Numerical simulation of damage effect for runway subjected to explosive loading

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Abstract. In order to study the blast damage effect of kinetic energy warhead. It is concerned with use the hydro code AUTODYN for the simulation of explosive loading interactions to multilayer runway. A study is presented including an investigation of the effect of blasting depth, layer of runway, boundary of target. Comparisons and analysis are made with crater size, crunch area radius, damage area and the peak pressure. Based on this analysis Based on the theoretical analysis and numerical simulation results, Preliminary rule between explosive effect and influence parameter is obtained. The simulated results have reference value for the design of the penetrator and damage evaluation.

1. Introduction
The blasting effect in layered media such as airport runway is a more complex problem, which involving the propagation of stress waves, the mechanical behavior of soil, gravel layer and concrete layer under high-temperature, high-pressure, high strain rate, the interaction between the detonation products, solid-state media and the solid multilayer medium [1-4]. It is difficult to use theoretical analysis. At present, numerical simulation combined with a small number of experiments is generally used for research [5-8]. Because there are much more factors affecting the blasting damage effect of airport runway [9-12], so the numerical simulation method can be adopted to reduce costly experimental. It is helpful to understand the action mechanism of the explosive through the interpretation of the experimental results.

The numerical simulation of explosive loading interactions on multilayer runway has been carried out. A preliminary analysis of the explosion destruction region as well as the effect factors was conducted. According to the existing experimental results, the relationship between the explosion damage area and the amount of charge were established.

2. Numerical modeling

2.1. Equation of state of detonation of aluminum-containing explosive
Detonation products are generally described by JWL state equation [10]:

\[ p = A \left( 1 - \frac{E}{R_1 V} \right) \exp(-R_1 V) + B \left( 1 - \frac{E}{R_2 V} \right) \exp(-R_2 V) + \frac{\omega (E + \lambda Q)}{V} \] (1)

Where \( E \) ， \( Q \) are specific internal energy before and after (CJ plat) respectively, \( A \) 、 \( B \) 、 \( R_1 \) 、 \( R_2 \) 、 \( \omega \)
are fitting parameters of the equation of state, $V$ is the specific volume, $\lambda$ is the combustion fraction of non-ideal ingredients.

The constants of explosive state equation are determined by cylinder test. The first, second and third term of Eqn.(1) is used to describe the expansion relation of detonation products in high-pressure stage, the medium-pressure stage and the low-pressure state. In the last stage of expansion of detonation products, the role contribution of the first two terms of the Eqn.(1) can be ignored. So in order to accelerate the solution speed, the JWL state equation can be converted to simple ideal gas equation of state ($\gamma=\omega+1$).

In the hydro code AUTODYN, there are two energy release model of aluminized explosives can be selected, which are Lee-Tarver ignition growth model and JWL-Miller model. The ignition growth model has three stages: ignition, growth and finish. This model has many parameters need to be determined.Compared with the ignition growth model, JWL-Miller expansion options is much simpler. The JWL-Miller energy release model can be presented as:

$$\frac{d\lambda}{dt} = a(1-\lambda)^p \rho^n$$  \hspace{1cm} (2)

Where $\alpha, m$ are energy release constant and energy release index respectively, $n$ is the pressure index. These parameters can be determined by explosion test. As distinct from aluminized explosive, Ideal explosive is fast in energy release when it is exploded in a concrete-like medium without the need for an energy release model, $\lambda=0$ in the equation of state.

2.2. The influence of artificial viscosity on the calculation results

Because the shock wave is a strong discontinuity, the strong discontinuity makes numerical integration difficult. Therefore, the artificial viscosity is used to smooth the strong discontinuity in several grids, so that the solution can be relaxed with the change of space. The artificial viscosity used in the Autodyn program is shown in the following formula [7, 8].

$$q = \begin{cases} 
2 \rho c_1 \left( \frac{V}{V_0} \right) \left( \frac{c}{c_0} \right)^2 \left( \frac{e}{e_0} \right) & \text{for } \frac{V}{V_0} > 1 \\
0 & \text{for } \frac{V}{V_0} \leq 1
\end{cases}$$  \hspace{1cm} (3)

Where: $c_1$ and $c_2$ are the coefficients of primary and secondary terms respectively (the default values are 0.2 and 1 respectively), $\rho$ and $c$ for the material density and speed of sound respectively. $D$ and $V$ are unit characteristic length and unit volume respectively. The values of $c_1$ and $c_2$ determine the number of units that the strong discontinuity needs to cross, Therefore, the numerical simulation model needs to make a compromise between the degree of mesh refinement and the simulation efficiency.

The artificial viscosity smoothes the strong discontinuity, so that the peak pressure of the blast wave calculated in the runway is smaller than the real value. The overpressure peak value can be increased by reducing the artificial viscosity appropriately. Numerical simulation shows that [7,8], the influence of lowering the primary term coefficient $c_1$ is much greater than that of the secondary term coefficient $c_2$, and the influence of the same artificial viscosity coefficient on the peak overpressure at different proportional distances is also different. In addition, the energy dissipation caused by runway heat conduction is not considered in the numerical calculation, which will lead to high frequency pseudo-oscillation after the peak value. When the artificial viscosity is lowered, the pseudo-oscillation will also be increased, but the specific impulse of its leading role in structural damage is not affected by this effect.

When simulating the explosion of aluminum-containing explosive, air blast parameters cannot be used to estimate the power completely. The formula design of aluminum-containing explosives is in a state of negative oxygen balance. During the explosion, oxygen in the air will supplement and participate in the oxidative exothermic reaction of aluminum powder. However, in the depth of the runway, the lack of oxygen around the participation, resulting in a considerable part of aluminium powder can not be oxidized. The actual explosion effect and air explosion is quite different.
Air is modelled by the ideal gas equation of state, in which the pressure is related to the energy by
\[ p = (\gamma - 1) \rho e \]  
(4)

Where: \( \gamma \) is constant. \( \rho \) is air density; and \( e \) is the specific internal energy. In the simulation, the standard properties of air from AUTODYN material library are utilized, i.e., air density \( \rho = 1.225 \text{ kg/m}^3 \) and \( \gamma = 1.4 \). The initial internal energy of air is assumed to be \( 2.068 \times 10^5 \text{ kJ/kg} \) \([7,8]\).

2.3. Influence of element mesh division on numerical simulation results
In finite element explosion calculation, the mesh division method and mesh size of explosives and runway structure have a direct impact on the calculation results, that is, the mesh dependence problem in numerical solution. Johansson et al \([10, 11]\) studies the mesh dependency by comparing static and dynamic loads. Considering the strain rate effect in the constitutive model, the common characteristics will change greatly. For example, the solution will be completely invalid if a few grids are selected, while the excessively accurate grid division will increase the computational time and the cumulative error at the same time. Joosef Leppanen \([12]\) also made a detailed work in the aspect of concrete penetration computing grid division, but did not clearly give a reasonable value of the grid.

For the mesh model of the numerical simulation of kinetic energy bomb explosion in concrete, the mesh division of explosive area has a great influence on the peak explosion pressure. Considering the analog efficiency ratio, explosives and their vicinity generally require an encrypted grid. Generally, the mesh length of the explosive area should be controlled below 5mm, and uniform mesh should be adopted in the concerned area. The mesh around the explosive can be increased gradually outwards in proportion, but its amplification coefficient should not exceed 1.2. In order to avoid the distortion of shock wave propagation caused by the drastic change of mesh size.

3. Description of target characteristics and interaction relations
Numerical simulation analysis of projectile body parameters: about 5kg of aluminium containing explosives, density is 1.71 g/cm³, detonation velocity \( D \) is 8000m/s, detonation pressure \( P_cJ \) is 29GPa, detonation pointed at the point of projectile tail axis.

In reference \([10,11]\), the first grade military airfield runway is generally a three-layer structure. The surface layer of the runway is made of concrete. The concrete uniaxial unconfined compressive strength \( f_c \) is 45MPa and the fracture strength is 4MPa. The second layer is the pebble bed. The third layer is the bottom layer, generally compacted soil. Under the compacted soil layer is the local natural soil layer (the fourth layer). The surface layer of the first level airport runway is 350mm thick, the pebble layer is 350mm thick, and the compacted soil layer is 500mm thick. The runway is generally composed of 4m in length and 4m in width or 4.5m in length and width.

4. Numerical simulation of runway static explosion damage effect
4.1. Numerical modeling of static explosion failure
Lagrangian grids are used for projectile body and target of each layer, and euler grids are used for air and explosives. Contact algorithm was used between projectile and target, and fluid-solid coupling algorithm was used between explosive and projectile and target. Explosive is described by High_Explosive_Burn model, and its isentropic expansion process is described by JWL equation of state. A common joint (solid connection) is used between the layers of the target. From detonation to quasi-static expansion of the product, the simulation program automatically converts the detonation product into an ideal gas.

The surface material is concrete, which is described by RHT model. The compressive strength of the concrete material is 45MPa. Since there is no suitable material model for pebble discrete medium at present, concrete material model is temporarily adopted instead, RHT model is also adopted, and the strength value is set as 10MPa. The pebbles are bonded with mortar, and their tensile strength is relatively low. The tensile strength here is 2MPa. At present, there is no suitable soil dynamic constitutive model for compacted soil structure. Although the Soil_and_Foam model was used to
simulate better soil, material parameters were lacking. Therefore, the concrete constitutive model is temporarily used instead in this paper, and its compressive strength value is 5MPa.

2D numerical simulation of static detonation of charge at different positions in 3-layer and 4-layer targets was carried out respectively. Among them, the four-layer target considers the impact of natural soil boundary during explosion in compacted soil. The calculation model of static explosive projectile target of three-layer target is shown in figure 2.

![Numerical simulation target and projectile](image)

Figure 1. Numerical simulation model of static explosion in 3 layer target.

### 4.2 Numerical simulation results and analysis

Numerical simulation was carried out for different buried depths of the charge in the runway structure, and the simulation results were shown in figure 2–figure 7. Figure 2 shows the failure of the explosive target in the three-layer medium. It can be seen from the figure that in the early stage of the explosion, the blast cavity and crushing zone are mainly formed, and the damage is mainly caused by the shock wave, and cracks begin to form in the target body. With the expansion of explosive products, the damage area gradually increases, the target crack gradually increases, expands and connects, and locally forms penetrating crack. In the axial direction of charge, due to the expansion of explosive products, larger fragments are formed, and eventually a blasting funnel pit is formed.

![Explosion failure of structures](image)

Figure 2. Explosion failure of structures on each floor of the runway (3-layer target structure).

Figure 3 and figure 4 respectively show the static explosion damage of the three-layer and four-layer targets. As can be seen from the figure, the target damage shows a trend of gradual increase-maximum-gradual decrease. When the charge axis is perpendicular to the static explosion on the runway surface of the airport, and the bottom surface of the charge shell is located between the surface layer and the pebble layer, the radius of the explosion funnel pit is the largest; When the bottom of the charging shell is located at the bottom of the pebble layer, the damage area caused by the explosion is the largest, and the distribution of penetrating cracks is dense, with good damage effect. With the decrease of the buried depth of charge, the energy of explosive wave and explosive product consumed in the air domain outside the road surface gradually increases, the damage range of the runway gradually decreases, and even "air cannon" phenomenon may appear within a certain range. With the further increase of the buried depth of charge, the explosive energy coupled to the ground gradually increases, and the phenomenon such as the reduction of blasting funnel pit, "bulge" and "concealed explosion" on the pavement gradually appears. Therefore, the primary factor restricting the power of kinetic energy penetrating ammunition is the explosive point position.
Figure 3. Dielectric damage of each layer of the runway (three-layer target structure).

(a) Surface structure explosion (dislocation)  (b) Surface layer-explosion between pebble
(c) Explosion in pebble bed structure  (d) Explosion between pebble-compacted soil
(e) Explosion of compacted soil structure (Implicit explosion)

Figure 4. Dielectric damage in each layer (4 layer target).

The crack propagation includes the dynamic crack propagation in the near zone and the quasi-static secondary crack propagation in the middle and far zone.

Figure 5. Explosive damage in 3 and 4 layers of targets (explosion between pebble-soil layers).

Figure 5 shows the explosive damage comparison of the three-layer and four-layer target in the pebbling-compacted soil layer. It can be seen from the comparison of static explosion damage effect between three-layer target and four-layer target that the boundary of the target, especially when the charge explodes in the compacted soil, has a certain impact on the target damage. The main effect is that the natural soil will absorb part of the energy of blast wave and explosion product expansion in the process of explosion, which leads to the relative decrease of the energy used for the destruction of surface layer and pebble layer. Therefore, in the further explosion calculation, the four-layer target calculation is closer to the real situation of runway.

Figure 6 and figure 7 respectively show the strain and pressure history curves of the interface points at different explosion locations in the four-layer target. It can be seen from the pressure curves of each point of the target that within a certain distance from the charging center, the target is mainly destroyed by compression (such as points Gauge 1-Gauge 4, Gauge10 and Gauge 11), while at a distance from the charging center, the target is mainly destroyed by stretching. At the interface of each layer (Gauge 11-Gauge 14, Gauge 16-Gauge 18), before the interface is detached, it only receives the compression stress, and after the bond between the two layers is detached, the stress drops to zero.
product is the main failure factor when the charge is buried deep.

little relation to the starting position and shape of explosive charge. The expansion of explosive heat (denoted as $D$) in the runway, the blast wave is the main damage factor.

The current target material model is quite different from the actual situation, so it is difficult to accurately predict the invasion and explosion. The pebble layer has the greatest influence on the stability of penetration trajectory and the comprehensive damage effect of penetration and detonation.

Figure 6. Strain history at different points of static explosion in a four-layer target.

As can be seen from the pressure curves at each point (figure 7), At the same distance from the charging axis (e.g. Gauge 10, Gauge 16), the pressure in the structure layer with higher wave impedance was higher than that in the structure layer with lower wave impedance. For example, compared with the corresponding point Gauge16 in the pebble layer and Gauge10 in the compacted soil layer, the peak pressure of the former is greater than that of the latter.

The effect of shock wave in the power of explosive is related to the detonation velocity (denoted as $D$), detonation pressure (denoted as $P$), loading density, detonation position, charging shape, etc. Generally speaking, the higher $D$ and $P$ are, the stronger the shock wave effect is. At the surface of the runway, the blast wave is the main damage factor.

The expansion work of explosive products in explosive charge power is closely related to explosive heat (denoted as $Q$), explosive capacity (denoted as $V$) and filling density of explosive charge, but has little relation to the starting position and shape of explosive charge. The expansion of explosive product is the main failure factor when the charge is buried deep.

The interface of the target has great influence on the propagation of explosion wave, the energy of explosion wave and the energy distribution of product expansion. The boundary condition of the target and the bonding condition between the layers of the target have certain influence on the final damage mode and effect.

Static explosive damage is related to target structure, material, explosive energy output form and other factors. The current target material model is quite different from the actual situation, so it is difficult to accurately predict the invasion and explosion. The pebble layer has the greatest influence on the stability of penetration trajectory and the comprehensive damage effect of penetration and detonation.
5. Preliminary theoretical analysis of static explosion damage

Based on the theoretical analysis of static explosion in the runway and the aforementioned numerical simulation, and combined with the preliminary experimental results, the blasting failure mechanism of concrete runway is preliminarily analyzed (as shown in figure 8). The parameters for measuring the blasting effect are given and the formula for calculating the blasting effect of runway is preliminarily established.

\[ R_i/d = 1.1426(\omega_0^{0.3}/d)^{0.7184} \]  

(5)
\[
\frac{R_1}{d} = 0.8636\left(\frac{\omega^{1/3}}{d}\right)^{2.333}
\]
\[
\frac{H}{d} = 1.2396\left(\frac{\omega^{1/3}}{d}\right)^{0.3664}
\]
\[
\frac{V^{1/3}}{d} = 0.8289\left(\frac{\omega^{1/3}}{d}\right)^{0.9450}
\]

Where, D, H and w are charge diameter (m), buried depth (m) and mass (kg) respectively; R1, R2 and V are the lip radius (m), visible radius (m) and volume (m³) of the funnel pit respectively.

6. Conclusions

The finite element analysis program of kinetic energy is used to simulate and analyze the explosive damage effect of aluminum-containing explosives in three-layer and four-layer runways. Combined with the related theoretical analysis and test results, the calculation formula of runway blasting effect is preliminarily established. The simulation analysis shows that treating each layer as a macroscopic isotropic homogeneous material can reflect some physical phenomena and laws of static explosion failure in the runway. However, there is still a certain gap in the reflection of crack growth, uplift, throwing and other phenomena in the process of explosion. Especially, in the calculation of crack formation and growth, it is difficult to reflect the impact of material heterogeneity and the bond belt between aggregate and mortar on penetration trajectory. Therefore, it is necessary to study the numerical models of macro and micro respectively from the macro and micro perspectives. And carry out mechanical properties experiments of relevant materials to obtain the static and dynamic mechanical properties parameters of relevant constituent materials. The macroscopic and microscopic numerical simulation models of materials are established by selecting appropriate constitutive models. On this basis, the static blasting numerical calculation is carried out to further reveal the runway blasting mode and mechanism.

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