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Analysis on the resistive force in penetration of a rigid projectile

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Abstract

According to the dimensionless formulae of DOP (depth of penetration) of a rigid projectile into different targets, the resistive force which a target exerts on the projectile during the penetration of rigid projectile is theoretically analyzed. In particular, the threshold V_c of impact velocity applicable for the assumption of constant resistive force is formulated through impulse analysis. The various values of V_c corresponding to different pairs of projectile-target are calculated, and the consistency of the relative test data and numerical results is observed.

Keywords: Rigid projectile; Constant resistive force; Impact velocity

1. Introduction

The penetration of a rigid projectile into thick target (metals, concrete, etc.) has been an intense research topic for many decades. The analysis of resistive force which a target exerts on the projectile during penetration is the basis of all relative problems. Usually the resistive force is obtained from the dynamic cavity expansion model.

The resistive force obtained from the dynamic cavity expansion model is usually expressed as the following form [1].

$$F = \frac{\pi d^2}{4}\left(A\sigma_y N_1 + B\rho V^2 N_2\right) \tag{1}$$

where d is the diameter of projectile shank; σ_y and ρ are yield stress and density of target material, respectively; A and B are dimensionless material constants [2–5]; V is the rigid-body velocity of projectile during penetration; N_1 and N_2 are the dimensionless parameters related to the nose shape of projectile and the friction coefficient μ [1]. In general, if the nose shape can be represented by the nose shape function $y = y(x)$ for an arbitrary nose shape, then the nose factors are defined as

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

$$N_2 = N^* + \frac{8\mu}{d^2}\int_0^h \frac{yy'^2}{1+y'^2}\mathrm{d}x, \tag{2b}$$

$$N^* = -\frac{8}{d^2}\int_0^h \frac{yy'^3}{1+y'^2}\mathrm{d}x. \tag{2c}$$

where h is the height of nose; and N^* in Eq. (2c) is defined as the geometry factor of projectile. Regarding the ogival and conical noses, the formulae of N_1, N_2 and N^* are very simple [1]. Obviously, the resistive force consists of two parts: quasi-static resistive force (target strength term) $AN_1\sigma_y$ and dynamic resistive force (inertial term) $BN_2\rho V^2$.

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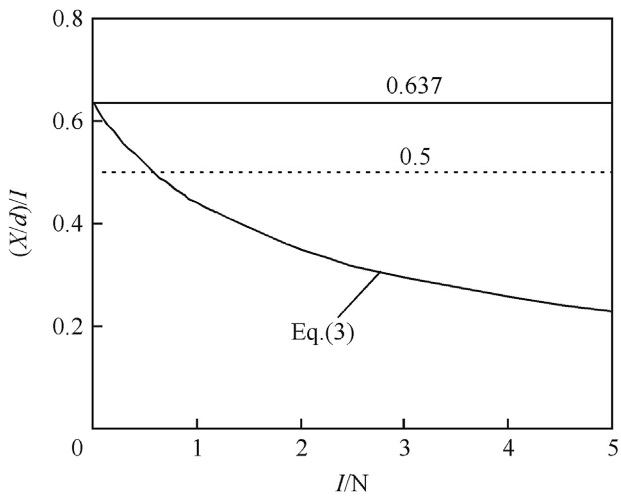

Fig. 1. Dependence of $(X/d)/I$ on I/N based on Eq. (3).

There have been many arguments about the contributions of the target strength term and the inertial term to the resistive force. For example, Batra and Wright [6] numerically analyzed the resistive force of an infinitely long, spherically-nosed rigid projectile penetrating into a rigid plastic target in a series of simulations, and found that the dimensionless constant B in Eq. (1) is just 0.0733, which is much smaller than that used in general analysis. Thus, they concluded that the dependence of the target resistive force on the impact velocity is much less than that obtained from the dynamic cavity expansion model. Forrestal et al. and Frew et al. conducted a series of penetration tests of concrete targets to measure the acceleration curves [7,8] and found that the effect of the inertial term is very small in the range of the impact velocity (<460 m/s). Forrestal and Warren's analysis on the penetration of ogive-nosed projectile into aluminum target also suggested that the resistive force is dominated by the target strength term when the impact velocity is below a certain value [9]. Recently, Rosenberg and Dekel conducted lots of simulations [10] and declared that, for different pairs of projectiles with various nose shapes (ogive, spherical, conical and flat) and target (aluminum and steel), the resistive force is constant and independent on the impact velocity in a certain range of impact velocities (<1.5 km/s). However, if the impact velocity exceeds a certain threshold value, the dynamic cavity expansion model, which includes both the target strength term and inertial term, is appropriate. Further more, the threshold of

Table 1
Summary of projectile parameters.

Nose shape	d/mm	L/d	M/kg	References
Ogival ($\psi = 3$)	5.5	10	0.0128	[10]
		20	0.02667	
Spherical	5.5	10	0.0128	
		20	0.02667	
Flat	5.5	20	0.02667	
Conical	7.1	10	0.025	
Ogival ($\psi = 3$)	76.2	7	13	[7] and [8]
Ogival ($\psi = 6$)	76.2	7	13	[7]

Table 2
A summary of material parameters of different targets.

Material	σ_y/MPa	ρ/(kg·m^{-3})	γ	E/GPa	A	B	References
Aluminum	400	2710	1/3	69	3.637	1.041	[10]
	800						
Steel	400	7850	1/3	200	4.348	1.133	
	800						
Concrete	23	2040	–	–	–	–	[7] and [8]
	39	2250	–	–	–	–	[7]

impact velocity depends on the nose shape of projectile and target material.

Chen and Li defined two dimensionless parameters [1], i.e. impact function I and geometry function of projectile$N$, and then analyzed the parameters which dominate the penetration dynamics of a rigid projectile in detail. In fact, based on the relative discussions about I and N, the respective effects of the target strength term and the inertial term in the dynamic cavity expansion model can be analyzed, too. Based on the previous preparatory work in Ref. [11], the present paper further analyzed the penetration of rigid projectile, and obtained some conclusions which have good agreement with the test data in Refs. [7,8] and the simulation results in Ref. [10].

2. Formulae of DOP

Based on Eqs. (1,2), Chen and Li [1], Li and Chen [5] indicated that the dimensionless DOPs of different target materials subjected to rigid projectile impact are only dominated by two dimensionless factors, i.e. impact function I and geometry function of projectile N, and the dimensionless formula of DOP subjected to the impact of rigid projectiles with various nose shapes is

$$\frac{X}{d} = \frac{2}{\pi} N \ln\left(1 + \frac{I}{N}\right) \tag{3}$$

where X is DOP, and the respective expressions of I and N are

$$I = \frac{I^*}{AN_1},\ I^* = \frac{MV_0^2}{d^3\sigma_y} \tag{4a, b}$$

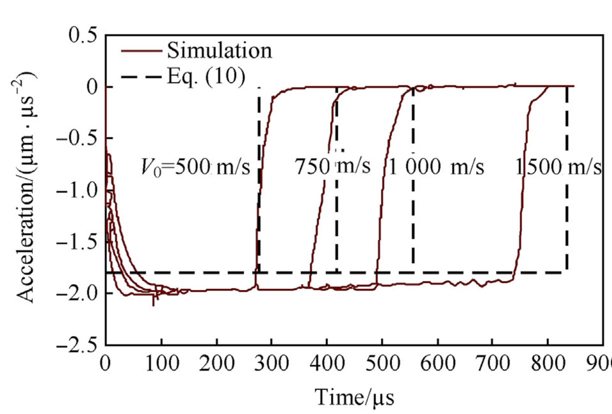

Fig. 2. Simulations and model predictions of decelerations *vs* time for projectile with L/d = 20 and ψ = 3 penetrating aluminum target with σ_y = 400 MPa at different impact velocities.