Simulation of Jet Penetrating Concrete Target Process

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Abstract. Jet penetrate concrete target is an extremely complicated mechanical problem. Based on explicit dynamic analysis program AUTODYN, the numerical model to simulate the process of jet penetrating multi-layer target (perforating gun, casing and concrete target) is established with Lagrange method. The large deformation, high strain rate dynamic processes of penetrating multilayer targets by jet was studied in this work. Numerical results show consistent agreements with experimental results, the errors of penetration depth and diameter are 4.27% and 5.26%, respectively. The dynamic response of the penetration process was discussed, including the shock wave and velocity at collision point of the tunnel. The simulation model and Lagrange algorithm used in this research were proved to be reasonable and feasible. This approach can provide a guidance for effectiveness evaluation of oil perforating charge.

1. Introduction
Oil perforating charge is a kind of shaped charge widely used in oil-gas fields, whose function is to communicate the wellbore and reservoir. The performance of perforating charge can be measured by experiment. The concrete target is used to simulate the underground rock.

Jet penetrating concrete target is an extremely complicated mechanical behavior. To fully describe its dynamic process, some factors, such as the geometric structure of the jet and the target, the elastoplastic deformation, the propagation of shock wave, the generation and propagation of fracture and damage, the friction effect and heat effect, the flow of target material and the impact phase change, must be considered. AUTODYN provides a mature material model to describe the mechanical behavior of materials under high-speed impact. The material parameters is determined on a large number of text data. The numerical results are also beneficial to the improvement of penetration theory model or empirical formula. The requirement of perforating charge property are mainly as follows: larger hole depth and aperture can be obtained under given perforating gun/casing combination and other technological and geological conditions, and it has certain stability during penetrating.

In this paper, A jet penetration model was established, and the penetration process of perforation jet was simulated. Besides, the dynamic response in the penetration process was analyzed and the numerical simulation results of hole depth and aperture were compared with the ground target test.

2. Perforation jet penetration model

2.1 Calculation model of penetration
The perforating charge uses the detonation wave formed by explosive explosion to crush the shaped charge cover and to form a high-speed metal jet stream to penetrate the rock layer and finally form the pore passage. This process can be divided into two stages. During the first stage the explosive explode and formed a jet. In the second stage the high-speed jet penetrates the rock layer. The jet forming
(stage 1) is characterized by large deformation, high strain rate, high temperature and pressure. For the second stage, the process of high-speed jet penetrating the reservoir rock is actually the problem of jet penetrating multi-layer target. The multi-layer target consists of a perforating gun wall, casing, cement sheath, and rock layer. In this paper, the finite element analysis of jet penetration process is carried out based on the analysis of jet forming. The interaction between the jet and various materials (structures) during perforating is fully considered. The perforating gun contact the inner wall first after the formation of the jet. The fluid between the perforating gun and the casing is wellbore fluid in actual perforating operation. The well fluid is not considered in the numerical simulation, so as to compare with the surface perforating test. The penetration process of shaped charge jet on multi-layer target is simulated. The perforating material and structural parameters adopted in numerical simulation are consistent with the actual shooting test, and the cement ring and rock layer material are replaced by concrete target. AUTODYN provides a complete result mapping function writing the results of a solution domain (including all physical quantities) into a mapping file that can be imported into another solution domain and enables mapping between different solvers. It is equivalent to solving the problem in stages, which is suitable for large-scale calculation with large solution domain, long solution time or needing change the solver in different stages[1].

Figure 1. The jet generation process simulation

Firstly, the jet forming process is calculated, as shown in figure 1. The jet results at 26 μs are outputted into the mapping file. In the jet penetration simulation, only a new Lagrange computational domain is needed to map the formed jet to the computational domain, and then a multi-layer target model is established for the jet penetration calculation. According to the symmetry, a two-dimensional axial symmetric model is established to improve the computational efficiency.

Figure 2. Calculation model of penetration

The interaction between the jet and the multi-layered target was also simulated with Lagrange method, as shown in figure 2. Firstly, the jet result solved by Euler method was mapped to the Lagrange solution domain, and the multi-layered target perforating gun, casing and concrete was built. In order to overcome the mesh distortion problem of Lagrange method and meanwhile take the target erosion and material failure during actual penetration into consideration, we need to set the erosion strain on the jet and all target materials. When the material reaches the corresponding erosion strain, Lagrange method will discard the corresponding grid. Erosion strain is not an actual physical parameter but a parameter considering erosion to prevent Lagrange mesh distortion. The minimum size of Lagrange grid is 0.3 mm and the maximum size of Lagrange grid is 0.5 mm in the model through optimizing the grid of penetration area. In order to simulate an infinite target and prevent shock wave reflection, transmit boundary condition is applied on the target boundary. Contact
boundary condition is set between the jet and the perforating gun, the casing pipe and the concrete target, and also between the casing pipe and the concrete.

2.2 Model material model
As metal materials[2-3], perforating gun and casing can be described by Shock state equation and Johnson Cook (JC) strength model. JC model is applicable to material deformation caused by high-speed collision or explosion (materials with large strain, high strain rate and high temperature). RHT model[4,5] is one of the most widely used material model in the concrete numerical simulation at present. It comprehensively takes into account pore pressure effect, strain rate effect, confining pressure effect, hardening and softening of strain rate, and has an objective description of the mechanical properties of concrete, which is extremely suitable for describing brittle materials such as concrete and rock. RHT model consist of five parts of failure surface, elastic limit, strain-hardening, residual failure surface and material damage. The Piecewise JC strength model is used to describe the red copper of the jet.

3. Dynamic analysis of penetration

3.1 Tunnel form and experimental comparison
Figure 3 (a)~(d) shows the penetration states at different moments. Obviously, the penetration speed is higher in the early stage of penetration and the depth of tunnel increases faster.

The depth of the main tunnel changes little from 350 μs to 600 μs. It indicates that the penetration process is mainly completed within the first 350 μs. The jet kinetic energy is almost completely consumed during this period. The velocity of residual jet (slug) is lower than that of the critical penetration, which results in the loss of the penetration ability.

The perforation tunnel at 350 μs is taken as the final tunnel of numerical simulation in this paper, and the depth of tunnel at the moment is 419 mm. The penetration velocity changes with time due to the velocity gradient of the actual jet. As thus the size of aperture fluctuates to some extent. The range of aperture size is 6.2~16.5 mm, and the mean value is about 11.4mm.

(a) 50 μs  (b) 200 μs
(c) 350 μs  (d) 600 μs

Figure 3. Penetration tunnel in concrete

According to seven groups of physical tests, the average depth values is 437.7 mm and the aperture is 10.85 mm. Compared with the numerical simulation results at 350 μs, the errors of depth and aperture are 4.27% and 6.48%, respectively. This indicates that the numerical simulation results are reliable and fully meet the design requirements. The depth of tunnel is slightly smaller than the test data. because the reason could be that the blasting height is not considered in this work, thus the subsequent clubbing or fracture jet still has penetration ability.

3.2 Penetration dynamics response
Figure 4 shows that the pressure change at the collision point during the whole penetration process. The period from 0 to 15 μs is the cratering stage. The pressure changes sharply from 0 to the peak value of 24.0 GPa. In this stage, the jet completed the penetration of the gun body and casing, and established shallow "pocket shape" holes in the concrete. The main penetration stage is from 15 to 315 μs, and most of the tunnel are formed in this period. Due to the existence of velocity gradient and fracture phenomenon of the jet, the steady state penetration stage in which each penetration parameter
remains unchanged could not be obtained. The penetration finishes after 315 μs, the pressure at the collision point reduces to 0

![Figure 4. Pressure variation at collision point](image)

4. Conclusion

Lagrange algorithm was used to conduct numerical simulation on the process of jet penetrating concrete target, and the influence of the shape cone angle, charge and concrete strength on penetration depth was studied. The conclusions are as follows:

1) Due to the accurate material model and the determination of material parameters, the calculated results are in good agreement with the shooting test data. The penetration depth of the calculated and the test are 419.0 mm and 437.7 mm respectively, and the error is 4.27%. The reliability meets the actual design requirements.

2) The penetration process is completed within 350 μs and the jet has lost its penetration capability. This phenomenon indicates that the concrete target has different responses before and after penetration.

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