Applied Ocean Research 59 (2016) 1–9

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

On the determination of the mesh size for numerical simulations of shock wave propagation in near field underwater explosion

Gaohui Wang[a,*], Yongxiang Wang[b], Wenbo Lu[a], Wei Zhou[a], Ming Chen[a], Peng Yan[a]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[b] Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, NY 10027, USA

ARTICLE INFO

Article history:
Received 18 February 2016
Received in revised form 30 April 2016
Accepted 19 May 2016

Keywords:
Mesh size effects
Underwater explosion
Shock wave propagation
Near field

ABSTRACT

It is well known that the accuracy of mesh-based numerical simulations of underwater explosion strongly relies on the mesh size adopted in the analyses. Although a numerical analysis of underwater explosion can be performed with enough accuracy by using considerably fine meshes, such fine meshes may lead to substantially increase in the CPU time and the usage of computer memory. Thus, how to determine a suitable mesh size in numerical simulations is always a problem confronted when attempting to study the shock wave propagation resulting from underwater explosion and the subsequent response of structures. Considering that there is currently no universally accepted method for resolving this problem, this paper aims to propose a simple method to determine the mesh size for numerical simulations of near field underwater explosion. To this end, the mesh size effects on the shock wave propagation of underwater explosion are carefully investigated for different charge weights, through which the correlation between mesh sizes and charge weights is identified. Based on the numerical study, a dimensionless variable (λ), defined as the ratio of the radius of charge to the side length of element, is introduced to be the criterion for determining the mesh size in simulations. It is interesting to note that the presented method is suitable for various charge weights. By using the proposed meshing rule, adequate balance between solution accuracy and computational efficiency can be achieved for different blast scenarios in numerical simulations of underwater explosion.

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1. Introduction

In recent years, there has been an increasing number of accidental explosions and terrorist attacks against different types of civilian and military facilities, especially since the 9.11 incident. Along with the development of advanced and threatening underwater weapons, the research and engineering communities have given significant attention to the dynamic response and damage mechanism of submerged structures [1–8] (e.g. marine structures, offshore structures, submarines, and dam structures) subjected to underwater explosion. Given the extreme nature of this physical problem, both the experimental and numerical analyses can be performed to investigate it. For blast experiments, specialized equipment and labor are required, making them fairly expensive and time-consuming. Furthermore, environmental protection concerns also put another constraint on underwater explosion testing.

In recent decades, numerical methods such as the finite element method (FEM) and the finite volume method (FVM) have been developed and successfully applied to analyze the transient response of submerged structures when exposed to shock loadings. As important tools for the prediction of blast effects, the accuracy of these mesh-based methods for underwater explosion simulations strongly depends on the mesh size used for the analyses. Although using extremely fine mesh sizes (usually a few millimeters to tens of millimeters) for blast analyses can ensure enough accuracy of the numerical results, the usage of such fine meshes is limited by the dimensions of the investigated problems and the capacities of computer and software. For example, one of the major features in the numerical simulation of blast wave propagation in large dam-water-foundation environments is the use of an adequate mesh size. It is impossible to use a mesh size of millimeters for this blast scenario at the current development level of computers. Thus, a method to determine the mesh size for cost-efficient yet reliable numerical simulations is of practical importance.

To date, several scholars have studied the mesh size effects in numerical simulations of blast wave propagation. Krauthammer and Otani [9] investigated the influence of mesh size, gravity and

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* Corresponding author.
E-mail address: wanggaohui@whu.edu.cn (G. Wang).

http://dx.doi.org/10.1016/j.apor.2016.05.011
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static load in the numerical simulation of reinforced concrete structures under the work of explosion shock loading. The study showed that the mesh size has a significant influence on the deformation and stress of structures. Chapman et al. [10] investigated the effects of mesh size on blast wave propagation. They found that a 3 mm mesh size provides a good blast wave shape. Luccioni et al. [11] discussed the effects of mesh size on pressures and impulses produced by blast loads. They believed that a 100 mm mesh is accurate enough for the analysis of shock wave propagation in urban environments. A model with coarse mesh can only be used to simulate explosion load propagation law qualitatively in a complex environment such as in the city. Shi et al. [12] studied the effects of mesh size (from 5 mm to 200 mm) on numerical results of blast wave propagation with a charge of 1000 kg TNT. They pointed out that a 100 mm mesh size is good enough to provide an accurate prediction of wave front arrival time and positive incident peak pressure at a scaled distance of 2 m/kg$^{1/3}$. Subsequently, a numerical modification method was proposed to correct the influence of the mesh size on the simulation results. Kim and Shin [13] established three test models (25–1000 mm, 400 mm, 25–200 mm, respectively) to analyze the sensitivity of numerical results for the explosive and seawater mesh sizes. They suggested that the mesh size of the explosive should be less than about 25 mm. Nam et al. [14] checked the mesh size dependency of finite element blast structural analysis. They found that the mesh sensitivity of blast analysis is not only influenced by the mesh size, but also affected by the explosive characteristics such as the amount of explosive and standoff distance. Shin et al. [15] performed a mesh refinement study to establish mesh sizes for air blast calculations. They recommend that a mesh size of $\bar{r}R/500$ should be sufficient to accurately predict overpressure histories in the near field, where R is the charge radius, $\bar{r}$ is the ratio of the distance of the shock front from the center of the charge to the charge radius, and the near field is defined as $1 < \bar{r} \leq 10$. Huang et al. [16] presented the mesh size effects on the peak pressure and impulse of underwater explosion using a one-dimensional 'wedge' model. In their study, different mesh sizes are used for various ranges of charge weights.

Apart from the aforementioned studies of mesh size effects in underwater explosion simulations, many researchers have also investigated the shock wave propagation characteristics and the dynamic response of structures to blast loadings with sufficient meshes. Their results show that the suitable mesh size for numerical analyses is blast scenario dependent. Wang et al. [17] used a 10 mm mesh size to investigate the shock wave propagation characteristics and cavitation effects of underwater explosion near boundaries. Zhou and Hao [18] used 500 mm and 250 mm element sizes to study the mesh sensitivity and to calibrate the accuracy of the numerical results. Although the model with 500 mm and 250 mm element sizes fails to capture the very sharp peak of the blast wave, using the mesh size of 250 mm gives a very good estimation of impulses. Foglar and Kovar [19] chose a 30 mm mesh size for concrete and reinforcement and 50 mm mesh size for air to study the blast resistance of fiber reinforced concrete and reinforced concrete bridge decks subjected to 25 kg of TNT charges. They found that the usage of smaller elements for both the concrete and air increases the calculation time enormously, but does not increase the quality of the results. Thiagarajan et al. [20] investigated the response and behavior of doubly reinforced concrete slabs subjected to blast loads with the mesh size of 25.4 mm. Wang and Zhang [21] studied the dynamic response and damage characteristics of concrete gravity dams subjected to underwater explosion with 100–200 mm mesh sizes. In their model, 100 mm element size is used for the high explosive and water in the central part of the charge. The mesh size increases gradually away from the charge center. Tang and Hao [22] conducted a numerical convergence test on various mesh sizes (1.56 mm, 3.13 mm, 6.25 mm, 12.5 mm and 25.0 mm), and found that the 6.25 mm mesh size yields similar results with the smaller meshes tested under close proximity explosion load. When they performed numerical simulations of dynamic responses of a large cable-stayed bridge to blast loads, the 6.25 mm mesh is used only at positions close to the blast center. Mesh size then increases gradually as the distance from the blast center increases. Jen and Tai [23] addressed the transient responses of a stiffened panel subjected to underwater shock loads using a 60 mm mesh size. Although these studies give some recommendations on selecting the suitable mesh size, further study is still needed to determine the proper mesh size for different blast scenarios, which may lead to substantial savings in computational time and computer memory.

In this study, an approach to determine the mesh size in numerical simulations of underwater explosion with relatively close scaled distance is proposed with different blast scenarios accounted for. The numerical simulations are carried out by using the two-dimensional axisymmetric model provided by the hydrocode AUTODYN [24]. As the departure point of the proposed approach, the mesh size effects on the shock wave propagation of underwater explosion are carefully investigated for different charge weights, through which the correlation between mesh sizes and charge weights is identified. Inspired by the analysis results, a dimensionless variable (λ), which is defined as the ratio of the radius of charge to the side length of element, is given as the criterion for the determination of the mesh size used in simulations. The range of the λ value is suggested to ensure an adequate balance between solution accuracy and computational efficiency for different blast scenarios in underwater explosion simulations.

2. Material models

Two kinds of materials are involved in the problem under investigation, namely, the high energy charge and the water. The Eulerian method is employed to model both the materials, where the space grid is fixed but the materials are allowed to flow through it. The finite volume method (FVM) is used to solve the Euler equation. The solver computes the effective volume closed by the element faces. The fluid flow characteristics such as mass, pressure, velocity, and specific internal energy in the closed volume are calculated at each time step by the conservation laws of mass, linear momentum, and energy, which are given as follows

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho \mathrm{d}V + \int_A \rho(\mu \times n)\,\mathrm{d}A = 0 \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho\mu_\mathrm{i} \mathrm{d}V + \int_A \rho\mu_\mathrm{i}(\mu \times n)\,\mathrm{d}A = -\int_A pn_i \mathrm{d}A \tag{2}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho E \mathrm{d}V + \int_A \rho E(\mu \times n)\,\mathrm{d}A = -\int_A \mu \times pn\mathrm{d}A \tag{3}$$

where ρ is the material density, V is the volume, A is the area, μ is the velocity vector, n is the normal vector of the element face, p is the pressure, E is the specific total energy. The fluid flow characteristics at each time step are obtained by applying Eqs. (1)–(3) to the material inside an Eulerian element and by specifying how transport terms are computed.

2.1. The equation of state for explosive

A rapid chemical reaction is triggered in high explosive process, which converts the charge into high pressure gas. In most hydrodynamic calculations involving detonation, the standard Jones, Wilkins, and Lee (JWL) equation of state [24] is the preferred choice for the equation of state for high-energy explosives and thus used

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