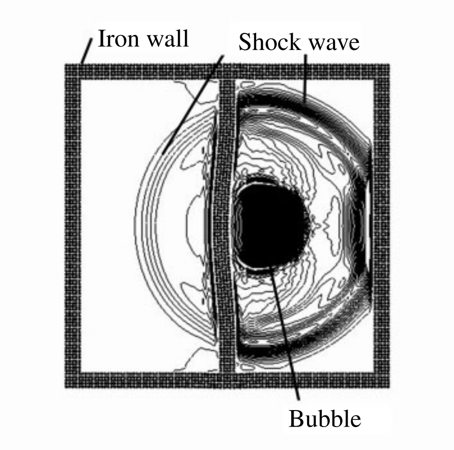


Fig. 5 Pressure distribution and deformation of the vessel's walls at 0.14 ms.

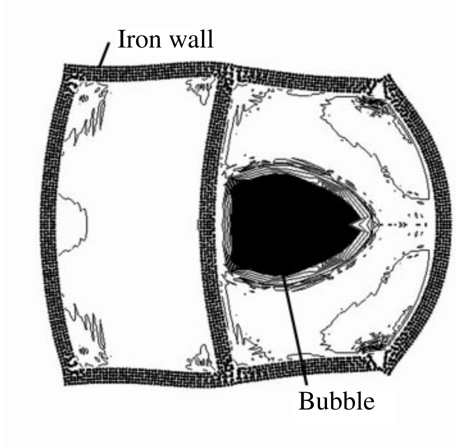


Fig. 6 Pressure distribution and rupture of the vessel's walls at 1.5 ms.

propagation, gas bubble expansion and metal rupture, were well reproduced in consideration of the metal thickness. The simulation presented that there was less deformation for the thicker walls. The shock propagation in water caused by the impact passing through the metal wall was also simulated. In conclusion, we are confident that the SPH method is one of the leading methods for the dynamics of explosion simulation.

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Smoothed Particle Hydrodynamics 法を用いた鉄容器内での水中爆発の数値解析

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2次元正方形容器中での水中爆発の数値解析をSmoothed Particle Hydrodynamics(SPH)法を用いて行った。SPH粒子は爆発によるデトネーションガス，容器に満たされた水，金属で出来た容器を良く再現した。水中を伝播する衝撃波は金属容器に衝突し容器を変形させた。そして，最終的には容器の角部が破壊された。さらに，衝撃波が金属壁を通り抜け，容器内を隣の部屋まで伝播する様子も観察された。本数値解析結果は，SPH法が流体－構造連成を含んだ爆発事故の再現に有用であることを示した。

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