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Experimental and numerical investigation of the centrifugal model for underwater explosion shock wave and bubble pulsation

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ABSTRACT

In this paper, similarity relation between model and prototype based on centrifugal similarity criteria was mainly studied, and it was proved that underwater explosion shock wave and bubble pulsation were in accordance with the centrifugal similarity. First, the similarity criteria of underwater explosion shock wave and bubble pulsation was derived based on π-principle. It shows that when model size is N times smaller than the prototype size, the acceleration of gravity should be expanded N times, so that the model and prototype can meet the similarity relation. Then centrifugal model tests including two different scaled model of 1/20 and 1/30 for the same prototype were conducted through LXJ-4–450 geotechnical centrifuge apparatus. Besides, corresponding model case and prototype case were numerical calculated by LS-DYNA code. The results of test and numerical calculation fit well and various parameters of model and prototype such as peak pressure of shock wave, secondary peak pressure, bubble radius and the period of bubble pulsation fit well too. It was concluded that the underwater explosion bubble pulsation affected by gravity meets the centrifugal similarity criteria and the model experimental study of the bubble pulsation characteristic or the collective effect of the shock wave and bubble should be conducted through centrifuge apparatus.

1. Introduction

The research of underwater explosion has an important position in the national economy and defense construction. The load effects of underwater explosion mainly include underwater shock wave and the bubble pulsation, and secondly, the surge effect on the target caused by underwater explosion. The study on shock wave in water has been relatively mature. Cole (1948) published the book “underwater explosion” in 1948, in which the a lot of experiments and theory research of shock wave in water were conducted. Underwater explosion generates a shock wave in the water and follows by a secondary shock waves with the bubble pulsating. And the bubble floats gradually in the process of pulsating because of the buoyancy (Snay, 1956). In 1917, Rayleigh (1917) first studied the bubble pulsation and established the motion equation of the spherical bubble in the incompressible flow field, that is, the "Ra(e)yleigh-Plesset" equation. Herring (1950) in 1941 and Keller & Kolodner (Keller and Kolodner, 1956a, 1956b) in 1956 considered the compressibility of fluid and improved the control equation of oscillating bubble. Geers and Hunter (Geers and Hunter, 2002; Geers and Park, 2005) established Geers-Hunter model in 2002. This model can be used to calculate the pressure, bubble radius and the bubble rising process in the flow field of shock wave and bubble pulsation after underwater explosion.

Finite element methods have also been used in bubble pulsation studies. Especially, the Arbitrary Lagrangian-Eulerian Multi-Material has been used by various authors such as Menon (1996), Chisum and Shin (1997), Abe et al. (2007), Yiannakopoulos et al. (2008), and Barras et al. (2012).

Shima et al. (1989) studied the whole process of the expansion and collapse of the elastic material near the wall through experiments, which provides a reference for the study of the bubble dynamics in the vicinity of the elastic material. Shima et al. (1984); Tomita and Shima (1994) produced bubbles by electric shock, and conducted experiments to present the bubble collapse processes near the wall in different conditions. They used high speed camera to observe the movement of hydrogen bubbles generated by the laser. And the interaction between bubble and bubble, bubble and boundary was also observed. (Tipton et al.) studied the expansion and collapse of the small bubbles near the wall by the experimental methods and numerical methods. At first, researchers produced bubbles by electric shock to simulate the motion characteristics of underwater explosion bubble, and studied the bubble with high speed camera and other technical means, however, there are

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some differences in the motion characteristics of the bubble generated by the electric spark in place of the explosion. P.Boyce, S.Debono (Boyce and Debono, 2003) conducted the explosion test in the outdoor pool, and photographed the motion of bubbles near the rigid wall, including the process of bubble pulsation and the formation of bubble jet by the high-speed camera. Klaseboer et al. (2005) also carried out underwater explosion test, studing the interaction between bubble and structure, and used high-speed camera to capture the expansion, collapse and rebound process of underwater explosion bubble, and found serious damage to the structure in the water caused by underwater explosion bubble load.

The underwater explosion test of small equivalent explosive can be carried out in the laboratory or special pool of underwater blasting; but the prototype experiment of large equivalent explosive usually has a huge cost, high risk, weak repeatability, and a lot of uncertainties. It is very difficult to study the variation and damage mechanism of explosion effect only through prototype test. While the traditional model test is limited by the similarity criteria, most of the explosive damage phenomenon and behaviors did not conform to the geometry similarity criteria only, and the traditional model test cannot be the real reaction for explosion effect of the variation and damage mechanism. Murphy (Murphy, 1950) pointed out that in the conventional 1 times gravity field, the scaled model test cannot reasonably simulate the gravity load. BE Gel'Fand et al. Gel'Fand and Takayama (2004) studied the underwater explosion similarity criterion and thought that the model test of underwater explosion shock wave does not need to consider gravity, and the shock wave peak, shock wave attenuation, impulse and energy density are the same with the geometric ratio, but the bubble pulsation must take the gravity effect into account. Taking into account the gravity effect of the scaled model experiment research, the centrifuge technology must be used. Schmidt and Housen (1987), Housen et al. (1983) conducted a series of research on the mechanism and related influencing factors of the explosion and impact crater with centrifuge technology. Kutter et al. (1985) conducted the experimental study on centrifugal model of underground tunnel explosion in three different acceleration conditions of 1g, 50g, 100g, verified the centrifugal model scale, and explored the effects of gravity under explosion load.

2. Theoretical background

The underwater explosion similarity criteria is the theoretical basis of underwater explosion model test study. The most basic parameter of model and prototype was characteristic length scale, denoted by λ_l. In order to predict the result of prototype test through model test, the similarity relation of various parameters between model and prototype must be studied first.

2.1. Empirical formulas for underwater explosion load

Underwater explosion load mainly includes shock wave and bubble pulsation. Cole has done a lot of research in underwater explosion and proposed the empirical formulas for the shock wave pressure which can be expressed as (Cole, 1948; Swisdak, 1978)

$$P(t) = P_m e^{(-t/\tau)} \tag{1}$$

where P_m is the peak pressure of shock wave(MPa), and τ is the shock wave decay constant(ms). P_m and τ can be expressed as

$$\begin{cases} P_m = k_p\left(\frac{\sqrt[3]{W}}{r}\right)^{A_p} \\ \tau = k_\tau \sqrt[3]{W}\left(\frac{\sqrt[3]{W}}{r}\right)^{A_\tau} \end{cases} \tag{2}$$

where W is the mass of the charge(kg), k_p, A_p, k_τ and A_τ are constants depending on the explosive charge types (here, for TNT charge, $k_p = 52.4$, $k_\tau = 0.084$, $A_p = 1.13$, $A_\tau = -0.23$) and r is the distance between explosive charge and target(m).

Cole also proposed the empirical formulas for the maximum bubble radius and the period of the bubble pulsation which can be expressed as

$$T = K_T \frac{W^{1/3}}{(H + 10.34)^{5/6}} \tag{3}$$

$$R_{max} = K_R \frac{W^{1/3}}{(H + 10.34)^{1/3}} \tag{4}$$

where K_T and K_R are constant for explosive charge (here, for TNT charge, $K_T = 2.11$, $K_R = 3.5$), W is the mass of the charge(kg), and H is the depth of charge(m).

2.2. Centrifugal similarity criteria

In the study of underwater explosion shock wave and bubble pulsation, it is assumed that the viscous force of the water medium can be ignored and the process of explosion is adiabatic. So that the following parameters which influence the process of explosion are considered: the explosive parameters including charge radius a, charge density ρ_c, detonation velocity D, and explosion heat Q, the medium parameters including water medium density ρ_0 and sound speed in water c, and other parameters including gravity acceleration g, atmospheric pressure P_0, the depth of charge h. The parameters to be calculated are the shock wave parameters including peak pressure P_m, time constant τ, standoff distance r, and the bubble parameters including maximum radius R and pulsation period T. So that

$$f(P_m, r, \rho_c, D, Q, c; P_0, \rho_0, a) = 0 \tag{5}$$

$$f(\tau, r, \rho_c, D, Q, c; P_0, \rho_0, a) = 0 \tag{6}$$

$$f(R, g, h, \rho_c, D, Q, c; P_0, \rho_0, a) = 0 \tag{7}$$

$$f(T, g, h, \rho_c, D, Q, c; P_0, \rho_0, a) = 0 \tag{8}$$

Then the atmospheric pressure P_0, water medium density ρ_0, and charge radius a are chosen to be basic parameters. Through π theorem, following equations can be got

$$f\left(\frac{P_m}{P_0}, \frac{r}{a}, \frac{\rho_c}{\rho_0}, \frac{\rho_0 D^2}{P_0}, \frac{\rho_0 Q}{P_0}, \frac{\rho_0 c^2}{P_0}\right) = 0 \tag{9}$$

$$f\left(\frac{\tau P_0{}^{1/2}}{a\rho_0{}^{1/2}}, \frac{r}{a}, \frac{\rho_c}{\rho_0}, \frac{\rho_0 D^2}{P_0}, \frac{\rho_0 Q}{P_0}, \frac{\rho_0 c^2}{P_0}\right) = 0 \tag{10}$$

$$f\left(\frac{R}{a}, \frac{\rho_0 g a}{P_0}, \frac{h}{a}, \frac{\rho_c}{\rho_0}, \frac{\rho_0 D^2}{P_0}, \frac{\rho_0 Q}{P_0}, \frac{\rho_0 c^2}{P_0}\right) = 0 \tag{11}$$

$$f\left(\frac{T P_0{}^{1/2}}{a\rho_0{}^{1/2}}, \frac{\rho_0 g a}{P_0}, \frac{h}{a}, \frac{\rho_c}{\rho_0}, \frac{\rho_0 D^2}{P_0}, \frac{\rho_0 Q}{P_0}, \frac{\rho_0 c^2}{P_0}\right) = 0 \tag{12}$$

The parameters of explosive charge and water medium are curtained in model test and the atmosphere pressure is constant. So that, ρ_c, D, Q, ρ_0, c and P_0 are all constant parameters and Eqs. (9)–(12) can be written as

$$P_m = f_1\left(\frac{r}{a}\right) \tag{13}$$

$$\tau = a f_2\left(\frac{r}{a}\right) \tag{14}$$

$$R = a f_3\left(ga, \frac{h}{a}\right) \tag{15}$$

$$T = a f_4\left(ga, \frac{h}{a}\right) \tag{16}$$