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Numerical analysis of the trajectory stability and penetration ability of different lateral-abnormal projectiles for non-normal penetration into soil based on Modified Integrated Force Law method

Qiran Sun, Yuxin Sun*, Yixin Liu, Ruiyu Li, Yayun Zhao

National Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, China

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ABSTRACT

The Integrated Force Law (IFL) approach is adopted and modified to provide a 2-D code for trajectory analysis of lateral-abnormal projectile based on the plane motion hypothesis and the spherical cavity expansion theory.

In the proposed Modified Integrated Force Law (MIFL) method of solving non-normal penetration problems, the force and moment integral equations are newly derived by taking the azimuthal angle of the axisymmetric projectiles into account that can be extended to various irregular rigid projectiles including the lateral-abnormal projectiles and numerically integrated with Romberg's method instead of Adaptive Simpson's method in the IFL method which can increase the error tolerance. The MIFL method is validated by making comparison between numerical results and analytical solutions. Then the influence of different friction coefficient conditions and other critical conditions for the trajectory instability of different lateral-abnormal projectiles including small angles of attack (AOA), various velocities are further discussed.

Combing with field test, the proposed model enables a satisfactory estimate of the trajectory deviation from initial direction under the non-constant friction coefficient condition and analyses the effect of trajectory stability on penetration ability of different lateral-abnormal projectiles.

1. Introduction

Numerical models have increasingly been employed in analysis of projectile penetration in soils to study issues that are difficult to address analytically [1], some of which include the friction effect [2–5], distribution of resisting forces and soil projectile interactions during penetration [5,6], solution of analytical derivations for normal-penetration depth [7], constitutive model of soil [8] and flow separation [9]. Numerical methods also solve the problems of the trajectory deviation for non-normal penetration [3,10–12]. For non-normal penetration problems, curvilinear motion is expected from the very beginning and a practically important scenario is that the projectile motion reverses toward the target surface [3]. The differential area force law (DAFL) method [10,13] and the local interaction models (LIM) [14] are proposed to predict the trajectory of a ballistic penetrator. And a general framework based on DAFL approach [3] is presented to study the curvilinear motion of the projectile and its stability during deep penetration with ABAQUS code. Combining the computational ease of the Poncelet Analysis with the computational accuracy of the DAFL method, the Integrated Force Law (IFL) method [12] using Adaptive Simpson's method to calculate the approximate solution of the force and moment integral to determine the force and moment acting on the projectile based on the spherical cavity expansion theory is proposed to study J-hook trajectory for non-normal penetration.

However, the investigations on projectile trajectory and stability mainly focus on the projectiles with common projectile shapes (Fig. 1) and many key questions remain inconclusive [3]. When the IFL method with Adaptive Simpson's method was adopted, the approximate solution of the force and moment integral only can be acquired by decreasing the error tolerance from 1.0$\mathbf{e}^{-6}$ to 1.0$\mathbf{e}^{-2}$ and the error ranges from as low as 2% to in excess of 200% [12]. Considering that the friction effect neglected in the IFL method has an important impact on penetration results [13–15], the trajectory instability has been simply discussed under the constant friction coefficient condition in Ref. [16] and still need further detailed analysis under different friction coefficient conditions.

The MIFL method will be present to provide a 2-D code for trajectory analysis of lateral-abnormal projectile based on the plane motion hypothesis. Then the non-constant friction coefficient condition will be compared with the constant friction coefficient condition including non-friction condition. Other critical conditions for the trajectory instability of different lateral-abnormal projectiles

* Corresponding author.
E-mail address: yxsun01@163.com (Y. Sun).

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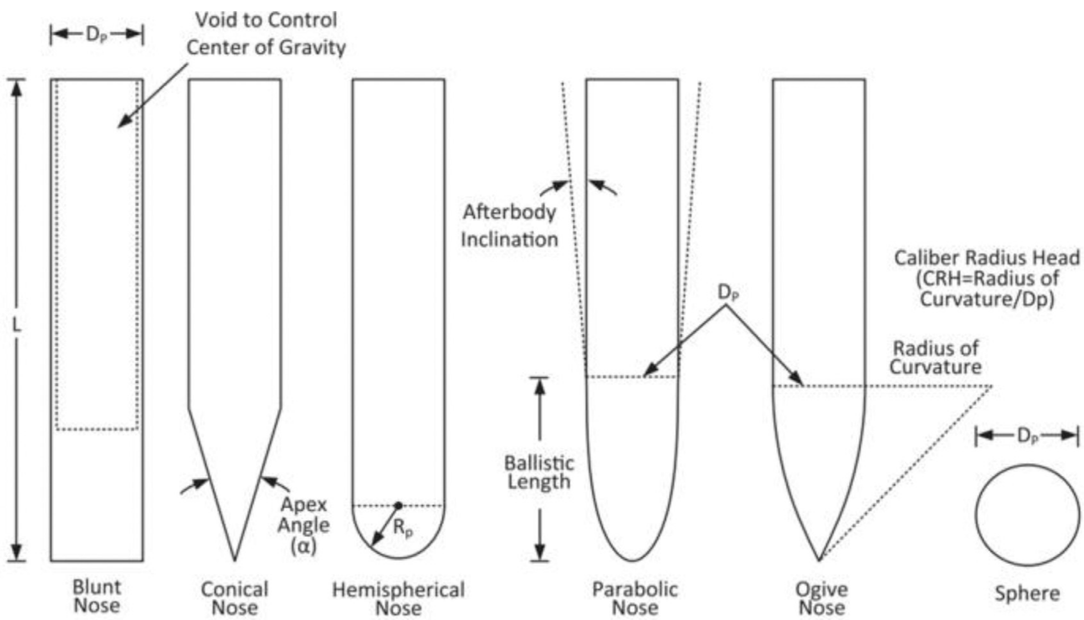

Fig. 1. Common projectile shapes and associated parameters [1].

will also be discussed with the MIFL method under the non-constant friction coefficient condition.

2. Modified Integrated Force Law (MIFL) method

The MIFL method is described based on the derivation of the force and moment integral equations used for the 3 dimensional model to calculate the 2 dimensional trajectories for non-normal impact with the azimuthal angle taken into account that can be extended to various irregular rigid projectiles including the lateral-abnormal projectiles. Under certain conditions, free-surface effects may become important, e.g. brittle target medium (concrete or rock) [17], large impact oblique angles [18], and shallow penetration depth [19]. For soil target and deep penetration, free-surface effects are less significant since soils are more ductile than brittle targets [3,17]. Furthermore, this study will focus on deep penetration problems for soil target. Therefore, the free-surface effects is legitimate to be ignored in the MIFL method.

2.1. Geometry of lateral-abnormal projectiles

Lateral-abnormal projectiles with different nose pin on the front of the penetrator (Fig. 2) are designed by the study on multi impact penetration [20], kinetic energy cavity penetrator weapon penetrating in a super-cavitation mode [21] and nose geometry for rigid penetrators [22–24]. The projectile #1 have conical nose pin on the front of the penetrator and the projectile #2 have blunt nose pin on the front of the penetrator. Those projectiles are still rigid axisymmetric projectiles during penetration into soil and the cross section of the projectile is shown in Fig. 2.

Two coordinate systems used to describe the orientation and position of the projectile at time t is shown in Fig. 3. The inertial coordinate system (ICS) is represented by [X-Y-Z] with the origin fixed to the point where the tip of the projectile impacts the soil and the x-axis along the soil interface. The weapon coordinate system (WCS) is represented by [x_w-y_w-z_w] with the origin fixed to the center of gravity (CG) of the projectile and the x_w-axis along the weapon centerline. The radius of arbitrary point P on the projectile surface

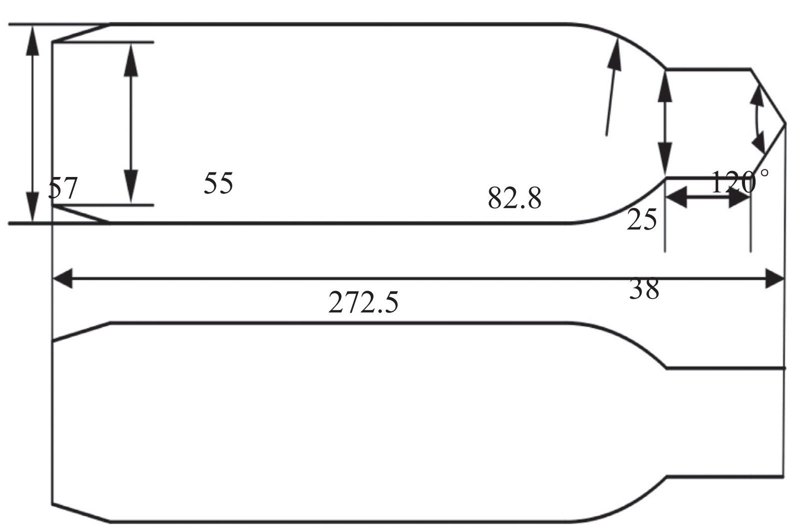

Fig. 2. Geometries of the lateral-abnormal projectiles.