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Research article

Study on the mesh size determination method of blast wave numerical simulation with strong applicability

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ABSTRACT

With the rapid development of computer hardware and software technology, numerical simulations have become one of the most important tools for studying propagation law of blast wave. Results of numerical simulations of explosion events greatly depend on the mesh size. The mesh size determination methods in the literature are relatively weak in generality. In this paper, a mesh size determination method with strong applicability is proposed. According to this method, the mesh size is the product of the scale coefficient and the third root of the equivalent TNT mass. The scale coefficient is related to the model dimension, scaled distance and simulation accuracy, and is independent of the TNT shape and the location of the detonation point. A large number of numerical simulation results confirm the accuracy of this method. The recommended scale coefficient to meet the engineering accuracy requirements is related to the model dimension and scaled distance. In general, when the scaled distance and model dimension are larger, the recommended scale coefficient will be larger. In this paper, the figures and tables of the recommended scale coefficients of 1D, 2D and 3D models varying with the scaled distance are given, and their rationality is verified by the existing numerical simulation events of blast wave. They can be used as a reference to determine the mesh size in numerical simulation of blast wave.

1. Introduction

Explosion will produce high-temperature and high-pressure gaseous detonation products at the moment, and cause blast wave in the surrounding air, which will make the surrounding structures bear large instantaneous load. It is of great significance for the anti-explosion analysis and design of engineering structures to accurately determine the blast wave parameters such as peak overpressure, maximum impulse and positive overpressure duration. At present, the formulas and charts given by scholars and institutions to determine these parameters mainly focus on the explosion in free air. Most other explosion conditions require special experimental research or numerical simulation. According to a large number of test results, Henrych [1] gave the calculation formulas of peak overpressure, positive phase hold time and positive scaled impulse of spherical TNT explosion in free air. UFC3-340-02 [2] gave curves of positive phase shock wave parameters versus scaled distance for a spherical TNT explosion in free air and a hemispherical TNT explosion on the surface at sea level. Yoshio Nakayama et al. [3] experimentally studied the explosion of large-scale and small-scale underground magazine model and confirmed the blast similarity law outside the underground magazine model. C. Fouchier et al. [4] experimentally at laboratory scale investigated blast wave propagation in the straight street, the T-junction, the cross junction, and the

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channeling. The test research is costly, labor-intensive, long cycle, dangerous, and cannot record the whole propagation process of the shock wave. The numerical simulation is low in cost, low in risk, and not limited by the space size and time length. It can provide complete data and clear graphics, save a lot of manpower and financial resources, reduce the test workload, and even replace some field tests that cannot be carried out [5]. However, the numerical simulation is time-consuming, and the accuracy of the results is greatly affected by the model algorithm, material constitutive relationship and mesh size. With the development of numerical simulation technology of blast wave, the model algorithm and material constitutive relationship have been developed relatively well. There are mainly *C*-J model and ZND model to describe explosive detonation process [6]. According to *C*-J model, the chemical reaction in the detonation process is completed instantaneously on infinite thin discontinuities. The initiation time of each point is determined according to the distance from each point on the explosive to the initiation point and the detonation velocity of the explosive. The original explosive is transformed into detonation reaction products instantaneously. Without considering the details of chemical reaction, the role of chemical reaction is reflected in the energy equation of fluid mechanics as if an additional energy is added. The *C*-J model can ensure sufficient accuracy in engineering. According to the ZND model, the unreacted explosive undergoes a shock wave pre-compression process at first, forming a compressed state of high temperature and high density, and then starts the chemical reaction. After a certain period of time, the chemical reaction ends, reaching the final state of the reaction. The ZND model needs to input the parameters of the explosive reaction rate equation and the JWL equation parameters of the unreacted explosive. For most explosives, these parameters lack sufficient test data support. In the numerical simulation of blast wave, the *C*-J model is basically used for the detonation process, the JWL equation of state is basically used for explosives and detonation products, the ideal gas equation of state is basically used for air, and the advertising algorithms are basically second order [7,8]. Under the condition that the mesh size of the model is appropriate, more accurate calculation results can be obtained. Therefore, the reasonable value of mesh size becomes an important factor that affects the simulation accuracy and the simulation time.

The main parameters of blast shock wave are affected by the mesh size differently. Positive phase impulse, positive phase hold time, and wave front arrival time are less affected by mesh size, while peak overpressure is greatly affected by mesh size [9–11]. Therefore, if the mesh size can ensure the accuracy of peak overpressure, it can also ensure the accuracy of other shock wave parameters. Some scholars have given the best mesh size to accurately calculate the peak overpressure of a specific TNT mass at a specific scaled distance [9,12–15]. Some scholars have further given the recommended mesh size for accurately calculating the peak overpressure of TNT with specific dimensions, specific shapes and arbitrary mass in a specific scaled distance range [16–22]. Some scholars have proposed a method to correct the low accuracy results obtained by using a larger grid size [10,23]. Some scholars have proposed a method of mesh size division based on progressive enlargement [21,24]. Some scholars have analyzed the relationship between model size and mesh size [25–27]. Some scholars have explored the influence of different mesh sizes of TNT and air on peak overpressure [15,25,28].

In the above-mentioned study on the mesh size of blast wave numerical simulation, the simulation software used by scholars mainly includes AUTODYN、LS-DYNA、ABAQUAS, etc. The dimensions of the model are one-dimensional, two-dimensional and three-dimensional. The explosive type is mainly TNT. The shape of the explosive is mainly spherical, cubic and cylindrical. The propagation medium of the blast wave is mainly air and water. Because of the different simulation software, model dimension, explosive shape, and the range of scaled distance, the recommended mesh size determination method proposed by scholars has a certain limitation and scope of application. Taking literature [10] and literature [12] as example, it is found that when the simulation software adopts AUTODYN, the TNT mass is 1000 kg, the shape is spherical, the scaled distance is 1 m/kg$^{1/3}$, and the peak overpressure simulation value is about 0.8 MPa, the mesh size required for the one-dimensional model given in Ref. [10] and three-dimensional model given in Ref. [12] is about 10 mm and 100 mm respectively. It can be seen that the mesh size required to obtain approximately the same simulation results at the same scaled distance for TNT of the same mass using different dimension models is quite different. Therefore, it is necessary to systematically study the mesh size determination of 1D, 2D and 3D models.

Inspired by the literature [16–22] and the blast similarity law [29,30], The purpose of the present study is to propose a more applicable method for determining the mesh size, as shown in Eq. (1). This method is not limited by charge shape and software type. It can be used for one-dimensional model, as well as two-dimensional and three-dimensional models. Therefore, it is widely applicable compared with the methods in the existing literature.

$$h_i = n_i \sqrt[3]{W} (mm) \tag{1}$$

Where: *i* represents the dimension of the model; for the one, two and three-dimensional models, *i* takes 1, 2 and 3 respectively; h_i and n_i represent the mesh size and scale coefficient of the *i*-dimensional model, respectively; W represents the mass of TNT in kg.

The meaning of this formula is that when the same dimension model uses different TNT mass for numerical simulation, different mesh sizes need to be used, and the mesh size is basically equal to the third root of TNT mass multiplied by the same scale coefficient. The simulation accuracy, scaled distance and model dimension should be considered when selecting the scale coefficient. In this paper, AUTODYN software will be used to discuss the accuracy of the mesh size determination formula in 1D, 2D and 3D models, and give the recommended scale coefficient at different scaled distances where the simulation accuracy meets the engineering requirements, so as to obtain the recommended mesh size. Then, the formula is applied to the explosion simulation conditions given in other literatures to determine the recommended mesh size of numerical simulation. The recommended mesh size obtained by using the formula proposed in this paper is compared with the mesh size given in other literatures to further verify the rationality of the formula in this paper.

When using AUTODYN software to simulate TNT detonation and shock wave propagation in free air, it mainly involves Euler multi-material algorithm, TNT and air material model and corresponding state equation, non-reflective boundary condition, etc. [8,31] The research of Chapman et al. [23] shows that the default values of AUTODYN can be used for the parameters of materials and equation of state to obtain better simulation results without changing the parameter values. Other scholars [10,15,18] who used AUTODYN to simulate blast wave also adopted the default parameter values and achieved good simulation results.

2. Numerical analysis model

In free air, the spherical explosive will diffuse outward in a spherical shape along the radius of the sphere from the initiation position after initiation. One dimensional centrosymmetric model and two-dimensional axisymmetric model can be used to simulate the three-dimensional diffusion of the blast wave, which will greatly reduce the number of meshes and improve the calculation efficiency. In this paper, the explosion of spherical TNT in free air is analyzed by using the one-dimensional wedge model and two-dimensional axisymmetric rectangular model [8] in the Euler 2D multi-material model provided by AUTODYN, as shown in Figs. 1 and 2. Both models involve high explosive TNT and air. The flow out boundary condition is set at the boundary of the air to allow the air to flow out, thus simulating the infinite boundary of the air medium.

For the three-dimensional simulation of blast wave, AUTODYN software provides remapping technology [8]. This technology can map and reproduce the calculation results of the one-dimensional model into the three-dimensional model to form the three-dimensional blast wave that continues to propagate in the three-dimensional model. In this paper, the one-dimensional numerical model adopts the one-dimensional wedge model [8] in the Euler 2D multi-material model provided by AUTODYN, as shown in Fig. 3. Length of the model $R_1 = 0.5\sqrt[3]{W}\,(m)$, Where 0.5 is the scaled distance, the unit is $m/kg^{1/3}$ and W is the TNT mass. The three-dimensional model adopts the Euler 3D ideal gas cube model [8] provided by AUTODYN, as shown in Fig. 4. The model is symmetrical about the x = 0, y = 0 and z = 0 planes, and the gauges are arranged along the x axis. At the lower corner of the left front side of the 3D model, that is, the point where x = y = z = 0, the one-dimensional model remapping file is imported. Flow out boundary conditions are set on the three surfaces far from the lower corner of the left front side to allow air to flow out, thus simulating the infinite boundary of the air medium.

The detonation process of TNT follows the Chapman – Jouguet (C – J) theory. The multi-material Euler-Godunov second-order solver is used for the 1D and 2D calculations [32]. This solver was developed following techniques initially developed by van Leer and is used for purely fluid and gas dynamic calculations or highly distorted structural materials. The single material Euler-FCT higher order solver is used for the 3D calculations [32]. This solver is based on the operator split algorithms and is used for single material gas dynamic problems.

High explosive TNT adopts JWL equation of state [8,33], as shown in Eq. (2).

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{2}$$

Where, P is hydrostatic pressure, V is relative volume, E is energy density, A, B, R_1, R_2 and ω are all material constants. When the explosive volume after explosion is more than 10 times of its initial volume, the program automatically converts its state equation into the ideal gas state equation for calculation. The default values of AUTODYN are used for all parameters in the equation. Among them, the initial density of TNT is 1.63 g/cm^3, and other material parameters adopt the values given by Lee et al. [34], as shown in Table 1.

Air adopts ideal gas equation of state [8,35], as shown in Eq. (3).

$$p = (\gamma - 1)\rho E \tag{3}$$

Where p is hydrostatic pressure, γ is the adiabatic index, ρ is the mass density and E is the energy density. The default values of AUTODYN are used for each parameter, as shown in Table 2.

3. Analysis of influence of mesh size on simulation results

3.1. Peak overpressure test value

Based on a large number of test data, henrych [1] gave the Equation of peak overpressure P_S of incident shock wave after explosion of spherical TNT in free air, as can be seen in Eq. (4).

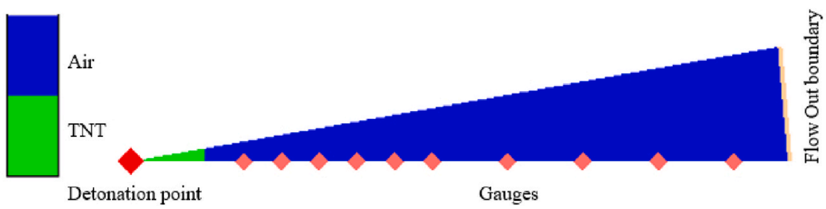

Fig. 1. 1D wedge model of spherical TNT explosion in free air.

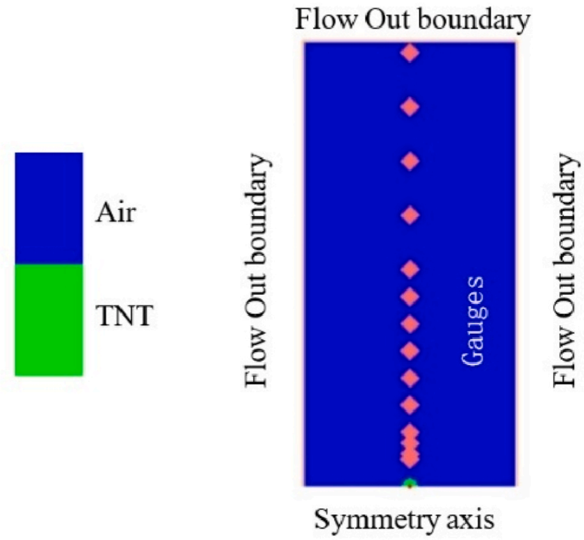

Fig. 2. 2D axisymmetric model of spherical TNT explosion in free air.

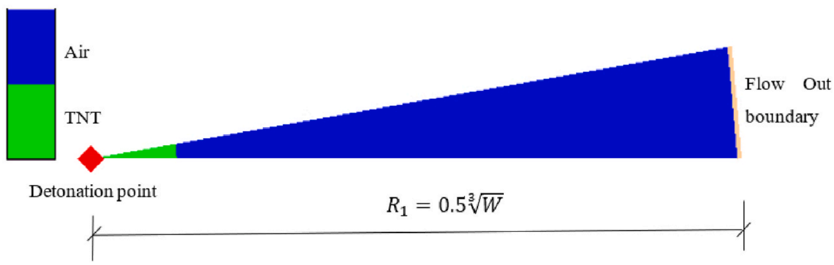

Fig. 3. 1D wedge model.

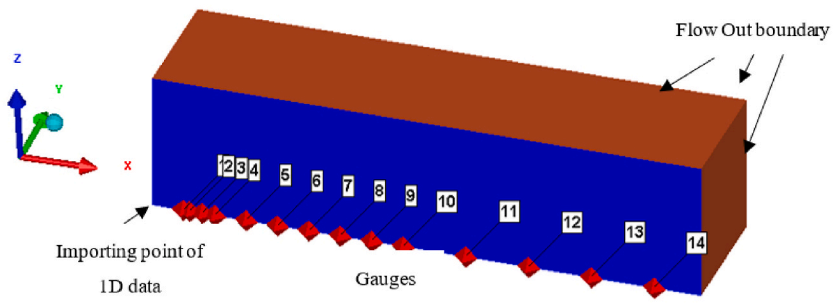

Fig. 4. 3D cube model.

Table 1
Explosive material parameters.

A (GPa)	*B* (GPa)	ω	R_1	R_2
373.75	3.747	0.35	4.15	0.90

Table 2
Ideal gas material parameters.

γ	P (kg/m^3)	E (J/kg)
1.4	1.225	2.068×10^5

$$P_S = \begin{cases} \frac{1.40717}{Z} + \frac{0.55397}{Z^2} - \frac{0.03572}{Z^3} + \frac{0.000625}{Z^4}, 0.05 \le Z \le 0.3 \\ \frac{0.619}{Z} - \frac{0.033}{Z^2} + \frac{0.213}{Z^3}, 0.3 \le Z \le 1 \\ \frac{0.0662}{Z} + \frac{0.405}{Z^2} + \frac{0.3288}{Z^3}, 1 \le Z \le 10 \end{cases} \quad (4)$$

Where, Z is the scaled distance, in m/kg$^{1/3}$; The unit of P_S is MPa.

UFC3-340-02 [2] also gives the relationship between the peak overpressure P_S test value of incident shock wave and the scaled distance Z after the explosion of spherical TNT in free air, as shown in Fig. 5. The unit of peak overpressure P_S in the figure is psi, and the unit of scaled distance is ft/lb$^{1/3}$. The units of peak overpressure and scaled distance can be converted into MPa and m/kg$^{1/3}$ respectively according to the following conversion Eqs. (5) and (6).

$$1(\text{psi}) = 0.006895(\text{MPa}) \quad (5)$$

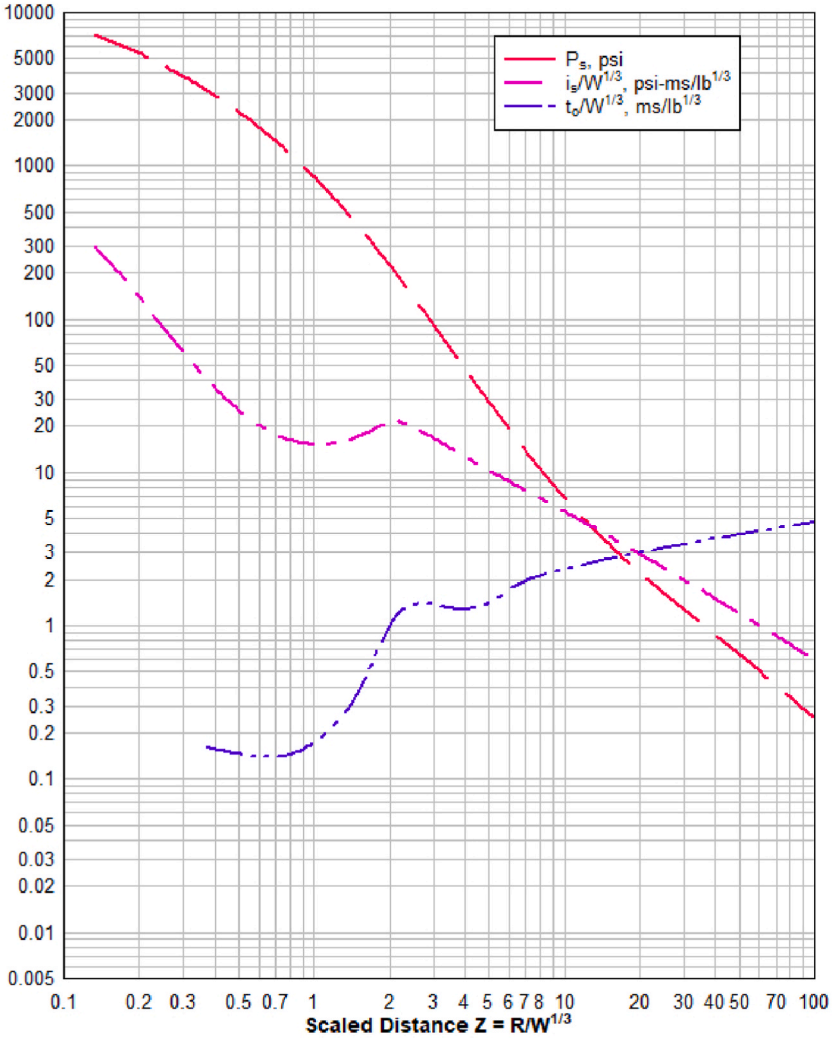

Fig. 5. Incident shock wave parameters of spherical TNT after explosion in free air.

$$1\left(\mathrm{ft}/\mathrm{lb}^{1/3}\right)=0.3969\left(\mathrm{m}/\mathrm{kg}^{1/3}\right) \tag{6}$$

According to the peak overpressure value and unit conversion Eqs. (5) and (6) given in UFC3-340-02, the peak overpressure value at the scaled distance Z of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7 and 8 $m/kg^{1/3}$ can be obtained through interpolation calculation. According to Henrych Eq. (4), the peak overpressure values at these scaled distances can also be obtained, which are plotted together with the values given by UFC3-340-02 and shown in Fig. 6. It can be seen from this figure that the smaller the scaled distance, the greater the difference between the two. When the scaled distance is greater than 0.4 $m/kg^{1/3}$, the difference between the two is very small. This result is attributed to the difficulty in testing the overpressure value of the adjacent explosive, and the accurate value cannot be obtained. Huang [36] pointed out that the overpressure test technology near the explosive charge surface is difficult, and the corresponding speed of the conventional overpressure test system is too slow to obtain the correct overpressure value. So far, there is no empirical formula that can better express the distribution of shock wave pressure field near the explosive core. Esparza E [37] also pointed out that when the scaled distance is less than 0.4 $m/kg^{1/3}$, the direct measured value of explosion shock wave parameters hardly exists. Rigby S E et al. [38] further pointed out that the semi empirical prediction data in this range are almost entirely based on parametric studies. Therefore, only within the range of 0.5–8 $m/kg^{1/3}$ of the scaled distance, the value given by UFC3-340-02 is taken as the reference for the accuracy of the peak overpressure simulation value.

3.2. Different TNT mass with the same mesh size

When the mesh size h of 1D model is 60 mm, and the TNT mass is 8, 27, 64 and 512 kg respectively, the overpressure time history curve at the scaled distance of 1 $m/kg^{1/3}$ is shown in Fig. 7. When the mesh size h of 2D model is 40 mm, and the TNT mass is 8, 125 and 512 kg respectively, the overpressure time history curve at the scaled distance of 0.5 $m/kg^{1/3}$ is shown in Fig. 8.

It can be seen from Figs. 7 and 8 that the greater the TNT mass, the closer the peak overpressure simulation value is to the value given by UFC3-340-02, and the greater the wave front arrival time t_A. The main parameter values of the overpressure time history curve and the relative errors with the values given in UFC3-340-02 are shown in Tables 3 and 4 respectively. It can be seen from these tables that although the wave front arrival times differ greatly when the TNT mass is different, $t_A/W^{1/3}$ is relatively close, and the relative error between the simulated value of $t_A/W^{1/3}$ and the value given by UFC3-340-02 decreases with the increase of TNT mass. In addition, the relative error between the peak overpressure simulation value and the value given by UFC3-340-02 is significantly greater than the relative error between the $t_A/W^{1/3}$ simulation value and the value given by UFC3-340-02. Therefore, the peak overpressure is the most sensitive to the mesh size, which is consistent with the conclusions of several literatures [9,10,39].

When the mesh size h of the 1D model is 60 mm and the TNT mass is 8, 27, 64 and 512 kg respectively, the relative error between the peak overpressure P_S numerical simulation value and the value given by UFC3-340-02 with the scaled distance is shown in Fig. 9. When the mesh size h of the 2D model is 40 mm and the TNT mass is 8, 125 and 512 kg respectively, the relative error between the peak overpressure P_S numerical simulation value and the value given by UFC3-340-02 with the scaled distance is shown in Fig. 10. When the mesh size h of the 3D model is 80 mm, the mesh size of the corresponding 1D model is 2 mm, and the TNT mass is 8, 125 and 512 kg respectively, the relative error between the peak overpressure P_S numerical simulation value and the value given by UFC3-340-02 with the scaled distance is shown in Fig. 11.

It can be seen from Figs. 9 and 10 that the relative error between the maximum TNT mass of 512 kg and the minimum TNT mass of 8 kg is nearly 2 times when the scaled distance is 0.5 $m/kg^{1/3}$. It can be seen from Fig. 11 that the relative error between the maximum TNT mass of 512 kg and the minimum TNT mass of 8 kg is nearly 5 times when the scaled distance is 0.5 $m/kg^{1/3}$. In general, when the mesh size is the same, the greater the TNT mass, the smaller the relative error between the numerical simulation results and the test

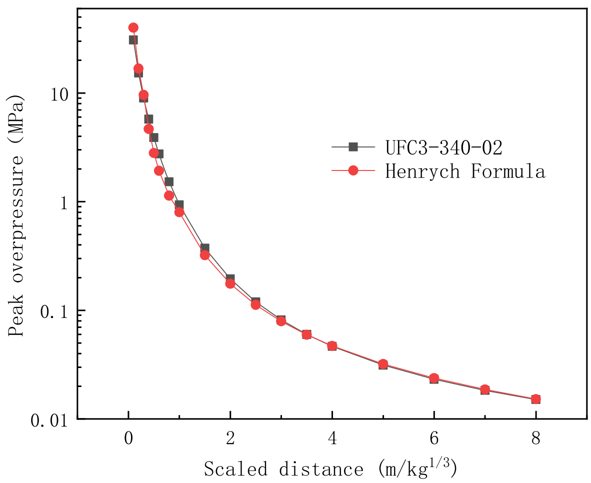

Fig. 6. Relationship between explosion peak overpressure test value of spherical TNT in free air and scaled distance.

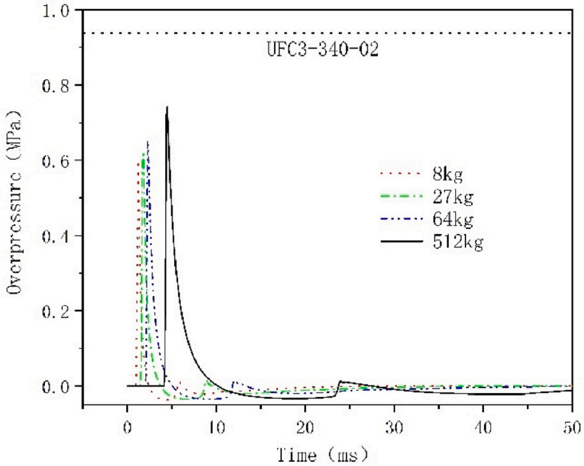

Fig. 7. Overpressure time history curve of 1D model with mesh size of 60 mm.

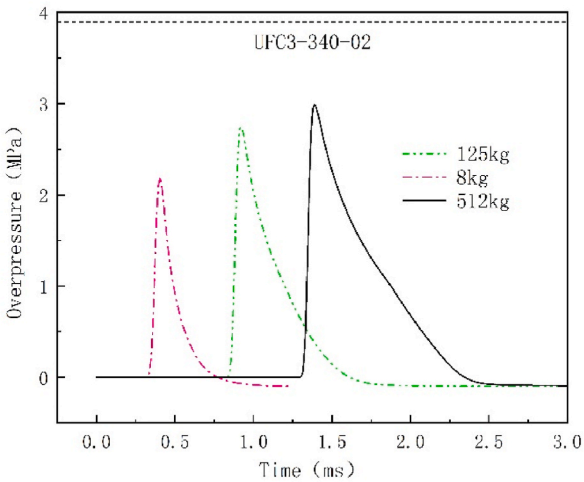

Fig. 8. Overpressure time history curve of 2D model with mesh size of 40 mm.

Table 3
Main parameter values of overpressure time history curve of 1D model with mesh size of 60 mm and relative error with UFC3-340-02.

TNT mass W (kg)	8	27	64	512
Wave front arrival time t_A (ms)	1.204	1.813	2.312	4.506
Scaled wave front arrival time $t_A/W^{1/3}$ (ms/kg$^{1/3}$)	0.602	0.604	0.578	0.563
Relative error with UFC3-340-02 (%)	13.4	13.8	8.8	6.1
Peak overpressure P_S (MPa)	0.602	0.640	0.660	0.754
Relative error with UFC3-340-02 (%)	−35.7	−31.7	−29.5	−19.5

Table 4
Main parameter values of overpressure time history curve of 2D model with mesh size of 40 mm and relative error with UFC3-340-02.

TNT mass W (kg)	8	125	512
Wave front arrival time t_A (ms)	0.404	0.921	1.387
Scaled wave front arrival time $t_A/W^{1/3}$ (ms/kg$^{1/3}$)	0.202	0.184	0.173
Relative error with UFC3-340-02 (%)	31.2	19.6	12.6
Peak overpressure P_S (MPa)	2.159	2.78	2.97
Relative error with UFC3-340-02 (%)	−44.5	−28.5	−23.6

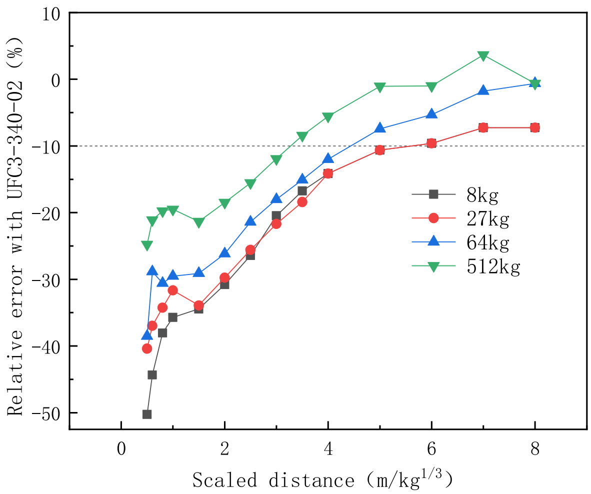

Fig. 9. Relationship between relative error of peak overpressure and scaled distance in 1D model with mesh size of 60 mm.

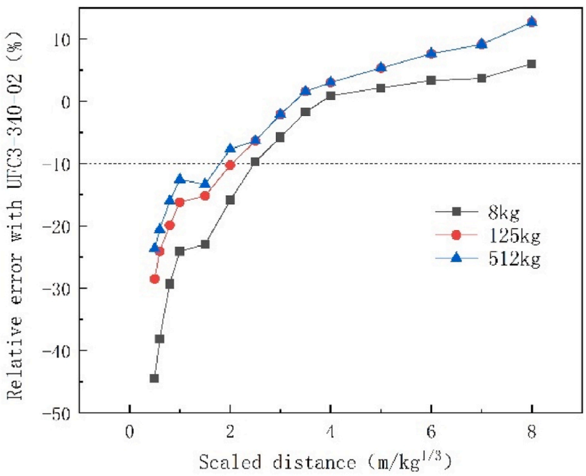

Fig. 10. Relationship between relative error of peak overpressure and scaled distance in 2D model with mesh size of 40 mm.

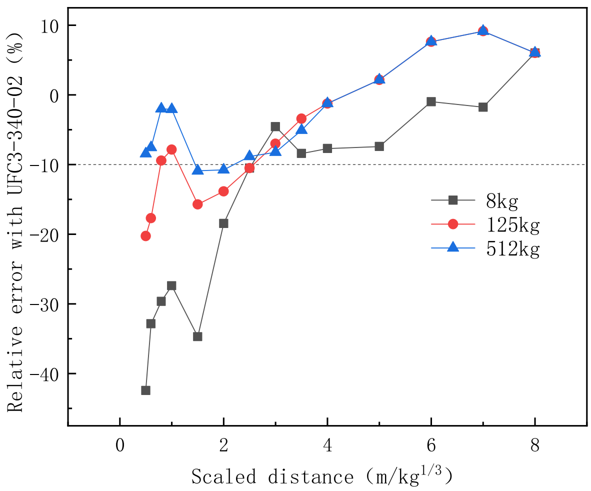

Fig. 11. Relationship between relative error of peak overpressure and scaled distance in 3D model with mesh size of 80 mm.

results.

These characteristics can be explained as follows. The physical quantities behind the detonation wave, such as pressure and energy density, are important to determine the initial condition for the blast wave propagation. In the numerical simulation, the physical quantities behind the detonation wave are greatly affected by the ratio of TNT mass to mesh size. The larger the ratio is, the larger the numerical simulation values of these physical quantities are and the closer to the actual values are. When the detonation front reaches the TNT/air interface, the blast shock wave with the physical quantities behind the detonation wave as the initial condition starts to propagate into the air. According to the relationship between the initial condition of blast shock wave and TNT mass and mesh size in numerical simulation, when the mesh size is the same, the greater the TNT mass, the greater the initial pressure of blast shock wave. Therefore, the greater the peak overpressure at the same scaled distance, that is, the smaller the relative error between the simulated value of peak overpressure and the test value of UFC340-02, as shown in Figs. 9 and 10.

3.3. Different mesh sizes for the same TNT mass

When the TNT mass of 1D model is 125 kg and the mesh size h is 5, 25, 50, 75 and 125 mm respectively, the overpressure time history curve at the scaled distance of 1 m/kg$^{1/3}$ is shown in Fig. 12. The main parameter values of the overpressure time history curve and the relative error with the values given by UFC3-340-02 are shown in Table 5. When the TNT mass of 2D model is 512 kg and the mesh size h is 8, 40, 80 and 200 mm respectively, the overpressure time history curve at the scaled distance of 0.5 m/kg$^{1/3}$ is shown in Fig. 13. The main parameter values of the overpressure time history curve and the relative error with the values given by UFC3-340-02 are shown in Table 6.

For any curve in Figs. 12 and 13, before the shock wave reaches the designated position, the pressure at that position is equal to the atmospheric pressure, that is, the overpressure is zero. When the shock wave arrives there, the pressure suddenly jumps from the atmospheric pressure to the maximum value, that is, the peak overpressure. After the wave front passes, the pressure drops rapidly, even lower than the atmospheric pressure, until it reaches the peak value of negative overpressure. The reason for the occurrence of negative overpressure is that the inertial motion of air particles caused by shock wave leads to the significant reduction of air density. Then the surrounding air flows there, and the pressure gradually rises to atmospheric pressure. It can be seen from Figs. 12 and 13 that the smaller the mesh size, the closer the peak overpressure simulation value is to the value given by UFC3-340-02, the smaller the wave front arrival time t_A, and the steeper the rising section of the curve, which is consistent with the conclusion given in literature [23].

It can be seen from Tables 5 and 6 that the scaled wave front arrival time and positive scaled impulse are less affected by the mesh size, and the peak overpressure is more affected by the mesh size. The simulation value of the positive scaled impulse of the 1D model given in Table 5 is significantly smaller than that given in UFC3-340-02, which is consistent with the simulation results in literature [23] and literature [10]. This may be because it is difficult to obtain accurate positive scaled impulse value through field test [10]. The simulation value of the positive scaled impulse of the 2D model given in Table 6 is slightly larger than that given by UFC3-340-02, which is completely different from the 1D situation in Table 5. At 0.5 and 1 m/kg$^{1/3}$, the positive scaled impulse given by UFC3-340-02 is 141.2 and 174.6 kPa ms/kg$^{1/3}$ respectively. The curve of the positive scaled impulse with the scaled distance decreases first, then increases, and then continues to decrease. As shown in Fig. 5, there is a minimum point and a maximum point. 0.5 and 1 m/kg$^{1/3}$ are just around the minimum and maximum points. Therefore, the simulation value of positive scaled impulse is slightly larger than the value given in UFC3-340-02 [2]. The research in literature [10] also shows that the positive scaled impulse simulation value is close to the value given by UFC3-340-02 at 0.4–0.7 m/kg$^{1/3}$, and the simulation value is far less than that given byUFC3-340-02 at 0.7~2 m/kg$^{1/3}$.

When the TNT mass W of the 1D model is 125 kg and the mesh size h is 5, 25, 50, 75 and 125 mm respectively, the relationship between the relative error of the peak overpressure P_S numerical simulation value and the value given by UFC3-340-02 and the scaled

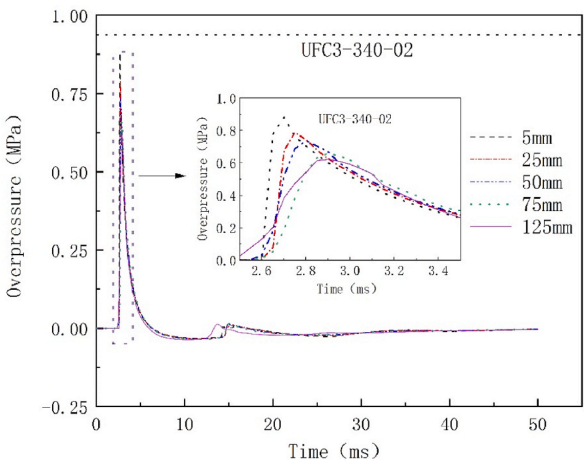

Fig. 12. Overpressure time history curve of 1D model with TNT mass of 125 kg.

Table 5
Main parameter values of overpressure time history curve of TNT mass 125 kg 1D model and relative error with UFC3-340-02.

Mesh size (mm)	5	25	50	75	125
Scaled wave front arrival time $t_A/W^{1/3}$ (ms/kg$^{1/3}$)	0.540	0.552	0.563	0.581	0.585
Relative error with UFC3-340-02 (%)	1.8	3.9	6.0	9.4	10.2
Peak overpressure P_S (MPa)	0.88	0.791	0.738	0.66	0.621
Relative error with UFC3-340-02 (%)	−6.0	−15.5	−21.2	−29.5	−33.7
Positive scaled impulse $i_S/W^{1/3}$ (kPa·ms/kg$^{1/3}$)	130.672	129.130	129.988	124.394	123.606
Relative error with UFC3-340-02 (%)	−25.2	−26.0	−25.6	−28.8	−29.2

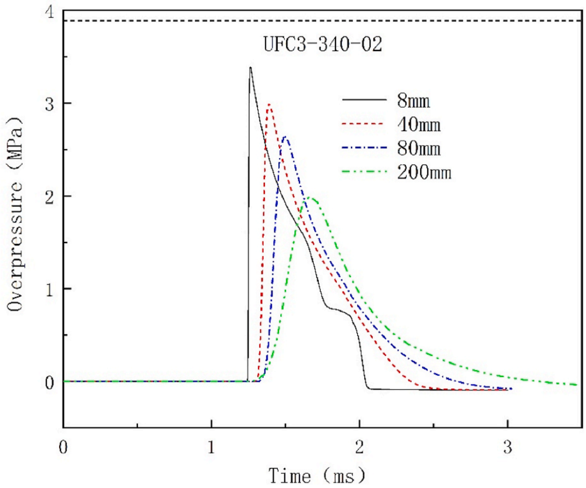

Fig. 13. Overpressure time history curve of 2D model with TNT mass of 512 kg.

Table 6
Main parameter values of overpressure time history curve of TNT mass 512 kg 2D model and relative error with UFC3-340-02.

Mesh size (mm)	8	40	80	200
Scaled wave front arrival time $t_A/W^{1/3}$ (ms/kg$^{1/3}$)	0.158	0.173	0.186	0.208
Relative error with UFC3-340-02 (%)	2.4	12.6	20.9	35.1
Peak overpressure P_S (MPa)	3.415	3.099	2.893	1.962
Relative error with UFC3-340-02 (%)	−12.2	−20.3	−25.6	−49.6
Positive scaled impulse $i_S/W^{1/3}$ (kPa·ms/kg$^{1/3}$)	150.575	150.4	149.375	147.488
Relative error with UFC3-340-02 (%)	6.6	6.5	5.8	4.4

distance is shown in Fig. 14. When the TNT mass W of the 2D model is 512 kg and the mesh size h is 8, 40, 80 and 200 mm respectively, the relationship between the relative error of the peak overpressure P_S numerical simulation value and the value given by UFC3-340-02 and the scaled distance is shown in Fig. 15. When the TNT mass W of the 3D model is 8 kg, the mesh size h is 20, 50 and 70 mm respectively, and the mesh size of the corresponding 1D model is 6 mm, the relationship between the relative error of the peak overpressure P_S numerical simulation value and the value given by UFC3-340-02 and the scaled distance is shown in Fig. 16.

It can be seen from Fig. 14 that when 5 mm mesh size is adopted in 1D model, the relative error is within ±10% at most scaled distances; at the scaled distance of 3 m/kg$^{1/3}$ or more for 25 mm mesh size, 3.5 m/kg$^{1/3}$ or more for 50 mm, 5 m/kg$^{1/3}$ or more for 75 mm, and 6 m/kg$^{1/3}$ or more for 125 mm, the relative error is all within ±10%. The relative error between the minimum mesh size of 5 mm and the maximum mesh size of 125 mm is nearly 5 times when the scaled distance is 0.5 m/kg$^{1/3}$. It can be seen from Fig. 15 that when 8 mm mesh size is adopted in 2D model, the relative error is within ±10% at most scaled distances; at the scaled distance of 2 m/kg$^{1/3}$ or more for 40 mm mesh size, 2.5 m/kg$^{1/3}$ or more for 80 mm, and 3 m/kg$^{1/3}$ or more for 200 mm, the relative error is all within ±10%. The relative error between the minimum mesh size of 8 mm and the maximum mesh size of 200 mm is nearly 5 times when the scaled distance is 0.5 m/kg$^{1/3}$. It can be seen from Fig. 16 that when 20 mm mesh size is adopted in 3D model, the relative error is within ±10% at most scaled distances; at the scaled distance of 3.5 m/kg$^{1/3}$ or more for 50 mm mesh size, and 2.5 m/kg$^{1/3}$ or more for 70 mm, the relative error is all within ±10%. The relative error between the minimum mesh size of 20 mm and the maximum mesh size of 70 mm is nearly 6 times when the scaled distance is 0.5 m/kg$^{1/3}$. Therefore, the mesh size has a great influence on the simulation accuracy of 1D, 2D and 3D numerical simulation of blast wave. In general, when the TNT mass is the same, the smaller the mesh size, the smaller the relative error between the numerical simulation results and the test results, that is, the higher the simulation accuracy.

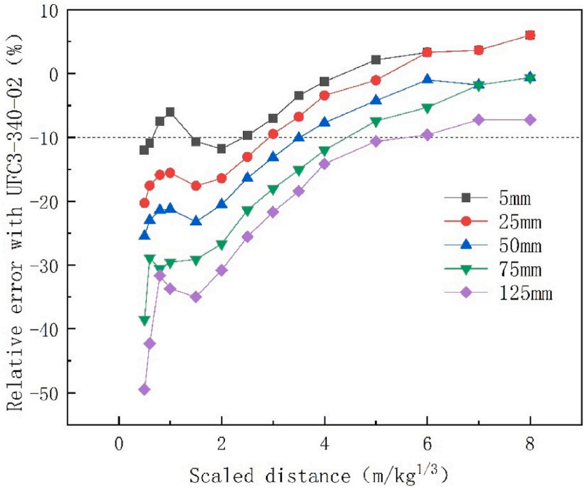

Fig. 14. Relationship between relative error of peak overpressure and scaled distance of 1D model with TNT mass of 125 kg.

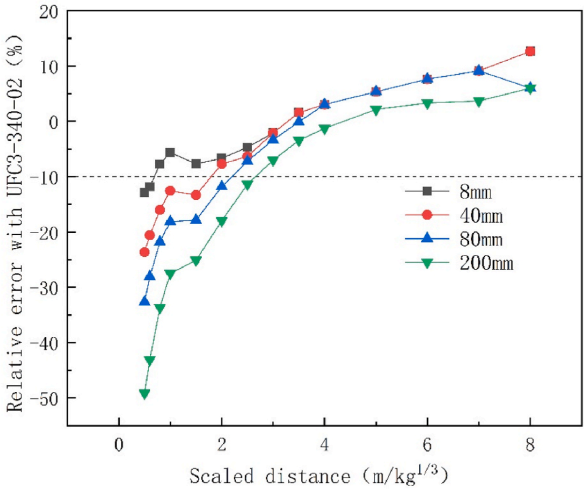

Fig. 15. Relationship between relative error of peak overpressure and scaled distance of 2D model with TNT mass of 512 kg.

The larger the scaled distance, the smaller the influence of mesh size on peak overpressure.

These characteristics can be explained as follows. The physical quantities behind the detonation wave, such as pressure and energy density, are important to determine the initial condition for the blast wave propagation. In the numerical simulation, the physical quantities behind the detonation wave are greatly affected by the ratio of TNT mass to mesh size. The larger the ratio is, the larger the numerical simulation values of these physical quantities are and the closer to the actual values are. When the detonation front reaches the TNT/air interface, the blast shock wave with the physical quantities behind the detonation wave as the initial condition starts to propagate into the air. According to the relationship between the initial condition of blast shock wave and TNT mass and mesh size in numerical simulation, when the TNT mass is the same, the smaller the mesh size, the greater the initial pressure of blast shock wave. Therefore, the greater the peak overpressure at the same scaled distance, that is, the smaller the relative error between the simulated value of peak overpressure and the test value of UFC340-02, as shown in Figs. 14 and 16.

4. Rationality verification of mesh size determination formula

In order to verify the rationality of the mesh size determination Eq. (1), the TNT mass W is taken as 8, 27, 64, 125, 343 and 512 kg in the 1D model, 8, 125 and 512 kg in the 2D and 3D model, the scale coefficients n_1 and n_2 are taken as 1, 2, 3, 4, 5, 6, 7, 10, 15, 20, 25 and 30, and the scale coefficients n_3 are taken as 10, 15, 20, 25, 30 and 35, respectively. The scale coefficient n_1 of the 1D model that provides mapping data for the 3D model is 3. Gauges are set at the scaled distances of 0.5, 0.6, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7 and 8 m/kg$^{1/3}$ of the three models respectively to record the peak overpressure value P_S. When the scale coefficients n_1, n_2 and n_3 are fixed to the same value respectively, the relative error curve of peak overpressure value corresponding to different TNT mass and the value

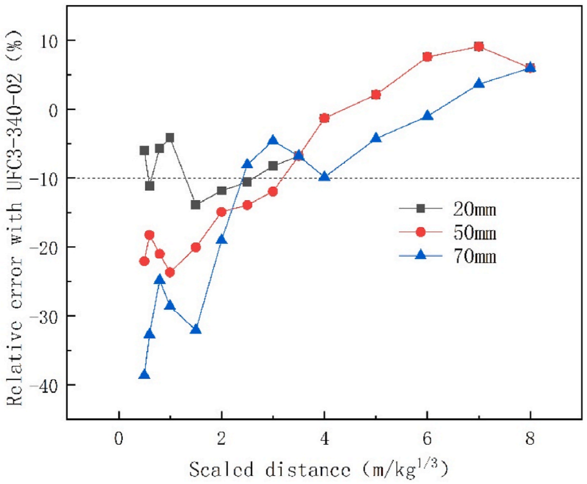

Fig. 16. Relationship between relative error of peak overpressure and scaled distance of 3D model with TNT mass of 8 kg.

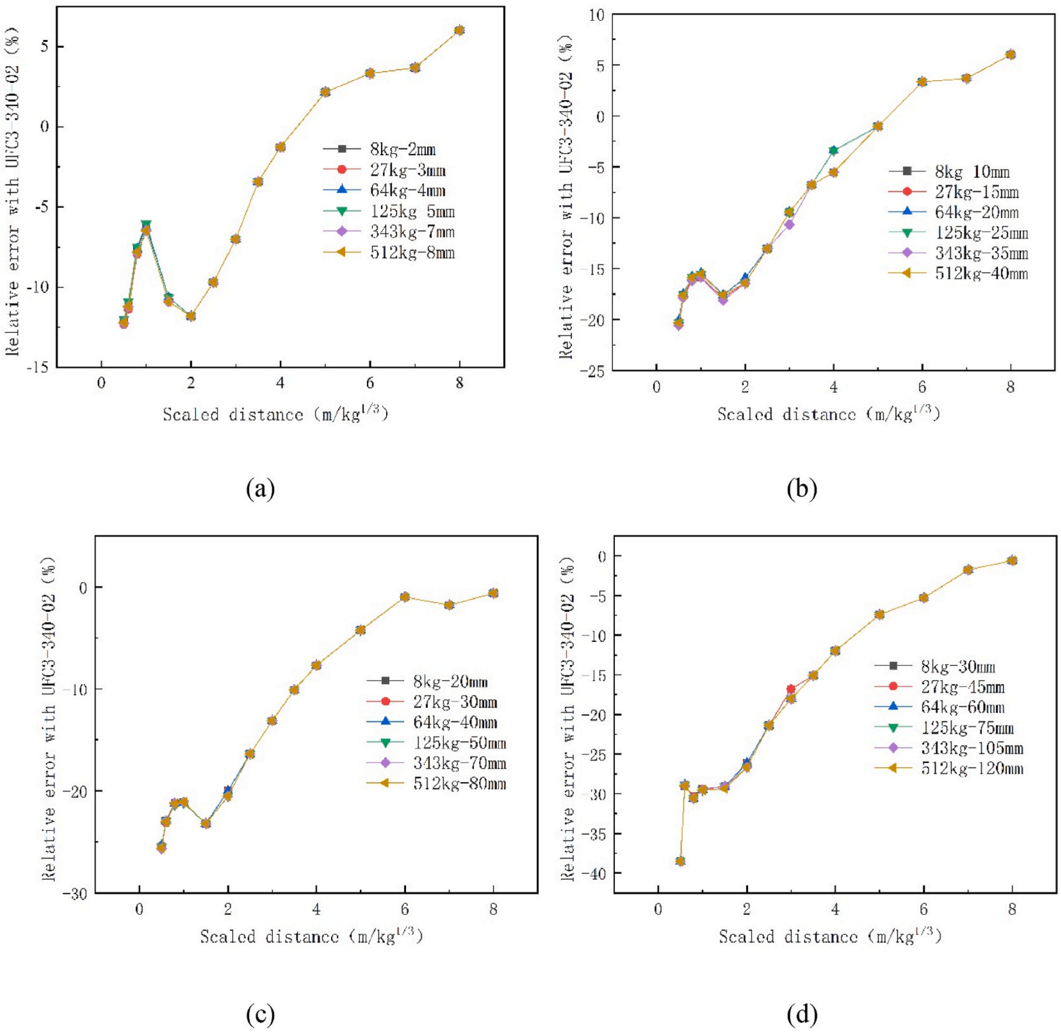

Fig. 17. Relationship between relative error of peak overpressure and scaled distance for different scale coefficients n_1 of 1D model (a) $n_1 = 1$; (b) $n_1 = 5$; (c) $n_1 = 10$; (d) $n_1 = 15$.

given by UFC3-340-02 with scaled distance basically coincides. Some curves are shown in Fig. 17(a-d)-19 (a-d). Fig. 17(a), (b), (c) and (d) give the Relationship between relative error of peak overpressure and scaled distance of 1D model for scale coefficients 1,5,10 and 15 respectively. Fig. 18(a), (b), (c) and (d) give the Relationship between relative error of peak overpressure and scaled distance of 2D model for scale coefficients 1,5,10 and 15 respectively. Fig. 19(a), (b), (c) and (d) give the Relationship between relative error of peak overpressure and scaled distance of 3D model for scale coefficients 10, 15, 20 and 30 respectively.

It can be seen from Fig. 17(a-d)-19 (a-d) that when the scale coefficient n_i of the three dimensional models is fixed to the same value respectively, and different TNT mass are numerically calculated using the mesh size determined by Eq. (1), the relative error between the peak overpressure simulation value and the value given by UFC3-340-02 is basically the same at the same scaled distance. That is to say, in order to obtain the simulation results with the same accuracy at the same scaled distance of the same dimension model, different TNT mass need to adopt different mesh sizes, and the mesh size is basically equal to the third root of explosive mass multiplied by the same coefficient. Therefore, the rationality of the mesh size determination Eq. (1) is verified.

It can also be seen from Fig. 17(a-d)-19 (a-d) that the relative error of peak overpressure is sensitive to the scaled distance and scale coefficient. Taking 1D model as an example, sensitivity analysis is carried out with the help of software Simlab to judge the influence of scaled distance and scale coefficient on simulation accuracy. Extended Fourier Amplitude Sensitivity Test method (Extended FAST) is chosen as sensitivity analysis method and the distribution of the parameters is discrete. The sensitivity indices of scaled distance and scale coefficient are 0.615 and 0.318 respectively. The interaction coefficients of scaled distance and scale coefficient are 0.694 and 0.397 respectively. Therefore, the scaled distance and scale coefficient have a great influence on the relative error of peak overpressure and have a great correlation with each other. For specific engineering accuracy requirements, it is important to find the relationship between the scale coefficient and the scaled distance for reasonably determining the mesh size.

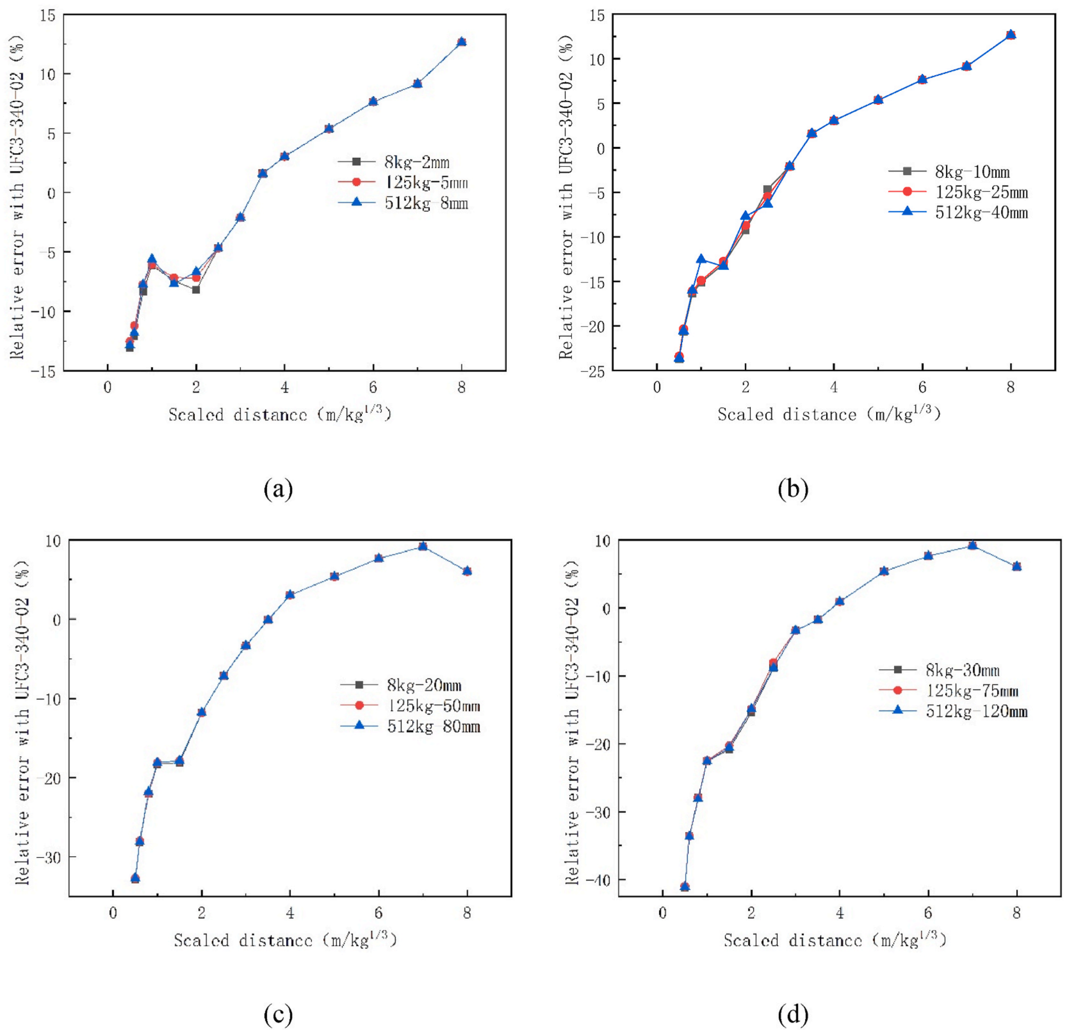

Fig. 18. Relationship between relative error of peak overpressure and scaled distance for different scale coefficients n_2 of 2D model (a) $n_2 = 1$; (b) $n_2 = 5$; (c) $n_2 = 10$; (d) $n_2 = 15$.

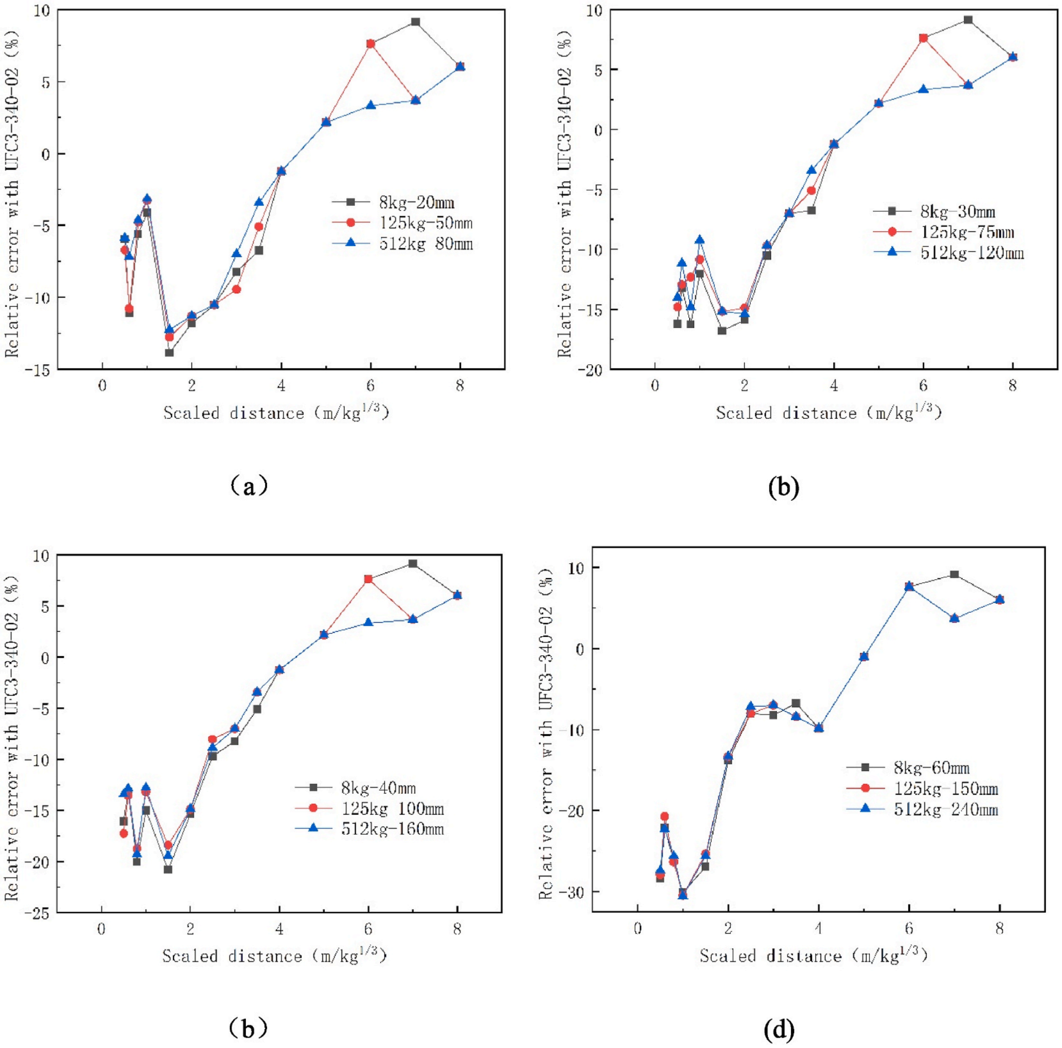

Fig. 19. Relationship between relative error of peak overpressure and scaled distance for different scale coefficients n_3 of 3D model (a) $n_3 = 10$; (b) $n_3 = 15$; (c) $n_3 = 20$; (d) $n_3 = 30$.

5. Recommended mesh size analysis

5.1. Calculation formula for recommended mesh size of 1D and 2D models

The relative error between the peak overpressure simulation value corresponding to different TNT mass and the UFC3-340-02 test value for 1D and 2D models at a specific scaled distance gradually decreases with the increase of the scale coefficient n_i. That is, the peak overpressure simulation value tends to decrease gradually, as shown in Fig. 20(a–d) and 21(a-d). The smaller the scaled distance, the smoother the trend. When the scaled distance is large, the trend appears as straight segments and spikes (drops), as shown in Fig. 21 (c) and (d). This shows that where the scaled distance is large, the relative error is less affected by the scale coefficient, and better simulation results can be obtained by using a larger scale coefficient. Meanwhile, at the spikes (drops), although the relative error of peak overpressure corresponding to two adjacent scale coefficients differs greatly, the difference of peak overpressure values is small. Taking Fig. 21(d) as an example, when n_2 is equal to 15 and 20, the corresponding relative error and peak overpressure are 5.3% and 2.2%, 0.033 MPa and 0.032 MPa, respectively. In the engineering field, the relative error is generally acceptable within ±10%. The reasonable scale coefficient n_{is} is defined as the relative error between the peak overpressure simulation value obtained by the scale coefficient and the value given by UFC3-340-02 is within ±10%. With the increase of scaled distance, the reasonable scale coefficient n_{is} tends to increase gradually.

The recommended scale coefficient n_{iR} is defined as almost the largest of the reasonable scale coefficients n_{is}. The recommended mesh size h_{iR} is defined as the product of the recommended scale coefficient n_{iR} and the third root of explosive mass $\sqrt[3]{W}$, as shown in Eq. (7).

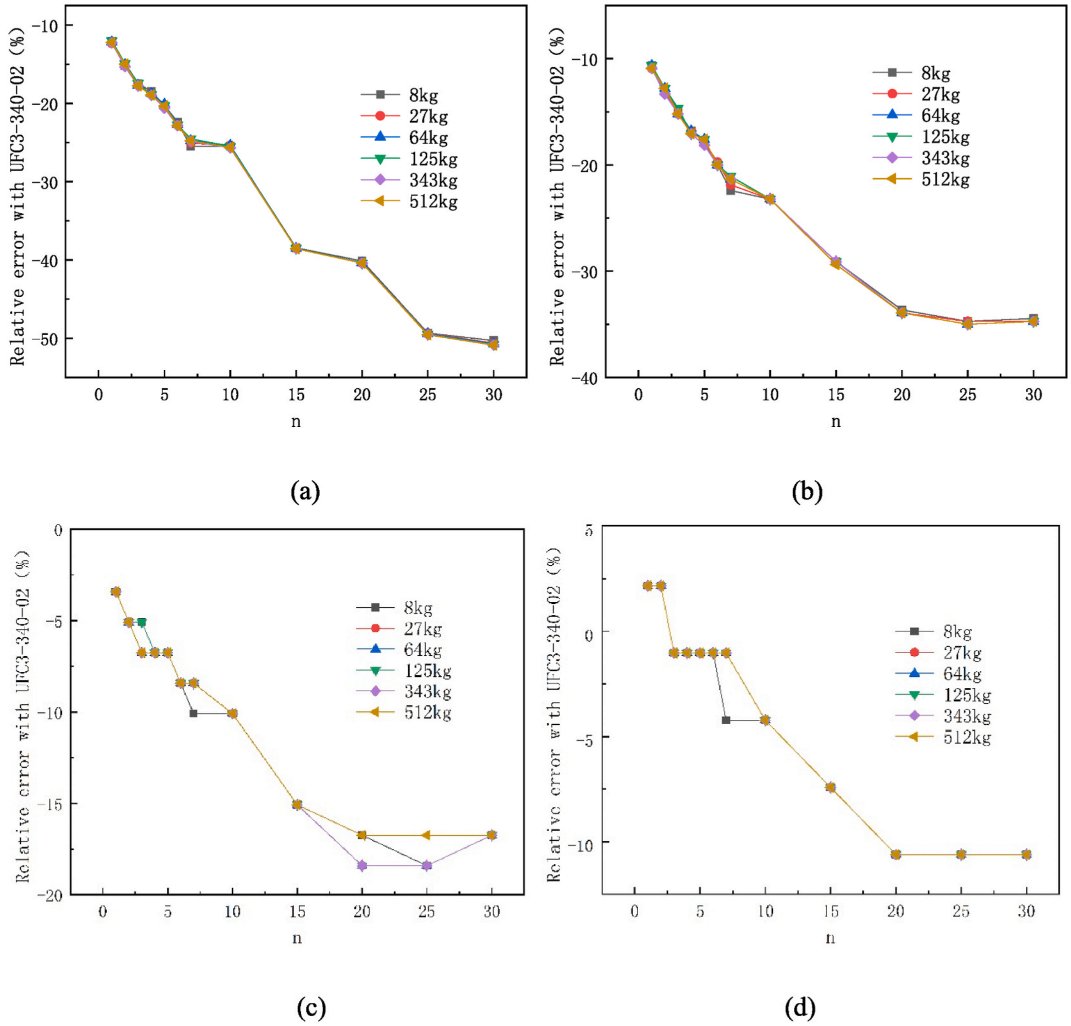

Fig. 20. Relationship between relative error of peak overpressure and scale coefficient for different scaled distances of 1D model (a) 0.5 m/kg$^{1/3}$; (b) 1.5 m/kg$^{1/3}$; (c) 3.5 m/kg$^{1/3}$; (d) 5 m/kg$^{1/3}$.

$$h_{iR} = n_{iR}\sqrt[3]{W}(mm) \quad (7)$$

When the scaled distance is less than 0.5 m/kg$^{1/3}$, it is difficult to accurately measure the peak overpressure value [36–38] through the test. The values given by various empirical formulas differ greatly [1,2], which is not suitable as the reference standard for numerical simulation values. In this paper, the mesh convergence judgment method proposed in literature [16] is used to determine the recommended mesh size in this scaled distance range. The criterion for convergence is that if the change of the target amount does not exceed 10% after the mesh size is reduced by multiple times, it is considered as convergence [16].

The relationship between the recommended scale coefficient n_{iR} and the scaled distance Z is shown in Figs. 22 and 23 when the scaled distance is 0.06–8 m/kg$^{1/3}$. Except that the recommended scale coefficient decreases when the scaled distance in Fig. 22 is 1.5 m/kg$^{1/3}$–2.5 m/kg$^{1/3}$, the coefficient generally increases with the increase of the scaled distance. At the scaled distance of 1.5 m/kg$^{1/3}$–2.5 m/kg$^{1/3}$ in Fig. 22, the reason for the decrease of the recommended scale coefficient may be that there is a small error in the UFC3-40-02 test results. For the convenience of application, the recommended scale coefficient n_{iR} is piecewise linear fitted with the scaled distance Z, as shown in Tables 7 and 8. Considering the possible error of UFC3-40-02 test results at the scaled distance of 1.5 m/kg$^{1/3}$–2.5 m/kg$^{1/3}$ in Fig. 22, it is recommended that the recommended scale coefficient n_{1R} should be the same value as that at the scaled distance of 1 m/kg$^{1/3}$, that is, 2.

By substituting the recommended scale coefficient n_{iR} given in Tables 7 and 8 into Eq. (7), the recommended mesh size of any TNT quantity in 1D and 2D models at a specific scaled distance can be obtained.

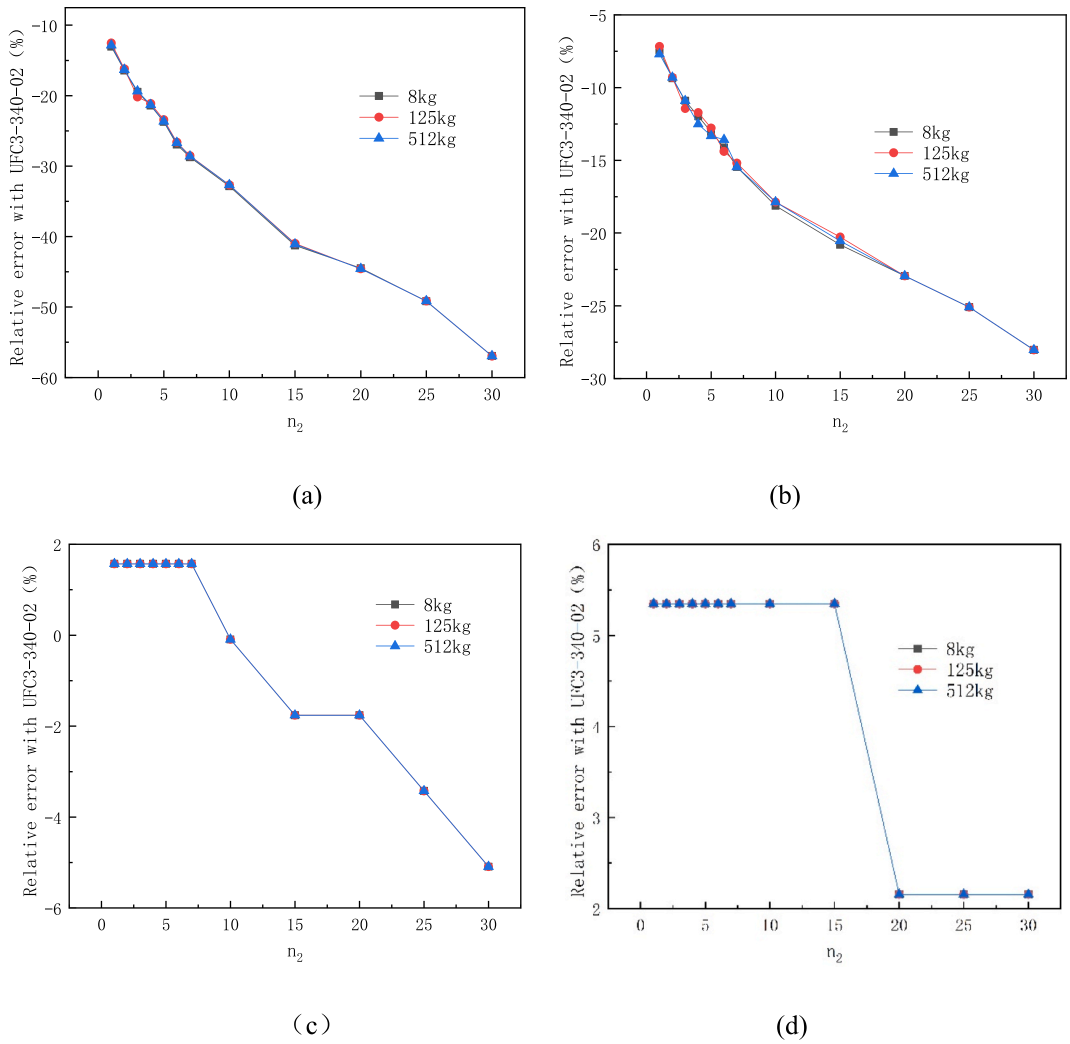

Fig. 21. Relationship between relative error of peak overpressure and scale coefficient for different scaled distances of 2D model (a) 0.5 m/kg$^{1/3}$; (b) 1.5 m/kg$^{1/3}$; (c) 3.5 m/kg$^{1/3}$; (d) 5 m/kg$^{1/3}$.

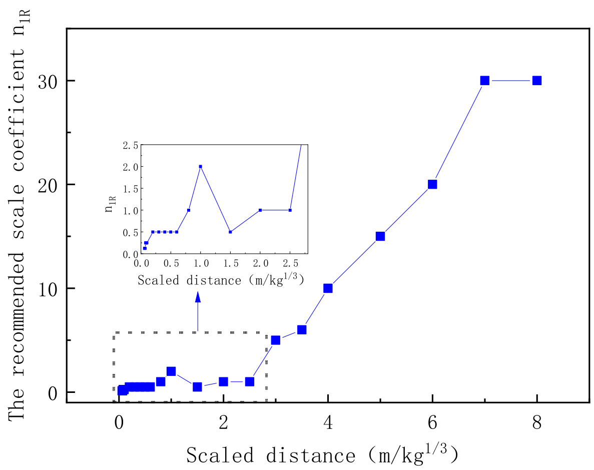

Fig. 22. Relationship between the recommended scale coefficient and scaled distance of 1D model.

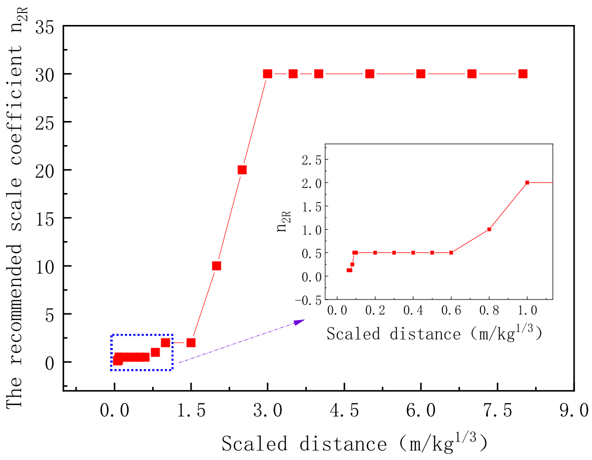

Fig. 23. Relationship between the recommended scale coefficient and scaled distance of 2D model.

Table 7
The recommended scale coefficient n_{1R} of 1D model.

Z	0.06–0.07	0.08–0.1	0.1–0.2	0.2–0.6	0.8	1–2.5	2.5–3	3–3.5	3.5–4	4–6	6–7	8
n_{1R}	0.125	0.25	2.5Z	0.5	1	2	6Z-13	2Z-1	8Z-22	5Z-10	10Z-40	30

Table 8
The recommended scale coefficient n_{2R} of 2D model.

Z	0.06–0.07	0.07–0.08	0.08	0.08–0.09	0.09–0.6	0.6–0.8	0.8–1	1–1.5	1.5–2	2–3	≥3
n_{2R}	0.125	12.5Z-0.75	0.25	25Z-1.75	0.5	2.5Z-1	5Z-3	2	16Z-22	20Z-30	30

5.2. *Rationality verification of calculation formula for recommended mesh size of 1D and 2D models*

5.2.1. *Rationality verification of calculation formula for recommended mesh size of 1D model*

In order to further verify the rationality of the recommended mesh size calculation formula proposed in this paper, it is applied to the 1D explosion simulation conditions given in the literature for comparative analysis. In literature [16], AUTODYN was applied to conduct 1D wedge-shaped numerical simulation of 22.68 kg spherical TNT explosion in free air, and the recommended mesh size for determining peak overpressure at 7 scaled distances was given. The comparison with the recommended mesh size determined by Eq. (7) in this paper is shown in Table 9.

At the 7 scaled distances, the recommended mesh size given in literature [16] and this paper is based on the mesh convergence analysis. However, the initial mesh size used by the two is different. Literature [16] uses 4 mm, and this paper uses 1.4 mm, which is calculated by the scale coefficient of 0.5 and TNT mass of 22.68 kg.The literature [16] uses 4 mm as the starting mesh size, which is directly set, without any specific basis. In this paper, 0.5 is used as the starting scale coefficient, which is based on the relative error between the numerical simulation value at 0.5 m/kg$^{1/3}$ and the value given by UFC3-340-02 is less than 10%. Therefore, the initial scale coefficient in this paper is relatively more reasonable. Although the initial mesh sizes given by the two are different, the recommended mesh sizes given by the two are relatively close at small scaled distances.

Literature [23] applied AUTODYN 1D wedge model to study the peak overpressure at the scaled distance of 1.19 m/kg$^{1/3}$ when 75 g spherical TNT explodes in free air with three mesh sizes of 1, 3 and 10 mm respectively. Considering the calculation accuracy and calculation time, it is considered that 3 mm is the recommended mesh size. Only from the perspective of calculation accuracy, 1 mm mesh size is the best. The recommended mesh size calculated according to the formula proposed in this paper is 0.8 mm, which is close to the 1 mm mesh size adopted in literature [23].

Table 9
Comparison of recommended mesh size (TNT mass 22.68 kg).

Scaled distance (m/kg$^{1/3}$)		0.054	0.058	0.071	0.088	0.177	0.353	0.53
Recommended mesh size (mm)	Literature [16]	0.5	0.5	0.5	0.5	1	2	4
	This paper	0.4	0.4	0.4	0.7	1.3	1.4	1.4
Relative error (%)		−29.2	−29.2	−29.2	41.5	30.0	−29.2	−64.6

Literature [40] applied AUTODYN 1D wedge model to study the peak overpressure at the scaled distance of 0.316 m/kg$^{1/3}$ when 10 kg spherical TNT explodes in free air with three mesh sizes of 0.5, 1 and 2 mm respectively. It was found that almost the same results were obtained with mesh sizes of 0.5 and 1 mm. The recommended mesh size calculated according to the formula proposed in this paper is 1.1 mm, which is very close to the literature [40].

5.2.2. Rationality verification of calculation formula for recommended mesh size of 2D model

In order to further verify the rationality of the recommended mesh size calculation formula proposed in this paper, it is applied to the 2D simulation conditions of spherical TNT explosion in free air given in the literature for comparative analysis.

In literature [27], LS-DYNA software was applied to conduct 2D rectangular numerical simulation of the explosion of 6 kg spherical TNT in free air. The TNT and the air were modeled with Multi Material Arbitrary Lagrange Euler (MMALE) formulation. The detonation process of TNT follows the Chapman – Jouguet (C – J) theory. The equations of state of TNT and air are JWL and ideal gas respectively. Advection between the steps in the model was controlled using the modified Van Leer advection algorithm which is second-order accuracy [27,41]. The recommended mesh size for determining the peak overpressure at 7 scaled distances was given. The comparison with the recommended mesh size determined by Eq. (7) in this paper is shown in Table 10.

The steps to determine the recommended mesh size are given in literature [27]. First, the grid convergence index (GCI) method [42] is applied to determine the accurate value of the peak overpressure numerical simulation, and then, the numerical simulation value corresponding to different grid sizes is compared with the accurate value of the numerical simulation, and the grid size corresponding to the numerical simulation value reaching 90% of the accurate value is the recommended grid size. In the range of comparative scaled distance, the recommended mesh size given in this paper is always smaller than that in literature [27]. Relatively speaking, the mesh size given in this paper is more conservative. With the reduction of scaled distance, the recommended mesh size given in literature [27] and this paper gradually approach. Although the software used in this paper is different from that in literature [27], the algorithms of the two software are basically the same, so the mesh size of the working conditions described in literature [27] can be better given by using the formula proposed in this paper.

The recommended mesh size calculation formula proposed in this paper is based on spherical TNT charge. In order to verify whether it is applicable to cylindrical charge, a two-dimensional axisymmetric model of cylindrical TNT explosion in free air as shown in Fig. 24 is established and analyzed by the mesh convergence judgment method proposed in literature [16]. The ratio L/D of the length to diameter of the cylindrical TNT is equal to 1. The initiation point is at the center of the cylinder. The gauges are arranged in the axial and radial directions to record the peak overpressure value. The flow out boundary allows air to flow out and simulates the infinite boundary of the air medium. The criterion for convergence is that if the change of peak overpressure is not more than 10% after the mesh size is doubled, it is considered as convergence. The rationality of the formula is verified according to the scaled distance range given in Table 8. The initial mesh size is determined by the recommended scale coefficient given in Eq. (7) and Table 8, where W is 8 kg. The propagation process of blast wave is shown in Fig. 25. It is verified that the relative error of peak overpressure obtained from the initial mesh size and 0.5 times of the initial mesh size is less than 10% in each scaled distance range. Therefore, the recommended mesh size calculation formula proposed in this paper is applicable to cylindrical charges.

The 2D simulation of the explosion of spherical and cylindrical charges in free air is carried out by using the recommended mesh size determined by Eq. (7). The peak overpressure simulation value within the range of 0.5–8 m/kg$^{1/3}$ is compared with the value given by UFC3-340-02, as shown in Table 11. Wherein, the peak overpressure of the cylindrical charge in the radial direction and the axial direction are given respectively. It can be seen from the table that when the scaled distance is greater than 3 m/kg$^{1/3}$, the relative error between the cylindrical charge and UFC3-340-02 in the radial and axial directions is less than 10%. Therefore, when the scaled distance is greater than 3 m/kg$^{1/3}$, the influence of the charge shape on the peak overpressure can be ignored. This is almost consistent with the 3.06 m/kg$^{1/3}$ given in literature [40] and the 3.2 m/kg$^{1/3}$ given in literature [43], which further illustrates the rationality of the calculation formula for the recommended mesh size proposed in this paper. In the range of 0.5–1.5 m/kg$^{1/3}$, the magnitude of peak overpressure is spherical $<$ cylindrical radial $<$ cylindrical axial. This is because the energy converged in the axial direction of the cylinder is the most, followed by the radial direction [43,44].

Some researchers [40,43,45–47] studied the influence of initiation configuration on the parameters of shock wave, and the research methods include both experiment and numerical simulation. The research results show that the shock wave parameters are different in the near-field and midfield regions when the cylindrical charge is detonated at the center, single end and double ends. In summary, the blast loads (peak overpressure and maximum impulse) resulting from the three considered initiation configurations can be sorted in descending order, i.e., single-end-initiated $>$ center-initiated $>$ double-end-initiated. When the charge mass is constant, no matter where the detonation is initiated, these numerical simulation studies all adopt the same mesh size and obtain better simulation results. Therefore, the mesh size is basically independent of the location of the detonation point, and the formula for calculating the recommended mesh size presented in this paper is applicable to the case of cylindrical charges detonating at any point.

Table 10
Comparison of recommended mesh size (TNT mass 6 kg).

Scaled distance (m/kg$^{1/3}$)		0.055	0.110	0.166	0.219	0.274	0.331	0.386
Recommended mesh size (mm)	Literature [27]	0.6	0.7	1.2	1.9	2.8	2.1	2.1
	This paper	0.5	0.9	0.9	0.9	0.9	0.9	0.9
Relative error (%)		−16.7	28.6	−25.0	−52.6	−67.9	−57.1	−57.1

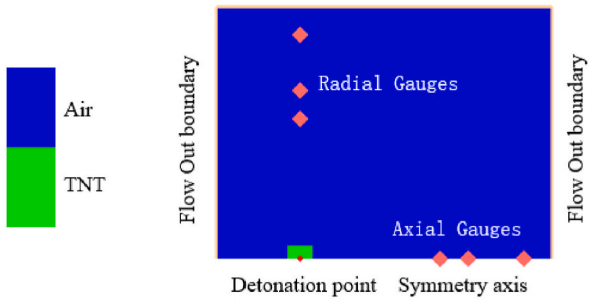

Fig. 24. 2D axisymmetric model of cylindrical TNT explosion in free air.

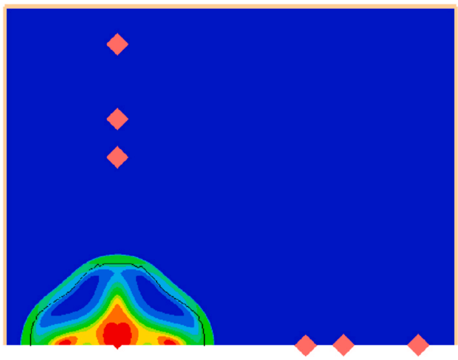

Fig. 25. Schematic diagram of blast wave propagation.

Table 11
Comparison of peak overpressure simulation values of spherical and cylindrical charges.

Scaled distance (m/kg$^{1/3}$)	Peak overpressure (MPa)				Relative error with UFC (%)		
	UFC3-340-02	spherical	cylindrical		spherical	cylindrical	
			radial	axial		radial	axial
0.5	3.890	3.5	5.111	8.3	−10.0	31.4	113.4
0.6	2.750	2.487	3.752	6.497	−9.6	36.5	136.3
0.8	1.524	1.397	1.984	3.201	−8.3	30.2	110.0
1	0.937	0.86	1.059	1.435	−8.2	13.1	53.2
1.5	0.374	0.339	0.367	0.511	−9.4	−1.9	36.6
2	0.195	0.177	0.17	0.155	−9.2	−12.8	−20.5
2.5	0.120	0.108	0.107	0.104	−9.7	−10.5	−13.0
3	0.082	0.075	0.072	0.073	−8.2	−11.9	−10.7
3.5	0.060	0.057	0.055	0.056	−5.1	−8.4	−6.8
4	0.047	0.045	0.044	0.045	−3.4	−5.6	−3.4
5	0.031	0.032	0.031	0.031	2.2	−1.0	−1.0
6	0.023	0.024	0.023	0.024	3.3	−1.0	3.3
7	0.018	0.019	0.018	0.019	3.7	−1.8	3.7
8	0.015	0.016	0.015	0.015	6.0	−0.6	−0.6

5.3. Calculation formula of reasonable mesh size of 3D model and its rationality verification

5.3.1. Analysis of influence of 1D model mesh size on calculation results

When the scale coefficient n_3 of the 3D model is equal to 10, 20, 30 and 35 respectively, and the scale coefficient n_1 of the 1D model corresponding to each n_3 is equal to 0.5, 1, 2 and 3 respectively, the relationship between the relative error of the peak overpressure numerical simulation value corresponding to 8 kg TNT and the value given by UFC3-340-02 with the scaled distance is shown in Fig. 26 (a–d).

It can be seen from Fig. 26(a–d) that when the scale coefficient n_3 and TNT mass W are respectively fixed to the same value, the relative error of peak overpressure corresponding to different scale coefficients n_1 at the same scaled distance is basically the same. This shows that the mesh size of 1D model has little influence on the calculation results of 3D model. Due to the small calculation amount of 1D model, smaller n_1 should be used.

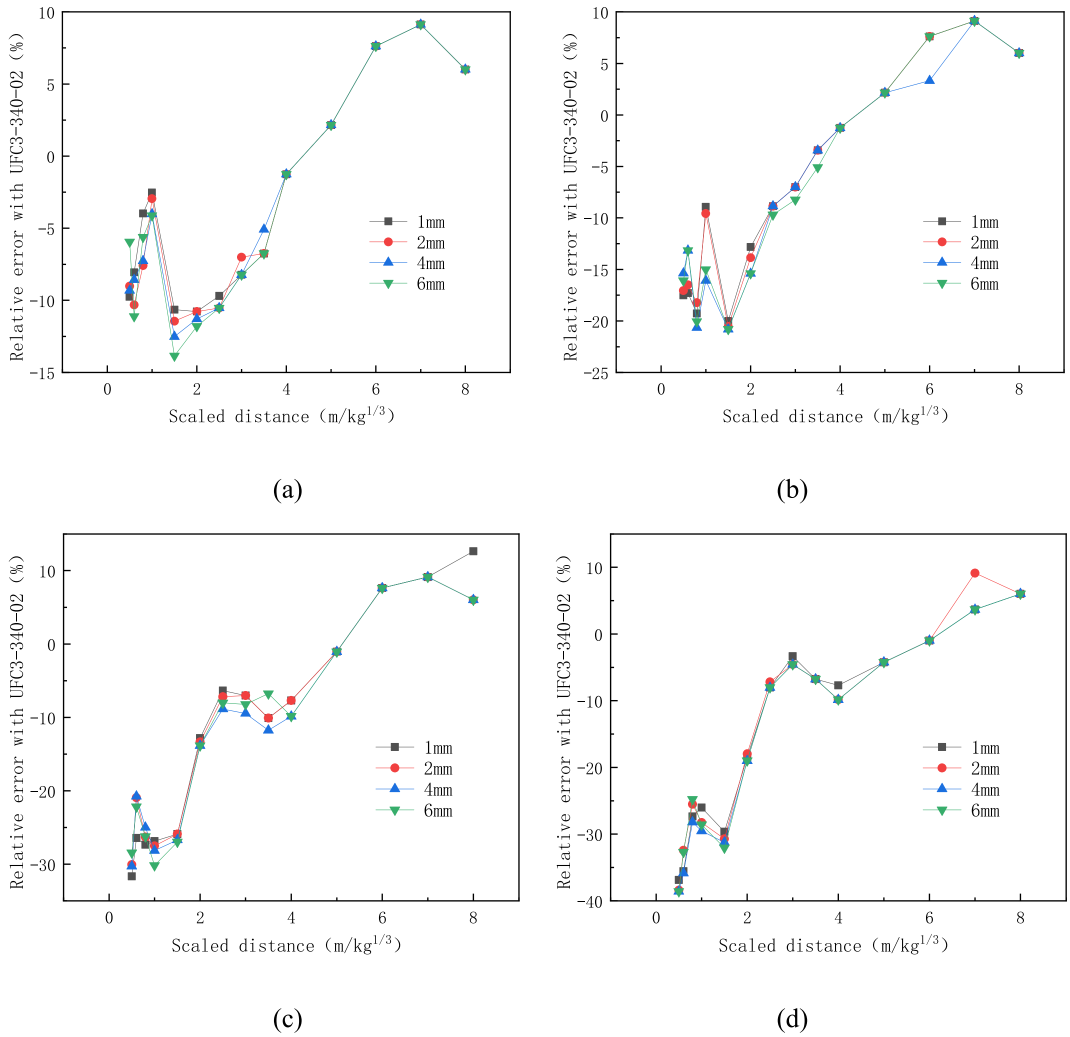

Fig. 26. Relationship between relative error of peak overpressure and scaled distance for different 1D remapped mesh size with the same 3D mesh size of 3D model (TNT mass 8 kg) (a) 3D model with 20 mm mesh size; (b) 3D model with 40 mm mesh size; (c) 3D model with 60 mm mesh size; (d) 3D model with 70 mm mesh size.

5.3.2. Calculation formula of reasonable mesh size of 3D model

When the scale coefficient n_3 of the 3D model is equal to 10, 15, 20, 25, 30 and 35 respectively, the relationship between the relative error of the peak overpressure numerical simulation value corresponding to 8, 125 and 512 kg TNT and the value given by UFC3-340-02 with the scaled distance is shown in Fig. 27(a–c). It can be seen that in the range of 0.5–2 m/kg$^{1/3}$, the relative error is fluctuating up and down. In the range of 2–8 m/kg$^{1/3}$, the relative error basically increases with the increase of the scaled distance.

In the engineering field, the relative error is generally acceptable within ±10%. If the reasonable scale coefficient n_{3S} is defined as the relative error between the numerical simulation results obtained by using the scale coefficient and the test results of UFC3-340-02 is within ±10% at most scaled distances, it can be seen from Fig. 26(a–d) that when n_3 is equal to 10, this requirement is met in the whole scaled distance range of 0.5–8 m/kg$^{1/3}$; when n_3 is equal to 10–35, this requirement is met in the scaled distance r 3 m/kg$^{1/3}$ or more. Therefore, when conducting 3D numerical simulation of TNT explosion in free air, the reasonable scale coefficient can be taken as 10 when the scaled distance is between 0.5 and 3 m/kg$^{1/3}$, and 10–35 when the scaled distance is greater than or equal to 3 m/kg$^{1/3}$.

When the scaled distance is less than 0.5 m/kg$^{1/3}$, this paper uses the mesh convergence judgment method proposed in literature [16] to determine the recommended mesh size. The criterion for convergence is that if the change of the target amount does not exceed 10% after the mesh size is reduced by multiple times, it is considered as convergence [16]. The values of reasonable scale coefficient between 0.06 and 0.5 m/kg$^{1/3}$ and 0.5–8 m/kg$^{1/3}$ are expressed in Table 12.

The reasonable mesh size h_{3S} corresponding to the reasonable scale coefficient n_{3S} is determined as follows:

$$h_{3S} = n_{3S}\sqrt[3]{W}(mm) \tag{8}$$

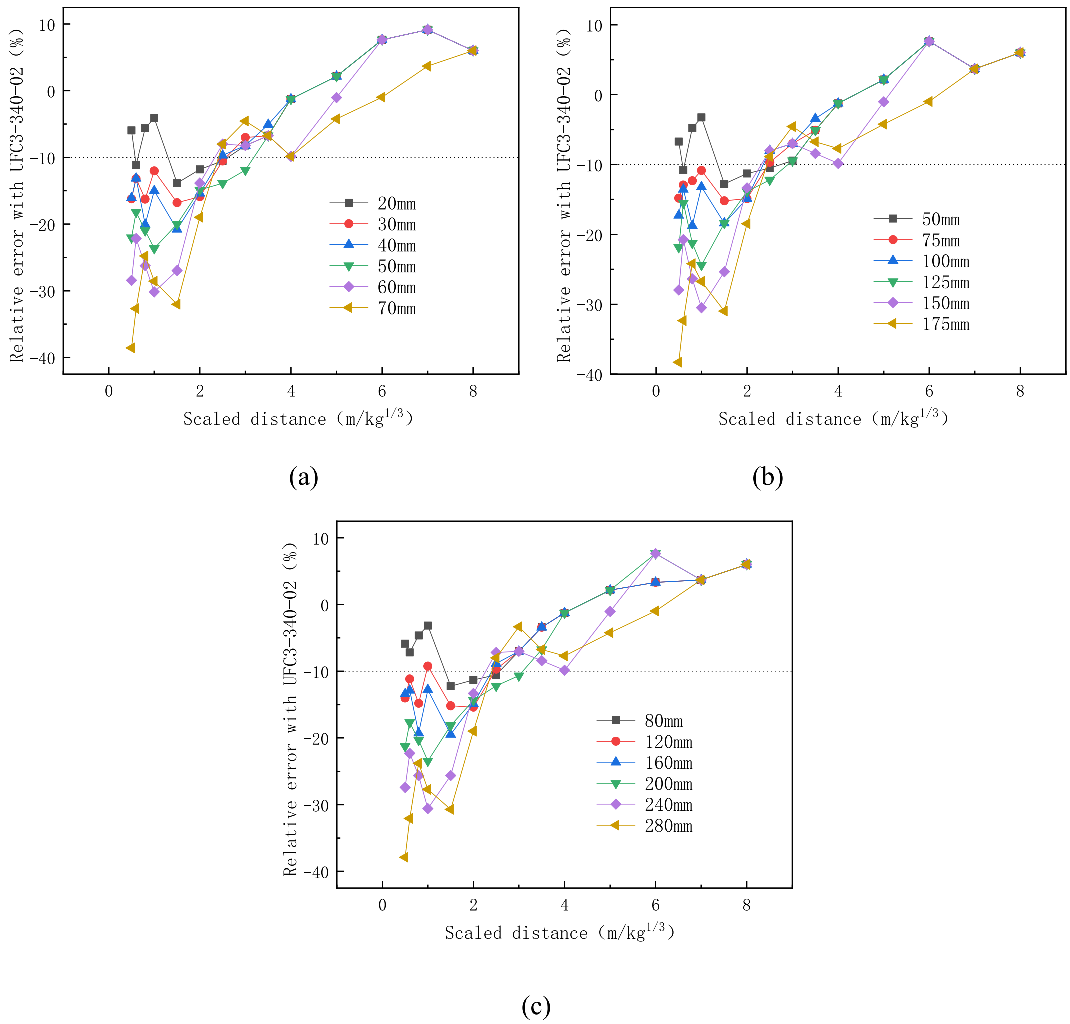

Fig. 27. Relationship between relative error of peak overpressure and scaled distance for different scale coefficient of 3D model with the same TNT mass (a) TNT mass 8 kg; (b) TNT mass 125 kg; (c) TNT mass 512 kg (the scale coefficient n_3 of the 3D model is equal to 10, 15, 20, 25, 30 and 35 respectively).

Table 12
The reasonable scale coefficient n_{3S} of 3D model.

Scaled distance (m/kg$^{1/3}$)	0.06–0.1	0.2	0.3	0.4–3	3–8
Reasonable scale coefficient n_{3S}	1.25	2.5	5	10	10–35

Table 13
Comparison table of reasonable mesh size.

Literature number	[12]	[9]	[13]	[48]	[49]	[24]	
Software name	AUTODYN		LS-DYNA				
Remapping technology	NO	YES	NO	NO	NO	NO	
TNT mass (kg)	1000	100	3	40	105	800	
TNT shape	Sphere	Sphere	Cube	Cube	Cube	Cylinder (Aspect ratio 3)	
Scaled distance (m/kg$^{1/3}$)	1	0.646	1.1	0.2	0.2	0.1	0.4–1.1
Recommended mesh size in literature (mm)	100	100	20	10.9	14.8	50	100
Mesh size calculated by Eq. (8) in this paper (mm)	100	46.4	14.4	8.5	11.8	11.6	92.8

5.3.3. Rationality verification of calculation formula for reasonable mesh size of 3D model

In order to further verify the accuracy of the reasonable mesh size calculation formula proposed in this paper, it is applied to the 3D explosion simulation conditions given in the literature for comparison, as shown in Table 13. It can be seen from the table that the mesh size obtained according to the formula in this paper is less than or equal to the value given in the literature at each scaled distance. Therefore, the mesh size calculation formula proposed in this paper is relatively conservative. Although the mesh size calculation formula given in this paper is based on AUTODYN software and its remapping technology through analyzing spherical TNT explosion, it is also applicable to LS-DYNA software, cube and cylindrical TNT explosion conditions, regardless of whether remapping technology is applied. Therefore, the mesh size calculation formula proposed in this paper has wider applicability.

The reasonable mesh size determination method given in this paper is based on the peak incident overpressure value of TNT explosion in free air. In order to verify whether the reasonable mesh size determination method is applicable to the numerical simulation calculation of reflected overpressure, according to Table 12 and Eq. (8), this paper calculated the numerical simulation mesh size of explosion conditions described in literature [50]. In literature [50], the cylinder-shaped explosive charge (HE) made of 0.5 kg TNT with diameter of 50 mm and height of 159 mm was placed 95 mm above the tire surface with tire inflation pressure of 0.60 MPa. Based on the explosive condition, the scaled distance is 0.22 $m/kg^{1/3}$. According to Table 12 and through linear interpolation, the reasonable scale coefficient is 3. According to Eq. (8), the reasonable mesh size is 2.38 mm, which is basically the same as 2–3 mm adopted by the literature [50]. This shows that the reasonable mesh size determination method is applicable to reflected overpressure with a single reflection.

In order to prove that this method is also applicable to the case of multiple reflections, it is conducted that a numerical simulation of an internal explosion test reported by literature [51]. The explosion test model in the closed structure is shown in Fig. 28(a–d) [51], dimensions on the Figure are in mm.

In Fig. 28 (a) and (b), '+' indicates the location of the detonation point. In Fig. 28 (c) and (d),' × ' indicate the position of gauges, and P1~P5 indicate the number of gauges. TNT charge is adopted, and the charge center is located at the geometric center of the structure, about 400 mm away from the inner surface of the roof. The explosive quantity increases gradually until the structure is damaged. TNT mass of 30, 100, 150, 200 and 250 g were used. In this paper, the explosion of two TNT mass of 150 and 200 g is numerically simulated. The numerical analysis uses the remapping technology of AUTODYN software. The 1D model is shown in Fig. 3. The length R_1 of the model is equal to 400 mm, which is the minimum of the dimensions of the 3D model in three directions. According to Table 7 and Eq. (7), when the TNT mass is 150 and 200 g, the mesh size of 1D model is 0.47 mm and 0.42 mm respectively, and 0.5 mm is adopted in this paper.

Considering that the effect of replacing the reinforced concrete structure with a rigid plane on the determination of the explosion load is very small [52], and according to the symmetry, a 1/8 model of the test structure is established as shown in Fig. 29. The three

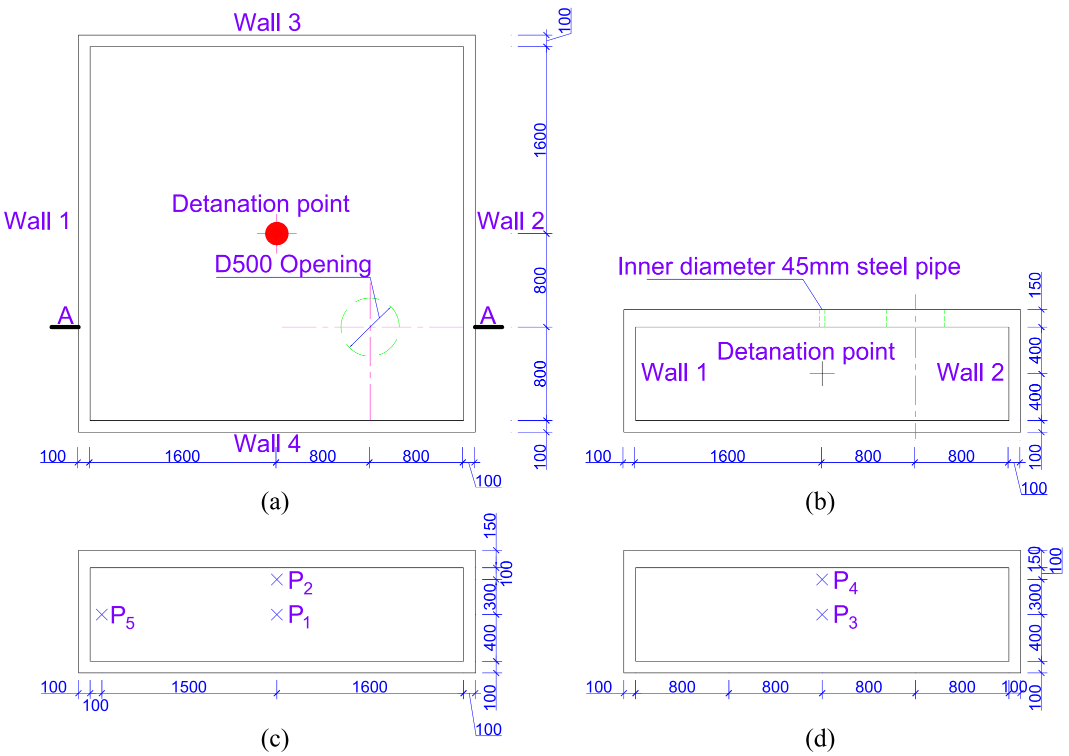

Fig. 28. Schematic diagram of explosion test in closed structure (a) Plan view; (b) Sectional drawing A-A; (c) Internal surface of wall 1; (d) Internal surface of wall 3.

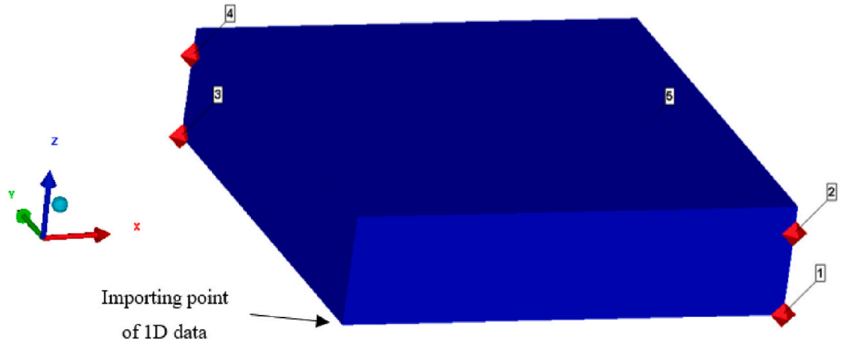

Fig. 29. 1/8 numerical analysis model of closed structure.

faces connected to the importing point of 1D data are symmetrical, and the other three are rigid. 1–5 is the number of gauges, corresponding to P_1~P_5 of the test structure. According to Table 12 and Eq. (8), the mesh size of 3D model corresponding to 150 and 200 g TNT mass is 5.3 mm and 5.8 mm respectively, and 6 mm is adopted in this paper.

The test and numerical simulation overpressure time history curves of 150 g TNT at gauge P_3 and 200 g TNT at gauge P_1 are shown in Figs. 30 and 31 respectively. It can be seen that the whole test and numerical simulation overpressure time history curves are different, but the peak overpressure is very close, and the relative errors are only13.1% and −6.92% respectively. This shows that the peak overpressure can be accurately predicted after the rigid boundary is used for explosion in the confined space, but the entire overpressure time history curve cannot be well simulated, which may require advanced analysis of the interaction between shock wave and structure.

The peak overpressure test and numerical simulation value caused by 150 and 200 g TNT at each gauge are shown in Table 14 and Table 15 respectively.

Due to the symmetry, the peak overpressure of gauges P_1 and P_3, P_2 and P_4 should be the same respectively. The simulation value meets this rule. The test value is basically satisfied except 150gTNT at gauge P_2 and P_4. The simulation value of peak overpressure corresponding to the two TNT mass at gauges P_1~P_4 is generally close to the test value, but the relative error at gauge P_5 is large. It is found that the test value at gauge P_5 is smaller than the numerical simulation value, and also smaller than the test value at gauges P_1 and P_3. Gauge P_5 is located near the junction of two walls, and its peak overpressure value should be greater than other positions [53]. It can be preliminarily concluded that the test peak overpressure at gauge P_5 may be wrong.

Therefore, the reasonable mesh size determination method and the rigid boundary are applicable to determining the peak overpressure of explosion in a fully or partially enclosed space in which there are numerous reflections. However, it is not ideal to simulate the entire overpressure time history curve.

5.4. Comparative analysis of the recommended scale coefficient

Fig. 32 shows the relationship between the recommended scale coefficient of 1D, 2D and 3D numerical simulation of TNT explosion in free air and the scaled distance. It can be seen from the figure that when the scaled distance is less than or equal to 1.5 m/kg$^{1/3}$, the recommended scale coefficient of the 3D model is greater than 1D and 2D, especially in the range of 0.4–1.5 m/kg$^{1/3}$, which is more

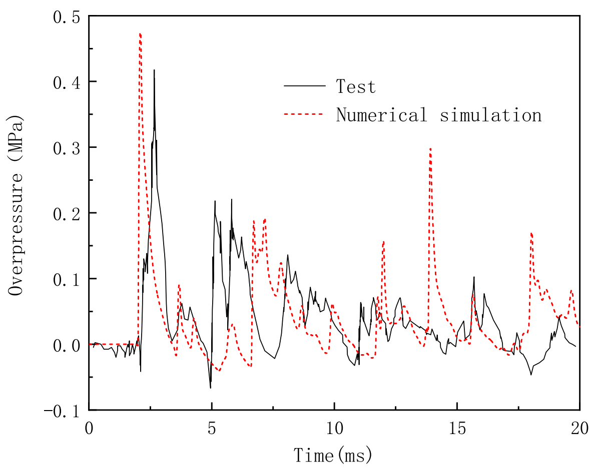

Fig. 30. Test and numerical overpressure time history curves of 150gTNT at gauge P_3.

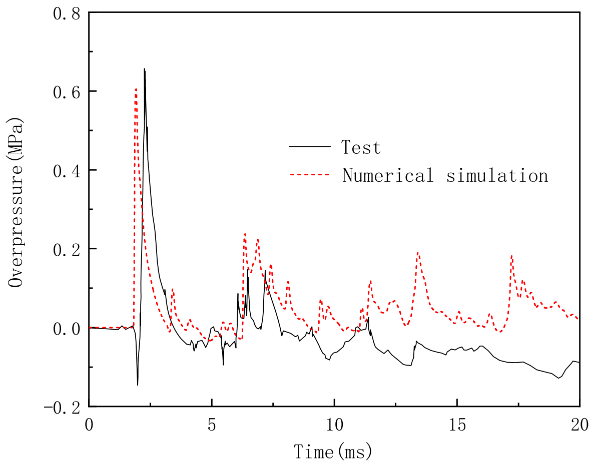

Fig. 31. Test and numerical overpressure time history curves of 200gTNT at gauge P_1.

Table 14
Comparison of peak overpressure test value and numerical simulation value of 150gTNT at each gauge.

Gauges	P_1	P_2	P_3	P_4	P_5
Test (MPa)	0.42	0.4	0.42	0.32	0.34
Numerical simulation (MPa)	0.475	0.318	0.475	0.318	0.537
Relative error (%)	13.10	−20.50	13.10	−0.63	57.94

Table 15
Comparison of peak overpressure test value and numerical simulation value of 200gTNT at each gauge.

Gauges	P_1	P_2	P_3	P_4	P_5
Test (MPa)	0.65	0.48	0.6	0.42	0.45
Numerical simulation (MPa)	0.605	0.41	0.605	0.41	0.581
Relative error (%)	−6.92	−14.58	0.83	−2.38	29.11

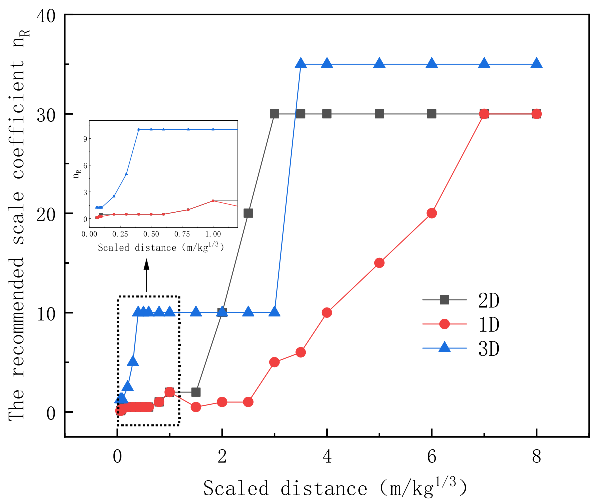

Fig. 32. Comparison of recommended scale coefficients of three dimensional models.

obvious. In the range of 2–3 m/kg$^{1/3}$, the recommended scale coefficient of the 2D model is greater than that of the 1D and 3D models. When the scaled distance is greater than or equal to 3.5 m/kg$^{1/3}$, the recommended scale coefficient of the 3D model is greater than that of the 1D and 2D models, but the difference is small. The recommended scale coefficient of the 1D model increases approximately in a straight line, and is equal to that of the 2D model at 7 $m/kg^{1/3}$, and then remains constant.

It should be noted that since the maximum scale coefficient used in the mesh size analysis of the 1D and 2D models in this paper is 30, and that used in the 3D model is 35, the recommended scale coefficient of the 1D and 2D models is determined to be 30 and that of the 3D model is determined to be 35 when the scaled distance is large. If the scale coefficient used in the mesh size calculation is larger, the better scale coefficient will be obtained. However, when 30 or 35 is adopted as the recommended scale coefficient, the number of meshes can be greatly reduced and the calculation time can be saved. Therefore, it is reasonable to conservatively adopt 30 or 35 as the recommended scale coefficient at a large scaled distance.

6. Conclusions

Based on the systematic analysis of the existing methods for determining the mesh size of the numerical simulation of blast wave in free air, this paper presents a general formula for determining the mesh size. According to the formula, the mesh size is the product of the scale coefficient and the third root of the equivalent TNT mass. Among them, the scale coefficient is related to the model dimension, scaled distance and simulation accuracy, and is independent of the TNT shape and the location of the detonation point. The formula is applicable to explosion in both open space and completely or partially enclosed space.

The main conclusions are as follows.

(1) The mesh size has a great influence on the accuracy of the numerical simulation of shock wave. Further analysis shows that the mesh size has different influence on the parameters of blast wave, and has the largest influence on the peak overpressure and less influence on other parameters.
(2) For the same dimensional model at the same scaled distance when the mesh size is equal to the third root of the explosive mass multiplied by the same coefficient, the relative error between the peak overpressure simulation value and the value given by UFC3-340-02 is almost the same for different TNT mass.
(3) The reasonable and recommended scale coefficients for scaled distances in the range of 0.06–8 $m/kg^{1/3}$ are given, and are further verified by the explosion simulation conditions in the literature. These coefficients can be used not only for spherical but also for explosion simulation of cubic and cylindrical TNT.
(4) In the range of 0.06–1 $m/kg^{1/3}$, the recommended scale coefficients of the 1D and 2D models are basically the same, and when the scaled distance is greater than 1 $m/kg^{1/3}$, the recommended scale coefficient of the 2D model is significantly greater than that of the 1D model. When the scaled distance is less than or equal to 1.5 $m/kg^{1/3}$, the reasonable scale coefficient of the 3D model is greater than the recommended scale coefficients of 1D and 2D, especially in the range of 0.4–1.5 $m/kg^{1/3}$. In the range of 2–3 $m/kg^{1/3}$, the recommended scale coefficient of the 2D model is greater than that of the 1D and the reasonable scale coefficient of 3D models. In the range of 3.5–8 $m/kg^{1/3}$, the reasonable scale coefficient of the 3D model is larger than the recommended scale coefficients of the 1D and 2D model, but the difference is not large. The recommended scale coefficient of the 1D model increases approximately in a straight line in this range, and is equal to that of the 2D model at 7 $m/kg^{1/3}$, and then remains constant.
(5) When the rigid boundary is used for numerical simulation of explosion in a confined space, the peak overpressure can be more accurately determined by using the mesh size determination method recommended in this paper, but the entire overpressure time history curve cannot be well simulated, which may require advanced analysis of the interaction between shock wave and structure.

Author contribution statement

Zhingping Kuang: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Zhonghui Liu: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

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