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Application of Smoothed Particle Hydrodynamics in analysis of shaped-charge jet penetration caused by underwater explosion

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ABSTRACT

A process of target penetration by a shaped-charge jet includes three main stages: charge detonation, formation of a metallic jet and its penetration of the target. With continuously increasing computational power, a numerical approach gradually becomes more prominent (combined with experimental and theoretical methods) in investigations of performance of a shaped-charge jet and its target penetration. This paper presents a meshfree methodology - Smoothed Particle Hydrodynamics (SPH) - for a shaped charge penetrating underwater structures. First, a SPH model of a sphere impacting a plate is developed; its numerical results agree well with the experimental data, verifying the validity of the mentioned developed method. Then, results obtained for different cases - for various materials of explosives and liners - are discussed and compared, and as a result, more suitable parameters of the shaped charge in order to increase the penetration depth are obtained - HMX and copper were chosen respectively as the explosive and the liner material. It follows by validation of a model of a free-field underwater explosion, developed to verify the effectiveness of the modified SPH method in solving problems of underwater explosion; its numerical results are compared with an empirical formula. Finally, the SPH method is applied to simulate the entire process ranging from the detonation of the shaped charge to the target penetration employing the optimal parameters. A fluid around the shaped charge is included into analysis, and damage characteristics of the plate exposed to air and water on its back side are compared.

1. Introduction

A strong discontinuous shock wave (Ming et al., 2016; Zhang et al., 2011; Kim and Shin, 2008; Rajendran and Narasimhan, 2001, 2006; Ghoshal and Mitra, 2016; Hung et al., 2005, 2009; Zhang et al., 2015a; Zhang and Liu, 2015) and a high-speed metal jet (Arnold and Rottenkolber, 2013; Feng et al., 2013; Liu et al., 2003; Molinari, 2002; Katayama and Kibe, 2001; Katayama et al., 2001; Chen and Liu, 2012; Yang et al., 2016; Baêta-Neves and Ferreira, 2015; Miyoshi, 2008) can be generated by a shaped charge associated with underwater explosion, which can cause damage in structures. In researches of a shock wave caused by underwater explosion, Zhang *et al.* (Ming et al., 2016; Zhang et al., 2011). presented its numerical and experimental analysis together with that of structure destruction. Rajendran and Narasimhan (2006, 2001) carried out a series of experiments to study damage characteristics of plates subjected to underwater explosion. Hung et al. (2005, 2009). provided an experimental investigation of a dynamic response of a structure subjected to underwater explosion. Although experimental research (Zhang et al., 2013, 2015b; Yin et al., 2016; Li et al., 2016; Han et al., 2016) is the most effective and direct method to investigate underwater explosions and their cumulative effect, it has some disadvantages: higher risk to human operators, non-repeatability and limited information acquisition. Therefore, a numerical method and theoretical analysis are usually combined with experiments to study the related load characteristics.

For analysis of a shaped charge, Liu *et al.* (Feng et al., 2013; Liu et al., 2003). developed two different models of a shaped-charge jet - with and without a charge - and studied the process of jet formation using a Smoothed Particle Hydrodynamic (SPH) scheme. Molinari (2002) presented a finite-element simulation of formation and fragmentation of a shaped-charge jet and its penetration in a plate. Katayama *et al.* (Katayama and Kibe, 2001; Katayama et al., 2001). proposed a numerical

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analysis method to simulate the jet-formation and penetration processes for a conically shaped charge. However, few published papers discussed a damage response of a steel plate to a shaped-charge jet associated with an underwater explosion. Computational difficulties caused by mesh distortion when using a finite-element method can be overcome by employing the SPH method since it is suitable for solving problems with large deformations thanks to its mesh-less nature; besides, its Lagrangian formulation makes it easy to capture material interfaces. Whereas the standard SPH method had poor performance in solving problems with a large density ratio (Liu and Liu, 2010), it could be modified to avoid the distortion of physical quantities.

In this paper, a modified SPH method based on volume approximation is utilized to simulate the formation of a metal jet and its target penetration. First, after a brief discussion of SPH, different material models used in the developed SPH model are established to analyse a metal-jet velocity and a penetration depth for the target. A cylindrically shaped charge surrounded by a spherical-segment liner is presented in the model. Three types of explosives are chosen - TNT, Composition B and HMX; as for the liner, three kinds of materials were employed - aluminium, copper and steel. After that, results obtained for different cases are discussed and compared, and as a result, more suitable parameters of the shaped charge are obtained. Finally, an SPH model with optimal parameters is developed to simulate the entire process of charge detonation, jet formation and its penetration into an underwater structure. Further, damage from a shock wave and the metal jet on the plate are analysed in detail. In addition, different cases of the plate exposed to air and water on its back side are discussed.

2. Theoretical background and numerical method

2.1. Basic features of SPH

The SPH method (Ming et al., 2016; Feng et al., 2013; Liu et al., 2003; Liu and Liu, 2010; Zhang et al., 2012; Swegle and Attaway, 1995; Colagrossi and Landrini, 2003; Liu and Liu, 2003; Zhang et al., 2015c, 2017a; Sun et al., 2017; Sun et al., 2016; Zhang et al., 2017b; Dobratz, 1981) provides an advantage of an accurate shock capturing thanks to its Lagrangian nature and of a mesh-less character shown to be very efficient in modelling of underwater explosions and accurate in capturing evolution of a metal jet with its large deformations. Two key steps are included in the formulation of SPH approximations - kernel and particle approximations (Liu and Liu, 2003). For kernel approximation, a field function $f(x)$ is described as integral representation in a continuous form using a kernel or smoothing function, given by (Liu and Liu, 2003)

$$\langle f(\boldsymbol{x})\rangle = \int_{\Omega} f(\boldsymbol{x}')W(\boldsymbol{x}-\boldsymbol{x}',h)d\boldsymbol{x}', \tag{1}$$

where $\langle f(x)\rangle$ is the approximated value; W is the smoothing function representing a weighted contribution; h is the smooth length; $\boldsymbol{x}$ is the position vectors of the particles.

Subsequently, a computational domain is discretized with a set of particles. As for particle approximation, the field function $f(x)$ and its derivative $\nabla f(x)$ are approximated as weighted sums over surrounding particles within the support domain, expressed as (Liu and Liu, 2003)

$$\langle f(\boldsymbol{x}_i)\rangle = \sum_{j=1}^{N}\frac{m_j}{\rho_j}f(\boldsymbol{x}_j)W_{ij}, \tag{2}$$

$$\langle \nabla\cdot f(\boldsymbol{x}_i)\rangle = \sum_{j=1}^{N}\frac{m_j}{\rho_j}f(\boldsymbol{x}_j)\cdot\nabla_i W_{ij}, \tag{3}$$

where $\langle f(\boldsymbol{x}_i)\rangle$ is the approximated value for particle i; N is the number of particles in the support domain; m and ρ denote the mass and density, respectively; W_{ij} is the smoothed function of a pair of particles i and j (the cubic spline function is employed in this paper).

Combined with Navier-Stokes equations applied for hydrodynamics of fluids and solids with material strength, standard discretized equations of an SPH particle approximation for the continuity, momentum and energy equations can be found in Liu and Liu (2003).

2.2. Modified equations

The standard SPH method is believed to have poor performance in solving problems with a large density ratio (Liu and Liu, 2010; Ming et al., 2017). To avoid the distortion of physical quantities, the modified SPH method (Zhang et al., 2015c) was applied based on volume approximation in simulations of a shaped-charge jet associated with underwater explosion. The conservation of mass, momentum and energy in SPH as well as the motion equation can be expressed as

$$\begin{cases} \dfrac{d\rho_i}{dt} = \rho_i\displaystyle\sum_{j=1}^{N}\frac{m_j}{\rho_j}(\boldsymbol{v}_i-\boldsymbol{v}_j)\cdot\nabla_i W_{ij} \\ \dfrac{d\boldsymbol{v}_\mathbf{i}}{dt} = -\displaystyle\sum_{j=1}^{N}\frac{m_j}{\rho_j}\left(\frac{\boldsymbol{\sigma}_\mathbf{i}+\boldsymbol{\sigma}_j}{\rho_i}+\Pi_{ij}\right)\nabla_i W_{ij} \\ \dfrac{de_i}{dt} = \dfrac{1}{2}\displaystyle\sum_{j=1}^{N}\frac{m_j}{\rho_j}\left(\frac{\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_\mathbf{j}}{\rho_i}+\Pi_{ij}\right)(\boldsymbol{v}_i-\boldsymbol{v}_j)\cdot\nabla_i W_{ij} \\ \dfrac{dx_i}{dt} = \boldsymbol{v}_i \end{cases}, \tag{4}$$

where $\boldsymbol{v}$,e, t, $\boldsymbol{x}$, $\boldsymbol{\sigma}$denote the velocity, energy, time, coordinates and stress, respectively; $W_{ij} = W(\boldsymbol{x}_i-\boldsymbol{x}_j,h) = W(|\boldsymbol{x}_i-\boldsymbol{x}_j|,h)$is the smoothed function of a pair of particles i and j (the cubic spline function is applied in this paper); r_{ij} defines the distance between particles i and j ; $\nabla_i W_{ij} = \frac{\boldsymbol{x}_i-\boldsymbol{x}_j}{r_{ij}}\frac{\partial W_{ij}}{\partial r_{ij}} = \frac{\boldsymbol{x}_{ij}}{r_{ij}}\frac{\partial W_{ij}}{\partial r_{ij}}$; Π_{ij} is the artificial viscosity (Liu and Liu, 2003).

2.3. Constitutive model

(1) Stress σ for fluids is composed of two terms: isotropic pressure P and viscous shear stress τ (Liu and Liu, 2003). Since the level of viscosity is small, it can be ignored in analysis of strong impacts such as a case of a shaped-charge jet associated with underwater explosion. The pressure P can be obtained from an equation of state (EoS).

Here, the Jones-Wilkins-Lee (JWL) EoS (Dobratz, 1981) is used for detonation products, because explosive gas with high temperature and high pressure is generated after explosive initiation, expressed as

$$P = A\left(1-\frac{\omega\eta}{R_1}\right)e^{-\frac{R_1}{\eta}} + B\left(1-\frac{\omega\eta}{R_2}\right)e^{-\frac{R_2}{\eta}} + \omega\eta\rho_0 e, \tag{5}$$

where ρ_0 and e denote the initial density and the specific internal energy per unit mass; A, B, R_1, R_2 and ω are the experimental fitting coefficients; η is the ratio of the density of detonation products to the initial density of the original explosive. Parameters of the EoS used in simulations are listed in Table 1.

Since water is highly compressed during the process of underwater explosion, a state equation fit for high-pressure conditions should be used. According to its different states, a Mie-Gruneisen equation of state (Steinberg, 1987) can be employed for water:

(a) In expansion state ($\mu < 0$)

$$p = \rho_0 C_0^2\mu + (\gamma_0 + a\mu)e, \tag{6}$$

(b) In compressive state ($\mu > 0$)