Numerical Simulation on Shock Wave of Underwater Moving Explosive

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Abstract. The shock wave characteristics of underwater moving explosive were studied with AUTODYN. The results show that the explosive velocity has different influences upon the peak overpressure in different directions and different distances. By converting the kinetic energy of the explosive into an equivalent static dose, the Cole empirical formula can be used to calculate the underwater peak overpressure in the direction of the explosive motion.

1. Introduction

The overpressure of the underwater explosion shock wave is an important parameter for the protection design of underwater weapons and warship structures. Compared with the study of air blast wave, the testing underwater is complicated, difficult to operate and costly. The numerical simulation of underwater explosion shock wave has great advantages by using AUTODYN. It can accurately simulate the shock wave propagation and bubble pulsation of the underwater explosion, which has become an important means of studying underwater explosion [1-3].

In former studies, more static explosions were taken into account, but the velocity of the moving explosive has a significant influence on the shock wave field [4, 5]. Especially there's little research on underwater dynamic explosion due to the environment limit.

Based on the AUTODYN software, numerical simulations of dynamic explosion underwater of spherical TNT were carried out and the influence of velocity on blast wave field was studied.

2. Theory of Underwater Explosion and Dynamic Explosion

2.1. Theory of Underwater Explosion

The classical theory of underwater explosion is the Cole empirical formula, which is in the form of [6]:

$$P_{\mathrm{m}} = k\left(\frac{W^{1/3}}{R}\right)^{\alpha} \tag{1}$$

Where W is the explosive amount and the unit is kg; R is the distance from the explosion center and the unit is m. For this formula, the value of material parameters: k=52.27 MPa, α=1.13.

2.2. Theory of Dynamic Explosion

In the air explosion, the shock wave field is unbalanced with moving explosive and the explosion parameters will change with the angle between the parameter's position and the explosive velocity [5]. According to reference [7], the kinetic energy of moving explosive can be equivalent to the increase of the static explosive and the equivalent static dose can be obtained:

$$W_{\mathrm{be}} = \frac{Q_{\mathrm{v}} + \frac{1}{2}u_0^2}{Q_{\mathrm{v}}} W \tag{2}$$

Where W_{be} is the explosive amount the equivalent static dose; Q_{v} is the explosion heat; *uo* is the velocity of the moving explosive; W is the mass of the explosive. For this formula, the value of material parameters: k=52.27 MPa, α=1.13.

3. Numerical Simulation of Dynamic Explosion Underwater

3.1. Model Parameters

The equation of state of water is based on polynomial equation, using different forms to reflect the different states of water in compression, expansion and neither compression nor expansion. Neglecting the influence of the water depth, the unit mass internal energy of the water is taken as 361.875 J/kg.

The JWL equation used for TNT is as follows:

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

In the formula, the value of material parameters: ρ=1.58 g/cm^2, E=4.19 MJ/kg. Unspecified model parameters take the default value.

3.2. Numerical Model

Based on the symmetry of the model, a two-dimensional axisymmetric model of underwater explosion was established, as shown in Fig. 1. For this model, the value of dimension parameters: a=2400 mm, b=1200 mm. The boundary is set as the outflow boundary. The explosive is TNT with a diameter of 10 mm, which is placed in the center of the water. The central detonation method is used. The model is divided into 1200×600 Euler grids. Along the angle of 0°, 45°, 90°, 135°, 180° from the moving direction and distance of 100 mm, 200 mm, 300 mm, 400 mm, 600 mm from the center of the explosion, 25 observation points are set.

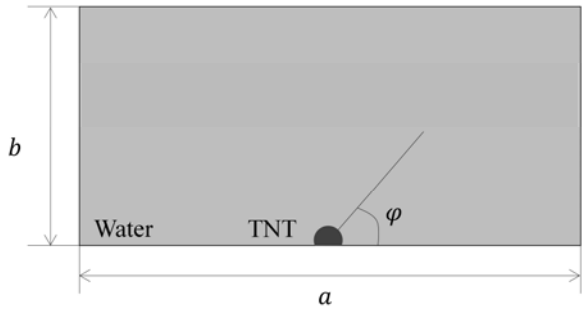


Figure 1. Two-dimensional numerical model of underwater explosion

3.3. Verification of numerical model

The calculation results of shock wave pressure at five observation points in the direction of u_0=0 m/s and φ=0° were compared with the results of the Cole empirical formula to verify the validity and correctness of the numerical model, as shown in Fig. 2 and 3.

Fig. 2 shows the time history of the shock wave pressure at five observation points. After rapidly rising to the peak value, the numerical calculation result has a multi-peak phenomenon. According to the comparison results of peak pressure in Fig. 3, the calculated results agree well with the empirical results in the case of $R/W^{1/3} \leq 1$, and accurately reflect the rule that the peak overpressure of underwater blast shock wave varies with distance.

3.4. Influence of Velocity on Shock Wave Field

The distribution characteristics of shock wave field in eight working conditions of u_0=0 m/s, 200 m/s, 400 m/s, 600 m/s, 800 m/s, 1000 m/s, 1400 m/s, 1900 m/s were studied. The influences of velocity on the peak overpressure and uniformity of the shock wave field were analyzed, and the relationship between the explosive velocity and the shock wave in different directions was established.

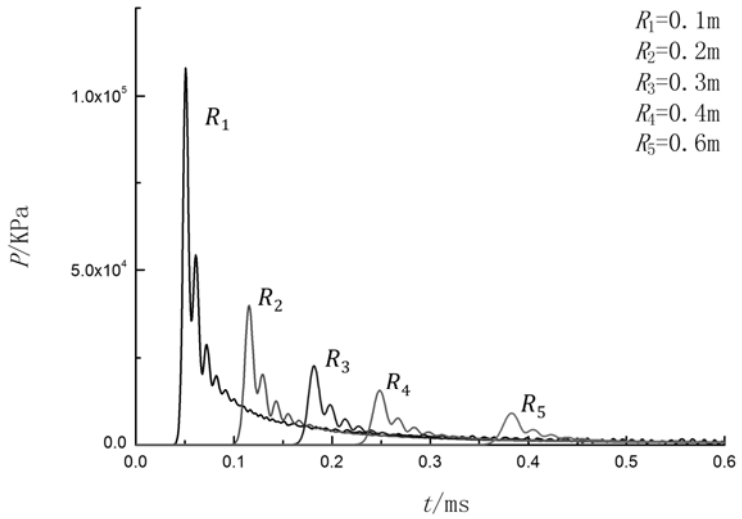


Figure 2. Pressure time histories at φ=0°

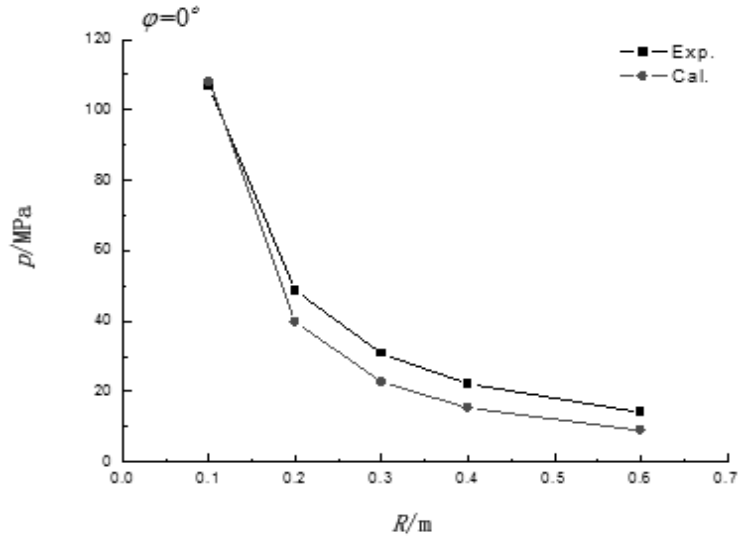
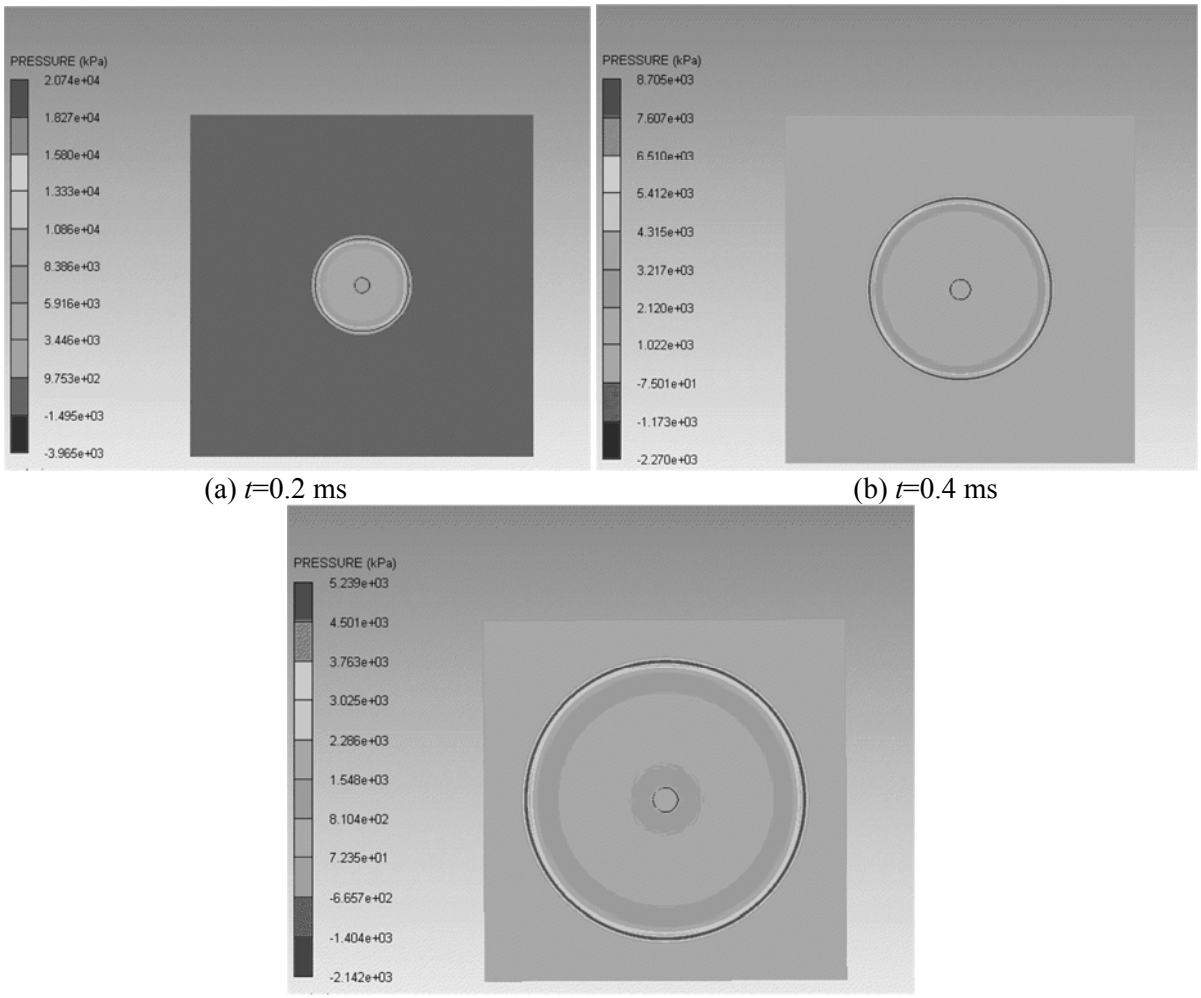


Figure 3. Comparison of peak overpressure results at φ=0°

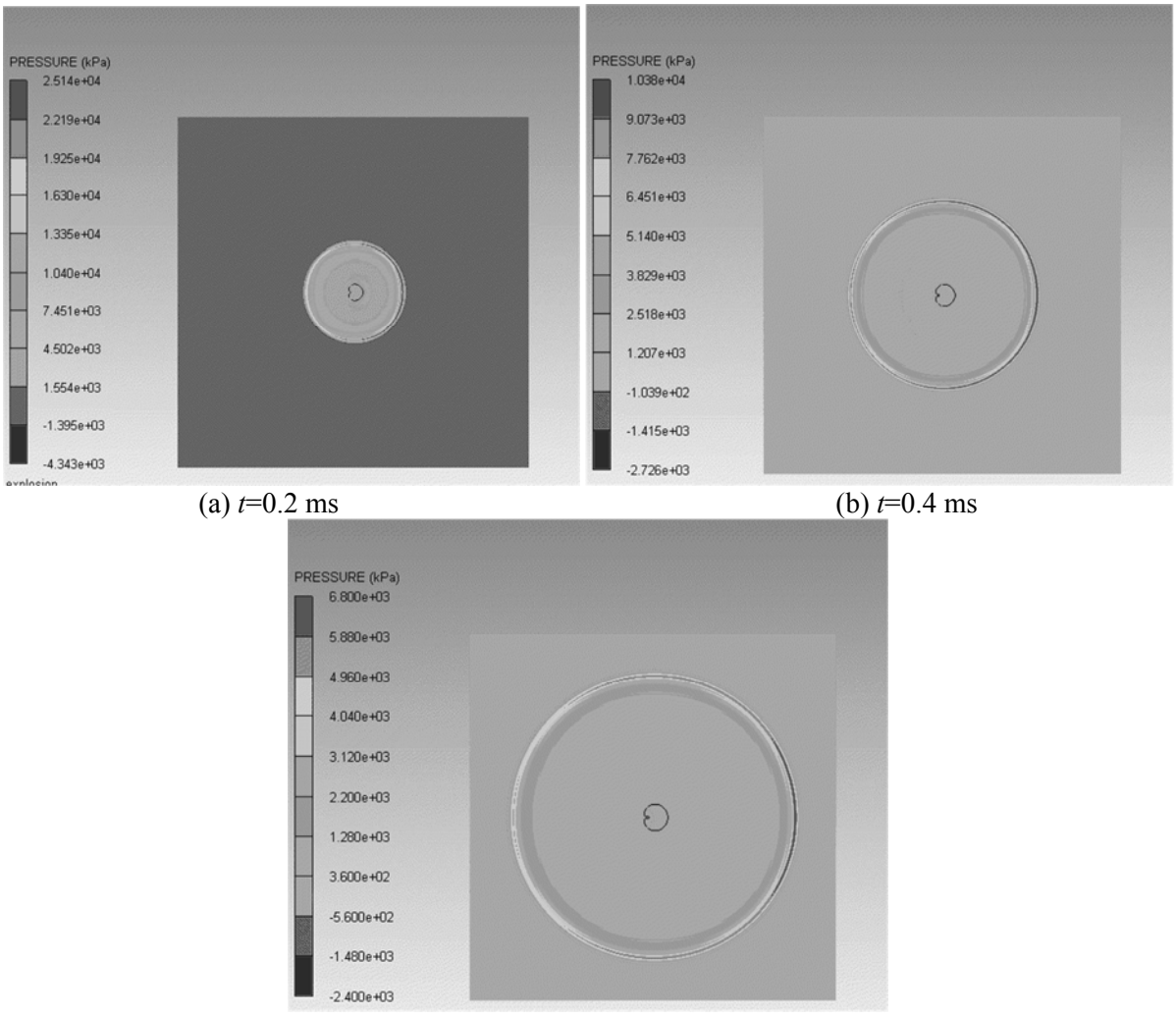
For 200 m/s and 1400 m/s, the pressure cloud diagrams at different times of explosion are shown in Fig. 4 and 5. Observing the process of dynamic explosion, the shock wave pressure field appears uneven when the explosive is turned from static to dynamic explosion. The shock wave pressure in the direction of the moving velocity is greater than that in the opposite direction. The explosion product also moves forward and the rear end of the explosion product is sunken. The influence of velocity on the explosion shock wave in the direction of φ=0° is shown in Fig. 6.



(a) t=0.2 ms (b) t=0.4 ms

(c) t=0.6 ms

Figure 4. Pressure fields of TNT explosion at 200 m/s



(a) t=0.2 ms (b) t=0.4 ms

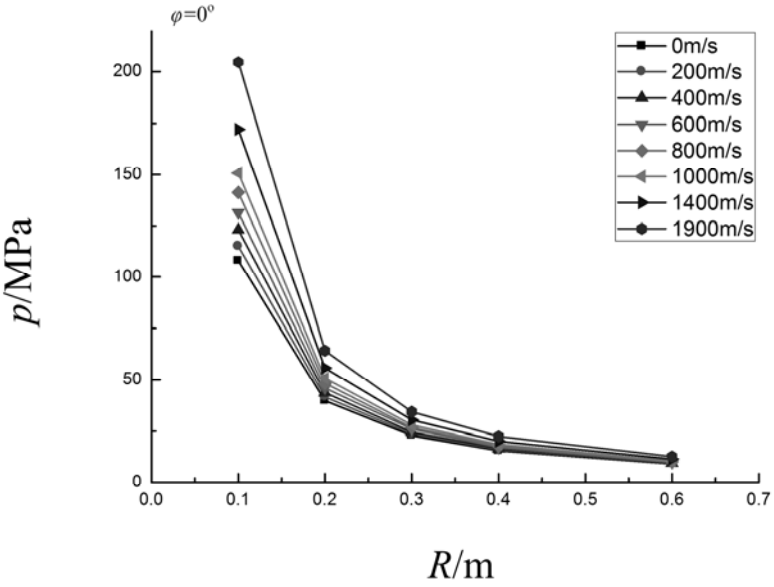
(c) t=0.6 ms

Figure 5. Pressure fields of TNT explosion at 1400 m/s

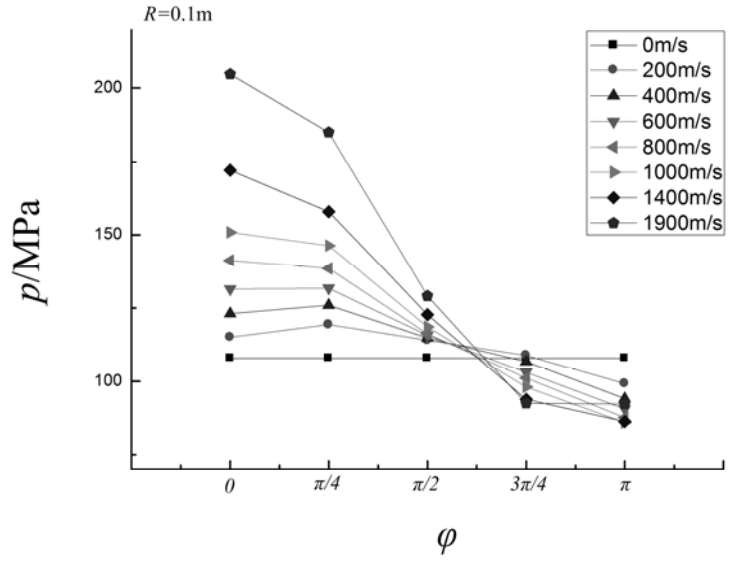
4. Results and Discussion

As shown in Fig. 6(a), while the velocity of motion at φ=0° and R=0.1 m increases from 0 m/s to 200 m/s, 800 m/s, 1400 m/s, the peak overpressure of the shock wave increases from 108 MPa to 115.1 MPa, 141.2 MPa, and 172 MPa, and the amplitudes are 6.5%, 30.7%, and 59.3%. The results indicate that velocity has a significant influence on the peak overpressure of the underwater explosion shock wave. At φ=0° and R=0.6 m, the peak overpressure increases from 9 MPa to 9.2 MPa, 10.2 MPa, and 11.4 MPa, and the amplitudes are 2.2%, 13.3%, and 26.7%, respectively, indicating that the farther away from the explosion center, the smaller the influence of velocity on the peak overpressure.

The directivity of the moving velocity results in the non-uniformity of the explosion field, and the influence is shown in Fig. 6(b). With the increase of velocity, the peak overpressure at the points of R=0.1m, φ=0°, 45°, 90° are larger than the static explosion conditions. While φ=135° 180°, the peak overpressure is smaller than the static explosion conditions except for the condition of u_0=200 m/s.



(a) influence of velocity on peak overpressure



(b) influence of velocity on uniformity

Figure 6. Influences of different velocities on shock wave

There is a critical angle of peak overpressure variation caused by the velocity, which decreases with the increase of velocity. At 200 m/s, the critical angle is between 135° and 180°. When the velocity increases, the critical angle is between 90° and 135°. The decreasing amplitude of the peak overpressure in the direction of 135° and 180° decrease with the increase of the velocity. The peak overpressure in the direction of 180° decreases with the increase of the velocity. When the velocity exceeds 1400 m/s, the peak overpressure increases with the increase of the velocity. The peak overpressure in the directions of φ=135° and 180° become closer with the increase of the velocity, in-dicating that the faster the explosive velocity, the smaller the influence of the velocity on the shock wave field in the region of 135° to -135° behind the shock wave field.

The relationship between the peak overpressure and the square of the velocity is shown in Fig. 7. It can be seen that the peak overpressure of the dynamic explosion underwater is basically proportional to the square of the velocity, that is, proportional to the kinetic energy of the explosive.

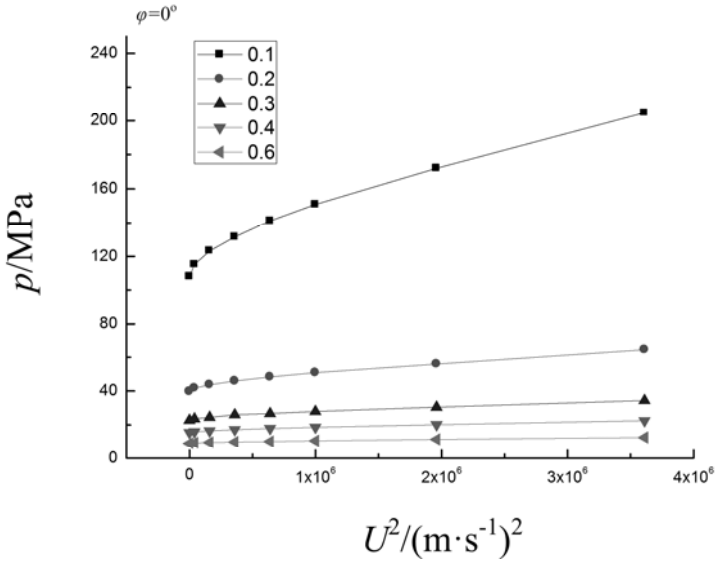


Figure 7. Relation between peak overpressure and the square of velocity

Based on the Cole empirical formula, a formula for dynamic explosion underwater can be obtained by converting the explosive kinetic energy into an equivalent static dose. We have

$$P_{\mathrm{m}} = k\left(\frac{W_{\mathrm{be}}^{1/3}}{R}\right)^{\alpha} \tag{4}$$

Where W_{be} is the equivalent static dose $W_{\mathrm{be}} = \dfrac{Q_{\mathrm{v}} + \frac{1}{2}u_{\mathrm{o}}^2}{Q_{\mathrm{v}}}W$ [7].

In the direction of 0°, the relative errors between the empirical formula of the peak overpressure in water and the numerical simulation results are shown in Tab. 1.

Table 1. Relative error between the peak overpressure calculation results of Empirical formula and numerical simulation (%)

distance (m) / velocity (m/s)	0.1	0.2	0.3	0.4	0.6
0	-1.4	22.3	35.6	44.4	56.3
200	-7.3	16.9	30.7	39.9	52.5
400	-12.9	12.2	26.5	36.3	48.0
600	-17.6	7.6	20.5	32.1	45.5
800	-22.4	3.7	18.4	28.5	42.1
1000	-26.3	0	15.2	25.4	38.9
1400	-33.0	-5.7	9.6	20.1	34.0
1900	-40.4	-13.3	2.6	13.5	28.1

As shown in Tab. 1, the errors are larger than 28% at R=0.6 m, which are consistent with the results in the verification of the numerical model when $R/W^{1/3}\geq 1$. The errors of other distances are mostly within 30% or even 10%, which indicate that the results of numerical simulation are relatively consistent with the results of the empirical formula, verifying the validity of the formula (4). But the formula requires further verification of test data.

5. Conclusions

Based on AUTODYN, the simulations of dynamic explosion underwater at different velocities are carried out. Combined with the empirical formula for comparative analysis, the following conclusions can be drawn:

The explosive velocity has a significant influence on the shock wave field. As the velocity increases, the peak overpressure of the shock wave increases in the direction of the explosive motion, but decreases in the opposite direction. When the position is farther away from the explosion center, the influence of velocity on the peak overpressure is smaller. The peak overpressure of dynamic explosion underwater is basically proportional to the kinetic energy of the explosive. By converting the kinetic energy of the explosive into an equivalent static dose, the Cole empirical formula can be used to calculate the peak overpressure underwater in the direction of the explosive motion.

The velocity of the explosive results in non-uniformity of the shock wave field. The critical angle of the peak overpressure variation decreases with the increase of the velocity. At 200 m/s, the critical angle is between 135° and 180°. When the velocity increases, the critical angle is between 90° and 135°. The faster the explosive velocity, the smaller the influence of the velocity on the shock wave field in the region of 135° to -135° behind the shock wave field.

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