Numerical simulation on continuous penetrating/blasting behavior of multi-projectiles against concrete target

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Abstract: Deep digger weapon system uses continuous kinetic energy and chemical energy of the penetrating/blasting projectiles to dig the concrete target. In the present paper, numerical simulations are conducted to study the continuous penetrating/blasting effects of multi-projectiles against concrete target. The simulation results show the KE penetration produces the crushing and rupturing zone, providing conditions for subsequent damage due to explosions. Then, the explosion further increases the diameters of the crushing and rupture area, and the cracks propagate inside the concrete target. The second penetration and blast further increase the depth and the damage area, achieving deep digger behavior to the concrete target. However, the throwing effect of secondary penetration/blast is slightly weaker than that of first one. Moreover, the simulation also shows the continuous penetrating/blasting behavior is influenced markedly by impact velocity.

1. Introduction
The rapid development of the long-range precision strike technology poses a serious threat to the survival of the important protection target. The ground reinforcement and extending to underground have been the development trend of the important protection target, such as the strategic command center, the large command and control center, the sites for the production and storage of the destruction weapons and so on.

Due to the development of the target characteristics of the important protection target and the operational requirements, the penetration technology and weapons have been developed rapidly. However, with the deepening and strengthening of the deep-buried target underground, the kinetic energy projectile loses the advantage, even sometimes it cannot destroy the protection target. For this purpose, in order to improve the kinetic penetration weapon and tandem penetration weapon in service, the new concept of penetration weapon technology is developed, such as the deep digger weapon system. The deep digger weapon system uses the digger technology similar to the “drilling” technology used in the oil or gas industry. In fact, the deep digger weapon system uses continuous kinetic energy and chemical energy of the penetrating/blasting projectiles to dig the concrete target.

Jin Fengnian et al. [1] studied the development and penetration of deep-drilling ground weapons,
summarized the representative research results of rock penetration theories and experiments, and analyzed the development trend of deep-drilling ground protection engineering technology in the new situation. Zhang Binwei et al. [2] carried out numerical simulation analysis of the piercing projectile penetrating the multilayer spaced concrete target, and proposed a method for calculating the residual velocity based on a nonlinear acceleration model. Zhang Deliang et al. [3] made a numerical analysis on the effect of penetrating projectile impacting the target plate, and analyzed the influence of target plate size and impact velocity on the effect of damaging the target. Yang Chao et al. [4] made a numerical analysis to study effect of body size of penetrating projectile, and concluded that the interaction between projectile and target plate does not accord with geometric similarity after the effective size. Zhang Youyuan et al. [5] studied the penetration ability of the armor-piercing projectile to target, and provided a basis for armor-piercing shell structure design. Wang Xuefei et al. [6] designed numerical simulations to study the normal penetration of projectile into the shell of explosive grenade, and obtained the relationship between the residual mass and the residual velocity of penetration.

In order to study the penetrating/blasting effect of multiple continuous penetrating/blasting projectiles on concrete targets, this paper, based on AUTODYN-2D software, simulates and analyzes the penetrating/blasting effect on concrete targets under different impact velocities, projectile diameters and charge types.

2. Modelling
The materials involved in this simulation mainly include concrete, steel, and explosives. CONC-35MPA in the AUTODYN material library is used for the concrete. P alpha equation of state and RHT model are used together to describe the concrete. The relevant material parameters are listed in table 1. SPH algorithm is selected with the particle size being 0.8mm. The concrete targets have a thickness of 350mm and a width of 300mm, shown in figure 1.

| Material | $\rho_{\text{solid}}$ (g/cm$^3$) | Soundspeed (m/s) | $P_e$ (MPa) | $P_s$ (GPa) | $n$ |
|----------|-------------------------------|------------------|-------------|-------------|-----|
| CONC-35MPA | 2.75 | 2920 | 23.3 | 6 | 3 |

$\rho_{\text{solid}}$ is Solid Density, $P_e$ is Initial Compaction Pressure, $P_s$ is Solid Compaction Pressure, and $n$ is Compaction Exponent.

The projectile shell uses STEEL 4340 from the AUTODYN material library. The Linear equation of state and Johnson Cook strength model are used in this case. The SPH particle size is set as 0.5mm. The relevant material parameters are listed in table 2.

| Material | $\rho_{\text{solid}}$ (g/cm$^3$) | $A$ (MPa) | $B$ (MPa) | $n$ | $C$ | $m$ | $T_{\text{melt}}$ (K) |
|----------|-------------------------------|-----------|-----------|-----|-----|-----|-----------------|
| STEEL 4340 | 7.83 | 792 | 510 | 0.26 | 0.014 | 1.03 | 1793 |

$\rho_{\text{solid}}$ is Solid Density, $A$ is Initial Yield Stress, $B$ is Hardening Constant, $n$ is Hardening Exponent, $C$ is Strain Rate Constant, $m$ is Thermal Softening Exponent and $T_{\text{melt}}$ is Melting Temperature.
To study the influence of explosives on digger effect, TNT, B explosive and OCTOL are chosen from the AUTODYN material library, and the JWL state equation is selected. The relevant material parameters are from the AUTODYN material library.

3. Results

3.1. Numerical simulation of continuous penetrating/blasting with different impact velocities
To study the influence of the impact velocity on the penetrating/blasting behavior, the impact velocities are chosen as 500m/s, 600m/s, 700m/s, respectively. The projectile, filled with TNT, has a diameter of 12mm and a length of 50mm.

Successive penetrating/blasting simulations are performed with three different impact velocities. The first penetration and penetration/blast effects are shown in figures 2 and 3, respectively. The influences of different impact velocities on first penetration effect are listed in table 3.

Figure 1. The model in initial state.

Figure 2. Target damages caused by first penetration at different impact velocities.
Figure 3. Target damages caused by first penetration/blast at different impact velocities.

Table 3. Data of the first penetration at different impact velocities.

| Impact velocities (m/s) | \( t_{1q} \) (ms) | \( H_{1q} \) (mm) | \( D_{1q} \) (mm) | \( D_{6\times1q} \) (mm) |
|-------------------------|------------------|------------------|------------------|------------------|
| 500                     | 0.212            | 47.20            | 19.76            | 75.74            |
| 600                     | 0.223            | 56.30            | 22.89            | 84.88            |
| 700                     | 0.181            | 58.10            | 25.70            | 93.28            |

\( t_{1q} \) is penetration time, \( H_{1q} \) is penetration depth, \( D_{1q} \) is diameter of crater, \( D_{6\times1q} \) is diameter of crushing zone. The subscript 1 represents the first penetration.

It can be known from the results in figure 2 that with the increase of the impact velocity, the penetration depth and the damage area become larger, and some cracks extend inside the target. The KE penetration produces the crushing and rupturing zone, providing favorable conditions for subsequent damage due to explosions. It can be seen from the table 3 that during the first penetration of the projectile, the penetration depth, the diameter of the crater and the diameter of the crushing zone, are all positively related to the impact velocity of the projectile. From the results in figure 3, it can be seen that under the pre-damage situation caused by the first penetration, the particles on the free surface of the target plate caused by subsequent explosion scatter further, the diameter of the crater significantly increases, and the diameters of the crushing and rupture area further increase. The cracks propagate inside the concrete target. With the increase of the impact velocity, the damage of the target becomes greater.

After the first penetration/blast, the second penetration begins immediately. The damages of the second penetration and penetration/blast are shown in figures 4 and 5, respectively. The influences of different impact velocities on the second penetration are listed in table 4.
Figure 5. Second penetration/blast damages at different impact velocities.

Table 4. Data of the second penetration at different impact velocities.

| Impact velocities(m/s) | \(t_{2q}\)(ms) | \(H_{2q}\)(mm) | \(D_{2q}\)(mm) | \(D_{b2q}\)(mm) |
|------------------------|----------------|----------------|----------------|----------------|
| 500                    | 0.202          | 53.10          | 15.90          | 54.06          |
| 600                    | 0.229          | 68.30          | 15.55          | 81.10          |
| 700                    | 0.277          | 96.20          | 13.40          | 93.07          |

\(t_{2q}\) is penetration time, \(H_{2q}\) is penetration depth, \(D_{2q}\) is diameter of crater, \(D_{b2q}\) is diameter of crushing zone.

By comparison, it can be seen from figures and tables above that due to the pre-damage made by the first penetration/blast, the depth of the second penetration is greater than that of the first penetration and it gets deeper and deeper with the increase of the impact velocity, while the diameter of crater is on the contrary. After the first penetration/blast, the crater depth increases as the impact velocity increases. The second penetration works on the basis of the first penetration, the distance between the projectile and the free surface increases with the increase of the impact velocity, which results in the crater diameter of the second penetration decreases as the impact velocity increases. The second penetration further increases the diameter of the internal crushing zone of the concrete target, a large number of cracks are also formed inside the target.

However, since the second penetration/blast is far away from the free surface of the concrete target, the throwing effect on the concrete is less obvious than the first one. At this time, when the explosive explodes, the detonation products and the broken shell mainly affect the walls of the crater, which further expands the diameter of the crater formed by the second penetration, but the extension degree is much smaller than that of the first penetration/blast.

3.2. Numerical simulation of continuous penetrating/blasting with different projectile diameters

For studying the influence of the projectile diameter on the penetration/blast behavior, projectile diameters are chosen as 14mm, 16mm, and 18mm, respectively. The projectile, filled with TNT, has a length of 50mm and a velocity of 500m/s. The damage results of the first penetration and penetration/blast under different projectile diameters are shown in figures 6 and 7, respectively. The influences of different projectile diameters on the effect of the first penetration are listed in table 5.
As can be intuitively seen from figure 6 and table 5 that with the increase of the projectile diameter, the damages caused by the first penetration increase. Due to the increase of the projectile diameter, the mass and kinetic energy of the projectile body increase relatively, which results in increases in the crater diameter and depth, the diameters of the crushing zone and the rupture zone. The variates listed in the table 5 are all positively related to the projectile diameter. Figure 7 shows some penetration/blast effects on the targets. the detonation further increases the damage effect. The diameter and depth of the crater caused by penetration/blast are larger than those of the penetration. and it can be clearly seen that they increases with the increase of the projectile diameter.

After the first penetration/blast, the second penetration begin immediately. The damages of the second penetration and penetration/blast on the target under different projectile diameters are shown in figures 8 and 9, respectively.
It can be seen that, similar to the results of secondary penetration/blast under different impact velocities, the secondary penetration/blast under different projectile diameters further expand the crushing zone and the rupture zone inside the target plate. However, it fails to cause further throwing effect on the free surface particles of the target plate. Like the first penetration/blast, with the increase of the projectile diameter, the corresponding charge also increases, which results in the overall increases of the crater depth and diameter, and the diameters of crushing zone and rupture zone.

3.3. Numerical Simulation of penetrating/blast with different charge types
TNT, explosive B, and OCTOL are chosen to study the influences of charge type on damage effects. The projectile diameter is 12mm, the projectile length is 50mm, and the impact velocity is 500m/s.

The effects of the first penetration and penetration/blast damages under different charge types are shown in figures 10 and 11, respectively. The influences of different charge types on the effect of the first penetration are listed in table 6.

Figure 8. Second penetration damages at different projectile diameters.

Figure 9. Second penetration/blast damages at different projectile diameters.

Figure 10. The damages of first penetration at different charge types.
As shown in figure 10 and table 6, the damage effects under different charge types caused by the first penetrations have no significant difference. As can be seen from figure 11, with the increase of the power of the explosive, the depth and diameter of the crater, the diameter of the crushing and rupture zone caused by the first penetration/blast become larger, and the throwing degree of free surface particles becomes more obvious. The damage effects of second penetration and penetration/blast under different charge types are shown respectively in figures 12 and 13, the influences of different charge types on the second penetration are listed in table 7.

**Table 6. Data of the first penetration at different charge types.**

| Charge type | $t_{1d}$ (ms) | $H_{1d}$ (mm) | $D_{1d}$ (mm) | $D_{fs1d}$ (mm) |
|-------------|---------------|---------------|---------------|-----------------|
| TNT         | 0.212         | 47.20         | 19.76         | 75.74           |
| Explosive B | 0.207         | 47.20         | 20.44         | 66.00           |
| OCTOL       | 0.211         | 48.00         | 20.58         | 66.86           |

**Figure 11.** The damages of first penetration/blast at different charge types.

**Figure 12.** The damages of second penetration at different charge types.

**Figure 13.** The damages of second penetration/blast at different charge types.
Table 7. The damage data of the second penetration at different charge types.

| Charge type | $T_{2q}$ (ms) | $H_{2q}$ (mm) | $D_{2q}$ (mm) | $D_{52q}$ (mm) |
|-------------|----------------|---------------|---------------|----------------|
| TNT         | 0.202          | 53.10         | 15.90         | 54.06          |
| Explosive B | 0.233          | 57.20         | 12.86         | 77.02          |
| OCTOL       | 0.237          | 60.02         | 13.60         | 70.88          |

It can be seen from figure 12 that the difference of the second penetration under different charge types mainly comes from the pre-damage caused by the first penetration/blast. Similar to the previous simulations, due to the pre-damage of the first penetration/blast, the depth of the second penetration is larger than the first one. From table 7, it can be known that with the increase of the explosive power, the depth of the second penetration slightly increases. As can be clearly seen from figure 13, similar to the first penetration/blast, with the increase of the explosive power, the diameters of the crushing zone and rupture zone caused by the secondary penetration/blast inside the target increase, and the diameter of crater formed by the explosion also increases.

4. Conclusion

Based on the numerical simulation of AUTODYN-2D software, the influence of three different factors on the continuous penetrating/blasting behavior is obtained. When the penetrating/blasting projectile is applied to the concrete target, the explosive effect increases the crater diameter and the crushing area significantly. The impact velocity, projectile diameter and charge type of the projectile have significant influences on the penetrating/blasting behaviors to concrete target. Compared with the first penetration/blast on the concrete target, the second one produces a greater penetration depth to the target plate, but because the explosion area is far away from the free surface, the throwing effect of the second penetration/blast to the free surface particles is lower than that of the first one.

References

[1] Jin Fengnian, Liu Li and Zhang Liping 2002 *Journal of PLA university of science and technology* 2(3) 34-40
[2] Zhang Bingwei, Shu Jiansheng and Li Yaxiong 2019 *Fire Control & Command Control* 44(9):88-97
[3] Zhang Deliang, Luo Zhongwen and Yu Shanbing 1997 *Acta Armamentarii* 18(2):102-6
[4] Yang Chao, Zhao Baoying and Tian Shiyu 2002 *Ordnance material science and engineering* 25(3):14-6
[5] Zhang Youyuan, Yue Mingkai and Zhang Wentao 2016 *Equipment Manufacturing Technology* 4(6):68-76
[6] Wang Xuefei, Yin Jianping and Zhao Feiyang 2018 *Journal of Ordnance Equipment Engineering* 39(12) 68-72