Numerical Simulation Study on Propellant Stability of Penetration Warhead

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Abstract. For the problem of charge stability of penetration warhead with a booster device. The process of projectile penetrating concrete is simulated by ANSYS/LS-DYNA with two different algorithms (FEM and FEM-SPH), the calculation results of numerical simulation and experience formula were contrasted with the experimental data. The results show that the FEM-SPH coupling algorithm can overcome the shortage of traditional finite element algorithm for dealing with large deformation issue. and the calculation result of FEM-SPH is most closely with the experimental data. The propellant structure can withstand the maximum overload is 29134g. It can provide a reference for the design of the booster warhead.

1. Introduction
High-tech war make the stable underground military targets become the main Fight object. Deep earth-penetration weapon became one of the favorite weapon. So, more research resource has input by military power countries. To complete the effective damage purpose, researchers are no longer satisfied with the conventional method that improves the projectile’s initial kinetic energy to increase the penetration depth. They began to propose some boosting methods to improve the velocity of projectile in the process of penetration target for increasing the penetration depth, it named earth penetration warhead (EPW) with boosting[1].

Boosting penetration warhead needs carrying propellant particles for booster charge. Preignition or breakage occurs when the propellant particles under the condition of the strong impact loading in penetration, which is harmful to the combustion of propellant, and it’s also has a great effect on the charge stability, safety and reliability[2]. Therefore, it’s meaningful to design a reasonable charge structure to ensure the particles powder’s integrity and stability under a high penetration overload[3].

Due to the higher cost and the difficulty of the experimental test, numerical simulation becomes a convenient, accuracy, extremely efficient and economical measure to evaluate the rationality and reliability of the design scheme. Traditional finite element method (FEM) has been developed a long time and has become more mature. However, the accuracy is poor in solving the structure involving extreme deformation problems[4]. Therefore, this paper discusses a charge structure which is composed by multi-layer steel boxes of propellant beds, using software ANSYS/LS-DYNA to simulate the process of warhead penetration concrete, Different algorithms (FEM with FEM-SPH) for the calculation precision of such problems are compared at first. Then the calculation results solved by the semi-empirical formula are compared with the simulation results and experimental data to analyze the stability...
of boosting charge. Finally, based on of the numerical simulation, concrete-penetration experiments are conducted to test the propellant stability in the process of penetration.

2. Numerical Simulation Model and Method

2.1. Simulation model

The typical charge structure of multi-stage boost penetration warhead is shown in Fig. 1. To analyze the mechanical behavior of propellant beds charge structure stability, the penetration overload of the projectile should be ensured first. Then mechanical behavior of propellant particles can be obtained.

Therefore, based on the propellant beds charge structure design index, a simplified model is established for the simplified model includes projectile, charge, propellant beds and concrete target. Considering the model is axisymmetric, a quarter projectile and target model is built to improve the computational efficiency, and the corresponding symmetric confine was set up. Projectile simulation model and computational grid are shown in Fig 2.

![Figure 1. Typical charge structure](image1)

![Figure 2. Projectile simulation model and grid](image2)

2.2. Material model

Projectile material used high-strength alloy steel which almost no mass loss and distortion in the process of penetration, therefore, isotropic and kinematic hardening plasticity model (*MAT_PLASTIC_KINEMATIC) can be used to describe the projectile material modal. The material parameters are shown in Table 1. [5]

| $\rho$ (g/cm$^3$) | E (GPa) | $\gamma$ | $\sigma_s$ (GPa) | G (GPa) | $\beta$ | C/S-1 | P | $fs$ |
|------------------|---------|---------|------------------|---------|--------|-------|----|------|
| 7.91             | 210     | 0.28    | 1.72             | 2       | 1      | 1670  | 8.45| 0.8  |

Steel charge box using Johnson-Cook material model with Gruneisen equation of state for numerical calculation, material parameters are shown in Table 2.

![Table 1. Material model parameter of projectile](image3)

| Johnson-Cook | Gruneisen |
|--------------|-----------|
| A(MPa)       | B(MPa)    | n  | C | m | $T_{in}$(K) | $T_{room}$(K) | $C_\beta$ | $S_1$ | $\gamma_0$ |
| 7.92$\times$10$^3$ | 5.1$\times$10$^3$ | 0.26 | 0.014 | 1.03 | 1793 | 294 | 0.4569 | 1.49 | 2.17 |

Target used the commonly plain concrete that the unconfined compressive strength is 30 MPa. Large strain, high strain rate and high pressure effect are conducted in the process of projectile penetration concrete, the J-H-C model was used to solve such problems by former research, we also used this model in this paper (*MAT_JOHNSON_HOLQUIST_CONCRETE). The yield function, equation of state, definition of damage and the selection of related parameters are reference in Refs.[6], material parameters are shown in Table 3.
Table 3. Material model parameter of concrete target

| \( \rho (\text{g/cm}^3) \) | \( G(\text{MPa}) \) | A | B | C | N | \( F_c(\text{MPa}) \) | \( T(\text{MPa}) \) | \( \varepsilon_{\text{max}} \) | \( \Sigma_{\text{max}}(\text{MPa}) \) |
|-----------------|----------|---|---|---|---|-------------|-------------|-------------|-------------|
| 2.4             | \( 1.253 \times 10^4 \) | 0.27 | 1.86 | 0.007 | 0.84 | 30          | 4           | 0.01        | 11.00 \( \times \) 10^5 |

\( P_{\text{crush}}(\text{MPa}) \) \hspace{1cm} \( \mu_{\text{crush}} \) \hspace{1cm} \( P_{\text{lock}}(\text{MPa}) \) \hspace{1cm} \( \mu_{\text{lock}} \) \hspace{1cm} D1 \hspace{1cm} D2 \hspace{1cm} K1 \hspace{1cm} K2 \hspace{1cm} K3 \hspace{1cm} \text{FS} \\
16.2 \hspace{1cm} 0.009 \hspace{1cm} 950 \hspace{1cm} 0.1 \hspace{1cm} 0.04 \hspace{1cm} 1 \hspace{1cm} 0.62 \hspace{1cm} -0.4 \hspace{1cm} 0.26 \hspace{1cm} -1

The small propellant particles in charge structure sustain high pressure in the penetration process. With transient and large deformation, the flow stress of small particles in some areas is far smaller than inertial force (and pressure) that its behaviors are close to the fluid. Thus, we using elastic plastic fluid constitutive relation in simulation. The constitutive model only describes the relationship between deviator stress and deviator strain it should accompany the Mie-Gruneisen equation of state express the stress tensor, ball tensor and the relationship between the energy and density, which can be more clearly to describe the high-speed impact problem. Related parameters are listed in Table 4. [7]

Table 4. Physical parameter of small particles powder

| \( \rho (\text{g/cm}^3) \) | \( \mu \) | K(\text{GPa}) | E (\text{GPa}) | \( \gamma \) |
|-----------------|------|-------------|---------------|---|
| 1.68            | 0.35 | 100.37      | 50.29         | 0.29 |
| D               | \( \Lambda_0 \) | \( \Lambda_1 \) | \( \Lambda_2 \) | \text{FS} |
| 1.5             | 0.88 | 0.51        | 0.1042        | -0.001 |

3. Calculation and experimental results analysis

In this paper, we coupling SPH and FEM to simulate the whole process of projectile penetration concrete, coupling structure of particles and finite element grid are shown in Fig 3.

As mentioned, considering the correctness of the penetration warhead loading, computational efficiency and precision, SPH isn’t mature in dealing with the interface, coupling algorithm of FEM and SPH has been adopted to solve this problem. The center of concrete target using SPH particles which will suffer high strain. Projectile and other parts target adopt finite element mesh divide, coupling algorithm is used to deliver density, pressure and other physical quantities between SPH particles and finite element node. The stress distributions of coupling algorithm and finite element method are shown in Fig 4. In this Figure we can see that the stress distribution of concrete was similar to different methods which illustrated the correctness of the coupling algorithm.
3.1. Penetration Depth Analysis

Penetration depth is an important damage index in evaluating earth penetration weapon, penetration depth is relatively easy to obtain in the test, which as a measure of the results of numerical calculation, two algorithms of projectile penetration concrete curves is shown in Fig.5. Grid method settings erosion failure in dealing with the problem of extreme deformation that affects the structure of loading, the calculated results of the penetration depth is larger than the coupling algorithm.

Penetration depth and some terminal effects index is used to evaluate the efficacy of the testing effect in early penetration experiment that established the widely used empirical formula such as Young formula, Bernard formula and Berezan formula in the field of protective engineering[8]. Although Young formula is pure empirical formula which inconsistent with dimensional. It has a high precision result in the velocity of 200m/s to 600 m/s.

Young formula is given when the velocity is over 61m/s, the penetration depth calculation expression as follows[9]:

$$\quad h = 0.000018SN \left( \frac{m}{A} \right)^{0.7} (v - 30.5)$$

Where $h$ is the penetration depth (m); $M$ is the projectile mass (kg); $A$ is the cross sectional area of projectile (m$^2$); $v$ is the initial velocity (m/s); $N$ is the shape coefficient of the warhead, for oval warhead, $N = 0.18L/d + 0.56$; where $L$ is the length of the projectile head; $d$ is the projectile diameter; $S$ is the penetration index, based on a lot of penetration test data, Young recommendation the value of $S$ as follows:

$$\quad S = 0.85K(11 - P)(tT)^{-0.6}(35/f_c)^{0.3}$$

Where $f_c$ is the penetration of unconfined compressive strength (kg/cm$^2$); $K = \left( \frac{F}{W} \right)^{0.3}$. For plain concrete, $F = 30$, $W$ is the ratio of target width to projectile diameter, if $W > F$, then $K = 1$; For thin target, $F$ reduce by half; $P$ is the volume reinforcement ratio of concrete; $t$ is the concrete pouring time (years), when $t > 1$ adopt $t = 1$; $T$ is the ratio of target thickness to projectile diameter, $0.5 \leq T \leq 6$; If

![Figure 4. Concrete Stress Distribution Pattern](image)

![Figure 5. Penetration Depth of Different Method](image)
there is no test data, $S = 0.9$. If $m \leq 182$ (kg), the penetration depth should multiply the correction factor $K_m = 0.46m^{0.15}$.

The experiment measured of penetration depth of projectile at the velocity of 602 m/s is 0.743 m, put the related parameters into Young formula to calculate the penetration depth, and compared the penetration depth of numerical simulation and Young formula with experiment, the result as shown in Table 6:

| Method            | FEM-SPH | FEM  | Young formula |
|-------------------|---------|------|---------------|
| Penetration depth | 0.762   | 0.798| 0.705         |
| Deviation         | 2.52%   | 7.14%| 5.24%         |

Above three kinds method show that FEM/SPH coupling algorithm is closer to experimental data, the simulation result is relatively reasonable.

3.2. Penetration overload analysis

Forrestal[10] based on cavity expansion theory proposed the semi-empirical method gets widely attention and reference. Forrestal method is well consistent with the experimental results for small radii projectile in the calculation of penetration concrete target. According to penetration condition, maximum penetration overload can be calculated from the following formula:

$$a_{\text{max}} = \left( s f_c + N \rho v_0^2 \right) \pi r^2 / (mg)$$

Where $v_0$ is the projectile penetration initial velocity; $m$ is the projectile quality; $r$ is the radius of the projectile; $N$ is the shape coefficient of the warhead, $N = 8\omega - 1 / (24\omega^2)$, and $\omega$ is the curvature of the warhead arc, and $\omega = s / 2r$, $s$ is the warhead arc radius; $\rho$ is the target density; $s \approx 82.6 f_c^{0.544}$, the empirical formula is obtained from penetration experiment data; $f_c$ is the one-way unconfined compression strength of concrete target; $g$ is the acceleration of gravity.

The maximum penetration overload is 30679g that taken by the Forrestal semi-empirical formula, finite element method to get the maximum penetration overload is 27512g, FEM-SPH coupling algorithm for calculating the maximum penetration overload is 29134g, two algorithms projectile penetration overload curve as shown in Fig 6.

![Figure 6. Penetration deceleration of different method](image-url)
As shown in the penetration overload curve, because of the FEM using erosion algorithm to delete the distortion grid that penetration overload of the FEM is smaller than FEM-SPH coupling algorithm.

3.3. Compare simulation to experimental phenomena
Penetration experimental photos are shown in Fig 7. Experiment projectile is almost intact after the penetration test, and the propellant particles are not damaged and combustion, which show that the propellant particles can be withstand high overload in the process of penetration.

![Figure 7. Experimental photos after penetration](image)

FEM-SPH coupling method simulation results clearly showed that each type target damage and deformation in the process of the cratering stage and under pit penetration stage. In cratering stage, near the location of impact the concrete particles broken up and fly away, produce a funnel crater. In stable stage of penetration, it will result a certain depth crater with the projectile continue to penetration target, the destruction of the target only near the hole, and show powder type damage. Surface particles flying of simulation results well consist with the high-speed photography (Fig 8). Results show that using FEM-SPH coupling algorithm can guarantee the clear of material interface, and avoid the grid delete and rezoning on the calculation of large strain, high strain rate and high pressure problems.

![Figure 8. Comparison between the high speed recording photos and simulation](image)

4. Conclusions
Two different algorithms (FEM and FEM-SPH) were used to simulation the penetration concrete process of earth-penetration warhead with booster. The results were compared with the experience formula and the experimental data. The comparison results show that the FEM-SPH coupling algorithm is more close to the experimental data, and the FEM-SPH coupling algorithm can overcome the shortage of traditional finite element mothed for dealing with extreme deformation problems. The maximum penetration overload of the calculation by FEM-SPH coupling algorithm is 29134g. Therefore, the propellant particles can withstand the maximum penetration overload is 29134g, and the duration of overload is 2.8ms which can meet the ignition design requirements of the booster.

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