Effect of Computational Parameters on Output Properties of Underwater Explosion by Intelligent Numerical Simulation

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Abstract. The computational parameters are of great influence on underwater explosion load. A one-dimensional wedge model is established to analyze the influence of boundary condition (BC), water domain and mesh density on the numerical simulation results. The results show that flowout BC is rigid boundary and transmit BC is not suitable for simulating the collapses phase of bubble pulsation. According to propagation distance of shock wave and its reflected wave, a simple method to calculate appropriate water domain is proposed. A positive correlation between mesh density ($\lambda$) and calculated peak pressure of shock wave ($P_m$) is found. When $\lambda$ tends to infinity, simulated $P_m$ in near field is quite reliable, but the values in relatively far field are lower than empirical results.

Keywords: Numerical simulation, Boundary condition, Water domain, Mesh density.

1. Introduction

The field of underwater explosion (UNDEX) and shock physics are both complex and fascinating. In order to reveal the truth of UNDEX event, many systematic theoretical analyses, mechanism experiments had been carried out since the early twentieth century [1-3]. Researchers found that an UNDEX can cause significantly more damage to targets than the same amount of explosive in air, which is of great value to underwater blasting [4].

Due to the complexity and high cost of UNDEX, numerical simulation has become an effective technology tool with the development of numerical simulation methods and computer technique. Barras modeled the bubble dynamics with Arbitrary Lagrange-Euler (ALE) formulation, and discussed the influence of domain size and boundary conditions [5]. With ALE adaptive numerical method, Pishevar tried to alleviate mesh-associated computational difficulties and locally improve accuracy in UNDEX simulations [6]. Moreover, some literatures showed grid density, equation of state, artificial viscosity can affect the computational results [7-9]. Although these studies put forward some recommendations on selecting computational conditions, they often gave qualitative descript rather than expected range of values.

In this paper, one-dimensional (1D) wedge model of a spherical TNT UNDEX is established. In order to obtain correct results, the effects of boundary condition, water domain and mesh density on the characteristics of shock wave and bubble pulse are studied in detail.
2. Methods

2.1. Computational model
The hydrocode AUTODYN can be used to simulate free field UNDEX to research shock wave propagation and bubble pulsation. Utilization of symmetry conditions allows the 3D spherical portion to be represented by an 1D axisymmetric wedge model in AUTODYN. This procedure not only reduces calculation time but also increases its accuracy due to the fine 1D mesh resolution, which is appropriate to model UNDEX phenomena and interactions with surrounding water.

The water and high explosive are both meshed with Euler grids, in which the materials can flow through them. The detonation point is located at the center of explosive charge. The Jones-Wilkens-Lee (JWL) equation of state (EOS) is often used to describe pressure-volume-energy relationship of detonation products of TNT [10]. The Polynomial EOS is used to describe the p-v-e relationship of water medium.

2.2. Empirical formulas
Cole et al. derived and fitted empirical formulas for the peak pressure of shock wave and bubble pulsation parameters, which are expressed as

\[
\Delta P_m = \begin{cases} 
4.41 \times 10^7 \left( \frac{W^{1/3}}{R^{1/5}} \right)^{1.5} & 6 \leq R / R_0 < 12 \\
5.24 \times 10^7 \left( \frac{W^{1/3}}{R^{1/13}} \right) & 12 \leq R / R_0 < 240
\end{cases}
\]  

(1)

\[
R_{\text{max}} = 3.383 \left( \frac{W}{h + 10.3} \right)^{1/3}
\]  

(2)

\[
T = 2.11 \frac{W^{1/3}}{(h + 10.3)^{5/6}}
\]  

(3)

Where \( \Delta P_m \) is the peak overpressure of shock wave, Pa; \( R \) is the detonation distance, m; \( W \) is the weight of TNT, kg; \( R_0 \) is initial radius of explosive charge, m; \( R_{\text{max}} \) is the maximum radius of bubble, m; \( h \) is the charge depth, m; \( T \) is the first pulsation period of bubble, s.

3. Results and Discussion

3.1. Influence of boundary conditions
A finite computational model is often established to simulate infinite problem in order to control the calculation scale within a certain range. Thus, special “artificial” boundary conditions (BCs) have to be set at the outer boundary of the finite computational domain, which are flowout BC and transmit BC and default BC. Here, the influence of these three BCs on UNDEX shock wave and bubble is compared and analyzed.

A series of 1D wedge mesh models are constructed and three BCs are set for each of it, respectively. The 50 g spherical TNT explosive is located in the center of 9000mm water domain. The pressure curves at \( R = 8950 \text{mm} \) are shown in Figure 1(a), as well as bubble radii \( r \) changing with time \( t \) are shown in Figure 1(b). It can be seen that the waveforms including reflected waves and \( r-t \) curves are completely coincident when adopting flowout BC and default BC. This means that flowout BC is the same as default BC, which is rigid boundary. When adopting transmit BC, there is no obvious reflected wave in the calculation shown in Figure 1(a), which indicates that transmit BC does work in 1D wedge model. However, severe oscillation coming from the boundary makes \( r-t \) curve no longer smooth in the collapse phase. Further comparison shows that starting time of oscillation is close to that of bubble collapse. This indicates that transmit BC is not suitable for simulating the collapses phase of bubble pulsation, which is consistent with the viewpoints of [11].
3.2. Influence of water domain

According to previous section, it can’t achieve ideal results in the 1D wedge model only relying on BCs. Therefore, it is important to determine a suitable water domain to balance the accuracy and efficiency. Based on the dynamic compatibility conditions, the shock wave propagation velocity $U$ can be expressed as

$$ U = \left( \frac{\rho}{\rho_0} \right) \frac{p - p_0}{\rho - \rho_0} + u_0 $$

(4)

Where $\rho_0$, $u_0$, $p_0$ are the density, velocity and pressure of the fluid in front of the shock wavefront; $\rho$, $u$, $p$ are the density, velocity, and pressure of the fluid immediately behind the shock wavefront. When $p$ and $u_0$ are given, in conjunction with the EOS of water, $U$ can be obtained. For the incident wave, $u_0$ is equal to 0, and $p$ can be expressed by Eq. (1). The results show that $U$ is less than 1500 m/s when $R > 90 R_0$. For the reflected wave, $|u_0|$ is always less than 20 m/s when $R > 600$ mm according to numerical calculation. In order to simplify the calculation process, the average speed $\bar{U}$ of incident wave is set to 1500 m/s, so does reflected wave. Therefore, if the reflected wave does not affect the first bubble pulsation, the radii of water domain $L$ is expressed as

$$ L \geq \frac{1}{2} \int_0^T U dt \approx \frac{\bar{U}T}{2} = \frac{2.11\bar{U}}{2} \frac{W^{1/3}}{(h+10.3)^{5/6}} $$

(5)

Figure 2. The trends of $R_{\text{max}}$ and $T$ with the increase of $\xi$
Similarly, if only the expansion stage of the bubble is considered, \( L \) should not be less than \( \bar{U}/4 \) approximately. In order to verify the correctness of results above, \( L \) is set to 10, 20, 30, 40, 50, 55, 60, 65 and 70 m respectively. And the results of \( R_{\text{max}} \) and \( T \) under different water domains are plotted in Figure 2, where \( \xi = L/\bar{U} \). It can be seen that simulated \( R_{\text{max}} \) and \( T \) no longer change when \( \xi \geq 1/4 \) and \( 1/2 \) respectively, which are consistent with the results above. Obviously, the conclusions can apply to the experimental design.

### 3.3. Influence of mesh density

The mesh density has an important influence on the results of numerical simulation. When the mesh density tends to infinity, the truncation error is zero. If omitting rounding error and observation error, the numerical simulation results equal to the exact solutions of mathematical models.

To study the influence of mesh density on the calculation results of UNDEX shock wave, the mesh sizes \( \Delta L \) are set to be 2.0, 1.5, 1.2, 1.0, 0.8, 0.6, 0.5, 0.4, 0.3, 0.2, 0.15 and 0.1 mm respectively. Here, two dimensionless variables \( \lambda = R_0/\Delta L \) and \( Z = R/R_0 \) are used to characterize the mesh density and detonation distance respectively. An outstanding advantage of \( \lambda \) is that \( \Delta P_m-Z \) curve does not change with the charge mass, when \( \lambda \) is constant [8].

![Figure 3. The influence of mesh density on the peak pressure](image)

The results of \( \Delta P_m \) under different \( \lambda \) are shown in Figure 3. It can be found that \( \Delta P_m \) increases with the increase of \( \lambda \), and the tendency gradually decreases. A power function (Eq. (6)) is used to fit the relationship between \( \Delta P_m \) and \( \lambda \) (see Figure 3). The R-squares are all greater than 0.99, indicating that the fitting results are good.

\[
\Delta P_m = a \lambda^b + c \tag{6}
\]

Since \( b \) is always less than 0, \( \Delta P_m \) is equal to \( c \) when \( \lambda \rightarrow +\infty \). Therefore, the exact solutions of the model are the values of \( c \). Assuming the Eq. (1) can describe the exact solutions of practical problem, the error between the results of Eq. (1) and the values of \( c \) is the model error between computational model and practical problem, which is shown in Figure 4. It can be seen that when \( 6 < Z < 16.5 \), \( |E| \) is less than 5%; when \( Z > 20.6 \), \( |E| \) is larger than 10%. The maximum \( |E| \) is 18.68% when \( Z = 74.15 \) and the average value of \( |E| \) is equal to 13.5%. It shows that even if mesh density is infinite, the error of simulated \( \Delta P_m \) in the far-field (\( Z > 16.5 \)) cannot fall within 5%, while simulated \( \Delta P_m \) only in relatively near field is more reliable.
4. Conclusions

By using 1D wedge UNDEX model, the influence of boundary condition, water domain and mesh density on the numerical simulation results are discussed. Three BCs are all appropriate to calculate initial shock wave. Flowout BC and default BC are functionally consistent, which can reflect wave to affect the bubble pulsation. Transmit BC can weaken the reflected wave but is not suitable for simulating the collapses phase of bubble pulsation due to the oscillation from boundary. To balance calculation accuracy and efficiency, a simple method to determine water domain is proposed by calculating propagation distance of shock wave and its reflected wave. With the increase of mesh density, calculated $\Delta P_m$ increases. When $\lambda$ tends to infinity, simulated $\Delta P_m$ in near field ($Z$) is quite reliable, but the values in relatively far field are lower than empirical results.

Acknowledgments

This work was financially supported by national key research program fund.

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