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Analysis of resistance of concrete target against penetration of eroding long rod projectile regarding flow field around the projectile tip

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ABSTRACT

Precise understanding of concrete target behavior when subjected to high velocity impact of an eroding projectile involves analysis and studying the plastic flow field around the penetrating projectile. In this paper, the flow field around an eroding projectile is reviewed and the main equations of it are presented. Assuming viscoplastic behavior and solving these equations results in determination of the thickness of plastic layer ahead of penetrating projectile. Results show that the strength of the target is proportional to the size of the incompressible zone. Furthermore, there is a direct relation between penetration velocity and pressure gradient at the beginning and end of the incompressible zone; the lesser the pressure gradient the smaller the penetration velocity which means the higher resistance of the target against penetration. Comparison between the results of the presented analysis and experimental data corroborates acceptable accuracy of the model.

1. Introduction

Resisting force in penetration processes is one of the most important parameters encountered in penetration analyses. When velocity of the projectile exceeds a critical value erosion phenomenon is occurred in one or both of the target and the projectile. The critical velocity depends on the material of the target and the projectile [1], and erosion is occurred because of very high-pressure (>2 GPa [2–4]) at the interface of the target-projectile. Therefore, penetration processes are divided into rigid penetration and eroding penetration. Penetration of rigid projectiles into metallic and concrete targets as well as penetration of eroding projectiles into metallic targets is investigated during the last six decades [5–10]. Forrestal model for penetration of rigid projectiles into metallic and concrete targets [5–7] and Tate's model for penetration of eroding projectiles [9,10] are known as reference models. Forrestal model is valid when the nose of the projectile has not considerable deformation and there is abrasion instead of erosion; maximum value of abrasion reported in Forrestal tests is about 4.6% [11–13]. It is necessary to say that there are difficulties for Forrestal model when impact velocity exceeds 600 m/s, which are because of lack of strength parameter independent of velocity of the projectile [13]. Forrestal tried to overcome this problem by introducing a new strength parameter, *R*, obtained from penetration tests, but test dependency of *R* reduces the generality of the model. It seems that the source of this deficiency is due to the independent role of strength parameter in model formulation. In other words, this parameter has an important role in target resistance, but it cannot be considered as a separate term, especially at high velocities.

Studies show that correct explanation of resistance force of the target in high velocity penetration processes depends on correct understanding and explanation of plastic flow field around penetrating projectile. This means that penetration resistance of the target is related to strength parameters of the target and the projectile provided we can represent a precise analysis for material flow around the projectile tip. Plastic strain is a specific parameter for illustration of plastic flow field. Plastic strain is a criterion for recognizing the regions ahead of the projectile. In these regions particles have axial and radial displacements and velocities; axial velocity determines the depth of penetration while the radial velocity influences the crater diameter. Fluid flow models have often used to describe the velocity field. The most extensive description for the flow field ahead of penetrating projectile has presented by Tate [9] who simulated this flow field with electrical current in a semi-infinite solenoid. Unlike the model presented by Yarin

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[14,15], Tate's model can predict the backward movement of flow from the projectile tip. Yarin improved his model for velocities up to 1500 m/s by combining his model with rigid penetration model [16]. Shape of the projectile tip in these models doesn't correspond to elliptic shaped of the eroding projectile assumed by Yarin, because the plastic region in the projectile decreases and mushroomed tip is flatted at higher velocities; this problem could be solved by inserting double sources at the projectile tip.

Stress analysis in target is the most important part of penetration analysis. In this paper, the plastic flow field around the projectile tip is investigated based on experimental observations and numerical simulations regarding compressibility and strain rate effects. Then, radial, circumferential and shear components of stress [17,18] are calculated and the thickness of incompressible layer in front of penetrating projectile is determined by solving the boundary value problem of cavity wall-incompressible layer. This region has an important role at determination of resistance of the target. Results of the presented analysis yields to obtain the basic components of the target strength associated with the merit of each one.

2. Description of plastic flow field during penetration of an eroding projectile

Equations of mass conservation and linear momentum during the flow of target particles because of high-pressure induced from projectile impact are as follows:

$$\dot{\rho} + \nabla \cdot (\rho v) = 0 \tag{1}$$

$$\rho \dot{\mathbf{v}} = -\boldsymbol{\nabla}\sigma + \operatorname{div}\mathbf{S} \tag{2}$$

Body forces are neglected in comparison with penetration induced pressure. Cauchy's stress tensor ($\boldsymbol{\sigma}$) is written as the sum of hydrostatic (σ) and deviatoric ($\mathbf{S}$) stresses:

$$\boldsymbol{\sigma} = -\sigma\mathbf{I} + \mathbf{S} \tag{3}$$

$$\mathbf{S}.\mathbf{I} = 0 \tag{4}$$

Since the reflected shear stress wave from the target surface reaches to the center of the projectile in a few microseconds, the steady phase of penetration begins and elastic deformations are negligible compared with plastic ones. The behavior of the target material assumed to be rigid-perfectly plastic. Based on Levy–Mises relations it could be written:

$$\mathbf{S} = \left(\frac{2}{3}\right)^{1/2} \frac{Y}{(\mathbf{D}.\mathbf{D})^{1/2}}\mathbf{D} \tag{5}$$

$\mathbf{D}$ and Y are stretching rate tensor and yield stress of the target material, respectively. In models taken from fluid flow, firstly the flow potential is obtained and then differentiating with respect to space yields to the velocity field. For instance, the modified model of Tate uses semi-infinite solenoid model and Yarin model combines a source and an uniform flow to produce the flow pattern. Velocity field at a cylindrical coordinate system is written in the form of equation (6):

$$(v_z, v_r, v_\theta) = (-\partial\Phi/\partial z, -\partial\Phi/\partial r, 0) \tag{6}$$

r, θ and z are cylindrical coordinate axes and v_r, v_θ and v_z are components of the velocity and $\Phi$is potential function. Velocity and deformation fields are related as:

$$\mathbf{D} = \frac{1}{2}\left(\nabla\mathbf{v} + \nabla\mathbf{v}^{\mathbf{T}}\right) \tag{7}$$

3. Simulation of the penetration of eroding projectile into the concrete target at high velocities

Since observation of steady phase of penetration involves the study of flow field around eroding projectile, several simulations were carried out and corroborated with Vladimir Gold experiments [4,19]. Schematic view and actual shape of cavity associated with sensor's locations for penetration of a long rod copper projectile at 1836 m/s are shown in Fig. 1 [4]. For validating the simulations, firstly the test reported in [4] is simulated; a copper projectile with a length of 19 cm and a diameter of 1.5 cm impacted at 1836 m/s against a cylindrical concrete target with the same length and diameter of 91 cm. Then, the results of simulations are compared with the reported parameters in [4] such as depth of penetration, residual mass and time history of the projectile tip. Axisymmetric finite element model of the process is shown in Fig. 2.

Average strength of the concrete target for 28, 46 and 48 days is equal to 0.374 kbar. RHT material model is used for concrete and P-alpha and polynomial equations of state are attributed to porous and compressible regions. Constants of the material model for the target associated with Johnson-Cook material model and linear equation of state coefficients for the projectile are taken from [20,21]. Total time of the process assumed equal to 800 μs.

Depth of penetration obtained from simulation is compared with experimental data in Fig. 3; the results are shown for the time after 30 μs to ensure the temporary phase is passed. Furthermore, velocity field of the target and particles of the projectile obtained from simulation are shown in Fig. 4.

Simulation results have a delay with respect to test data, because the sensors located on the target fail at the arrival time of shock wave; therefore, the time history shown in Fig. 3 shows good

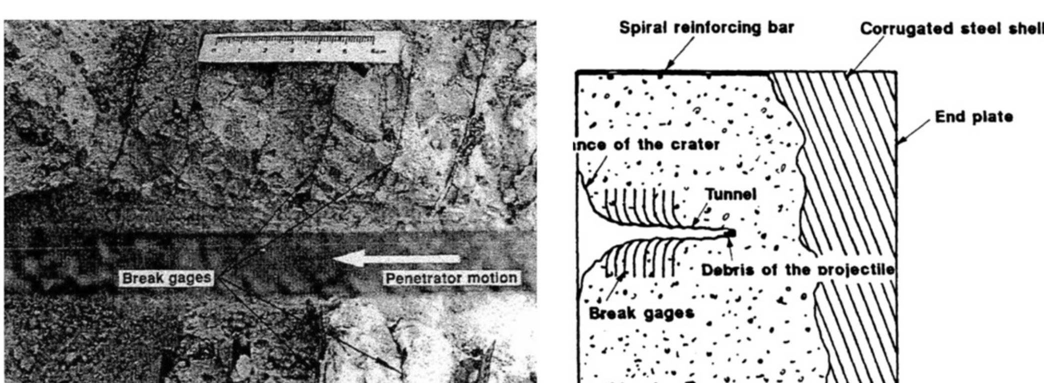

Fig. 1. Actual shape (left) and schematic view (right) of cavity and sensors locations [4].