Numerical study on the damage behavior of concrete target influenced by penetration velocity and target properties

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Abstract. The influence of initial penetration velocity and target properties on the damage behavior of concrete target by kinetic energy (KE) projectiles are studied numerically. Numerical models of penetration at different velocities were established, the failure of concrete and the law of the impact at different initial velocities ranging from 950 m/s to 1500 m/s on the damage behavior of concrete target is obtained. Damage process of concrete target slabs with different strengths and thicknesses under various impact load was carried out and the relationships between the damage behavior and the target strength ranging from 35 MPa to 95 MPa and the thickness ranging from 1 m to 2 m were obtained. Combination with the experiment results demonstrates that, the descent rate of the initial velocities increase as the initial velocities were improved. The higher the strength of the target, the less the residual velocity decrease caused by increasing the strength of the target. Under the condition of the same thickness increase amplitude, higher totally thickness of the targets results in greater penetration resistance. Furthermore, the overload peak value and the oscillation period of the impact load are positively related to the initial velocity and target thickness. With the increase of penetration depth, the impact load presents a first dramatic increase, then gradual decrease trend with obvious oscillations.

1. Introduction

Concrete is currently one of the most commonly used building materials in the field of national defense. It is used to construct protective structures for important fortifications such as ammunition depots, weapon launching platforms, and command posts. The damage behavior of concrete under the kinetic energy projectile penetration has always been a key research object in the field of national defense. However, due to the multidisciplinary aspects of weapons, materials, physics, mechanics, and the complexity of concrete materials, the research has become very important. Therefore, the research on the kinetic energy projectile penetrating the concrete target has practical military needs and important scientific research significance.

Both the penetration velocity and the parameters of the concrete target have an important influence on the damage behavior of the concrete. Werner S [1] obtained the resistance curve of plain concrete under five kinds of water-cement ratio, and described the damage of concrete during the penetration
process by the angle of energy. Warren T L [2] proposed a method to correct the velocity decay data based on the experiments of kinetic energy projectile penetrating 23 MPa and 39 MPa concrete targets, which solved the problem that there is currently no internationally recognized accelerometer calibration program.

Feng [3] obtained the overload time-history changes of penetrating thick concrete targets with sharp ovoid warheads of different CRH values based on the mesoscopic discrete element model (LDPM). The acceleration curve during the process of normal penetration and oblique penetration of concrete was obtained by replaying the acceleration storage instrument on the projectile [4]. Xue [5] used steel hoop to reinforce the concrete target, and through numerical simulation, it was proved that steel hoop can reduce the effect of boundary effect on the penetration performance of the projectile. Liu [6] conducted normal penetration test on concrete with strength of 80 MPa by using an ovoid projectile with diameter of 30 mm, and discussed the penetration depth and other damage characteristics of concrete at different initial velocities of 315 m/s ~ 800 m/s. At present, domestic and international researches mainly focus on the damage of thin concrete targets and semi-infinite concrete targets at low initial speeds, and there is less research on the damage of thick concrete targets at high initial velocities.

In this paper, numerical simulation methods are used to study the damage of the high-initial velocity kinetic energy projectile penetrating the thick concrete target to obtain the penetration velocity and the target parameters from the influence of penetration performance. The law of the influence of penetration velocity and target parameters on the damage behavior of concrete was obtained.

2. Simulation model
The shape of the projectile is designed as a three-stage structure of the warhead, rod and tail plate. The material is high-strength steel (PCrNi3MoV steel) with a density of 7.83. There is almost no deformation and erosion during the penetration process. The projectile is oval-nosed, with a length of 20 cm and a diameter of 10 cm. The thickness of the tail plate of the projectile is 1.5 cm. It is connected by a quarter arc with a radius of 3 cm. The size of the concrete target is 200cm×200cm×100cm, and both the projectile and the concrete target are axisymmetric structures.

The Lagrangian algorithm was used to studying the influence of penetration velocity and target parameters on the damage of concrete. The contact between the projectile and the concrete target was set to erosion contact. When failure occurred, the grid unit was deleted and redefine the contact surface of the projectile and target inside the target. The material model of the concrete is HJC constitutive model, combined with the maximum hydrostatic tensile stress and the maximum principal strain failure parameter defined by the contact with erosion to control the failure inside the concrete together.
The material of the projectile is high-strength steel (PCrNi3MoV steel), which is an isotropic non-linear hardening material. A bilinear follow-up hardening model is adopted which considers the effect of strain rate on the strength of the material and also considers the failure strain. The effect of the model is suitable for the study of kinetic energy projectile penetration into concrete.

Table 1. The parameters of the HJC model.

| ρ (g/cm³) | G (100GPa) | A    | B    | C    | N    | f_c (100GPa) |
|----------|------------|------|------|------|------|--------------|
| 2.44     | 0.1486     | 0.79 | 1.60 | 0.007| 0.61 | 0.00048      |

| T (100GPa) | ε₀ | ε_min | ε_max | P_c (100GPa) | u_c | p_l |
|------------|----|-------|-------|---------------|-----|-----|
| 4.0E-5     | 1.0E-6 | 0.01  | 7.00  | 0.00016       | 0.001 | 0.008   |

| u_l | D₁ | D₂ | K₁ | K₂ | K₃ | FS |
|-----|----|----|----|----|----|----|
| 0.10| 0.04| 1.00| 0.85| -1.71| 2.08| 0.4 |

The concrete material adopts the HJC constitutive model. This model considers the compaction state of the material and accumulates material damage. It can simulate large strain, large strain rate of the material. The constitutive model parameters are shown in table 1.

The HJC constitutive model is suitable for describing compression failure of concrete materials, but lacks the description of tensile failure. The introduction of the erosion failure criterion can improve this problem in the penetration problem of kinetic energy projectile. The erosion failure parameters are shown in table 2.

Table 2. The parameters of erosion failure.

| MID | EXCL | MXPRES | MNEPS | EFFEPS | VOLEPS | NUMFIP | NCS |
|-----|------|--------|-------|--------|--------|--------|-----|
| 2   | 1234 | --     | --    | --     | --     | --     | --  |
| MNPRES | SIGP1 | SIGVM | MXEPS | EPSSH | SIGTH | IMPULSE | FAILTM |
| -4E-5 | 1234 | 1234 | 0.08 | 1234 | 1234 | 1234 | 1234 |
3. Simulation analysis

After the projectile comes into contact with the target surface, severe collision, friction, and shear occur to form an open pit area. After the projectile enters the concrete, it continues to squeeze and shear the concrete at the front of the projectile while crushing the concrete around the projectile at high speed. A penetration channel is formed, the diameter of the penetration channel is slightly larger than the diameter of the projectile. During the penetration process, cracks caused by failure form and extend around the target.

While the projectile penetrates the concrete, the stress shock wave also propagates in the concrete, resulting in internal stress in the concrete target. After the stress shock wave reaches the free end of the rear of the target plate, it forms a tensile wave. Since the ultimate tensile strength of concrete is very low compared to the ultimate compressive strength, tensile failure has occurred before the projectile arrived. The rear of the target plate formed an inverted conical plug block.

![Simulation of the penetration process](image)

**Figure 3.** The simulation of the penetration process.

At once the projectile contacts with the concrete target, a stress jump will be formed on the concrete surface, and a red stress shock wave will be transmitted around the target as the figure 4 shows. During the penetration, some units will be deleted and some units will be crowded out, then the stress is redistributed. It can be seen from the figure that the stress is propagated to the free surface of the target back and reflected internally, which superimposes with the stress wave to form a blue negative pressure tensile wave, which makes the area near the target back become a strong tensile zone, resulting in tensile failure of the rear area of the concrete target and spalling. After the projectile reaches the crack zone, it will collide and squeeze with the concrete block that has been stretched out, resulting in the redistribution of stress, and the crack will extend around to the back of the target, forming an inverted conical plug block.
Figure 4. Stress propagation during penetration.

It can be seen from figure 5 that the time-history curve of the residual velocity under different initial velocities is a smooth curve, indicating that the impact of the initial velocity of penetration on the penetration performance is similar. The residual velocity decreases rapidly when the penetration velocity is large in the early stage, then decreases with the penetration velocity, and then decreases more and more slowly in the later stage, and finally penetrates the concrete target.

At the same time, with the increase of initial velocity, the descending rate of penetration velocity becomes larger. As can be seen from figure 5, the descending rate of velocity of initial velocity at 1500 m/s is significantly larger than that of incident velocity at 950 m/s at the same instant. It indicates that the penetration resistance of concrete target is enhanced with the increase of the initial velocity.
Figure 5. Time-history curve of residual velocity.

The calculation formula of equivalent mutilate diameter of concrete target is shown below:

$$\text{Deq} = \left( d_1 d_2 d_3 d_4 \right)^{\frac{1}{4}}$$

$d_1, d_2, d_3, d_4$ is the mutilate diameter in four vertical directions. Four vertical directions are selected from the target surface of the numerical simulation results to measure the mutilate diameter and calculate the equivalent mutilate diameter. The red arrow is the selected direction. As can be seen from figure 6, the larger the initial velocity, the larger the equivalent mutilate diameter, and the more serious the damage of the target plate.

Figure 6. Equivalent mutilate diameter of the front target at different initial velocities.
Chen established a three-stage model of the penetration process and conducted a lot of theoretical analysis and experimental research on it [7-8]. The process of concrete penetration under high initial velocity is divided into three stages: pit opening stage, tunnel stage and slug stage. The internal damage of concrete target plate can be described by three-stage area size. The average size of each area under different speeds was obtained, and the thickness ratio of each area to the target plate was: 26 % in the open pit area, 37 % in the tunnel area, and 37 % in the slug area, which could provide reference for the experimental results of the high-velocity penetration of the concrete.

![Figure 7](image1.png)

**Figure 7.** The three-stage features of penetration.

**Table 3.** Residual velocities and three-stage characteristic dimensions at different initial velocities.

| Initial velocity (m/s) | Residual velocity (m/s) | Pit opening depth (cm) | Tunnel depth (cm) | Plug thickness (cm) |
|------------------------|-------------------------|------------------------|------------------|-------------------|
| 950                    | 635.3                   | 25                     | 41               | 34                |
| 1100                   | 700.5                   | 30                     | 32               | 38                |
| 1300                   | 815.7                   | 28                     | 34               | 38                |
| 1500                   | 908.2                   | 25                     | 36               | 39                |

With 15 MPa as the interval, it is divided into 35 MPa, 50 MPa, 65 MPa, 80 MPa and 95 MPa. The initial velocity is set as 1300 m/s, and the target plate with a thickness of 1 m is used for numerical simulation of concrete penetration.

![Figure 8](image2.png)

**Figure 8.** Residual velocity at different target strength.

As shown in figure 8, with the increase of the strength of the target, the residual velocity of the projectile body decreases continuously. When the initial strength of the target is small, the residual velocity decreases greatly due to the increase of the target strength. When the initial strength of the
target plate is large, the residual velocity decrease caused by increasing the strength of the target is not obvious.

The concrete material set in the numerical simulation has the continuity assumption. When the projectile penetrates the concrete target, the concrete material near the warhead changes into a plastic flow state, which reduces the impact of the uniaxial compressive strength of the material on the overload during the projectile's penetration. Therefore, when the strength of the target is high, the decrease of the residual velocity caused by increasing the strength is not obvious. When the strength of the target is low, the concrete material is easier to enter the plastic flow state, which reduces the resistance of the projectile, so the residual velocity is larger.

The thickness of the target plate was divided into four grades: 1.2m, 1.4m, 1.6m and 1.8m. The finite element model of penetration was re-established and simulated. The initial velocity was set to 1300 m/s, and the strength of the target plate was set to 50 MPa.

![Figure 9. Residual velocity of projectiles with different thickness targets.](image)

With the increase of the thickness of the concrete target plate, the residual velocity continues to decrease. At the same thickness interval, the greater the thickness of the concrete target plate, the more the residual velocity decreases. As the thickness of the target plate increases, the anti-penetration ability of the target plate also increases.

In the process of projectile penetration, with the increase of target thickness, the penetration velocity in the slug stage decreases, and the penetration capability decreases significantly compared with that in the pit opening stage and tunnel stage, so the velocity decays rapidly.

![Figure 10. Overload time-history curve of projectiles under different thickness target plates.](image)
The penetration overload curves of concrete target of different thickness are shown in figure 10. The four curves of target plates of different thickness are similar, all of which rise rapidly in a straight line first, coincide in the rising process, and then fall to the lowest point. Then, the overload of the projectile keeps oscillating, and the oscillation period increases with the increase of the thickness of the target.

The overload peaks of the four curves are almost the same, because the contact area between the projectile and the concrete target affects the overload peak. When the projectile completely enters the target, it can be considered that the contact area between the projectile and the target under different thicknesses is equal, and the resistance value of the projectile is equal to the overload peak.

4. Conclusions
The overload peak value of the projectile and the damage degree increase along with the initial velocity. The residual velocity decreases as the strength of the target increases. The greater the strength of the target, the less the decrease of the residual velocity caused by increasing the strength of the target. The residual velocity decreases with the increase of the thickness of the concrete target. The peak overload of the projectile with different thickness concrete target is almost equal, and the overload oscillation period increases with the thickness. With the increase of the penetration depth, the overload of the projectile continues to decrease. Under the same thickness interval, the anti-penetration performance of the concrete target improves as the thickness of the target increases.

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