Impact of explosive charge mass on reflected shock wave of high explosion

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Abstract. Overpressure is an important metric of the destructive effect of the shock wave produced by high explosion. Investigating the overpressure of shock wave on the surface is an essential way for evaluating the power of explosive device. This study has important implications for quantitative analyses for establishing the relationship between parameters of reflected shock wave by using the numerical simulation software AUTODYN with different TNT explosive charge mass. The research indicates that with the increase of explosive charge mass, the initial value of peak overpressure of high explosive increases and the attenuation rate accelerates, it also provides the condition that the similarity law can be established in the relationship between peak overpressure and scale distance.

1. Introduction
The blast wave produced by high explosion play a crucial role in evaluating the warhead power. During the past decades, the rapid development of precision guided weapons makes the distance between the blast point and the target closer and closer, which makes the damage effect of blast wave more and more prominent. The instantaneous change of temperature and pressure makes the shock wave have a seriously destructive effect on human and buildings in surrounding. The effect of shock wave is generally characterized by the peak overpressure, positive pressure time and specific impulse[1]. Besides, the peak overpressure which is described as the maximum pressure exceeding the ambient pressure is the most considerable parameter of shock wave. The results from this study could serve as a reference of the analyses peak overpressure of shock wave of surface high explosion.

It is generally considered that the peak overpressure of shock wave is a function of scale distance. On this basis, a large number of experimental studies have been carried out and many empirical formulas have been summarized [2]. However, in the true sense, previous research has few studies on the explosion occurred near ground in the free field, thus, more detailed research should be considered in the impact of explosive charge mass on reflected shock wave of high explosion. These result from the numerical simulation on the high explosion occurs on the surface is significant to provide the information on the parameters of reflected shock wave increases the peak overpressure at the same distance. Because the overpressure is the largest when the surface condition is regarded as rigid ground, as reported by previous studies[3], setting the rigid ground as the reflected condition is a very effective and simplified method to calculate the parameters of the reflected flow field of the shock wave, and numerical simulation is considered to be the key technology to establish the relationship between the physical parameters with different explosive charge mass.
2. Methods and data

2.1. Calculation Model and Parameter Setting

AUTODYN is an explicit finite element analysis program for simulating highly nonlinear dynamic problems of solids, fluids, gases and their interactions. The two-dimensional revolution model embedded in AUTODYN is used to describe the actual explosion space, and the multi material Euler solver which is suitable to compute the variable parameters of reflected shock wave of near-surface explosion. The width is set to 90m and the height is 32.5m in the dimension of the computational domain. To give consideration to the operation time and complexity of computing procedures, the compute zone within 17.5m × 17.5m is set as fixed grid and the size of meshes is 53.4mm * 53.4mm from the coordinate origin of the model, and gradient meshes is used in simulation in the far-field area to achieve these objectives.

The outflow boundary condition which is considerate as outflow directly in the distal and top end, and the bottom end is set as rigid ground. In order to record the overpressure at different distances, 100 monitoring points with three kinds of monitoring distance (0.25 m, 0.5m and 1.35m) is utilized. The geometric centre of the explosive is set as the initial point of detonating explosion which is located at the middle of the axis. The computational domain is illustrated in Figure 1.

![Figure 1 Parameters of computational domain of detonation.](image)

2.2. Material model and equation of state

The equation of state JWL is utilized to simulate the TNT explosions [4], and the relationship between the parameters of pressure generated by TNT explosive can be defined as Eq.1.

\[
P = A \left( 1 - \frac{\omega}{R_1 v} \right) e^{-R_1 v} + B \left( 1 - \frac{\omega}{R_2 v} \right) e^{-R_2 v} + \frac{\omega E}{v} \tag{1}
\]

Where P is the pressure of TNT explosion; v is the relative volume of TNT explosives; E is the internal energy; A, B, R1, R2 and ω are material parameters obtained by using C-J condition, isentropic line tangent to Rayleigh line, Hugoniot relation and isentropic line through C-J point, and the parameters are shown in Table 1, where the ED is the energy density, DP is donation pressure, and DV is donation velocity:

| C-J | JWL |
|-----|-----|
| ED/ kJꞏm⁻³ | DP/ kPa | DV/ mꞏs⁻¹ | A/ kPa | B/kPa | R₁ | R₂ | ω |
| 6×10⁶ | 2.10×10⁷ | 6930 | 3.7377×10⁸ | 3.7471×10⁶ | 4.15 | 0.90 | 0.35 |

Air material model and a linear form of equation are used to describe air material and its constitutive relation and state. The form expression of ideal gas can be determined as the following formula.

\[
P = (\gamma - 1) \rho e + p_o \tag{2}
\]
Where: $\gamma$ is the ideal gas constant, and $\gamma = 1.4$; $\rho$ is density, and $\rho = 0.001293 \, g / cm^3$, $e$ is internal energy; $P_0$ is the initial pressure, and $p_0 = 100kPa$. The ground is set as a rigid reflector.

3. Results and discussions

3.1. Explosion process analysis

According to the computing model established by AUTODYN, the velocity and pressure distributions of TNT explosion pressure at different measuring points can be observed. The change of TNT explosion pressure under the explosive charge mass from 100g to 1kg can be seen from the distributions, and the variations of peak overpressure with time can be obtained, as shown in Figure 2.

![Figure 2a](image1)

- a) The distribution of the reflected shock wave of TNT explosion with the explosive charge mass is 100g

![Figure 2b](image2)

- b) The distribution of the reflected shock wave of TNT explosion with the explosive charge mass is 500g

![Figure 2c](image3)

- c) The distribution of the reflected shock wave of TNT explosion with the explosive charge mass is 1kg

Figure 2 The distribution of the reflected shock wave of TNT explosion with the explosive charge mass from 100g to 1kg.

When the explosive charge mass is 1000kg, the simulated velocity and pressure distributions is shown clearly in Figure 3:
Figure 3 The distribution of the reflected shock wave of TNT explosion with the explosive charge mass is 1000kg.

The variation of peak overpressure with time can be observed in the result of numerical simulation, it indicates that the variation has obvious correlation with the explosive charge mass, the peak overpressure of the 4 cases (the explosive charge mass is 100g, 500g, 1kg, 1000kg) have been collected for calculating the functional law, and the most rational one that can describe the relationship between peak overpressure and time is the power exponent formula which is consistent with:

\[ \Delta P_{\text{max}1} = 2607 \times t^{-1.028} \]

(3)

\[ \Delta P_{\text{max}2} = 6203 \times t^{-1.016} \]

(4)

\[ \Delta P_{\text{max}3} = 1.29 \times 10^4 \times t^{-1.413} \]

(5)

\[ \Delta P_{\text{max}4} = 4.379 \times 10^4 \times t^{-3.147} \]

(6)

Where the \( \Delta P_{\text{max}1} \sim \Delta P_{\text{max}4} \) is the peak overpressure of the explosive charge mass from 100g to 1000kg, and t is time. It can be seen from the above formulas that the attenuation ratio of peak overpressure increases with the explosive charge mass. When the charge mass is 100g or 500g, the time attenuation index in the function formula has no obvious change, when the explosive charge mass is 1kg or 1000kg, the attenuation index increases obviously, and as well as the initial peak overpressure. The velocity and pressure distributions of TNT surface explosion of the explosive charge mass from 100g to 1000kg shows that the initial overpressure, overpressure time and shock wave expansion speed increase with the explosive charge mass of TNT explosive.

3.2. The functional relationship between peak overpressure and scale distance

For obtaining a better understanding of the variation on the peak overpressure, the linkages between the peak overpressure and scale distance is summarized in Table 2:
Table 2 Summary of the peak overpressure and scale distance with the charge mass (CM) from 100g to 1000kg.

| CM/kg | Z/(m·kg^{-1/3}), P_{max}/kPa |
|-------|-------------------------------|
| 0.1   | Z1 4.49 7.54 12.72 15.71 24.44 31.43 38.92 47.14 54.63 70.35  |
|       | P_{max1} 2653 1182 445 374 216 167 145 132 126 118  |
| 0.5   | Z2 4.38 9.18 13.17 17.06 18.81 20.12 21.87 27.55 34.11 50.73  |
|       | P_{max2} 6194 2127 956 597 487 430 379 273 208 172  |
| 1     | Z3 0.21 0.83 1.18 1.53 1.81 2.08 2.29 2.67 3.61 4.31  |
|       | P_{max3} 12890 3148 1728 989 671 500 419 317 211 180  |
| 1000  | Z4 0.10 0.50 1 1.50 2.50 4 8 11 14 17  |
|       | P_{max4} 43800 4800 1300 560 180 70 20 12 8 6  |

To analysis the relationship of peak overpressure and scale distance, least square method is used to fit the functional relationship, and the data fitting curve shown in Fig. 4 can be obtained reasonably:

Figure 4 Function curve of peak overpressure and scale distance of explosive charge mass from 100g to 1000kg.

The result above estimates the average correlation coefficient between the calculating curve and the experimental data of numerical simulation is 0.9962, and the fitting curve with the lowest correlation coefficient (0.9931) is when the TNT explosive charge mass is 1kg, and the highest correlation coefficient (0.9997) exist when the charge mass is 1000kg. To a certain extent, it shows that the similarity law is satisfied for TNT explosive with different explosive charge mass. From the fitting calculation, it can be seen that the power exponent formula is more rational for describing the relationship between the peak overpressure of shock wave and the scale distance in the numerical simulation. Therefore, the peak overpressure of TNT reflected shock wave can be determined as the power exponent formula:

$$ P = k \cdot Z^{-\alpha} $$

(7)

In the fitting function, the scale distance is defined as: $ Z = \frac{r}{\sqrt{W}} $, and the variation of coefficients and exponents with the explosive charge mass is shown in Table 3.
Table 3  Coefficient and index of the function which describe the relationship between peak overpressure of reflected shock wave and scale distance.

| CM (kg) |  k   |   α   |
|---------|------|-------|
| 0.1     | 26800| 1.542 |
| 0.5     | 69700| 1.634 |
| 1       | 1942 | 1.216 |
| 1000    | 1642 | 1.426 |

It can be concluded from the above analysis that under different TNT explosive charge mass, the relationship between peak overpressure and the scale distance of TNT explosion can be described as the similar law. However, when different kinds of explosives explode, the conditions to meet the similar law are different. If there is a little difference between the explosive charge mass, the function curve of peak overpressure and the scale distance basically coincides, and the relationship can be obtained as shown in Fig. 5. The function curve of charge mass of 0.1kg and 0.5kg is also basically coincident from the computed initial point, but compared with the case which the quantity is 1kg, there is a certain deviation in the small scale distance. The coincidence point on the function curve between the case 1000kg and 1kg is $z = 0.35$, but the case which the explosive charge mass is 0.1kg, 0.5kg or 1kg, the coincidence point is $z = 0.2$, consequently, it indicates that similarity law can be used to describe the relationship between the peak overpressure and scale distance, and the applied scope of the formula has been given.

Figure 5  Comparison on the relationship between peak overpressure and scale distance of the explosive charge mass from 100g to 1000kg.

4. Conclusions
In this paper, the numerical simulation method is used to compute the reflected shock wave, and four cases of the explosive charge mass from 100g to 1000kg TNT explosion are set up. Through the analysis of the propagation process of reflected shock wave, the variation of reflected shock wave on rigid ground with time and scale distance can be observed in the numerical simulation. The result shows that the explosive charge mass is one of the factors that have effect on the initial peak overpressure and the attenuation ratio. In addition, it has important implications for understanding the functional linkages between peak overpressure and scale distance, and also reveal the condition that the similarity law can be established in the objects. Finally, there is still limitation to the study should be considered, only the four kinds of explosive charge mass and the condition of positive reflection of the shock wave from the rigid ground is computed. For more in-depth study of the reflection of the shock wave from the near ground high explosion, more detailed division of explosive charge mass and the distribution of the shock wave on different surface condition should also be considered by utilizing numerical simulation and real explosion test, so as to provide technical support for accurately evaluating the damage effect of surface explosion.
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