The Influence of Attack Angle on Projectile Trajectory and Fuze in Oblique Penetration

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Abstract. Oblique deep penetration is a common form of projectile penetration into the target. In view of the fact that most of the research work is focused on the trajectory of vertical penetration, the trajectory and law of oblique penetration are discussed in this paper. This paper studies the impact of different initial angles of attack on projectile trajectory and fuze impact in oblique penetration by simulating projectile penetrating target with LS DYNA software. The results show that with the increase of attack angle, the deflection of trajectory is more obvious, the penetration depth is smaller, and the impact acceleration amplitude of fuze is larger. The research content of this paper provides a reference for oblique penetration of concrete target and impact performance of fuze, and is of great significance for the construction and protection of underground fortifications.

1. Introduction
Deep penetration ammunition is the use of the kinetic energy of ammunition to penetrate deep underground fortifications to damage targets. It is an effective weapon that mainly strikes at the enemy's important underground solid military targets, such as underground bunkers, underground command posts, ammunition depots, and underground launch bases. As the control device of detonating warhead charge, fuze needs to meet certain anti impact performance. Therefore, it is important to study the influence of different factors on penetration trajectory and fuze impact ability in oblique penetration.

Many teams have conducted oblique penetration studies. Xue et al. [1-3] established an engineering model of oval shaped projectile penetrating concrete with inclination and angle of attack, and obtained the relationship between the trajectory of projectile head and inclination, angle of attack and velocity. Then they got the penetration depth, crater size, deflection angle and other parameters at different speeds through penetration experiments and numerical simulation, and the results were in good agreement. Sun et al. [4] established the penetration depth model and the depth formula for Projectile Oblique Penetration into concrete, and verified the correctness of the model and formula by LS-DYNA. Zhang et al. [5] used LS-DYNA software to simulate the trajectory trend and law of shaped projectiles with different impact angles and attack angles. It is found that the influence of high attack angle on the attitude elevation angle of shaped projectiles is much greater than that of penetration angle. Gao et al. [6] studied the influence of initial angle of attack on the trajectory deflection of oblique penetration of concrete, and found that the negative angle of attack has a certain inhibition effect on the trajectory deflection of oblique penetration, while the positive angle of attack has an amplification effect.

There are many factors that affect the process of oblique deep penetration, mainly including the shape of the head of the projectile, the angle of incidence, the initial angle of attack, and the velocity of the projectile [7]. This paper mainly studies the influence of different initial angles of attack on projectile
trajectory and fuze impact in oblique penetration. The deep penetration finite element model is established in LS-DYNA finite element software. By comparing the oblique penetrator concrete targets with different angles of attack, it is found that as the angle of attack increases, the deflection of the ballistic trajectory is more obvious, the penetration depth is smaller, and the acceleration amplitude of fuze is greater. By comparing the oblique penetration of reinforced concrete at different angles of attack, it is found that as the angle of attack increases, the ballistic deflection angle and the fuze acceleration amplitude also increase, and the penetration depth decreases. However, due to the influence of steel bars, the degree of change is relatively random. Finally, the law of oblique and deep penetration under different angles of attack is summarized, and the future work is prospected.

2. Establishment of finite element model

2.1. Projectile structure and target plate structure

Eight groups of finite element models are established, which are composed of projectile body, fuze, concrete target slab and steel bar. The first four groups of models are that the projectile penetrates the concrete target slab obliquely at 2°, 4°, 6°, and 8° angles of attack at 20° incident angle. The last four groups of models are that the projectile penetrates the reinforced concrete target slab obliquely at 2°, 4°, 6°, and 8° angles of attack at 20° incident angle.

The projectile material is 35CrMnTiA, with a diameter of 17.5cm and an overall length of 150cm. The oval length accounts for 1/3 of the total length. A groove is opened with the tail of the projectile, where the fuse is mounted. The fuze material is Al. The concrete target board is made of C30 concrete with a size of 600×200×700cm. The steel bar is made of Q235 material with a diameter of 1cm. The spacing between bars to the mesh is 16cm. The distance between each layer of steel mesh is 40cm. The first layer of steel mesh is 20cm away from the intrusion surface, and there are 17 layers of steel mesh. Due to the symmetrical characteristics of the projectile, fuze, and target structure in terms of shape and load, the 1/2 model is used for modeling. The overall structure is shown in Figure 1.

2.2 Finite element model of projectile and target

The meshing of the finite element model adopts the Lagrangian algorithm. The projectile, fuze and target all uses the SOLID164 element type, and hexahedral element is used to divide mapping mesh.

Steel bars use beam element type to bear bending stress. The divided mesh model is shown in Figure 2. The projectile, fuze and rebar adopt ideal elastoplastic model with failure strain, and parameters of the material model are shown in Table 1. The concrete adopts the HJC model and self-defined failure criterion model. Parameters of the material model are shown in Table 2.
Table 1. Parameters of projectile, fuze and rebar material model.

| Material    | Constitutive model | Density | Elastic modulus | Poisson's ratio |
|-------------|--------------------|---------|-----------------|-----------------|
| Projectile  | 35CrMnSiA          | RIGID   | 7.85            | 206             | 0.33            |
| Fuze        | Al                 | PLASTIC_KINEMATIC | 2.7     | 70              | 0.3             |
| Rebar       | Q235               | PLASTIC_KINEMATIC | 7.85   | 210             | 0.269           |

Table 2. *MAT_JOHNSON_HOLMQUST_CONCRETE concrete material model parameters.

| RO          | G     | A      | B   | C   | N   | FC   |
|-------------|-------|--------|-----|-----|-----|------|
| 2.44        | 0.1240| 0.79   | 1.6 | 0.007 | 0.61 | 3.0e-04 |
| T           | EPS0  | EFMIN  | SFMAX | PC | UC | PL | UL |
| 2.9e-05     | 1e-06 | 0.01   | 7   | 1.0e-04 | 0.007 | 0.008 | 0.10 |
| D1          | D2    | K1     | K2  | K3  | FS  |
| 0.04        | 1.00  | 0.85   | -1.71 | 2.08 | -0.01 |

After the finite element model is established, the concrete and the steel bar share nodes to connect [8]. The ASTS contact algorithm is used between the projectile and the fuze, and the ESTS contact algorithm is used between the projectile, concrete and steel bar. Symmetrical boundary constraints are imposed on the 1/2 model symmetry plane, and fixed constraints are imposed on the concrete boundary plane. The initial velocity of the projectile is set to 560m/s. The simulation time is 35ms. After the control set is completed, the solution is solved in ANSYS solver.

3. Simulation results and analysis

3.1 Oblique penetration of concrete targets at different angles of attack

In order to summarize the trajectory and law of the oblique penetration of the plain concrete target for different angles of attack, the finite element software is used to obliquely penetrate the concrete target at 2°, 4°, 6°, 8° attack angles. The penetration trajectory is shown in Figure 3, the penetration depth is shown in Figure 4, and the fuze acceleration amplitude result is shown in Figure 5.

Figure 3. Oblique penetration to plain concrete target at 2°, 4°, 6° and 8° attack angles.

Figure 4. Projectile penetration depth map.
It can be seen from Figure 3 and Figure 4 that the angle of attack has a great influence on the deflection of the projectile. As the angle of attack increases, the deflection of the ballistic trajectory is more obvious, and the depth of penetration is smaller. After the Projectile Oblique penetrated the target plate, the concrete unit are pushed away by the projectile. Due to the action of attack angle, the left and right sides with the projectile are subjected to unbalanced force, which made the projectile deflect. With the decrease of the velocity of the projectile, the unbalanced force will gradually decrease, and the projectile will finally move along a straight line. Figure 5 shows that with the increase in the angle of attack, the contact area between the projectile and the target increases, and the resistance of the projectile increases, so the impact force transmitted to the fuze increases.

3.2 Oblique penetration of reinforced concrete targets at different angles of attack
In order to find out the motion track and law of oblique penetration of reinforced concrete target plate with different attack angles, numerical simulation is carried out at 2°, 4°, 6° and 8° attack angles. The trajectory, the penetration depth and the fuze acceleration amplitude result are shown in Figure 6, Figure 7, Figure 8.

![Figure 5. Curve of the fuze acceleration amplitude.](image)

Figure 5. Curve of the fuze acceleration amplitude.

![Figure 6. Oblique penetration to reinforced concrete target at 2°, 4°, 6° and 8° attack angles.](image)

Figure 6. Oblique penetration to reinforced concrete target at 2°, 4°, 6° and 8° attack angles.

![Figure 7. Projectile penetration depth map.](image)

Figure 7. Projectile penetration depth map.
Figure 8. Curve of the fuze acceleration amplitude.

It can be seen from Figure 6 and Figure 7 that when the target plate is reinforced concrete, the effect of attack angle on penetration phenomenon is similar to that of plain concrete. As the angle of attack increases, the deflection of the ballistic trajectory becomes more obvious, and the penetration depth becomes smaller. The addition of steel bars adds more random resistance to the concrete target and adds the randomness of deflection. So that the penetration depth and deflection angle are not as uniform as the penetration concrete target plate. However, the overall deflection angle still increases as the angle of attack increases. Figure 8 shows that the larger the angle of attack, the higher the acceleration amplitude of fuze.

4. Conclusion
In this paper, LS-DYNA numerical simulation is used to study the influence of different initial attack angles on the oblique penetration process of the projectile into target plate (plain concrete and reinforced concrete), and the following conclusions are obtained:

Under the condition of initial velocity of 560m/s and incident angle of 20°, when the projectile penetrates the plain concrete target plate obliquely at the angles of attack of 2°, 4°, 6° and 8°, the deflection and fuze acceleration amplitude increase with the increase of attack angle. While the penetration depth decreases with the increase of attack angle.

Under the condition of initial velocity of 560m/s and incident angle of 20°, when the projectile penetrates the reinforced concrete target plate obliquely at the angles of attack of 2°, 4°, 6° and 8°, the increase of the angle of attack increases the projectile deflection degree and fuze acceleration amplitude and decreases the penetration depth. But the penetration depth and deflection angle are not as uniform as that of the plain concrete target plate.

This paper only studies oblique penetration at the same position, which has some limitations. In the future, we can study the oblique penetration by adjusting the projectile mass, projectile shape, projectile position, angle of attack, and shape of steel bar of numerical simulation. And then we can observe the different conditions such as penetration depth, penetration amplitude, penetration pulse width and so on. By means of simulation, the cost and safety of the test is compensated, and the comparison results are provided for the test results. At the same time, simulation results can be used as a reference to the construction and protection for underground fortifications.

Reference
[1] Xue, J.F., Sen, P.H., Wang, X.M. (2016) Engineering calculation model for oblique penetration into concrete target by earth penetration weapon. Acta Aeronautica et Astronautica Sinica. 37(06):1899-1911.
[2] Xue, J.F., Sen, P.H., Wang, X.M. (2017) Experimental study and numerical simulation of projectile obliquely penetrating into concrete target. Explosion and Shock Waves. 37(03):536-543.
[3] Xue, J.F., Sen, P.H., Wang, X.M. (2016) Research on Ricochet and Its Regularity of Projectiles Obliquely Penetrating into Concrete Targets. Chinese Journal of Explosives & Propellants. 39(02):54-58.
[4] Sun, H.X., Niu, H., Lu, F., Liu, S.L., Zhang, Y. (2018) Research on oblique angle effect during
oblique penetration into concrete. Engineering Journal of Wuhan University. 51(12):1080-1085.

[5] Zhang, Y.L., Li, Y.C., Zhang, J., Zhao, K., Ye, Z.B., Ma, J. (2018) Study on Penetration Law of Special-shaped Projectile to Soil Target With Finite Thickness. Journal of Ballistics. 30(02):60-66.

[6] Gao, X.D., Li, Q.M. (2014) Trajectory Analysis of Projectile Obliquely Penetrating into Concrete Target at Attack Angle. Acta Armamentarii. 35(S2):33-39.

[7] Zhou, Y. (2009) The Numerical Simulation of Effects of Trajectory in Soil for Earth Penetrating Shell. Nanjing University Of Science And Technology. Nanjing.

[8] Ma, T.B., Wu, J., Ning, J.G. (2019) Experimental and numerical study on projectiles’ high-velocity penetration into reinforced concrete. Explosion and Shock Waves. 39(10):83-93.