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Representation of nose blunting of projectile into concrete target and two reduction suggestions

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ABSTRACT

The high-speed projectile often has significant mass loss and nose blunting when it penetrates into the concrete target, which usually decreases the penetration performance of projectile. A shape-evolvement model is constructed to predict the shape evolvement and penetration performance of projectile in the present manuscript. The penetration process and projectile are respectively discretized in the temporal and spatial dimensions. The shape evolvement is obtained by the projectile outer surface receding point by point. During a discrete time step, the governing equation is derived for the receding displacement based on the thermal mechanism of mass loss. The related friction work between the projectile and target is obtained based on the energy conservation law, which avoids the determination of the specific form for friction. The model is validated by the experimental results. Furthermore, two suggestions are provided to reduce the projectile nose blunting by distributing the refractory material in the projectile nose. Both schemes achieve the prescribed aim and then enhance the penetration performance of the projectile. Finally, the underlying assumptions in the model are analyzed, and the possible reasons are discussed for the deviation between the model prediction and the experimental result.

1. Introduction

Since concrete is usually used to construct the underground fortifications, it is of crucial importance to study the penetration performance of projectile into concrete target. During high-speed penetration into the semi-infinite concrete target, the projectile normally has significant mass loss and nose blunting, decreasing its Depth of Penetration (DOP) [1–3]. Furthermore, the structural failure and ballistic trajectory deflection of projectile are also partially due to the mass loss and nose blunting. Therefore, their mechanism and representation have drawn interests in the field of the terminal ballistics [4].

In summary of the experimental data from Refs. [5,6], Silling and Forrestal [7] indicated that the mass loss of projectile is proportional to its initial kinetic energy. The proportional coefficient is fitted by the experimental data. The efforts were exerted to find the influence factors of the proportional coefficient or even develop its analytical formula in the work afterward, such as Refs. [8–10]. It is noted that the Moh's hardness of aggregate is one important influence factor for the proportional coefficient [8].

Observation of the residual projectile indicates that abrasion and cutting are the cause of mass loss for projectile during penetration [4,8–16]. Which one is dominant is decided by the strength/hardness of projectile material. The abrasion mechanism is dominant when the projectile material strength/hardness is large, while the cutting mechanism may become significant if the projectile strength/hardness is small. However, due to the complexity of the cutting process, only abrasive mass loss is qualitatively represented up to now, such as Refs. [9,11,14–16]. In this way, we only focus on the mass loss of projectile coming from the peeling of the molten surface layer on projectile in the present manuscript. The heat needed is totally transformed from the friction work between the projectile and target. Based on this mechanism, Jones et al. [11] demonstrated that the mass loss of projectile is proportional to the friction work between the projectile and target and reverse proportional to the melting heat of projectile material.

The question is how to derive the friction work between the projectile and target. Since the dynamic friction between the projectile and target has observable velocity dependence during high-speed penetration [14], it has no unified expression up to now. This is a huge obstacle for deriving the friction work through integrating the friction along the penetration path. In the present manuscript, the friction work is obtained by means of the energy conservation law, which avoids the determination of the specific form of friction.

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Actually, only small part of initial kinetic energy of projectile is consumed by the lost mass of projectile, which should has little influence on the performance of projectile. However, the mass loss generates blunter projectile nose, which provides larger drag force during penetration and thus decreases its DOP. This highlights the necessity of the study on the projectile nose blunting.

By observing the projectile shape before and after penetration, several nose blunting laws were proposed. Davis et al. [14] fitted the contour of projectile nose by a polynomial and then constructed the evolution equations to evaluate the nose shape change. Typically for the ogvial projectile, its nose shape is assumed to keep ogival but with a smaller CRH (Caliber-Radius-Head) value as the penetration progressing [8,15–18]. The hypothetical nose blunting laws determine the distribution of mass loss of projectile. Constantly, the projectile should be homogeneous and the nose should be axial-symmetrically blunted. Actually, asymmetrical nose blunting may occur during penetration [5,6], which could not be described by this method. Nose blunting of inhomogeneous projectile could not be described by this method, neither.

In order to overcome the shortcomings above, the projectile shape variation is determined by the projectile outer surface receding point by point. Hence, the receding velocity is the key. A few formulae were derived to represent it, such as Refs. [7,10,19,20]. Up to now, it is reasonable to obtain the receding velocity by extrapolating the formula for the total mass loss of projectile to its local area, as indicated by Refs. [7,10]. Inserting the receding velocity into the commercial FEM or other numerical software, the projectile shape variation could be determined. Since the local shape variation of projectile is represented, the nose blunting process is detached from the hypothetical nose blunting law, and it has the potential to determine the nose shape variation of inhomogeneous projectile and asymmetrical nose blunting process. Due to these merits, it is the very method adopted in the present manuscript.

Based on the previous work, a shape-evolvement model is constructed by projectile outer surface receding point by point in the present manuscript. The governing equation is derived for the receding displacement of the outer surface through extrapolating the formula for the total mass loss to the local area. The mass loss of projectile is closely related with the friction work between the target and projectile, and the friction work is obtained according to the energy conservation law. The shape-evolvement model is validated by comparison between the model predictions and experimental results. Furthermore, two schemes are proposed to reduce the projectile nose blunting, and the improvements are investigated based on the model.

2. Shape-evolvement model

We firstly divide the penetration process into n parts. The discrete time interval is indicated as Δt_i, $i = 1,2,3,\ldots,n$. The sum of each time interval $\sum_{i=1}^{n}\Delta t_i$ should be equal to the total penetration time T, but the length of each time interval may not be the same.

Assuming the projectile is always axial-symmetrical during the whole penetration process, the projectile could be simplified as 2D. Another assumption is that the mass loss of projectile only occurs on the current projectile nose, and then only the current projectile nose is investigated in the shape-evolvement model. Assuming the receding direction of projectile outer surface is vertical to the projectile axis, with the coordinates constructed in Fig. 1, the original projectile nose is evenly discretized into nox parts along the X axis, and the length of each part is l_c along the X axis at time $t = 0$ ms. It should be noted that the origin of the coordinates is the original nose tip of projectile and the coordinates moves along with the projectile. At time t_i, the spatial discretization of projectile along the X axis is shown in Fig. 1, and the contour of projectile is comprised of a series of discrete points $(x_{(i,j)},y_{(i,j)})$, $j = 1,2,3,\ldots,\text{nox} + 1$. Note that $t_1 = 0$ and $t_i = \sum_{k=1}^{i-1}\Delta t_k (i \geq 2)$. This accomplishes the spatial discretization of projectile.

The subscripts i and j denote the Sequence Number (SN) in the temporal and spatial dimensions, respectively. The angle between the tangential line of projectile outer surface and the projectile axis on each point $(x_{(i,j)},y_{(i,j)})$ is denoted as

$$\theta_{(i,j)} = \tan^{-1}\frac{y_{(i,j)} - y_{(i,j+1)}}{x_{(i,j)} - x_{(i,j+1)}}, \quad i = 1,2,3,\ldots n, \quad j = 1,2,3,\ldots \text{nox} + 1. \tag{1}$$

Especially, $x_{(i,\text{nox}+2)} = x_{(i,\text{nox}+1)} + l_c$, $y_{(i,\text{nox}+2)} = d/2$. Here d is the diameter of projectile.

By discretizing the penetration process and projectile respectively in the temporal and spatial dimensions, the projectile shape variation could be represented by the receding displacement of each point on the projectile outer surface during a discrete time interval.

2.1. Governing equation of receding displacement

Supposing that the projectile mass loss totally comes from the removal of melted boundary surface layer of projectile and the heat needed is totally transformed from the friction work between the target and projectile, the increment of projectile mass m could be expressed as follows [11].

$$\mathrm{d}m = \frac{\mathrm{d}W_t}{\kappa q} \tag{2}$$

Here symbol d indicates the increment of following variable during time step dt, W_t is the friction work between the target and projectile, $\kappa = 4.18$ J/cal is the mechanical equivalent of heat and q is the melting heat of unit-mass projectile material. It is noted that dt could be any time step Δt_i, $i = 1,2,3,\ldots,n$.

Since the mass loss only occurs in the current projectile nose, in the current projectile shank, the friction work should be zero, and the geometry should be unchanged, i.e., the receding displacement should be zero. Herein, the right side of Eq. (2) is

$$\frac{\mathrm{d}W_t}{\kappa q} = \int_0^b \frac{2\pi y w_t \mathrm{d}t}{\kappa q \cos\theta}\mathrm{d}x, \tag{3}$$

in which b indicates the x coordinates of the transition point from the projectile nose to shank, $w_t < 0$ is the friction work rate per unit outer surface of projectile, $y = y(x)$ is the function of the generatrix

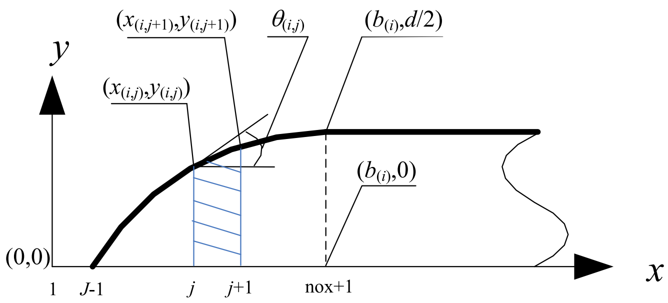

Fig. 1. Spatial discretization of projectile at time t_i