Numerical simulation of dynamic response of underwater supercavitating projectile structure based on after-effect enhancement of kinetic penetration

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Abstract. Aiming at the underwater supercavitating projectile, a damage mode of enhanced effect after kinetic penetration is proposed. The structure of energetic projectile with prefabricated breaking groove is designed, which can not only ensure the projectile strength in underwater motion, but also release the filling agent to the interior of the target through the projectile fracture when hitting the target. Based on ANSYS/LS-DYNA finite element analysis software, the equivalent model of supercavitating energetic projectile penetrating low-carbon steel shell of mine in three-phase domain is established. The dynamic response of the projectile in the stage of underwater motion and penetration is obtained by analyzing the force of the key parts of projectile and observing the deformation of the projectile structure. By changing the initial velocity and landing angle of the projectile, analyzing the law of velocity variation and penetration depth of the projectile, observing the deformation of the projectile structure and the phenomenon of the energetic agent disperation when penetrating the steel plate, the quantitative conclusion of the damage effect of the energetic projectile on the typical mine target under different working conditions is obtained. The research results have reference value for the structural design and power evaluation of underwater supercavitating energetic projectile.

1. Introduction

Damage enhanced energetic projectile is a new type of projectile with energetic materials as an important part. When the projectile strikes or penetrates the target, the energetic material reaches a specific activation threshold, and reacts violently with the structure. In a short time, it releases a lot of heat to make the target deflagrate or explode. Compared with the traditional inert metal projectile, this kind of projectile has a more significant after-effect enhancement effect. At present, it has become a research hotspot and an important development direction in the field of terminal damage.

Common energetic materials include teflon (PTFE/AL), potassium perchlorate (KCLO₄), aluminum fluoride (AlF₃), etc [1-3]. The domestic related units have carried out research on the damage enhanced energetic projectile in the aspects of theoretical analysis, numerical simulation and experimental research. Jun PENG [4] and others introduced the after-effect enhancement effect and
characteristics of typical projectiles at home and abroad, such as active fragments, active projectiles and active energy accumulation projectiles and summarized the design, processing, application, key bottlenecks and future development trend of the technology. Si-yi MENG [5] used AUTODYN to analyze the simulation test of hypervelocity impact of energetic bar and kinetic bar on metal target. The results showed that under the same conditions, the P/D value of the target plate impacted by the energetic rod is smaller than that of the kinetic rod, and the damage effect was related to the impact velocity, the impact angle and the characteristics of the target plate. Yang ZHAO [6] studied the load change of a new type of energetic projectile during the water stage through ANSYS/LS-DYNA. He summed up the changing rule of the impact peak value of the water medium to the projectile body and the energetic material, providing reference for the structural design of the new energetic projectile. Lin WANG [7] and others carried out the experimental research on the penetration of hollow projectile made of bainite steel and 35CrMnSi into A3 metal target plate, and revealed the relationship between the deformation of projectile, mass erosion and material microstructure, especially the relationship with adiabatic shear band. Xu [8] studied the damage effect of the projectile with PTFE/Al/W active material on 2024-T3 aluminum plate, analyzed the impact speed on the protrusion degree of the petals and penetration size of the target plate, and the chemical energy released by the active material had a significant impact on the damage of the aluminum plate.

Through the special long conical structure and high muzzle velocity, supercavitating projectile [9] can generate natural supercavitation while navigating in water, which makes the navigation resistance less and maintains high-speed and stable underwater trajectory, thus improving the range of projectile and the ability to damage the target. Based on the conventional supercavitating projectile [10], the structural design and safety analysis of the projectile [11] are carried out in this paper. Under the condition of structural integrity of the new energetic projectile in underwater trajectory, the after-effect enhancement such as internal charge or component deflagration caused by underwater penetration into the shell of mine can be realized.

In this paper, the physical process of underwater penetration of supercavitating energetic projectile into mine target is analyzed. Based on the ANSYS/LS-DYNA finite element analysis software [12], a simulation model of the penetration of the supercavitating energetic projectile into the steel plate in the water environment is established. The dynamic response of projectile in water and penetration stage is obtained by analyzing the force on the typical part of projectile and observing the deformation of projectile structure. The law of projectile velocity variation and penetration characteristics of projectile under different working conditions are studied. The action process of energetic projectile on steel plate is analyzed to find out whether the projectile is reliable to break and release energetic agent, achieving the effect of damage enhancement.

2. Simulation modeling

2.1. Model establishment
The geometric model is composed of five parts: water, air, supercavitating projectile, energetic material and target plate. To cite the supercavitating projectile structure in reference [10], it is assumed that the supercavitating energetic projectile consists of cylindrical aluminum alloy body and conical tungsten alloy head. The inner cavity of the projectile is filled with energetic materials, and a
prefabricated breaking groove is designed at the body of the projectile as a dangerous section. The specific projectile model is shown in figure 1. For the typical 10mm low-carbon steel shell of mine, the target plate size is 16cm×16cm×10mm, and the curvature is 3.75m⁻¹. The front end of the target plate is water environment and the back end is air environment. The typical impact velocity of energetic projectile is 300m/s and cm-g-μs unit system is adopted for simulation. The specific geometric model is shown in figure 2.

![Figure 1. Model diagram of supercavitating energetic projectile.](image1.jpg)

![Figure 2. Geometric model of underwater penetration of supercavitating energetic projectile into target plate.](image2.jpg)

2.2. Parameter setting
Eulerian grid is used to model water medium and air medium, and multi-material ALE algorithm is used for the element. Lagrangian grid is used to model supercavitating projectile and target plate, and multi-material fluid solid coupling algorithm is used between projectile, target plate and water, air. The erosion between projectile and shell is simulated by 3D Surface to Surface Eroding algorithm. Three-dimensional non-reflecting boundary are imposed on water and air to simulate the infinite environment. The null material is used for water and air, the Johnson cook material failure model is used for projectile and target, and the Gruneisen adiabatic entropy increase state equation is used. The oxidant is replaced by soil material of Soil and Foam, and the SPH algorithm is used to simulate the movement process of solid particles. The specific material parameters are shown in Table. 1, where ρ is the material density, G is the shear modulus, E is the elastic modulus, PR is the Poisson ratio, D is the failure parameter, BULK is the bulk modulus, A₀, A₁ and A₂ are the plastic yield constants.

| PART | ρ( g/cm³) | G(GPa) | E(GPa) | PR | D       |
|------|-----------|--------|--------|----|---------|
| PART 1 | 1.02      | Null   | Null   | Null | Null    |
| PART 2 | 1.25E-03  | Null   | Null   | Null | Null    |
| PART 3 | 17.6      | 136    | 350    | 0.28 | 1.5     |
| PART 4 | 2.77      | 26     | 69     | 0.33 | 1       |
| PART 5 | 3.83      | 77     | 195    | 0.27 | 0.8     |

2.3. Simulation results
The simulation results are shown in figure 3. It can be seen from the figure that the projectile has a relatively small deformation and the water environment is not broken through. The target plate deformation is significant, and the deformation area is large. This shows that the prefabricated breaking groove has a good protective effect.

![Figure 3. Simulation results.](image3.jpg)
For this kind of slender projectile, adding the global hourglass control, taking the time step factor TSSFAC as 0.6 and the fluid solid coupling penalty function factor PAFC as 0.1, reducing the contact stiffness SLSFAC to 2 without model penetration, and limiting the ratio of ALE element size to LAGRANGE element size within 2:1 to control the negative volume problem under three-phase coupling high-velocity impact. Through debugging in the keyword of CONSTRAINED LAGRANGE IN SOLID, the minimum percentage of activation of fluid substance in coupling unit FRCMIN is taken as 0.3, the leakage control penalty function coefficient PLEAK is taken as 0.18, the default value of leakage control switch ILEAK is selected, and the sliding condition of euler automatic boundary EBC is set to better reduce the leakage phenomenon of this model. By selecting the DT2MS value as -0.16 for local mass scaling, the mass increment of the whole model is 0.9% and the solution time of the model is reduced by 88.7%, which greatly improves the calculation efficiency while ensuring the accuracy and reliability of the numerical simulation results.

2.3. Model assumption

(1) It is assumed that the first critical state and the second critical state of the projectile body strength check have been met, and the state of the energetic material inside the projectile is stable before penetrating the target plate.

(2) The whole simulation process lasts only 1500ms, gravity can be neglected.

(3) The whole process of projectile penetrating the target plate is considered to be adiabatic, the heat exchange between projectile, water and air can be neglected.

(4) The connecting structure between the tungsten alloy head and the aluminum alloy body is ignored, and glue operation is used in modeling.

3. Calculation results and analysis

3.1. Dynamic response analysis of energetic projectile

In order to study the dynamic response of supercavitating energetic projectiles in the navigation stage and the penetration stage respectively, this section selects typical test points to study the stress change rule of the projectile and analyzes the deformation of projectile structure in the process of penetration.

3.1.1. Stress analysis of projectile. In the simulation test, the supercavitating energetic projectile starts to move at an initial velocity of 300m/s and a distance of 10cm in front of the steel plate. In order to study the stress condition on the typical parts of projectile in the navigation stage and penetration stage, five test units of element 1~5 are taken for stress analysis, and the specific location is shown in figure 3. The measured data are processed by smoothing filter in Origin to get the stress change of each test unit, as shown in figure 4.
Figure 4. Von mises stress time-history curve of Element 1-5.

It can be seen from figure 4 that when the projectile is in the navigation stage (0–333μs), there is a reacting force between the projectile and the steel plate in the water medium. The Von Mises stress of Element 1 oscillates in the range of 410-780MPa, and its peak stress exceeds the yield limit of 680MPa of tungsten alloy material. The warhead has small deformation. The average stress of Element 2 at the joint of warhead and body is 60MPa, the vibration amplitude is gentle, and the effect of body vibration is the least. The average stress of Element 3 at the front end of the cavity surface structure is 182MPa, which is smaller than that of Element 5 at the back end of the cavity surface structure, whose average stress is 189MPa. The stress of Element 4 on the surface of prefabricated breaking groove is about 239MPa, and its peak stress exceeds the yield limit of aluminum alloy material by 280MPa. There is a slight extrusion deformation on the surface of prefabricated breaking groove.

When the projectile is in the penetration stage (333~800μs), the Von-Mises stress of Element 1 at the warhead rises sharply to 1260MPa, which exceeds the strength limit 1240MPa of tungsten alloy. The material is eroded and the warhead produces upsetting deformation. For the remaining four test units, with the increase of penetration depth of projectile, the velocity difference between the projectile body and head due to inertial makes each test unit suffer axial compression in turn, and the measured Von-Mises stress increases accordingly. When the test units contact the steel plate, the stress values decrease briefly and then rise sharply. The Von-Mises stress values of Element 2 at the joint of projectile head and body and Element 3 at the front end of cavity surface structure are stable at 295MPa and 312MPa respectively, and the materials at corresponding parts have obvious axial compression deformation. The Von-Mises stress values of Element 4 on the surface of the prefabricated breaking groove and Element 5 at the rear end of the cavity surface structure rises rapidly to 525MPa and 537MPa respectively, which exceeds the strength limit 520MPa of aluminum alloy. After a period of time, the materials are eroded.

In summary, the law of stress mean value of five test points during the whole time course is as follows: Element 1> Element 4> Element 5> Element 3> Element 2.

3.1.2. Structure deformation of projectile. Because of the incompressibility of the water medium, before the energetic projectile contacts the target plate, the force between the warhead and the target plate increases obviously, and the warhead has been slightly deformed.

In the pit-opening stage (333–495μs), the tungsten alloy head is eroded with the increase of penetration depth and further deformed. When the projectile penetrates the steel plate, the head length
is shortened from 6.2cm to 3.5cm. With the mass loss, the head mass decreased from 10.3g to 8.0g.

In the stable penetration stage (495~800μs), the cavity part of the projectile body and steel plate undergo adiabatic shear, and the cavity deforms in axial tension and radial compression. When the aluminum alloy medium is extruded and flows to the prefabricated breaking groove, the contact area between the projectile body and the steel plate increases. Because of the inertia of the warhead, the cavity is further stretched. When the tensile stress it bears exceeds the strength limit of the aluminum alloy material, the projectile breaks at the dangerous section, and the solid powder agent in the cavity is thrown out inside the target shell. The front part of the projectile continues to cause kinetic damage to the internal structure of the mine at a residual velocity of 220m/s, and the rear part of the projectile is stuck on the steel plate. In this process, the mass loss is mainly concentrated in the cavity position, and the mass of the projectile decreases from 11.4g to 10.4g. Because the ratio of target size to projectile diameter of the simulation model is 13, considering the boundary effect of the target plate, the elasticity of the steel plate recovers at the end of the penetration stage, there is a certain rebound in the rear of the projectile. The deformation process of the projectile structure is shown in figure 5.

![Deformation of projectile head and body](image)

(a) Deformation of projectile head.  
(b) Deformation of projectile body.

Figure 5. Time-history chart structural deformation of energetic projectile.

3.2. Study on penetration characteristics of energetic projectile

Based on the analysis of projectile velocity variation under the typical penetration velocity of 300m/s, the underwater action process between projectile and target in different stages is studied. In order to obtain the damage effect of energetic projectiles on typical underwater targets under different working conditions, this section changes the initial velocity and impact angle of the projectile, analyzes the change rule of the residual velocity and penetration depth of the projectile, observes the deformation effect of the projectile structure when penetrating the steel plate and the throwing situation of energetic agent.

3.2.1. Time history analysis of projectile velocity change. Figure 6 shows the time history graph of the projectile vertically penetrating 10mm steel plate at an initial velocity of 300m/s. It can be seen from the figure that in the water navigation stage of 0~330ms, the velocity of the projectile under the resistance of the water medium decreases and the velocity is 289m/s when it contacts the target plate;

In the pit-opening stage of 330~499ms, the tungsten alloy head contacts the steel plate. The dynamic friction coefficient of tungsten and steel is 0.4, and the projectile velocity dropping rate is slightly gentle. The projectile body continues to fly due to the inertia, resulting in a velocity difference of 5m/s between two parts and axial compression of the body.
In the stable penetration stage of 499–1500ms, the contact material of projectile and target changes, and the contact sliding friction coefficient of the aluminum alloy and the steel is 0.6, which increases by 50%; When the medium of the projectile body is squeezed into the breaking groove, the increase of the contact area between projectile and target leads to the increase of penetration resistance and dropping rate of the projectile velocity. The warhead maintaining its inertia and continuing to fly, the cavity structure is further stretched. The projectile broke at the low-strength prefabricated breaking groove at 676ms, and the oxidant is thrown into the target shell successfully. The front part of the projectile continues to fly at the velocity of 223m/s, and the rear part of the projectile reaches its maximum penetration depth at 792ms.

![Figure 6. Velocity time-history curve of energetic projectile.](image)

While the projectile reaches the maximum penetration depth, there is interaction between the projectile and the target. When the rebound force of projectile is less than the anti shearing force of the target material, the projectile is firmly stuck on the target plate, and vibrates for a long time until kinetic energy is exhausted; When the rebound force of projectile is relatively large, it will cause shear damage to the breach of the target plate, and the projectile will rebound; When the initial velocity of projectile is further increased, the penetration depth will increase and the projectile will penetrate the target plate. Under the condition of underwater vertical penetration, the ballistic limit velocity of this type of projectile is 230m/s. The curve changing law reflects the different mechanism involved in the process of energetic projectile penetrating the target plate. The damage mode with enhanced after-effect can be realized by achieving the effect of semi-penetration into the target plate.

### 3.2.2. Analysis of damage effect of projectile.

Under the condition of vertical penetration into 10mm steel plate, the energetic projectile penetrates the steel plate when the initial velocity is in the range of 230–250m/s. The projectile breaks at the prefabricated breaking groove, and the oxidant is thrown inside the target shell. At the end of penetration, the elastic recovery of the steel plate makes the rear part of the projectile rebound, and the water medium will flow into the target shell from the breach; When the initial velocity of the projectile is in the range of 250–400m/s, the energetic projectile is stuck on the steel plate. The projectile breaks at the prefabricated breaking groove, the oxidant is thrown inside the target shell, and the front part of the projectile continues to fly at a certain residual velocity. Low carbon steel material has high strength and low ductility. The purpose of after-effect enhancement can be achieved by changing the initial velocity of energetic projectile in the above velocity range. The specific penetration effect is shown in figure 7.
Figure 7. Effect chart of energetic projectile penetrating 10mm steel plate at different velocities.

Figure 8 shows the law of the residual velocity of the projectile changing with the initial velocity when the energetic projectile penetrates 10mm steel plate vertically. The energetic projectile breaks when the initial velocity is in the range of 230~400m/s. The velocity of the front part of the projectile changes in the range of 0~345m/s, increasing with the increase of the initial velocity of the projectile, and the increase rate shows a downward trend. The residual kinetic energy of the front part of the projectile is in the range of 0~476J, which can continue to damage the internal structure of the target shell under some conditions.

Figure 9 shows the law of the penetration depth of the projectile changing with the initial velocity when the energetic projectile penetrates 10mm steel plate vertically. When the initial velocity of the projectile is in the range of 230~400m/s, the projectile successfully penetrates the target plate and breaks in the prefabricated breaking groove. The penetration depth of the rear part of the projectile changes in the range of 0~44mm, increasing with the increase of the initial velocity of the projectile, and the increase rate shows a downward trend. Within this velocity range, the projectile doesn’t penetrate the steel plate.

Figure 8. Relationship between residual velocity and initial velocity of penetrating target plate.
Figure 9. Relationship between penetration depth and initial velocity of penetrating target plate.

When the supercavitating projectile is sailing at high velocity underwater, once there is an angle of attack between the axis direction of the projectile and the velocity direction of it, the projectile will suffer a great turning moment caused by the water medium. Based on the simulation without angle of attack, the influence of impact angle on the damage effect of steel plate penetration is studied. The initial velocity of projectile is 300 m/s. As shown in figure 10, when the impact angle is in the range of 0–32°, the projectile breaks at the prefabricated breaking groove. The rear part of the projectile is stuck on the target plate with the oxidant thrown successfully, and the front part of the projectile continues to cause kinetic damage to the internal structure of the shell at a certain residual velocity. When the impact angle is in the range of 33–48°, the projectile breaks at the prefabricated breaking groove. The front part of the projectile is stuck on the steel plate, and the rear part of the projectile is rebounded by the target plate with the oxidant thrown outside the target shell. When the impact angle is in the range of 49–90°, the projectile is extremely twisted to produce ricochet phenomenon, and the tungsten alloy warhead is broken.

Figure 10. Effect chart of energetic projectile penetrating target plate at different angles.

In summary, to achieve the enhanced effect after damage, the effective impact angle of the energetic projectile is 0–48° when penetrating the steel plate at the typical velocity of 300 m/s. Because of the long conical structure, the effective impact angle of the projectile is smaller than that of the conventional blunt head projectile, which makes it easier to produce ricochet. The target shell is made of low carbon steel, which has high strength and low ductility. After the projectile penetrates the steel plate, it is more likely to break due to adiabatic shear. This type of projectile has a good penetration effect on steel structure target, but a high requirement for a high impact angle.

4. Conclusions

Based on the numerical simulation analysis of the supercavitating energetic projectile penetrating 10 mm steel plate underwater, the following conclusions can be obtained:

1) In the whole time course, the load on the head of the energetic projectile is the largest, the stress
at the prefabricated breaking groove is greater than that at the front end of the cavity surface structure but less than that at the back end of the cavity surface structure, and the stress at the joint of the projectile head and body is the smallest.

2) Under the typical impact velocity of 300m/s, the energetic projectile can maintain the structural integrity in the underwater trajectory.

3) The energetic projectile can break when penetrating the 10mm steel plate in the range of 230–400m/s. The rear part of the projectile is stuck or rebounded by the steel plate. The front part of the projectile continues to cause kinetic damage to the internal structure of the target at a certain residual velocity, and the agent is thrown successfully.

4) When the energetic projectile penetrates the 10mm steel plate in the range of 230–400m/s, the residual velocity of the front part of the projectile is 0–345m/s, which increases with the increase of the initial velocity of the projectile. The rising rate shows a downward trend, and the residual kinetic energy is 0–476J.

5) The energetic projectile can not penetrate the 10mm steel plate with the velocity during 230–400m/s. The penetration depth of the rear part of the projectile is 0–44mm, which increases with the increase of the initial velocity of the projectile, and the rising rate shows a downward trend.

6) To achieve the effect of damage enhancement, the effective impact angle of the steel plate is 0–48° when the energetic projectile penetrates at the typical velocity of 300m/s.

7) Under the condition of underwater vertical penetration to 10mm steel plate, the ballistic limit velocity of energetic projectile is 230m/s.

8) Under some working conditions, the water medium will enter the target shell through the target plate break. Alkali metals such as sodium and potassium can be added to energetic agents to intensify the damage effect.

9) When energetic projectile penetrates the 10mm steel plate, the upsetting deformation of warhead is serious and the mass loss is a bit large. Tungsten alloy material with high strength and hardness should be selected to reduce the ballistic limit velocity of projectile and improve the penetration capacity.

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