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Short communication

A note on the deep penetration and perforation of hard projectiles into thick targets

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ABSTRACT

Two models were proposed in this note. Firstly, by assuming that the resistance acting on the projectile keeps unchanged during the penetration process, the new mean resistance approach based on dynamic cavity-expansion approximation was proposed. A simple unified model was further given to predict the depth of penetration (DOP) of different nose-shaped hard projectiles penetrating into diversified targets (e.g. concrete, metal, rock). Besides, the related mean resistance coefficient was confirmed as 0.4 based on the parametric analyses. Secondly, an experiment-based simplified semi-analytical perforation model for the thick concrete slab was obtained, in which the rear crater height was suggested as 2.5 times of the projectile diameter, and the ejecting velocity of rear shear fragment was advised as 20% of the residual velocity of projectile after perforation. The existing method for predicting the rear crater height was improved and the kinetic energy carried by the rear scabbing fragments were considered quantitatively. Finally, by comparing with the available test data, the prediction accuracy for DOP and residual velocity as well as the concise expressions of our models were validated.

1. Introduction

Terminal ballistic parameters of hard projectiles penetrating/perforating into targets (e.g. concrete, rock, metal and etc.) are the main focuses for both defense engineers and weapon designers. The related experimental, analytical and numerical studies can be referred from the reviews by Li et al. [1], Corbett et al. [2] and Anderson and Bodner [3]. The empirical formulae (e.g. *NDRC*, *ACE*, *BRL* and etc.) drawn by fitting the test data have been widely cited and some of them are the fundamentals of the design code (TM5-855-1, TM-1300) of protective structures. However, the empirical formulae are only applicable within the tests acquired parametric ranges, some of them even are unit-dependent. Numerical simulations can provide visible information on damage, stress and deformation field, while the related constitutive parameters of the targets are difficult to be determined. Experiment-based analytical (semi-analytical) approach could be the most efficient and economical way to study the local effects of projectile impacting on the target.

As for the projectile penetrations, based on the cavity-expansion model, by assuming the normal stresses acting on the projectile's nose equal to the expansion stresses of the spherical or cylindrical cavity, Forrestal et al. [4–8] and Warren et al. [9] proposed a series of formulae to predict DOP of ogive-nosed projectiles penetrating into soil [4], concrete [5], ductile metal [6–8] and rock [9] targets. For the complexity of the cavity-expansion model, by introducing a dimensionless empirical parameter S which is dependent only on the concrete compressive strength, Forrestal et al. [10,11] and Frew et al. [12] simplified the expressions of the cavity-expansion stress and applied it in the projectile penetrations of concrete targets. Furthermore, by considering the boundary influence of the target, Forrestal et al. [13] and Frew et al. [14] proposed another dimensionless parameter R to describe the penetration resistance. However, the equivalent target strength parameter R must be confirmed by the actual projectile penetration test data and the prediction function was lost. By introducing the dimensionless projectile-nosed geometry function N and impact factor I, as well as considering the projectile-target interfacial frictions, Li and Chen [15,16] extended the Forrestal formula to the dimensionless form which can be applied for projectile with arbitrary nose profiles into diversified targets. Since the target strength parameter S used in Refs. [10–12,15,16] was obtained by fitting the test data of ogive-nosed projectile penetrating into normal strength concrete, Wu

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et al. [17] further regressed the expression of S for high-strength concrete (HSC) and the projectile nose shapes were considered, which was validated by the penetration tests on HSC with the compressive strength increased up to ~250 MPa. The resistances acting on the projectile during the penetration in the above studies are dependent on the instantaneous velocity of the projectile. For the derivation of DOP, this makes it more complicated in integrating the motion equation, especially when the projectile-target frictions were considered.

As for perforation of thick concrete slab, based on three-stage (cratering + tunneling + shear plugging) perforation model, Chen et al. [18] and Li and Tong [19] have proposed the formulae for ballistic limit (the minimum initial impact velocity of the projectiles to perforate the targets with given thickness) and perforation limit (the minimum thickness of target required to prevent the perforation), as well as the residual velocity after perforating. By further considering the kinetic energy carried by the ejected fragments on the rear face of the concrete slabs, Wu et al. [17] proposed the expression to predict the residual velocity of projectile after perforations. Recently, by introducing the energy dissipated through the fracture of ejecting fragment into pieces, Grisaro and Dancygier [20] proposed a modified energy balance model of the projectile perforating on the concrete slab. However, the perforation limit in the model of Grisaro and Dancygier [20] was obtained by curve-fitting the test data and only applied for residual velocity predictions.

The height of rear crater and the ejecting velocity of rear shear fragment are the two key factors in the projectile perforation model for thick concrete slab. However, the rear crater height equation proposed in Refs. [18,19] was very complex and its accuracy was not validated for the lack of test data. More recently, in Ref. [21], we have conducted a series of projectile perforation tests on concrete panels with thicknesses ranged from 100 mm to 300 mm, the striking and residual velocities of the projectiles as well as the dimensions of front impact crater and rear shear crater were recorded in detail.

In the present paper, a unified equation to predict DOP for deep penetration and a simplified perforation model for thick concrete slab are presented by proposing three experiment-based key parameters. They are the mean resistance coefficient $\mu = 0.4$ for mean resistance penetration model, the ratio of rear crater height to projectile diameter $H_c/d = 2.5$ and the ratio of the ejecting velocity of rear concrete fragment and residual velocity of perforated projectile $\eta = 0.2$. Model predictions are in reasonably good agreement with the available test data for both penetration and perforation.

2. Deep penetration model

2.1. Mean resistance

The instantaneous axial resistance F_z acting on the projectile during penetration consists of two parts, the quasi-static resistance term and the dynamic term (or the inertial term) arising from the projectile velocity [10,11,16].

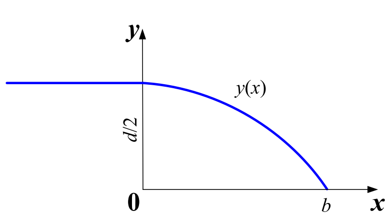

Fig. 1. The half profile of longitudinal section of projectile with a general nose shape.

$$F_z = \frac{\pi d^2}{4}\left(N_1\sigma_s + BN_2\rho_0 V^2\right) \tag{1a}$$

$$N_1 = 1 + \frac{8\mu_m}{d^2}\int_0^h y\,\mathrm{d}x \tag{1b}$$

$$N_2 = \frac{8}{d^2}\int_0^h \frac{yy'^3}{1+y'^2}\mathrm{d}x + \frac{8\mu_m}{d^2}\int_0^h \frac{yy'^2}{1+y'^2}\mathrm{d}x \tag{1c}$$

where d and V are the shank diameter and the instantaneous velocity of projectile, respectively. ρ_0 is the density of the target, σ_s is a measure of quasi-static target material strength, B is the coefficient of dynamical resistance from cavity-expansion analysis, N_1, N_2 are projectile nose shape factor, μ_m is the sliding friction coefficient in impact, $y = y(x)$ is the nose shape function as shown in Fig. 1 [16].

Without considering the initial impact cratering stage, the DOP P can be integrated from Eq. (1) and Newton's second law [10].

$$P = \frac{2m}{\pi d^2 BN_2\rho_0}\ln\left(1 + \frac{BN_2\rho_0 V_0^2}{N_1\sigma_s}\right) \tag{2}$$

where m and V_0 are the mass and the striking velocity of projectile, respectively. The deviation of considering the entrance crater effects or not is about $kd/2$ for penetration depth based on the work of Chen and Li [16], where kd is the depth of crater (Forrestal et al. [10] and Li and Chen [15] have suggested $k = 2$ and $k = 0.707 + h/d$, respectively). The entrance cratering region was neglected since it has little influence on deep penetrations. The resistance in Eq. (1) is complicated since it is dependent on the instantaneous projectile velocity. In this paper, we'll present a mean resistance equation that remains unchanged during the penetration process. Fig. 2 illustrates the typical deceleration–displacement curve (red dashed line 0–1–2–3, in the web version) of the projectile penetrating into concrete target which could be obtained from Eqs. (1) and (2). For rigid projectile penetration, the ascending and descending parts 0–1 and 1–2 were corresponding to the projectile cratering and tunneling stages, respectively. And the projectile stopped penetrating at point 2. For simplicity, the mean deceleration which is only dependent on initial striking velocity (black solid line 0–1′–2′–3) was proposed and illustrated in Fig. 2. The precondition of which is that the works done by the actual and mean resistances were equal, that is to say the areas $A_1 = A_2$ was satisfied in Fig. 2.

By introducing a mean resistance coefficient μ into Eq. (1), the mean resistance F_m can be written as

$$F_m = \frac{\pi d^2}{4}(1+\mu\delta)N_1\sigma_s \tag{3a}$$

$$\delta = \frac{I_0}{N} = \frac{BN_2\rho_0 V_0^2}{N_1\sigma_s} \tag{3b}$$

The parameter δ denotes the ratio of dynamic to quasi-static resistance. I_0 and N are two dimensionless parameters proposed by Chen and Li [16].

$$I_0 = \frac{mV_0^2}{N_1\sigma_s d^3}, \quad N = \frac{m}{B\rho_0 d^3 N_2} \tag{4}$$

As for concrete and ductile metal targets, the related parameters in Eq. (3) were suggested as follows