Research Article

Numerical Simulation of Multifunctional Projectile Penetrating Reinforced Concrete Target Plate Based on Sensor Data Acquisition

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The main material of a type of multifunctional warhead is energy-containing material, which mainly relies on the projectile’s own kinetic energy to hit the target plate to achieve the function of penetrating reinforced concrete, so it needs the bullet material to have high strength and be able to withstand the high overload when penetrating reinforced concrete. At present, the composite energy-containing material structure with Al, Zr, Ti, and other materials as PTFE-based reducing agents is the mainstream direction of research on high-strength energy-containing materials. LS-DYNA is used to establish a simulation model to simulate and analyze the tapping power. The relationship curve between material strength and attack depth is established and compared with the experimental data of traditional steel material attack ammunition to finally determine the strength limit of energy-containing material compared with traditional attack ammunition. The simulation results show that the composite energy-containing material multifunctional projectile can accomplish the tapping task of penetrating 1.2 m reinforced concrete under the premise that the percentage of W powder is not higher than 80%. This study has a certain reference value for the selection of energy-containing materials for multifunctional warheads. For the low-velocity penetration below 400 m/s, the effect of frictional resistance of the head as well as the sidewall on the penetration depth can be ignored, but the overload curve when considering the sidewall friction is more realistic. Using a combination of experimental and theoretical methods, the influence of the projectile material on the mass erosion of high-speed kinetic energy projectiles was studied, and the Jones erosion model based on the thermal melting principle was improved. Based on the cavity expansion theory, the calculation method of the shape evolution of the bullet head was established. The comparison with the experimental results shows that the improved model is applicable to different types of soft and hard materials and can accurately calculate the mass erosion amount, erosion depth, and shape evolution of the bullet head.

1. Introduction

Penetration mechanics refers to the mechanics of a high velocity or hypervelocity projectile impacting a target body and drilling into or penetrating the target body [1]. It is widely used in military engineering (such as armor, antiarmor, and drilling weapons) and civil engineering (such as nuclear power plants, concrete dams, spacecraft, and automobile protection), so this problem has been a hot research area in the international impact engineering community and military research departments of various countries. Earth Penetrating Weapon (EPW) is a weapon that can effectively attack hard targets and targets buried deep underground. It attacks the target by invading several meters or even tens of meters underground and explodes, which has a killing effect that is difficult to achieve with other attack methods [2]. As the level of protection increases, there is an urgent need to improve the penetration capability of the drilling weapon. Kinetic energy is proportional to the quadratic of velocity, so increasing the initial velocity of the projectile is the most important way to enhance its penetration and damage capabilities. In addition, increasing the velocity of the projectile can also improve its surprise defense capability and enhance its combat performance [3]. In recent years, the
focus of research on projectile penetration of concrete and other hard targets has shifted from the general drilling projectile (penetration initial velocity below 600 m/s) to the advanced drilling projectile (penetration initial velocity bounded by 1000–1500 m/s) [4]. A large number of experimental results show that the penetration of the projectile can be divided into three regions according to the projectile impact velocity \( v_0 \), namely, (1) rigid projectile region \((v_0 < 1000 \text{ m/s})\), (2) deformable/erosive projectile region \((1000 < v_0 < 3000 \text{ m/s})\), and (3) hydrodynamic region \((v_0 > 3000 \text{ m/s})\) (the division of these regions is related to the projectile target; the above critical velocity is only an approximate value).

In the rigid projectile zone, a simplified engineering analysis model can be used to better analyze the projectile penetration process [5]. In the hydrodynamic zone, the hydrodynamic model can give more reasonable prediction results [6]. Only the “deformable/erosive projectile zone” has not been sufficiently studied, and no systematic theory has been developed yet. In this zone, significant mass loss [7], reduction of the penetration efficiency, and even ballistic instability (severe deviation of the penetration trajectory from the initial velocity direction) occur, bending the damage of the projectile structure [8], which seriously affects the penetration capability of the projectile. In addition, due to the angle of attack, inclination, angular velocity, and other factors, the practical applications are nonpositive penetration of the projectile to the target, and the nonpositive penetration will produce very obvious transverse loads, which will affect the structural stability of the penetrating body, and the current analysis of the ballistic and projectile transverse loads under nonpositive penetration is far less adequate than under positive penetration [9]. The researchers gave experimental values of the coefficient of friction between different metals at pressures up to 180 MPa and velocities up to 550 m/s. The researchers’ theory can be used to calculate the coefficient of friction of steel bullets (with velocities up to 1000 m/s) moving in geological materials or concrete. In view of the above, this paper investigates the behavior of high-speed nonpositive penetration of concrete by an elastomer from the perspective of theoretical analysis, numerical simulation, and experiments [10]. The main work is based on the differential surface force method to establish the ballistic prediction methods for nonpositive intrusion of rigid projectiles and intrusion/through finite thick targets and to analyze the influencing factors of mass erosion, ballistic deflection, and axial/transverse overload of projectiles [11]. The test sets up a total of 8 layers of reinforced concrete targets, based on the majority of the current building floor thickness settings, the top floor slab thickness of 300 mm, the rest of the floor slab thickness of 180 mm, length and width of 4 m, the vertical spacing of 3.5 mm between the targets, the target surface and the ground normal direction angle of 15, the target plate strength of 40 MPa, and volume reinforcement rate of 0.3%. The initial velocity of the projectile is 688 m/s when shot horizontally from the center of the reinforcement grid.

In this paper, a combination of theoretical analysis, numerical simulation, and experiments is used to investigate the endpoint effect of nonpositive penetration of a projectile through concrete. Ballistic prediction methods for nonpositive penetration of rigid projectiles through semi-infinite targets and nonpositive penetration of rigid/erosive projectiles through finite thick targets are proposed. For this purpose, the intrusion resistance model is first studied, the cratering depth model is established, and the mass erosion and free surface effect models are improved. On this basis, the study gives the influencing factors of the intrusion trajectory and the axial/transverse overload of the projectile, and the results of the study can provide the theoretical basis for the material selection, intrusion capability prediction, structural response analysis, and structural optimization of the high-speed nonpositive intrusion body. Based on the kinetic finite element software LS-DYNA, the process of vertical penetration of rigid projectiles into concrete, aluminum, and steel targets is investigated. By extracting the time course curves of axial overload of projectiles and comparing them with experimental data, the role of inertia term in penetration resistance and the applicability of cavity expansion theory to different target plates are studied. Based on the dynamic spherical cavity expansion theory of concrete material, an intrusion model considering the sidewall friction of the projectile is established to study the effect of sidewall frictional resistance on the depth of intrusion, the overload curve, and the composition of the intrusion resistance under different initial velocities. The above work can lay the foundation for the analysis of force and motion of kinetic energy projectile in a concrete medium.

2. Related Work

A numerical simulation method refers to the solution of a set of partial differential equations consisting of physical equations (conservation of mass, conservation of momentum, and conservation of energy) and material intrinsic relations for all material points in the intrusion process with the help of an electronic computer. Compared to experimental methods, numerical simulations are highly reproducible and allow easy and systematic study of the effect of a parameter, which is difficult to achieve in experiments. Compared with the analytical method, the numerical simulation method can use more complex intrinsic structure relations to obtain a more complete physical picture of the penetration process [12]. In particular, the very high experimental cost of kinetic energy projectile intrusion into the target plate highlights the advantages of numerical simulation. According to the discretization method, numerical simulation methods can be classified as finite cell method, finite difference method, discrete element method, and meshless method [13]. According to the coordinate description method, numerical simulation programs can be divided into two categories, Lagrange type and Euler type. The representative nonlinear dynamics programs are DYNA, AUTO-DYN, ABAQUS, and EPIC. The numerical simulation method also has many limitations [14]. As a basis, the intrusion resistance model of the projectile is firstly studied, the applicability of the cavity expansion theory to different types of target plates is analyzed and compared, the intrusion model considering sidewall friction is established, and the
mass erosion and Warren free surface models are improved. The research results can provide theoretical support for the prediction of the penetration capability, structural response analysis, structural optimization, and material selection of high-speed nonpositive penetrators.

Firstly, the reliability of the numerical simulation depends on the accuracy of the intrinsic model, and it is still difficult to find an intrinsic model that can completely and accurately describe the dynamic mechanical properties of concrete and other brittle materials; secondly, some of the parameters of the intrinsic model are difficult to be determined directly by simple experiments, and the strain rate varies greatly during the whole invasion process [15]. Once again, in the accuracy of the contact algorithm, the material on both sides of the target contact surface will produce violent motion, large deformation and "erosion," and the shape of the target interface needs to be constantly updated in the calculation process [16]. The friction coefficient between the targets needs to be determined when studying the high-speed penetration of kinetic energy projectiles into metal, concrete, or soil (penetrators with velocities up to 1000 m/s and pressures up to hundreds of MPa). However, tribology is mostly concerned with the frictional behavior at relatively low velocities and pressures.

The coefficient of friction was experimentally studied for pressures up to 3 GPa and velocities up to 30 m/s. The researchers gave experimental values for the coefficient of friction between different metals for pressures up to 180 MPa and velocities up to 550 m/s [17]. The researchers analyzed a large amount of experimental data on the friction coefficient of steel against steel and concluded that at lower velocities (less than 1 m/s) the friction coefficient strongly depends on the surface state; at higher velocities, the friction coefficient becomes increasingly dependent on the pressure and sliding velocity at the interface; at very high pressures and velocities, the friction coefficient becomes very small. The relationship between the coefficient of friction and the pressure \( p \) and sliding velocity \( v \) is given by the researchers, and the dots are from the researchers’ experimental results. As can be seen from the literature above, the coefficient of friction decreases with increasing pressure and velocity.

### 3. Ballistic Stability of a Multilayer Reinforced Concrete Target Penetrated by a Bullet

#### 3.1. Ballistic Stability

To facilitate the study, the initial Lprojectile attitude angle is defined as \( \gamma \) and the projectile attitude angle at any position during the invasion process is \( \gamma \). Then, the projectile attitude deflection angle at any position during the invasion process is

\[
\Delta \lambda = \lambda - \lambda_0.
\]  

In fact, in the process of obliquely penetrating the reinforced concrete target plate, the deflection of the projectile in all directions will occur due to the asymmetry of the projectile force, which will in turn affect the destruction of the reinforced concrete target plate, leading to more complex ballistic stability problems. Therefore, the following assumptions are made to simplify the problem:

1. The projectile is considered a rigid body
2. The change in the angle of the projectile is always in the XZ plane
3. The combined force on the projectile can be decomposed into two mutually perpendicular resistances, that is, the decomposition force \( f \) and the decomposition force \( df \) in the direction of the normal direction of the velocity of the projectile

The equation of motion of the center of mass is given by

\[
\begin{align*}
\frac{d^2 x}{dt^2} &= f \sin \alpha + f \cos \alpha, \\
\frac{d^2 y}{dt^2} &= f \sin \alpha - f \cos \alpha, \\
I a_u &= M, \\
a_u &= \frac{d^2 \phi}{dt^2},
\end{align*}
\]

where \( I \) is the rotational inertia of the projectile and \( a \) is the angular acceleration of the center of mass.

The joint solution yields the deflection angle of the projectile, whose value depends on the deflection moment \( M \):

\[
\phi = \frac{\pi}{2} - \int (-M) dt.
\]

Figure 1 shows the ballistic deflection diagram of the projectile penetrating a multilayer reinforced concrete target. In the process of penetrating the multilayer spaced target, the projectile attitude is deflected, and the attitude angle and ballistic deflection displacement increase layer by layer, and the penetration trajectory shows a gradual deviation from the horizontal axis.

The projectile penetration into each layer of reinforced concrete target slab can be divided into 4 stages as follows:

1. The projectile head invades the target body stage: under the premise of the existence of the angle of inclination and angle of attack, the upper and lower surfaces of the arc-shaped section of the projectile head are subjected to different forces, and the projectile body is deflected
2. The bullet body penetrates the opening stage of the target plate: the arc-shaped section of the bullet head has completely passed through the back of the target plate, and the bullet body begins to invade the target body. The target plate has formed a complete conical plug, while the side of the projectile body is still in contact with the target plate and the radial force on the side of the projectile body gradually increases, so the long axis of the elliptical projectile hole
3.2. Test Conditions and Finite Element Model. As shown in Figure 2, this paper uses the test of an ovoid projectile obliquely penetrating a multilayer spacer target at the State Key Laboratory of Explosive Science and Technology as the background for the simulation verification. The bullet diameter is 250 mm, the L/D ratio is 4.8, the bullet weight is 290 kg, the rotational inertia \( J_c \) is 35.32 kg/m², and the length \( l_c \) from the center of mass to the bullet head is 0.68 m. The bullet head is composed of three circular arcs, and the bullet head curve is simplified with \( CRH = 1.75 \). The rigid body motion with the direction of the velocity of the center of mass and the rotation around the center of mass is along a certain trajectory movement to the next layer of the target plate.

Assuming that the velocity direction of the projectile is always in the same plane with the projectile axis during the process of projectile penetration into the target plate, the penetration process can be regarded as symmetric, and the 1/2 model is established for the projectile and the target plate to simplify the calculation. In the model, both the projectile and the concrete use SOLID164 cell type, which is composed of 8 nodes and is mainly used as a solid cell for 3-dimensional explicit structures. The reinforcement is of type BEAM164, which is used only for displaying the dynamics analysis and supports all nonlinear features. The protruding part of the projectile is simplified to an ovoid head, considering that the head shape is as consistent as possible with the actual one; otherwise, it would affect the projectile deflection. In order to make the simulation conditions consistent with the test conditions, a separate modeling method is used to establish the reinforcement and concrete separately, and the interaction between the reinforcement and concrete is simulated by coupling the reinforcement constraints in the concrete with keywords. Among them, the reinforcement of each target plate is arranged as a two-layer bidirectional setup, where the diameter of the reinforcement of the first target plate is 8 mm and the spacing between the reinforcement is 200 mm, and the diameter of the reinforcement of the remaining three target plates is 6 mm and the spacing of the reinforcement is 200 mm.

TrueGrid meshing software is used for the 3:1 mesh sparsity gradient. The length of the dense area is 10 times the elastic diameter, and the width is 4 times the elastic diameter. The model uses SOLID164 cell type for both the elastic body and concrete, while BEAM164 cell type is used for the steel reinforcement, and the steel reinforcement and concrete are treated in a noncommon node manner. The surface erosion contact algorithm “CONTACT_EROSION_SURFACE_TO_SURFACE” is used to describe the interaction between the projectile and the target, and in order to avoid excessive unit distortion, when the unit deformation reaches a certain threshold, the \( \text{MAT_ADD_EROSION} \) algorithm is used to delete the Failure cells, add the maximum tensile principal stress failure criterion and the maximum hydrostatic tensile stress criterion as a two-way judgment basis, and jointly simulate the tensile failure suffered by the concrete material during the intrusion process. The influence of the grid on the deflection of the projectile’s attitude angle can be seen that the curve of the deflection of the attitude angle differs greatly when the grid is larger, and the change of the projectile’s attitude during the invasion process is basically the same for \( \lambda = 0.8 \) and 0.96. Figure 3 shows the effect of the grid on the velocity of the projectile, and the time-range curves of the projectile velocity do not change much in the four cases. Therefore, \( \lambda = 0.96 \) is chosen to balance the computational efficiency and simulation accuracy.

In order to study the effect of the rebar grid size on the stability of the ballistic path of the projectile penetrating the multilayer reinforced concrete, a simulation condition is set. The diameter of the projectile is \( D = 250 \) mm, the initial velocity of the projectile is \( v = 800 \) m/s, and the projectile is incident horizontally from the center point of the reinforcement grid. The inclination angle is 15°, the angle of attack is 0°, the thickness of the four-layer reinforced concrete target plate is 300 mm, a double-layer reinforcement grid is set, the protective layer thickness of the reinforcement is 30 mm, the diameter of the reinforcement d is 8 mm, and the vertical distance between the target plates is 3.5 m. The
The projectile body is horizontally injected into the reinforced concrete target body, the front row of reinforcement is evenly distributed on both sides of the projectile body, and under the premise of the existence of the inclination angle, the size of the reinforcement grid is changed. The relative position of the projectile body and the back row of reinforcement bars is changed. As shown in Figure 4, the number of collisions with transverse bars is 3 for \( S/D = 1.0, 0.8, 0.6 \), and 2 bars which are located on the upper surface of the projectile body and 1 bar which is located on the lower surface of the projectile body for \( S/D = 1.0, 0.8 \). Two bars are located on both sides of the projectile body, and 1 bar is located at the axis of the projectile body for \( S/D = 0.6, 0.4 \). The number of collisions with transverse bars is 11, 6 bars are located on the upper surface of the body, and 5 bars are located on the lower surface of the body.

Calculation of the full 8-layer reinforced concrete target of the numerical simulation of the calculation time is too long; simulation of the first four layers of the law of the target plate can meet the requirements; according to the test data in the literature, this chapter carries out the finite element intrusion simulation for the first four target plates.

3.3. Effect of Reinforcement on Ballistic Stability. Figure 5 gives the time course curve of the angular velocity of the projectile axis under different reinforcement grid sizes, and it can be seen from the figure that the angular velocity of the projectile axis after penetrating the reinforced concrete target plate increases with the increase of the number of layers of reinforced concrete target plate. When the arc segment of the bullet heads out of the target plate back to start, there is a positive bending moment. As the projectile body moves downward, the moment of the projectile body will be increased, causing the projectile axis deflection angular velocity increasing until the tail of the projectile body just entered the reinforced concrete target plate when it reaches the maximum value. After that, the projectile tail further squeezes the reinforced concrete target plate, the inclined side of the projectile body and the reinforced concrete target plate contact area is reduced, and the projectile body is subject to a reduced moment, causing the projectile axis deflection angular velocity to decrease. Therefore, a downward "convex" angular velocity curve of the bullet axis is formed. For oblique intrusion, the plastic deformation zone of the reinforced concrete target plate in the initial stage of the intrusion is mainly concentrated within 5 times the elastic diameter, and the plastic deformation zone of the target plate gradually increases with the deflection of the elastic body. The plastic deformation zone of the target plate requires fine mesh size, and then the mesh gradually transitions from fine to coarse to the periphery in order to reduce the calculation scale.

From the figure, it can be seen that the projectile penetrates four layers of reinforced concrete target, and with the increase of the number of layers of reinforced concrete target plate, the attitude angle after penetrating the reinforced concrete target plate increases continuously and the ballistic deflection displacement increases continuously. In \( S/D = 0.6 \), the reinforcement exacerbates the increase of the projectile attitude angle, and the exacerbation effect is more significant with the increase of the number of target plate layers. In \( S/D = 1.0 \), the longitudinal reinforcement collides with the projectile to a lesser extent; in \( S/D = 0.8, 0.6 \), the number of colliding reinforcement is the same, but as \( S/D \) decreases, the location of the rear row collision moves from the upper surface of the projectile to the direction of the projectile tip, the range of collision between the longitudinal reinforcement and the projectile increases, the rear row of longitudinal reinforcement "convex" outward increases, the transverse reinforcement moves upward. The bending angle decreases, resulting in the increase of the posture angle of the bullet. The second deflection (except for the first layer) will occur after penetrating the multilayer reinforced concrete target plate, mainly because the angle of attack will be generated after penetrating the first layer of reinforced concrete target plate, and the upper surface of the projectile body will be further squeezed with the target plate.

4. Numerical Simulation of Sensor Data Acquisition

The mass erosion of the projectile is not considered in the calculation. Figure 6 shows the experimental and theoretical calculation results for vertical penetration, and the spalling depth is the depth of the conical crater formed on the back of the target in the experiment, and the experimental and theoretical calculation results for nonpositive penetration are shown. Regardless of vertical penetration or nonpositive penetration, the method proposed in this chapter can predict the residual velocity of the projectile relatively accurately within 16% error. In the experiment, the penetration phenomenon occurred in Case 4, and the residual velocity was less than 30 m/s. In the theoretical calculation, the penetration depth of the projectile was 524 mm, which did not penetrate the target, and the tip of the projectile was 76 mm away from the back of the target, but there was a 305 mm deep conical crater on the back of the target in the experiment.
Figure 7 shows the intrusion trajectories for both cases with/without considering erosion. It can be seen that due to the asymmetric erosion causing the asymmetric structure of the projectile, the lateral deflection $X$ for the same vertical penetration depth $Z$ is consistently larger than that for the no-erosion case. However, due to the passivation of the bullet head after considering erosion, the final vertical intrusion depth $Z$ of the bullet is lower than that of the rigid body intrusion, and the final lateral offset $X$ is also lower than that of the rigid body intrusion. It can be seen that after considering the erosion of the projectile, the peak axial and lateral overloads are larger than that of the rigid body penetration due to the passivation of the projectile head shape. Until 0.5 ms, the angular velocity of the projectile is always greater than zero, so the external normal velocity $v_n$ of any microelement on the upper half of the projectile head is greater than the external normal velocity at the corresponding position on the lower half, and the stress $r$ of any microelement on the upper half is greater than the stress at the corresponding position on the lower half. The upper half side is more severely passivated than the lower half side before 0.5 ms. The asymmetry of the projectile structure when considering asymmetric erosion causes the transverse load, angular acceleration, angular velocity, and attitude angle of the projectile to be greater than the rigid body erosion. However, after considering erosion, it causes passivation of the head of the projectile, increase of the intrusion resistance, shorter intrusion time, and smaller intrusion depth, and the final attitude angle of the projectile is smaller than that of the rigid body intrusion.

When the number of colliding transverse rebar is the same, the rebar grid size decreases and the residual velocity of the projectile remains basically unchanged; when $S/D = 0.2$, the residual velocity of the projectile shows a sudden decrease, which is due to the increase in the number of longitudinal rebar fractures on the one hand and the increase in the projectile attitude angle due to the secondary deflection on the other hand, and the contact area between the side of the projectile and the reinforced concrete increases, resulting in a significant decrease in the kinetic energy of the projectile.

The influence of the back side of the target plate on the penetration/intrusion process was analyzed. The calculation condition is chosen to be a nonpositive penetration of a 0.45 m (7d) thick concrete target with an inclination angle of 15.9° and a velocity of 406.8 m/s. Figure 8 shows the axial overload, lateral overload, attitude angle, velocity, and vertical displacement of the projectile and the intrusion trajectory for the three cases. These three cases are as follows: (1) considering the front and rear free surface effect-penetration, the free surface effect of the front and back of the target plate is considered in the calculation; (2) considering
only the front free surface effect–penetration, only the free surface effect of the front of the target is considered in the calculation, ignoring the attenuation effect of the back of the target on the expansion stress of the cavity, and considering the thickness of the target, the stress of the unit is 0 when any unit on the surface of the projectile penetrates the target plate; (3) only considering the front free surface effect–semi-infinite target intrusion, the calculation only considers the free surface effect on the front of the target, and ignoring the thickness of the target body, this case is the semi-infinite target intrusion problem. These three cases are called curve 1, curve 2, and curve 3. The axial and transverse overload peaks of the projectile in the three cases are basically the same, and the axial overload peak is slightly smaller when considering the free surface effect on the back of the target. For curves 2 and 3, the axial and lateral overloads of the projectile before it leaves the target coincide completely. After that, for curve 2, the axial overload gradually decreases to zero as the projectile gradually penetrates the target, while for curve 3, i.e., penetrating the semi-infinite target, the axial overload suddenly drops to zero when the projectile velocity is zero. When the vertical distance between the bullet tip and the back of the target is less than 4d (target thickness is 7d, which is 0.51 ms), the back of the target starts to affect the penetration resistance significantly.

From Figure 9, it can be seen that when the target is thin (e.g., 300 mm), the intrusion overload reaches the peak and then decreases rapidly without a clear plateau. When the target is thicker (e.g., 600 mm), the penetration overload has an obvious plateau. In addition, due to the low velocity of the projectile on the target (405.1 m/s), the effect of the inertia term in the penetration resistance is not obvious, and the penetration resistance after the projectile enters the stable penetration can be regarded as a constant, which is consistent with the conclusion that when the projectile velocity is lower than 400 m/s, the inertia term in the penetration resistance can be ignored and the resistance is regarded as a constant. The impact velocities of these four conditions are all around 405 m/s, so the peak overload is basically the same. When the target thickness is less than or equal to 500 mm, the projectile can penetrate the target plate, and when the target thickness is 600 mm, the depth of intrusion of the projectile is 524 mm. Appropriate adjustment of the target thickness can be obtained under the incidence conditions of the ultimate penetration thickness. Therefore, in the case of known residual velocity of the projectile, the method given in this chapter can predict the ultimate penetration thickness and ballistic ultimate velocity, etc.

In this paper, we propose a method to deal with the free surface effect before and after the finite thick target and establish a ballistic prediction method for the nonpositive intrusion of eroding projectile into the finite thick target based on the improved mass erosion model, differential surface force method, and improved free surface model. The comparison with the experimental data shows that the
The length of the tail skirt and the shape of the warhead have less influence on the ballistic offset, and increasing the length-to-diameter ratio is conducive to improving ballistic stability. The axial/transverse overload of the projectile is inversely proportional to the projectile size, and the force environment of the small-sized projectile is significantly worse than that of the large-sized projectile. The closer the center of mass of the bullet is to the tip, the smaller the ballistic offset and the smaller the peak transverse overload. A moderate amount of negative angle of attack can improve ballistic stability when the inclination angle is penetrating. When the inclination angle is within 20°, it has little effect on the overload of the projectile. The greater the initial inclination or angular velocity, the greater the ballistic deflection and the greater the change in attitude angle. The angle of attack can significantly increase the lateral overload of the projectile, especially the positive angle of attack, which seriously affects the stability of the projectile structure. The results of the study can be used to predict the axial/transverse overloads, displacements, intrusion strokes, and attitude angles of nonpositive intrusion projectiles and provide references for the structural design of high-speed intrusion bodies.

5. Conclusion

In this paper, the nonpositive penetration process of the projectile into the concrete target is studied from the perspectives of theoretical analysis, numerical simulation, and experiment. Based on the analysis and comparison of the applicability of cavity expansion theory to different types of targets, an intrusion model considering sidewall friction is established, and Jones mass erosion and Warren free surface models are improved. The results can provide a theoretical basis for the prediction of the penetration capability, structural response analysis, structural optimization, and material selection of high-speed nonpositive penetrators. In this paper, the nonlinear dynamics program LS-DYNA is used to study the role of the target inertia term in the penetration resistance of kinetic energy projectiles from the perspective of penetration overload. The cavity expansion theory overestimates the role of the inertia term and is not applicable to
metal targets; for brittle targets such as concrete, there is a critical velocity, and when the velocity is lower than the critical value, the target strength term plays a decisive role and the resistance in the tunneling area can be regarded as a constant, while when the velocity is higher than the critical value, the role of the inertia term in the penetration resistance is more obvious. The cavity expansion theory is applicable to the brittle target, and the damage number $D$ of the target can be used to characterize the role of the inertia term in the resistance to penetration of the target. Based on the cavity expansion theory, an intrusion model considering the friction of the sidewall of the projectile is established, and the influence law of sidewall friction on the intrusion is studied. When the initial velocity of the projectile is between 800 and 1300 m/s, ignoring the sidewall friction will bring at least 10% deviation to the intrusion depth. In the future, the final vertical intrusion depth, lateral displacement, and attitude angle of the projectile are smaller than those of the rigid body intrusion.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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