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Finite Spherical Cavity Expansion Method for Layering Effect**

Xiangzhen Kong **Qin Fang*** **Hao Wu** **Yadong Zhang**

(*State Key Laboratory for Disaster Prevention & Mitigation of Explosion & Impact, PLA University of Science & Technology, Nanjing* 210007, *China*)

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ABSTRACT A decay function for the layering effect during the projectile penetrating into layered targets is constructed, which is obtained via the theoretical solution of a dynamically expanding layered spherical cavity with finite radius in the layered targets that are assumed to be incompressible Mohr-Coulomb materials. By multiplying the decay function with the semi-empirical forcing functions that account for all the constitutive behavior of the targets, the forcing functions for the layered targets are obtained. Then, the forcing functions are used to represent the targets and are applied on the projectile surface as the pressure boundary condition where the projectile is modeled by an explicit transient dynamic finite element code. This methodology is implemented into ABAQUS explicit solver via the user subroutine VDLOAD, which eliminates the need for discretizing the targets and the need for the complex contact algorithm. In order to verify the proposed layering effect model, depth-of-penetration experiments of the 37 mm hard core projectile penetrating into three sets of fiber concrete and soil layered targets are conducted. The predicted depths of penetration show good agreement with the experimental data. Furthermore, the influence of layering effect on projectile trajectory during earth penetration is investigated. It is found that the layering effect should be taken into account if the final position and trajectory of the projectile are the main concern.

KEY WORDS finite spherical cavity expansion, layering effect, depth of penetration, projectile trajectory

I. Introduction

Projectile penetration into various targets has been investigated extensively based on the dynamic spherical cavity expansion or semi-empirical models (e.g. see further details for soil target[1], concrete target[2,3] and limestone target[4]). In these models, the target response is always represented by a forcing function which can be determined by the dynamic spherical cavity expansion theory or the semi-empirical method. These models can also be combined with an FE code to investigate the deformation and trajectory of the projectile, in which the target response is represented by the forcing function as the pressure boundary condition[5–8]. This methodology is usually termed as the uncoupled simulation approach, which eliminates the need for discretizing the target as well as the need for the contact and erosion algorithms, and therefore, reduces the computer time and memory requirements.

The accuracy of the uncoupled simulation approach depends on how well the forcing function approximates the actual situation. It should be noted that the forcing function determined by the dynamic

* Corresponding author. E-mail: fangqinjs@139.com
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spherical cavity expansion model or the semi-empirical method is based on the infinite homogeneous target assumption. It cannot be directly applied on the projectile surface when penetrating the layered targets. This is because the forcing function is affected by other layers during the penetration, i.e., the layering effect. Surprisingly, there are limited investigations on this issue[9], and many key problems remain inconclusive. Macek and Duffey[9] developed a finite spherical cavity expansion model to account for the layering effect. In order to obtain the forcing function with the consideration of layering effect, they assumed uniform layered spherical expansion for the cavity with finite radius in the layered geologic targets considered to be incompressible and damaged Mohr-Coulomb materials. They also pointed out that it was essential to assume the incompressibility, because without this assumption the time-dependent wave propagation and reflection relative to the moving projectile would need to be tracked, which would greatly complicate the solution procedure. However, the fully incompressible forcing function will overestimate the target resistance[10]. Treating the targets as incompressible Mohr-Coulomb materials, by assuming that the cavity expansion produces plastic-elastic response regions, He[11] constructed a decay function for the layering effect, which is further improved in the present study, as will be shown in §2.2.3.

Treating the targets as incompressible Mohr-Coulomb materials, by assuming that the cavity expansion produces plastic-cracked-elastic response regions, the decay function for the layering effect is firstly constructed. Then, by multiplying the decay function with the semi-empirical forcing functions, the forcing functions for the layered targets are obtained, which are applied on the projectile surface as the pressure boundary condition to investigate the depth of penetration (DOP) and trajectory of the projectile during earth penetration. In §II, the decay function for the layering effect is constructed based on the theoretical solution of a dynamically expanding layered spherical cavity with finite radius in the layered targets. In §III, the implementation of the proposed model into ABAQUS explicit solver via the user subroutine VDLOAD is briefly described. The presented layering effect model is validated in §IV before the investigation of the projectile trajectory in typical layered targets. Finally, the conclusive remarks are presented in §V.

II. Finite Cavity Expansion Method for the Layering Effect

In this section, the modified semi-empirical forcing functions which approximate the responses of layered targets are developed. This involves obtaining a new decay function, and then multiplying the semi-empirical forcing functions proposed by Forrestal and his colleagues[1,4,12] by the above decay function.

The sliding frictional resistance at the interface between the projectile and the target is neglected for the following two reasons: (i) the frictional coefficient is velocity dependent and difficult to determine; (ii) the frictional effect has been lumped into the empirical constant R in the forcing function.

2.1. Semi-empirical forcing function for infinite homogeneous target

The semi-empirical forcing function for the infinite homogeneous target was given by Forrestal and his colleagues[1,4,12] and is shown as follows:

$$\sigma_n = R + B\rho_0 v_n^2 \tag{1}$$

where σ_n is the semi-empirical forcing function for the infinite homogeneous target; ρ_0 is the density of undeformed target material; B is an empirical constant, depending mostly on the compressibility of the target material; and R is also an empirical constant, which is obtained by curve-fitting of the experimental data of normal penetration under the condition that all parameters but the striking velocity are held constant. With this method, all the constitutive behavior of the target, along with any frictional resistance, is lumped into the empirical constant R[7]. Forrestal and Luk[1] gave the parameters in Eq.(1) for the soil target.

However, the post-test observations for both concrete and rock targets[3,4] indicate that there are two regions associated with the penetration of brittle materials. The first region is a conical cratering region that is generally about twice of the projectile diameter in depth. The second region is the so-called tunneling region, which starts from the end of the cratering region to the final depth of penetration ($H_{\rm pen}$). In the tunneling region, Forrestal et al.[3] gave $B = 1$ and $R = Sf_c$ for the concrete target,