Research progress of anti-penetration yaw technology for concrete protective structures

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Abstract. Concrete protective structure is an important part of national defense engineering. It is of great significance to study its development status and penetration mechanism. This article summarizes the recent research status of concrete protection yaw technology, and summarizes the existing yaw technology by distinguishing materials and structural asymmetry. The anti-penetration and yaw mechanism of the protective structure is summarized: The first is to analyze the effects of warhead shape and material, the incident state of the projectile, the configuration of the reinforcement and the aggregate parameters on the resistance to the penetration and yaw. The second is angle of attack effect and contact theory; the third is to analyze the role of numerical simulation in the research of yaw technology; and put forward suggestions for future research work.

1. Introduction

In preparation for modern military struggles, military powers have vigorously developed military strike methods such as penetration techniques and ground-drilling weapons, which have improved strike accuracy and penetration depth, and promoted the development of protective technology and engineering [1-3]. In the future high-tech local war, high-intensity precision strikes outside the zone will be the basic model. High-precision strikes have risen to 35% in the Kosovo war, the Afghan war has risen to 60%, and the Iraq war has risen to 68% [4, 5]. Precision guided and ground-drilling weapons are rapidly growing in use, efficient and accurate, posing a serious challenge to the protection project.

Figure 1 shows the thickness of the current ground-fighting weapon or precision-guided weapon that penetrates or destroys the concrete protective layer. SAP is a small penetrating projectile, AP is a normal penetrating projectile, CP is a compound penetrating projectile, and PEN is a nuclear energy penetrating projectile. The figure shows that the thickness of the concrete protective layer required for the protection of earth-moving weapons with an incident angle of less than 20° and an impact velocity of more than 400m/s is much larger than that of a conventional weapon with an angle of incidence of
45° and an impact velocity of 250 m/s [6-8]. Therefore, it is not feasible to increase the thickness of the protective layer to resist the attack of weapons. More effective measures must be taken to make the strike weapon deviate from the target.

![Diagram of concrete protective layer resisting strike weapon](image)

Figure 1 Concrete protective layer resists the safe thickness of the strike weapon [6]

In 1987, ROHANIB first proposed the concept of yaw and designed a simple yaw plate of steel bar structure for testing [9]. After that, structures such as shaped grids and triangular reinforced concrete hollow beams cast from different materials can be used to deflect the projectile. Protective engineering generally uses layered protective layers, which are camouflage layer, cover layer, dispersion layer and isolation layer. The shielding layer is the main protective layer for engineering anti-strike, and the yaw technology is one of the main defense technologies of the shielding layer. A large number of experimental results show that the yaw technology is set by the yaw structure, so that the warhead and the deflection layer are momentarily subjected to strong asymmetrical forces, and the motion posture changes, and the deflection phenomenon occurs. The change of the penetration attitude can effectively increase the missile body. Penetration resistance, which greatly reduces the depth of further penetration of the projectile, effectively preventing the weapon from penetrating and destroying the internal structure.

2. Research status of protective yaw technology

In recent years, the research guiding ideology of the yaw technology of underground protection engineering can be summarized as the macroscopic non-uniformity of the medium, the discontinuity of the stratification of the section, and the deflection of the geometrical shape. The specific two aspects are as follows:
2.1 The material is asymmetrical

High-strength materials such as block stones, corundum stones, steel balls are added to the protective layer. The projectile is subjected to a huge asymmetric force when it penetrates a special high-strength medium, resulting in a large angle of attack and angular velocity, which deflects or destroys the projectile.

Military units such as the US Air Force Civil Support Bureau, the Army Corps Waterway Test Station, the Naval Weapons Center, and the Air Force Equipment Laboratory made a series of anti-penetration tests using boulder layers in 1982, 1987, and 1991 [10-13]. It is found that the anti-penetration ability of the block stone concrete cover layer is related to the characteristics of the weapon and the block stone. The weapon features include: the strength of the projectile material, the aspect ratio and the diameter of the projectile. The anti-penetration characteristics of the block stone concrete are mainly There are: stone concrete strength, stone strength, stone size and stone content. The test found that: 1) the thickness of the stone layer and the arrangement of the stone, affecting the movement of the projectile and the change of the stress field. The change causes discontinuous penetration, which in turn leads to a decrease in penetration energy; 2) the shape and size of the stone, which affects the way the projectile strikes the stone. The special impact modes include oblique impact and yaw impact, which in turn cause the phenomenon of bouncing and the destruction of the projectile; 3) the proportion of the stone and the mass of the concrete, which affects the energy consumption of the projectile.

The Engineering Academy of PLA University of Science and Technology has studied the anti-penetration characteristics of corundum block concrete. The test results show that corundum block stone concrete has good anti-penetration ability. Compared with ordinary concrete of the same strength grade, the depth of penetration in corundum gravel is reduced by about 10% [14, 15]; the larger the particle size of corundum block, the tighter the arrangement, the stronger the anti-penetration performance of corundum block concrete [16].

Lu conducted an anti-penetration test on steel ball steel fiber reinforced concrete. The research shows that the anti-penetration ability of reinforced concrete is replaced by reinforced concrete as the anti-penetration layer. The depth of penetration is small, the cracks are small and shallow, and the back has no collapse, which has a rebound effect on the projectile [17].

2.2 Structural asymmetry

The special structure is used to induce deflection, and the profiled or layered structure is designed on the surface or inside of the structure. The projectile is subjected to a large asymmetric force during the impact process, resulting in a large angle of attack and deflection angle is generated, causing the missile body to stall, deflect, or destroy.

2.2.1 Surface irregularities. Chen developed an RPC composite engraved layer with a yaw ball on the surface [18, 19]. The high-strength RPC column ball is characterized by its excellent performance and high ceramic strength, and the two are bonded to form a composite yaw structure. The surface of the yaw layer is spherical, densely arranged, and has high material strength. The experimental results show that the anti-penetration performance of the RPC composite cover layer with yaw ball on the surface is enhanced. When the projectile penetrates, the damage occurs to different extents. The ballistics deflect obviously, and with the increase of the velocity of the projectile, the deflection angle
of the projectile is first. Increase the trend after decreasing. The basic layer integrity was good after the test, and no large-area craters and collapse occurred.

2.2.2 Shaped structure. In the 1980s, after extensive research and investigation, the United States found that the protection of modern earth-boring weapons requires that the stone block or concrete thickness is too large and consumes a lot of manpower and material resources. Based on the effectiveness of the protective measures (such as stagnation, deflection and damage of the projectile) and the practicability (material, construction, cost and repair, etc.), it is considered that the multi-layer triangular plate scheme has superior performance. Related experiments show that if the projectile is deflected before hitting the target, that is, changing the angle between the spring velocity vector and the axis, the projectile's penetrating ability will be weakened [20]. The experimental results show that the two-layer overlapping triangular reinforced concrete hollow beam slab structure is effective for the deflection and stagnation of the projectile.

In 1991 and 1992, the US Navy conducted a series of anti-penetration tests using reinforced concrete grids [21-23], and studied the effects of geometric shapes, materials, compressive strength, and steel content. The test shows that the deflection of the projectile is related to the density, compressive strength and toughness of the concrete. The toughness of the nylon fiber reinforced concrete is better than that of the steel fiber. Because of the high strain rate, the steel fiber is easily pulled off and does not work. It can absorb energy with stretching. After using the shield grid scheme, the amount of concrete can be reduced by 17% and the volume can be reduced by 22%.

2.2.3 Hierarchical structure. The layered section structure is adopted, and the structure design is discontinuous interface, so that the projectile is subjected to the uneven stress field when it penetrates, and the motion posture changes, resulting in the yaw or destruction of the projectile.

The composite material shielding layer is composed of a masonry concrete surface layer, a reinforced concrete base layer and a thick thickness buffer layer of a certain thickness. When the projectile strikes the concrete layer continuously obliquely, it causes a large inclination angle and a yaw angle, causing the projectile to deviate from its initial trajectory and even jump or break. The penetration of the projectile in the concrete layer is discontinuous. When the projectile breaks through a piece of stone, the new penetration process begins again, causing the resistance of the impedance body to suddenly increase, causing the body to rotate or deflection.

Chen found that the abalone shell nacre structure is a bioceramic composite composed of inorganic aragonite and organic collagen protein. Inorganic aragonite exists in the form of polygonal flakes in the nacre, parallel to the surface of the shell, forming a dense layered microstructure, and a small proportion of organic collagen bound inorganic aragonite sheet, the layered structure has a relatively high strength, stiffness and fracture toughness. It provides guidance and methods for the design and preparation of bionic high performance ceramic composites for the yaw layer.

Shi applied the principle of bionics to develop a honeycomb staggered layered steel tube confined concrete bullet-proof structure with short concrete-filled steel tube columns as the basic unit [23-27]. The bullet-proof structure uses concrete filled steel tube as the basic unit to form a honeycomb structure layer, and then multiple structural layers are alternately overlapped to form a bullet-proof layer. Under the influence of the intensity gradient, deflection and damage occur during the
penetration of the projectile, and the friction energy is consumed to improve the anti-penetration performance of the structure.

3. Yaw mechanism research

3.1 Influencing factors

There are many factors influencing the penetration of concrete into ballistic deflection. The research on the penetration of concrete at home and abroad mainly adopts theoretical approach, on analytical methods, experimental research and numerical simulation methods. The theoretical analysis is mainly based on the theory of cavity expansion and considering the influence of free surface effects to study the penetration problem. Since the penetration deflection is difficult to control during the experiment and is limited by the test technique, it is difficult to obtain the motion parameters during the penetration process. The empirical formula is also difficult to use on a large scale due to its own shortcomings. Therefore, the development of computers has made numerical simulation more and more applicable in the research of penetration problems. The following sections mainly distinguish the shape and material of the warhead, the incident state of the projectile body, the configuration of steel reinforcement and the parameters of random aggregate.

3.1.1 Warhead shape and material. Warhead parameters including oval, ovate and concave ovate, as well as different ovulation positions, warhead lengths, and head combination material warheads, all have an effect on the deflection of the mid-ballistic deflection and the yaw moment during penetration [28-30].

1) The shape of the warhead is an important factor affecting the depth of penetration. The oblique penetration of the steel target plate by projectiles with different head shapes such as pointed oval, truncated oval and concave truncated oval. The results show that the truncated oval-shaped projectile has a small deviation angle, and the penetration ballistic stability is relatively good, followed by the concave and pointed oval projectiles.

2) The small cylinder diameter and material type of the warhead are important factors affecting the depth of penetration. The deformed head body reduces the penetration resistance and increases the depth of penetration. When the penetration speed of the projectile is less than the crack propagation speed, the small cylinder advances into the target body to form a cracking zone, which reduces the resistance of the main warhead, thereby improving the penetration efficiency of the projectile, thereby increasing the depth of penetration.

3) The diameter and material type of the small cylinder of the warhead are important factors affecting the depth of penetration. The special-shaped projectile reduces the penetration resistance and increases the depth of penetration. When the projectile penetration speed is less than the crack propagation speed, the small cylinder penetrates the target in advance to form a cracking zone, reducing the resistance of the main warhead, thereby improving the projectile penetration efficiency and increasing the depth of penetration.

3.1.2 Projectile incident state. When the projectile penetrates, the incident state including the penetration speed, the angle of incidence and the rotation will have an effect on the penetration deflection [31-35].
In the low-to-medium speed penetration experiment (U<800m/s), there is no significant deformation or mass change of the intrusion projectile, and the penetration path has no significant deviation. The vertical depth of penetration is similar to the penetration speed. The target diameter ratio, coarse aggregate, and steel bar configuration have a greater impact on the penetration path. With the increase of impact velocity, in the high-speed penetration test (1km/s<U<2km/s), the deformation, damage and erosion of the projectile during the penetration process begin to increase, with the increase of the incident angle of the projectile. The probability of large-angle yaw increases sharply, and the deflection angle of the projectile increases. The influence of the incident angle on the depth of penetration and the deflection angle increases with the increase of the incident angle. When the high-hardness alloy body pairs When the impact velocity of concrete is greater than 2km/s, it begins to gradually transition to fluid penetration. At this time, the effect of the body erosion is remarkable, and the phenomenon that the body bends and the ballistic deflection is dissipated. The larger the incident velocity, the smaller the deflection angle of the projectile, and the influence of the incident velocity on the deflection angle tends to decrease with the increase of the incident velocity.

The greater the angle of incidence, the more pronounced the effect of the angle of incidence on the depth of penetration and deflection angle. As the angle of incidence increases, the depth of penetration gradually decreases. Through numerical simulation, it is found that when the incident angle reaches a certain value, the surface of the target is affected by the free surface, the asymmetrical resistance of the projectile is affected, and the trajectory of the projectile is deflected upward. When the incident angle increases again and the curvature of the ballistic curvature reaches a maximum value, a bouncing phenomenon occurs.

The effect of rotation on the penetration deflection is that under the condition of positive penetration, the rotation has a great influence on the residual velocity of the projectile and has little effect on the ballistic deflection. As the rotational speed increases, the residual speed increases and the projectile penetration capability increases. Under oblique penetration, the rotation has a significant effect on the residual velocity and ballistic deflection of the projectile. However, the increase of the velocity of the projectile does not always increase its penetrating ability, which is related to the incident angle and the penetration velocity. Rotation causes the projectile to deflect outside the incident surface, and its deflection direction is related to the direction of rotation of the projectile.

3.1.3 Configuration of steel bars. The anti-penetration impact capability of reinforced concrete is determined by the combination of concrete properties and the configuration of the steel bars, such as material strength, reinforcement ratio, steel bar diameter, mesh size, layer spacing, relative position of steel bars and projectiles [36, 37].

The configuration of the steel bar will greatly affect the penetration of the hole, the extent of the damage and the deflection of the ballistics. It is found that [35]: When the projectile penetrates the reinforced concrete, the impact of the free surface can be effectively attenuated due to the tensile effect of the first row of steel mesh. This results in a relatively small depth and diameter of the crater. On the other hand, when the projectile collides with the steel bar, it is subjected to the asymmetrical force and the moment. The direction of the centroid speed changes to produce the angle of attack, and the rotation of the body around the yoke produces a yaw angle, which will be attacked during the subsequent penetration. The angle and yaw angle penetrated and deteriorated the penetration conditions. The study also found that the steel bar inhibits the deflection of the projectile, and the
higher the rib ratio, the stronger the constraint deflection effect on the projectile. During the process of projectile penetration, the asymmetry force of the steel bar is affected, and the tail of the projectile may be restrained by the unbroken steel bar. The steel bar has a superposition effect on the warhead and the tail of the projectile, so that the penetrating ballistics are deflected.

3.1.4 mortar strength and aggregate. According to the analysis of the material properties of the concrete, the mortar and the aggregate together provide axial resistance to the projectile, and the difference between the random non-uniform aggregate force and the mortar resistance provides the lateral force causing its deflection. Mortar strength, aggregate strength, ratio of projectile diameter to aggregate diameter have a significant impact on ballistic deflection [38].

When considering the composition in the mesoscopic state, the ballistic deflection angle increases as the strength of the concrete mortar decreases, and conversely, as the strength of the aggregate increases. As the strength of the aggregate decreases and the strength of the mortar increases, the deflection angle of the projectile decreases, and the influence of the change in mortar strength on the ballistic deflection greater than that of the aggregate. When the compressive strength is small, the sensitivity of the deflection of the projectile to the change of mortar strength is significantly greater than the change of the strength of the aggregate. Aggregate particle size is an important factor causing the deflection of the projectile, and it has a great correlation with speed. As the average aggregate particle size and the ratio of the diameter of the projectile increase, the residual velocity of the projectile decreases. As the average aggregate particle size to the elastomer diameter ratio increases, the peak acceleration increases.

3.1.5 bounce. The bounce is a special phenomenon produced by the projectile during the oblique penetration process. It is the phenomenon that the projectile breaks into the target medium and then jumps out from the surface of the medium and continues to move in the air. When the angle of inclination or angle of attack of the warhead is greater than a certain critical angle, a bouncing will occur [39].

Duan carried out a jump experiment of a certain large aspect ratio projectile obliquely penetrating into concrete, and gave the critical enveloping angle envelope of the projectile. And the conclusion [40]: First, when the same projectile penetrates into the same strength target plate, as the penetration speed increases, the critical jump angle of the projectile gradually becomes larger, and the critical angle of the projectile's critical bounce angle increases with the speed. The sensitivity of increasing is gradually weakened. Second, the projectile penetrates the target plate of different strengths at the same speed. As the strength of the target increases, the angle of the critical bounce of the projectile becomes smaller. Third, there is a certain deviation between the experimental results and the empirical analysis results, and the experimental results of the critical jump angle of the projectile are larger than the empirical analysis results, but the deviation is basically within 3°.

The reasons for this difference are as follows: the target plate used in the experiment is a reinforced concrete target, and the steel bars in the target plate have a restraining effect on the ballistic deflection during the projectile penetration process, which can effectively weaken the influence of the free surface, and the elastic body and the steel bar In the event of collision, it is affected by the asymmetrical force and the moment. The direction of the centroid speed changes to produce the angle of attack, and the rotation of the body around the yoke produces a yaw angle, which further leads to
the phenomenon of bouncing. In normal concrete targets, there is no steel bar to limit the deformation of the projectile during the penetration process, so the critical bounce angle of the projectile is very small.

3.2 Theoretical analysis

The commonly used theory of penetration has the theory of conservation of energy momentum, cavity expansion theory, differential surface force method, and local interaction theory. The theoretical support can reveal the partial penetration mechanism and understand the whole penetration process. However, the analysis model is to analyze a specific penetration mechanism, and the scope of use has certain restrictions. The actual penetration process is complex and varied. The analysis model will use empirical formulas and parameters that are difficult to determine, so that the analysis model has certain error.

3.2.1 Mechanical model and angle of attack effect. The material structure of the real yaw structure layer is complex and the structure is various [41]. In essence, the impact dynamics theory can be utilized on the basis of the simplification of the force model, and the force state of the projectile hitting the yaw material can be simplified as shown in Fig.3. Assume the following conditions: 1) the shaped body is simplified into a spherical shape; 2) the projectile and the shaped body material are strong enough to be not damaged during the impact; 3) the spherical body has only normal deformation and no tangential deformation; 4) the spherical surface is sufficient smooth, Ft can be ignored. Based on the above assumptions: the projectile is subjected to two forces; one is gravity G, its action point is the centroid B of the bomb; the other is the collision force Fn, and its action point is the collision point M, the line of action of the two forces intersects The warhead transitions the center Q of the arc so that they form a planar force system.

![Figure 2](https://via.placeholder.com/150)

**Figure 2** Force diagram of the projectile impacting the spherical body

3.2.2 Contact Theory: Based on the Hertz contact theory, Guo and Chen established a contact force model for the elastoplastic collision between the projectile and the deflection layer [18-19]. The macroscopic elastoplastic constitutive relation of the contact body was derived, and the differential equation of motion of the projectile during the impact process was obtained. The influence of projectile inclination angle and target plate strength on projectile penetration was analyzed, and the influence of factors such as contact material characteristics, hit speed and geometric parameters on the recovery coefficient, contact time, and contact force were also analyzed.
The theoretical analysis method can obtain a clear change process of the penetration parameters, and has certain reference value for engineering applications. However, how to make reasonable assumptions for rough storage is a major difficulty. It is also necessary to add modified ballistic experimental data, and the accuracy of the parameters of the target material is significantly affected by the model assumptions and parameters, so that there is a certain error in the theoretical analysis method. The next step of the study can consider more yaw related factors and continuously improve the theoretical model of yaw penetration.

3.3 Numerical simulation

With the rapid development of computer technology, numerical simulation has become one of the main methods to study the dynamic response of penetration, which is widely used and cost-effective. Through the numerical simulation, the complete solution of the whole penetration process can be given, and the whole penetration process can be simulated to make up for the deficiency of experimental research and theoretical analysis. The numerical simulation of penetration yaw at home and abroad mainly focuses on the following aspects:

1) Verify the simulation. The analysis of the impact of missile target parameters on penetrating yaw is compared with the previous experimental research and theoretical analysis conclusions. For example: Peng designed a composite bullet-proof layer structure consisting of a layer of mortar block stone, two layers of yaw slabs, and two layers of steel fiber reinforced concrete. Through penetration test and numerical simulation analysis of large-caliber shell, it was found that in the structure of the composite shroud layer, the block stone layer pre-stressed the missile body, and the yaw plate caused the missile body to bounce or deflect and damage, which weakened the penetration performance.

2) Explore the constitutive model. The new kinetic constitutive model is studied and applied to the numerical simulation of yaw penetration to investigate the influence of different constitutive models on the penetration performance. For example, Xiao established the FEM-SPH coupling calculation model of the oval-shaped projectile penetrating steel plate, and studied the influence of the friction coefficient between the projectiles on the calculation result of the residual velocity of the projectile. The rotation of the projectile is positively penetrating and with different incidence. The effect of residual velocity and ballistic deflection when the angle obliquely penetrates the steel plate.

3) Design the protective structure. By numerical simulation, the biased materials and structural forms are compared and analyzed, and the nonlinear dynamic solutions of multiple material superpositions and the correlation of the penetration process are solved, which provides methods and ideas for the protection of yaw structure design. For example, Zhang proposed a nonlinear acceleration model based on the Young formula, which can solve the residual velocity of concrete passing through each layer.

4. Conclusion

In summary, the research on the yaw technology of protective structures at home and abroad mostly focuses on experimental research and empirical formulas. The relevant theoretical models and numerical simulations are still in their infancy, and the mechanism of penetration and damage is still unclear. The next issues worth solving are:
1) Develop yaw experimental techniques and detection methods, record the evolution law of the body erosion and the shape of the target damage, and provide the basis for theoretical research and numerical simulation of yaw penetration.

2) For the high-speed/ultra-high-speed penetration process, the material near the interface of the projectile is approximated by fluid, and how to apply high-strength materials and structural yaw to reduce the penetration damage under high-speed/ultra-high-speed penetration conditions.

3) Combining new materials, new structures, new construction techniques, researching the optimal matching of materials and structures, developing a protective structure with better yaw effect, improving economy and practicability, and popularizing and applying them to practical engineering.

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