Study of explosion loads of Near–field Underwater Explosion

F J An*, X Li, J Liu, C Wu

School of Mechatronical Engineering, Beijing Institute of Technology, China

ABSTRACT

The shock wave of near-field underwater explosion is investigated experimentally and numerically. Three TNT charge of different shapes are detonated in the water tank. The framing &scanning ultra-high-speed photography system is applied to obtain the initial movement and trajectories of shock wave and detonation gas. Use the Arbitrary Lagrangian–Eulerian (ALE) method of LS-DYNA software to simulate the processes of near-field underwater explosion. Comparisons with the experimental tests are conducted to verify the results of numerical solutions. The movement characteristics of explosion loads are matched well. On the basic of experiments and simulations, the engineering formula of pressure for near-field shock wave is built.

1. INTRODUCTION

As an important physical phenomenon with high temperature and high pressure, underwater explosion has been studied since early last century. It is an effective means of fatal damage to ships and other marine structures. According to the distance to explosion center, the study of underwater explosion is always divided into two parts: near field and far field. With the deepening of the study of damage effect of marine weapons and anti-blast protection of ships, the problem of near-field underwater explosion and contact underwater explosion has gradually become the focus of the current underwater explosion research. However, due to the particularity of near-field underwater explosion, such as high pressure, high-speed particle motion, acute entropy increase and strong damageability, the study of near-field underwater explosion has been a difficulty for scholars. Although scholars at home and abroad have done a lot of research work on the problems of near-field underwater explosion and contact underwater explosion, there is still a lack of uniform understanding of the near-field characteristics. And it has not yet formed a classical formula similar to the pressure and the specific impulse formula for far-field shock waves presented by Zamyshlyayev and Cole, to a certain extent, which restricts the application and development of the damage effect of marine weapons and the anti-blast protection of ships.

For near-field underwater explosion and contact underwater explosion, it is the key to obtain exact characteristics of free-field underwater explosion for the study of the liquid-solid coupling effect and the damage effect. At present, a variety of test methods have been developed in the testing technology of underwater explosion both at home and abroad. But most of them can not be applied in the near-field test for various reasons. Some scholars find optical measurement method or the combination of different measurement methods can be

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*Corresponding Author: anfengjiang@bit.edu.cn

useful. Liddiard [1] used high speed photography to measure the shock wave generated by the explosion of spherical Pentolite explosives in purified water. The shadow technology was used to obtain high-speed photography of shock waves in water, and then the distance-time relationship of the shock wave and the velocity of shock wave which is a function of distance were obtained. Bruceton [2] used camera to measure the pressure of underwater explosion. The experiment result was close to the theoretical value. Brousseau [3] conducted a water tank experiment with aluminized explosives. He got very clear wave front and trajectory of the underwater shock wave with the framing camera and the scanning camera. JiBo Zhao, JinHe Li et al [4-6] studied the JH-9005 explosive's near-field shock wave trajectory and propagation in water with application of the high speed framing camera, high speed scanning camera, copper-manganese pressure gauge, PVDF pressure gauge and other means. The results of the optical testing were consistent with the testing results of the pressure gauge, indicating the feasibility of the test and the data analysis method. They also applied this method to the study of the near-field underwater explosion shock wave of aluminized explosive, and obtained the influence that different aluminum-oxygen ratios have on the peak pressure of the shock wave generated by underwater explosion.

Due to the limitation of the near-field test method of underwater explosion, the current researches mainly focus on the peak pressure and pressure attenuation law in the study of the underwater explosion load. And the numerical simulation method is the most widely used research method. To obtain exact experiment data of underwater explosion fluid field, we find that, in the near field of 1 ~ 10 times the radius of the charge, the data of the wave front and bubble size at different times can be obtained by high speed framing photography or high speed scanning photography to derive the peak pressure attenuation law and the bubble pulsation period. So we combine these two optical measurement methods and develop a framing &scanning ultra-high speed photography system in our study.

In the water tank, carry out the underwater explosion test using a small amount of explosives of three shapes. Measure evolution images and trajectories of shock wave and detonation gas of TNT charge by the framing & scanning ultra-high speed photography system. What's more, apply the Arbitrary Lagrangian–Eulerian (ALE) method using LS-DYNA software to simulate the near-field underwater explosion of TNT charges of different shapes and sizes, and obtain the motion and load characteristics of shock wave.

2. NEAR-FIELD UNDERWATER EXPLOSION TEST

The test uses three kinds of TNT charge with different shapes and sizes in Table 1. Place the charge in the middle of the glass tank. Use the framing & scanning ultra-high speed photography system to shoot the explosion field of 600mm × 600mm after the blast. The framing photography can accurately obtain six images of the shock wave at any time after the blast. The scanning photography can obtain the trajectory image of the shock wave along the axis of the explosive.

Here only gives the results and analysis of the first two experiments. For spherical charge, as shown in Figure 2, during the shock wave propagation and the spread of detonation products, their boundaries are maintained mainly as good sphericity. As for cylindrical charge, its spherical tendency is obvious in Fig 3. As shown in Fig 4 and Fig 5, the upper scan line represents the shock wave propagation in water after the blast, the inferior scan line represents the spread of detonation gas.

According to the test results, obtain the movement characteristic of the initial shock wave generated by spherical TNT charge with a radius of 35mm as shown in Figure 6. The movement characteristic of the initial shock wave generated by cylindrical TNT is shown in Figure 7.
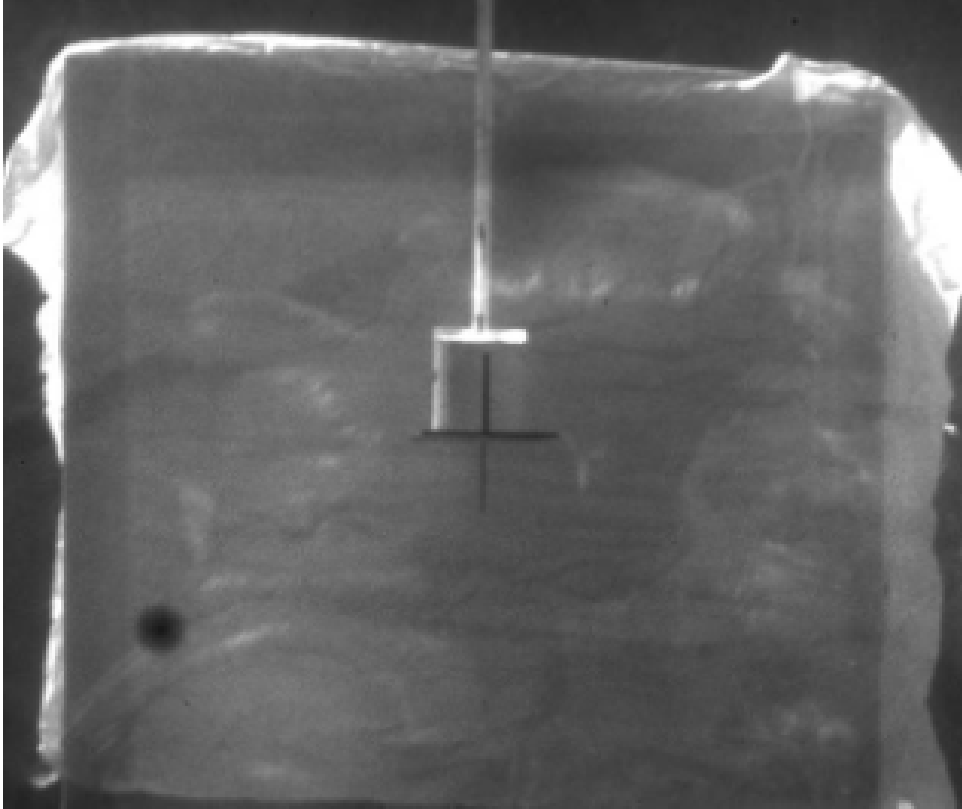

Fig 1 Experiment arrangement

Tab 1 Experiment conditions

Number	Explosive	Charge Shape	Charge Size/mm	Charge Mass/g	Detonation
1	TNT	Sphere	SR35mm	287.35g	Center Detonation
2	TNT	Cylinder	Ø60 × 66mm	298.58g	End Face Center Detonation
3	TNT	Cylinder	Ø25 × 50mm	39.27g	End Face Center Detonation

According to the trajectory of shock wave, the scanning trajectory of shock wave can be fitted by

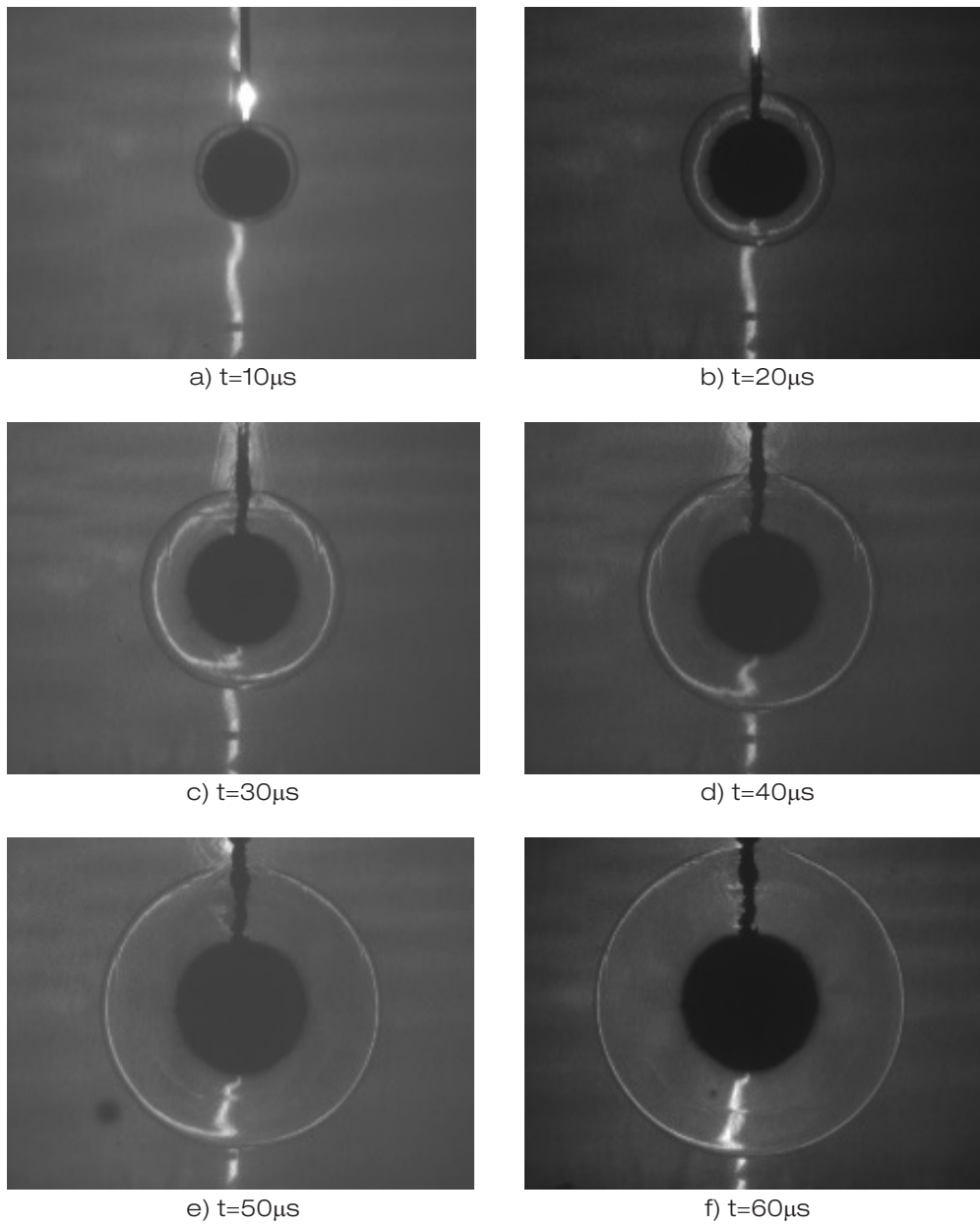$$\frac{x_W}{D_{CJ}} = A_1[1-\exp(-B_1 t)] + A_2[1-\exp(-B_2 t)] + \left(\frac{C_0}{D_{CJ}}\right)t \qquad (1)$$

a) t=10μs

b) t=20μs

c) t=30μs

d) t=40μs

e) t=50μs

f) t=60μs

Fig 2 Framing photography results of SR35mm TNT
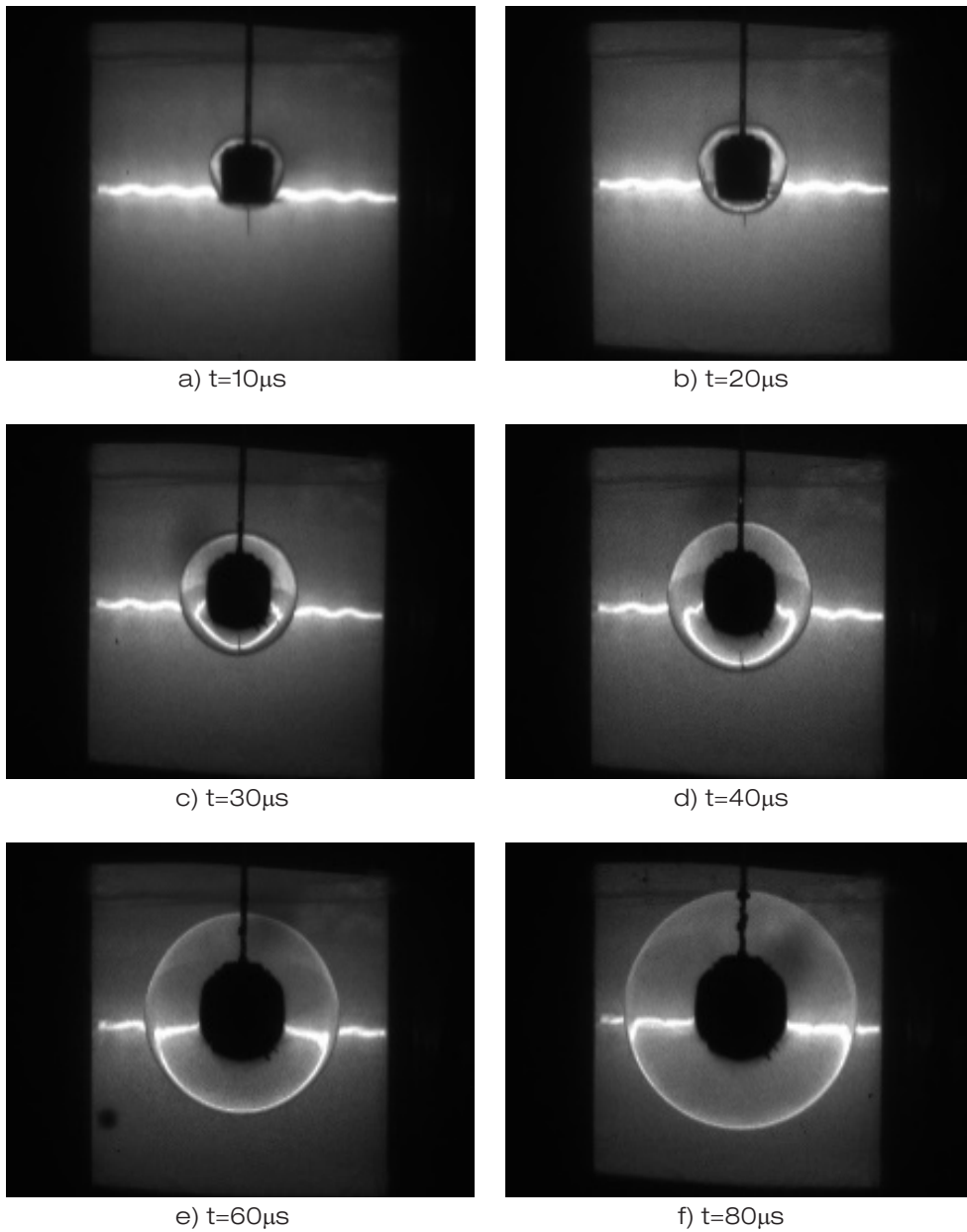
a) t=10μs

b) t=20μs

c) t=30μs

d) t=40μs

e) t=60μs

f) t=80μs

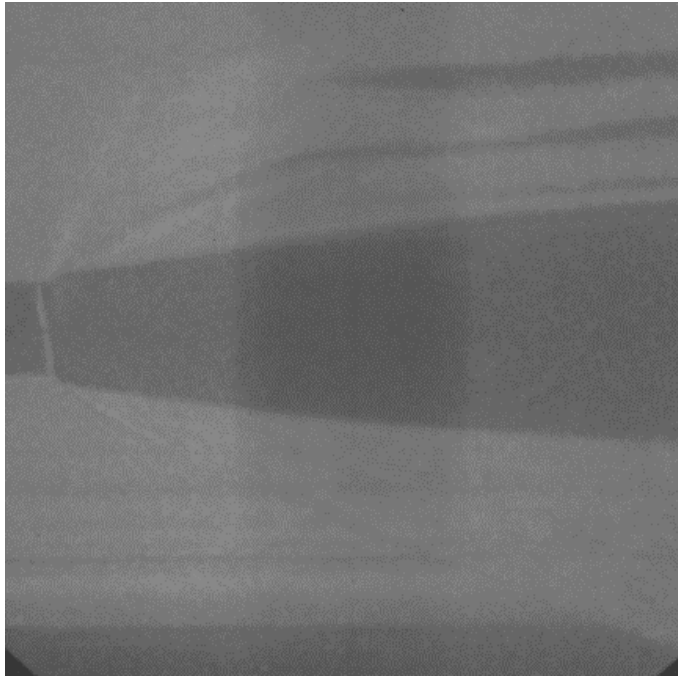Fig 3 Framing photography results of ⌀**60 × 66mm** TNT

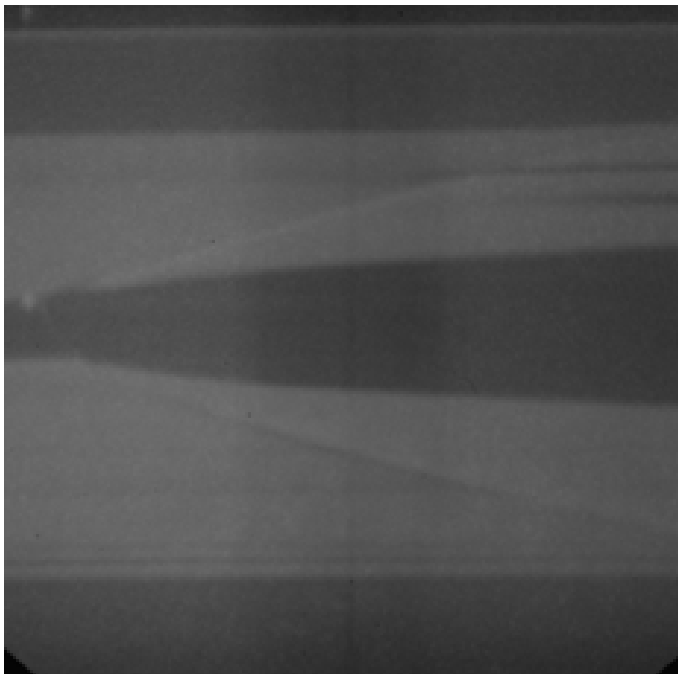Fig 4 Scanning photography result of SR35mm TNT

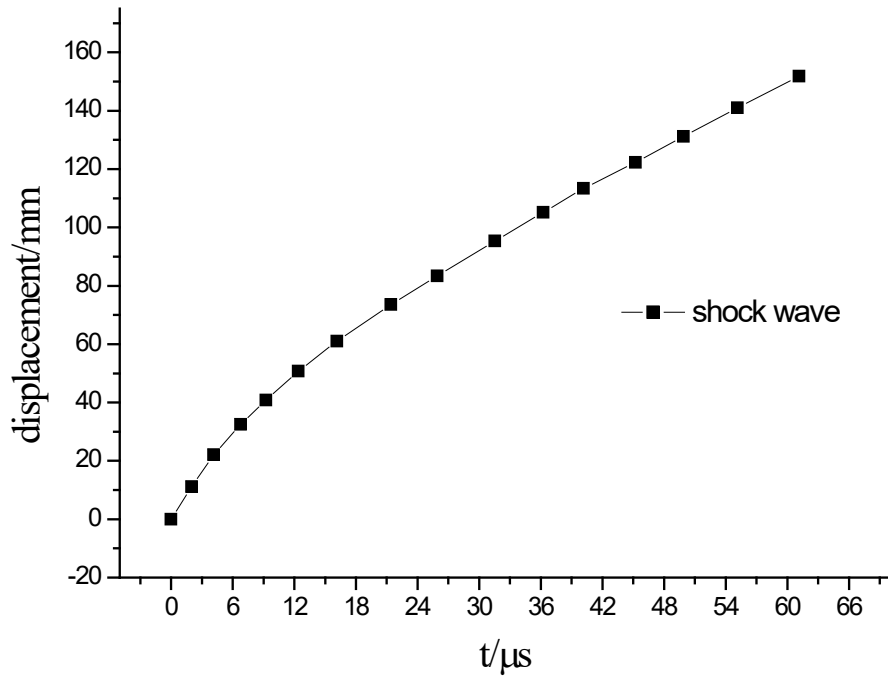Fig 5 Scanning photography result of ⌀**60 × 66mm** TNT

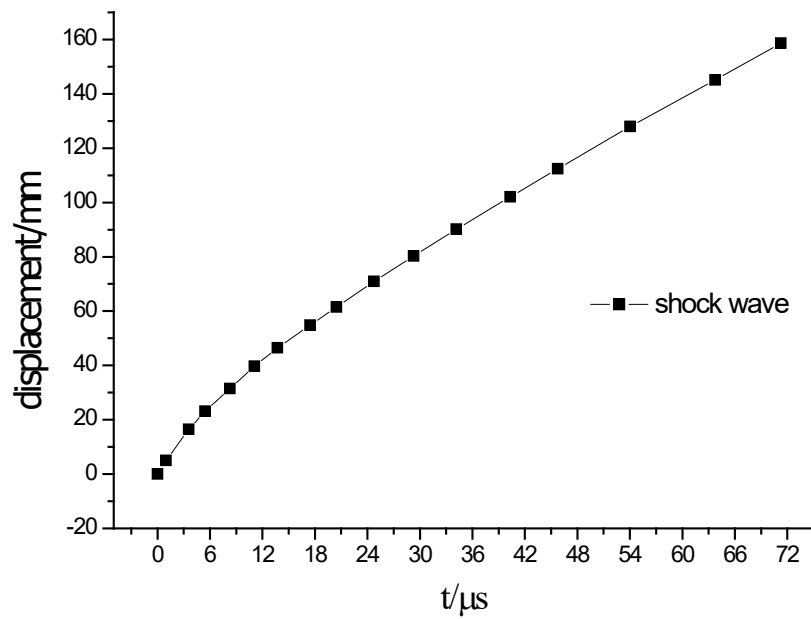Fig 6 The trajectories of shock wave for spherical TNT charge

Fig 7 The trajectories of shock wave for cylindrical TNT charge

Its differential equation is：

$$\frac{D_{\mathrm{W}}}{D_{\mathrm{CJ}}} = A_1 B_1 \exp(-B_1 t) + A_2 B_2 \exp(-B_2 t) + \left(\frac{C_0}{D_{\mathrm{CJ}}}\right) \qquad (2)$$

Where D_{CJ} represents the detonation velocity of the explosive in km/s, and for a TNT explosive charge it is 6.950 km/s; C_0 represents the speed of sound in water, in km/s, C_0 =1.647 km/s; A_1, A_2, B_1, B_2 are fitting constants, and they vary according to different charge shapes.

So we can get the velocity of near-field shock wave, D_W, for different charge shapes by experiments.

3. NUMERICAL SIMULATION

Apply the Arbitrary Lagrangian–Eulerian (ALE) method using LS-DYNA software to simulate the near-field characteristics of the underwater explosion of different shaped charges. As the fluid domain model is relatively simple, use LS-PrePost for geometric modeling, meshing and other operations, and then generate the K file for calculation that can be calculated by LS-DYNA. The final calculation results can be seen through LS-PrePost.

There are complex physical processes for underwater explosion during the detonation gas pulsation, like deformation, expansion, splitting and splashing. So we use the ALE grid unit to cover the possible movement space of the fluid objects, such as detonation products, water and air. The material interface reconstruction of ALE multi-material unit is carried out by modifying volume ratio to simulate the load characteristics of detonation gas in the complex fluid-solid coupling space.

3.1. Explosive

In LS-DYNA, the explosive is described with the *MAT_HIGH_EXPLOSIVE_BURN material model and the *EOS_JWL state equation. The specific form is

$$p(V, E) = A\left(1 - \frac{\omega}{R_1 V}\right)\exp(-R_1 V) + B\left(1 - \frac{\omega}{R_2 V}\right)\exp(-R_2 V) + \frac{\omega E}{V} \qquad (3)$$

Where V is the relative specific volume of the detonation product; E is the specific energy per unit volume, which has the dimension of pressure; A, B, R_1, R_2 and ω are five undetermined parameters. The JWL equation of state takes into account the work behavior of the gas product at high pressure, medium pressure and low pressure respectively. In equation (3), at high pressure the main contribution is the first term, and the second term gives the major contribution at medium pressure. At low pressure the last term gives the largest contribution and this term is simply an alternative form of the ideal gas law.

Tab 2 TNT's parameters and constants used in simulation

ρ /(kg·m⁻³)	D_{CJ} /(m·s⁻¹)	p_{CJ} /GPa	ΔQ /(MJ·kg⁻¹)	A/GPa	B/GPa	R₁	R₂	ω
1570	6850	19.1	4.40	374.2	3.23	1.0	4.15	0.30

3.2. Water

In LS-DYNA, air and water are usually described using the *MAT_NULL material model, which does not take into account deviatoric stress calculations, and the suitable equation of state (EOS).

For water medium at high temperature and high pressure, there are many forms of equation of state. The Mie-Grüneisen equation of state divides pressure and internal energy into cold pressure, cold energy and hot pressure, hot energy respectively. It's widely used in LS-DYNA and other softwares. The pressure of water is given as follows:

While μ > 0 (compression):

$$p = \frac{\rho_0 C^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{1+\mu} - S_3 \frac{\mu^3}{(1+\mu)^2}\right]^2} + (\gamma_0 + a\mu)E \qquad (4)$$

While μ < 0 (tension):

$$p = \rho_0 C^2 \mu + (\gamma_0 + a\mu)E \qquad (5)$$

Where μ represents the condense ratio; C represents the speed of sound; S_1, S_2, S_3 are constants, usually determined by the data of the impact experiment of water medium; γ_0 is the Grüneisen coefficient; a is the correction factor of Grüneisen coefficient.

Tab 3 Water's parameters and constants used in simulation

ρ /(kg·m⁻³)	C/(m·s⁻¹)	S₁	S₂	S₃	γ_0	a	E_0 /MPa
1000	1480	2.56	-1.986	0.2268	0.4934	0.0	0.2054

3.3. Air

Assuming that the air satisfies the ideal gas equation of state, use the *EOS_LINEAR_POLYNOMIAL polynomial equation of state:

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)\rho_0 E \qquad (6)$$

Where p is the pressure; $C_i\,(i=0,\cdots,3)$ represents a constant with a pressure dimension; $C_i\,(i=4,\cdots,6)$ is a dimensionless constant; $\mu=\rho/\rho_0-1$; E represents the specific internal energy.

Tab 4 Air's parameters and constants used in simulation

ρ /(kg·m⁻³)	C_0 /GPa	C_1 /GPa	C_2 /GPa	C_3 /GPa	C_4	C_5	C_6	E_0 /GPa
1.25	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.2533

To analyze the movement characteristic and pressure attenuation law of shock wave for different shaped charge, a numerical model for a free field underwater explosion is established using six kinds of TNT charge in Table 5.

Tab 5 Numerical simulation conditions

Number	Explosive	Charge Shape	Charge Size/mm	Charge Mass/g	Detonation
1	TNT	Sphere	SR18mm	39.82g	Center Detonation
2	TNT	Sphere	SR35mm	292.74g	Center Detonation
3	TNT	Sphere	SR50mm	853.47g	Center Detonation
4	TNT	Cylinder	Ø60 × 66mm	298.58g	End Face Center Detonation
5	TNT	Cylinder	Ø70 × 77mm	474.13g	End Face Center Detonation
6	TNT	Cylinder	Ø80 × 88mm	707.74g	End Face Center Detonation

4. RESULTS AND DISCUSSION

The Hugoniot relation of the water medium and the momentum equation on the Hugoniot line are expressed as:

$$D_W = 1.483 + 25.306\lg(1+\frac{u_W}{5.19}) \qquad (7)$$

$$P_{\mathrm{m}} = \rho_0 D_W u_W \qquad (8)$$

The peak pressure P_m of shock wave in underwater explosion experiments can be determined according to equations (2), (7), (8).

It can be found from the calculation and analysis of three spherical TNT with different charge sizes that it has a nearly same variation trend for peak pressure at the same specific distance $\overline{R}=W^{1/3}/R$, as shown in Figure 8. This demonstrates that the attenuation of peak pressure has a certain law in near-field flow zone. The peak pressure calculation formula of the near-field shock wave is obtained by fitting the results of test and numerical simulation:
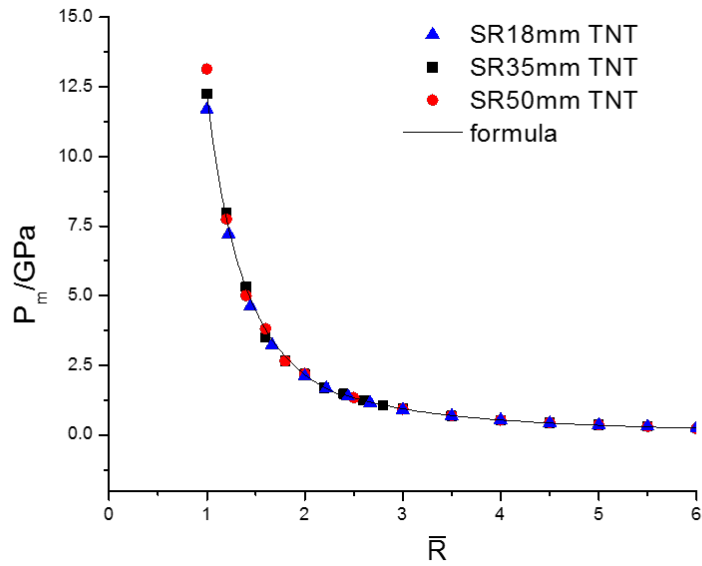
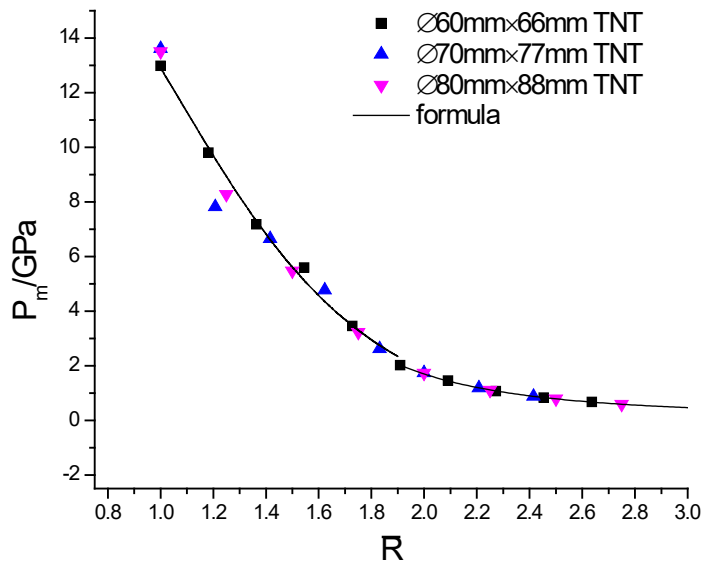Fig 8 Numerical results of peak pressures of shock wave for spherical TNT

Fig 9 Numerical results of peak pressures of shock wave for cylindrical TNT

Do the same work on cylindrical charge. From the calculation and analysis of three

$$P_{\mathrm{m}} = \begin{cases} 2.517\left(\dfrac{1.885}{\bar{R}}\right)^{2.5}, & \bar{R}=1.0\sim2.4 \\[3mm] 2.318\left(\dfrac{1.885}{\bar{R}}\right)^{1.933}, & \bar{R}=2.4\sim6.0 \end{cases} \tag{9}$$

Where W represents the charge mass in grams; R represents the standoff distance in centimeters, which is the distance from the measuring point to the center of the explosive charge; P_m represents the peak pressure at the measuring point, in GPa.

Do the same work on cylindrical charge. From the calculation and analysis of three cylindrical TNT with different charge sizes, it has a similar regularity of pressure attenuation with spherical charge, as shown in Fig.9. We also obtain the peak pressure calculation formula of the near-field shock wave for cylindrical charge (with an aspect ratio $\dfrac{D}{H}=1:1.1$) at the measuring point of which $\theta=0$ (along the axis):

$$P_{\mathrm{m}} = \begin{cases} 473.60\left(\dfrac{1.013}{\bar{R}}\right)^{-2.352}\times0.02808^{\bar{R}}, & \bar{R}=1.0\sim1.9 \\[3mm] 10.47\left(\dfrac{1.013}{\bar{R}}\right)^{5.937}\times3.032^{\bar{R}}, & \bar{R}=1.9\sim3.0 \end{cases} \tag{10}$$

Where $\bar{R}=W^{1/3}/R$, R represents the standoff distance in centimeters, which is the distance from the measuring point to the detonation point (the center of end face) as shown in Fig 10.

The scope of application of cylindrical charge's peak pressure calculation formula (10) is under 3 times the height of the charge rather than 6 times. It's because the spherical tendency end at about 3 times the height of the charge. After this point, the influence of charge shape and detonation position on the change of peak pressure can be ignored. So in the farther field, the peak pressure calculation formula of cylindrical TNT charge can be described in a form like the spherical charge's.
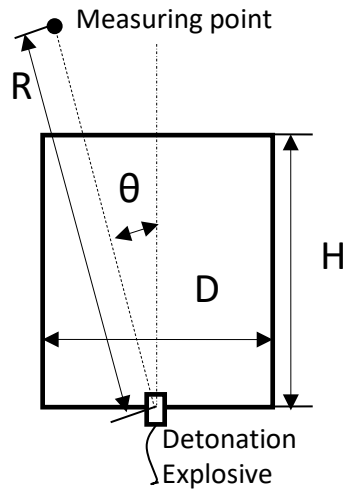
Fig 10 Measuring parameter diagram

5. CONCLUSIONS

The research on the near-field load of underwater explosion is of great significance to the design of efficient damage warhead and the anti-blast protection of ships.

We study the near-field shock wave of underwater explosion generated by different shaped charges according to its motion characteristics from two aspects of experiment and numerical simulation. In the test, the movement processes of shock wave and detonation gas within 80 μs are obtained by the framing & scanning ultra-high speed photography system. At the same time, the ALE method of LS-DYNA software is used to calculate the motion characteristic of near-field shock wave and the variation characteristic of the peak pressure of shock wave under various charge conditions. According to our research, we summarize the initial movement law of shock wave generated by underwater explosion and establish the peak pressure's engineering calculation formula of the near-field shock wave. In our study, we also get some other research progress. Because of space constraints, we will give them in the future.

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