Analysis on Damage Mode of Armor-piercing Projectile to Soil Target

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Abstract. Aiming at the reliability problem of armor-piercing projectile acting on soil target, experimental research and numerical simulation were carried out. The damage modes of armor-piercing projectile to soil target under different conditions were analyzed, and the characteristics of metal jet penetrating soil were studied. The results indicate that, there is a problem of reliability of fuse action in penetrating soil targets, if the soil strength is enough, the projectile will immediately explode and form metal jet when it touches the soil, if the soil strength is insufficient, the armor-piercing projectile will penetrate the soil, when the reaction force is enough, the armor-piercing projectile will explode and form metal jet, otherwise the armor-piercing projectile cannot explode, but the projectile will cause penetration damage to the soil.

1. Preface
The effect of armor-piercing projectile on target is realized by the metal jet generated after its explosion. The timely formation of metal jet when armor-piercing projectile contacts target is the premise to ensure the penetration effect[1-2]. However, sometimes due to the reasons of target or operation, armor-piercing projectiles cannot form metal jet in time. In this paper, several possible situations of armor-piercing projectiles striking soil targets were analyzed.

2. Test and analysis

2.1. Test results
In test, a certain type of armor-piercing projectile was used to shoot the target. The structure of the armor-piercing projectile is shown in Figure 1 and the target is shown in Figure 2. The target consists of two steel plates and two wooden boards on the side. The steel plates constitute the front and rear target plates of the target. One is to fix the soil in the target, the other is to provide the medium environment for armor-piercing projectile. In order to avoid the influence of steel plate factors, the thickness of the steel plate is relatively thin, and the target is filled with soil. The damage results to the target are shown in Figure 3.
Figure 1. Structural diagram of armor-piercing projectile.

Figure 2. Targets.

(a) Front steel plate. (b) Side board. (c) Back steel plate.

Figure 3. Target damage results.

As can be seen from Figure 3 a), the armor-piercing projectile hit the side of the front target plate and did not detonate immediately. Instead, the projectile penetrated through the front steel plate. The diameter of the hole is about 105 mm, which corresponds to the diameter of the armor-piercing projectile. In the figure b), the part marked with circle is the damaged part of the side board. It is also a cut-like effect caused by penetration of armor-piercing projectile. The picture c) shows the damage effect of the back steel plate, there is no penetrating trace of projectile, the damage effect is caused by the explosive impact of the armor-piercing projectile. Moreover, from the damage shape, the armor-piercing projectile exploded in the target, indicating that the projectile had completely or nearly
completely penetrated into the soil of the target. From the radius of the holes in the front target plate, it is obvious that they are not semi-circular enough. Therefore, the head mechanism of the armor-piercing projectile fuse may not hit the front steel plate. It can be inferred that the projectile penetrates the target soil from the side board and explodes in the soil after penetrating a certain depth.

2.2. Preliminary analysis

Whether an armor-piercing projectile can detonate depends mainly on whether the fuse can work reliably. The piezoelectric fuse is used in the armor-piezoelectric projectile, whose action process is that when launching, under the action of recoil force, the fuse is released, and the electric detonator is connected to the piezoelectric crystal circuit through the reed and the electric pole, the fuse is in the standby state. When touching the target, under the action of the target reaction, the fuse head is compressed and deformed, the piezoelectric crystal is pressed to produce voltage, the electric detonator detonates, and then the projectile is detonated. Therefore, whether the fuse can be detonated reliably depends on the magnitude of the reaction force when it hits the target. If the reaction force is too small, the head of the fuse does not deform, or the deformation is too small, the piezoelectric crystal cannot generate voltage, so the electric detonator cannot be detonated, the armor-piercing projectile will penetrate the target. When the reaction force is enough, it will detonate.

From the process of armor-piercing projectile destroying target, the fuse head mechanism did not hit the front target, but penetrated into the soil from the side board, and detonated when the reaction force in the soil was enough, resulting in the damage effect of Figure 3.

3. Numerical simulation analyses

The armor-piercing projectile shown in Figure 1 includes fuse, head snail, projectile body, charge, tail, tracer, etc. The total weight is about 9.5kg. The diameter of the centering part is 105mm, the head screw material is 40MnCrMo, the mass is 1.8kg, and the projectile material is 21MnNiMo. According to the parameters of armor-piercing projectile, such as structure size and weight, the projectile body model was modeled. The projectile body model is shown in Figure 4.

According to Figure 4, the numerical simulation model of projectile penetrating the target shown in Figure 2 was established by the software AUTODYN. 40MnCrMo and 21MnNiMo materials adopt STEEL4340 steel model in AUTODYN model library, and made rigid treatment to the model. The initial penetration velocity of armor-piercing projectile was 1000 m/s. The material of the steel plate of target was modeled by IRON-ARMCO model in AUTODYN model library, and the soil was modeled by SAND model. The model is shown in Figure 5.

In order to facilitate observation and research, observation points were taken from the projectile body. The position of observation points is shown in Figure 6. Figure 7 shows the penetration state when the
penetration time is 0.146ms, at this time, not only the snail part completely penetrates the soil, but also the thicker part of the projectile begins to penetrate the target.

Figure 6. Location of observation points.  
Figure 7. Penetration effect at 0.146ms.

Figure 8 and Figure 9 are the variation of the relevant parameters of observation points 1 and 7 with time during penetration.

![Velocity variation with time.](image1.png) ![Acceleration variation with time.](image2.png)

(a) Velocity variation with time. (b) Acceleration variation with time.

Figure 8. Penetration parameters variation of observation point 1.

![Velocity variation with time.](image3.png) ![Acceleration variation with time.](image4.png)

(a) Velocity variation with time. (b) Acceleration variation with time.

Figure 9. Penetration parameters variation of observation point 7.

From Figure 8 and Figure 9, it can be seen that the velocity of the projectile is not always in the process of deceleration, but there is a small fluctuation in the penetration process, which is caused by the mechanical properties of soil and the shape of the projectile, which also causes the complexity of the acceleration variation. The acceleration is the direct reflection of the force exerted on the projectile body.
It can be seen from Figure 8 and 9 that if the head mechanism of the armor-piercing projectile directly penetrates the steel target plate, the acceleration is the greatest when it contacts the target plate, and the reaction force on the head of the fuse is the greatest. At this time, if the head of the fuse is deformed enough, the projectile body is most likely to detonate and form metal jet. If the fuse deforms little, the projectile will penetrate the steel plate and penetrate the soil. In the process of penetrating the soil, the acceleration of the projectile has been in a state of sudden change, varying or decreasing, and the peak value is not always decreasing, but also varying or decreasing. This reflects that when the projectile penetrates the soil, the reaction force received by the fuse is varying or decreasing. When the head of the fuse is deformed enough, the projectile will be detonated and the target will be destroyed. If the reaction force is not enough, the projectile will be detonated, and it will penetrate the whole target and will not explode to form a metal jet.

Based on the above analysis, there are three possible modes of action if the armor-piercing projectile is used to directly attack the soil target, the first is that the soil strength is sufficient, and the reaction force that armor-piercing projectile is subjected to when it begins to penetrate can make the fuse work normally, initiating the explosion to form a metal jet, and the metal jet begins to penetrate the soil medium, the second is that the fuse acts when the projectile penetrates a certain depth of soil, the third is that the soil strength is not strong enough, and the reaction force of the projectile in the whole process of penetrating the soil is not enough to make the fuse function. The projectile does not explode and cannot form metal jet, and the damage to the soil medium is only caused by the penetration of the projectile.

4. Numerical simulation of metal jet penetrating soil

The structure and size of the shaped charge are shown in Figure 10. The material of liner is copper, the outer diameter is 80 mm, the inner diameter is 76 mm, and the thickness is 1.857mm. The diameter of explosive is 80mm and the height of explosive is 160mm.

4.1. Material model

AUTODYN software was used to simulate with Euler-Lagrange coupling algorithm. Euler unit was used for air, explosive and liner, and Lagrange unit was used for target plate. The equation of state and its parameters of soil were the same as those of the previous contents. The physical model of air was the γ Form equation of state of ideal gas, equation of state parameters γ was 1.4.

\[ p = (γ - 1) ρ e \] (1)

RX-08-BV in AUTODYN software material library was selected for explosive, and its physical model was JWL equation of state:

\[ p_s = Ae^{-\sigma ρ} + Be^{-\sigma ρ} + \frac{C}{\rho^{1+ω}} \] (2)

where \( \sigma = \frac{ρ_0}{ρ} \), \( A,B,R_1,R_2,ω \) are JWL model parameters, RX-08-BV material parameters are shown in Table 1.
Table 1. JWL equation of state parameters for RX-08-BV.

| $A$ (MPa) | $B$ (MPa) | $R_1$ | $R_2$ | $W$ |
|-----------|-----------|-------|-------|-----|
| 698993.9  | 129010    | 4.3   | 1.2   | 0.3 |

The equation of state of the liner material model COPPER was shock, the strength model was Piecewise JC, and the rest is empty [10].

4.2. Establishment of numerical model

The explosive height of shaped charge was 200mm and the soil thickness was 1000mm. Since the penetration process can be considered as an axisymmetric model, a two-dimensional model was used to simulate the penetration process. The numerical simulation model is shown in Figure 11. The shape and velocity distribution of metal jet formed at 0.048ms were obtained by calculation as shown in Figure 12.

![Figure 11. Model of metal jet penetration into soil.](image)

![Figure 12. Metal jet shape and velocity distribution at 0.048ms.](image)

From Figure 12, it can be seen that the shape of the metal jet obtained by the numerical simulation model is very good, the maximum velocity of the metal jet head is 6776.7m/s, the velocity of the club part is much smaller than that of the jet part, and there is an obvious velocity gradient along the metal jet.

4.3. Analysis of penetration process

The process of metal jet formation and penetration into soil is shown in Figure 13. It can be seen from Figure 13 that the metal jet prolongs and breaks continuously in the process of penetrating the soil, which also leads to the decrease of the penetration ability of the metal jet. Figure 14 is a stress...
distribution of metal jet penetrating the soil at different times. From Figure 14, it can be seen that the color of metal jet changes gradually, which indicates that the velocity of metal jet and the penetration ability of metal jet to the soil decreases continuously during the penetration process. Therefore, besides continuous fracture, the decrease of the velocity of metal jet is also the main reason for the gradual decrease of penetration ability. In addition, the fluid properties of metal jet make the penetration depth of metal jet not particularly deep. When penetration reaches 0.597 ms, the penetration depth of soil is 711 mm. It can be seen that although the velocity of metal jet can reach several kilometers, its penetration depth is not very deep.

![Figure 13. Formation and penetration of metal jets into soil.](image)

(a) 0.009 ms.          (b) 0.021 ms.          (c) 0.057 ms.          (d) 0.126 ms.          (e) 0.597 ms.

Figure 13. Formation and penetration of metal jets into soil.

![Figure 14. Stress distribution of metal jet penetrating soil at different time.](image)

(a) 0.015 ms.          (b) 0.12 ms.          (c) 0.21 ms.          (d) 0.597 ms.

Figure 14. Stress distribution of metal jet penetrating soil at different time.

However, the perforation ability of metal jet is very strong. Figure 15 shows the shape of the perforation hole after the penetration. The maximum diameter of the perforation hole is 85.4 mm, and the diameter of the orifice is 52.6 mm, which is obviously larger than the diameter of the metal jet.

![Figure 15. Shape of enlarged hole after penetration.](image)

5. Conclusion

The penetration of armor-piercing projectiles into soil targets can be well analyzed by means of numerical simulation and experimental research. The research results show that there is a problem of reliability in the operation of armor-piercing projectiles against soil targets. Because the strength of soil is not as strong as that of steel and armor targets, the reaction force to the head fuse mechanism may be insufficient. When armor-piercing projectiles penetrate directly into soil, they may not explode, or they may explode when penetrating into soil, or they may not explode at all times, which results in different damage modes to soil targets. Metal jet breaks continuously during penetration process and the velocity
of metal jet drops continuously, the ability of metal jet to penetrate soil is not very strong, but it has certain perforation ability.

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