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Rigid and eroding projectile penetration into concrete targets based on an extended dynamic cavity expansion model

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ABSTRACT

A hyperbolic yield criterion and Murnaghan equation of state were introduced to describe the plastic behavior of concrete material under projectile penetration, and an extended dynamic cavity expansion model was proposed. Then, a unified one-dimensional resistance of concrete target to projectile penetration was formulated, in which the projectile nose shape influences were taken into account by three non-dimensional coefficients. Furthermore, combined with the Newton's second law and Alekseevskii-Tate equations, both rigid and eroding projectile penetration models into concrete targets were established. By comparing with the existing tests data as well as prediction results of previous model based on the linear yield criterion and equation of state, the proposed models were verified. Besides, a series of practical parameters of hyperbolic yield criterion and Murnaghan EOS for the extended dynamic cavity expansion model were given and verified.

1. Introduction

Dynamic cavity expansion models have been widely applied to determine the resistance of projectiles penetrating into various targets, e.g., concrete [1–4], soil [5], rock [6,7], sand [8] and ceramic [9]. When a proper yield criterion, equation of state (EOS) and plastic flow rule are introduced for describing the plastic behavior of targets. The solution of the dynamic cavity expansion model can be derived analytically or numerically with the similarity transformation method (provided no length scale is associated with the spherical cavity expansion model).

In the existing works, aiming to simplify the solution procedure, the linear yield criteria were adopted in the dynamic cavity expansion models, such as the original and modified forms of Tresca [1], Drucker-Prager [4] and Mohr-Coulomb [2,3,5,7,8] criteria, in which the Drucker-Prager yield criterion is actually identical with that of Mohr-Coulomb in the spherical cavity expansion due to the fact there is no intermediate principle stress. For the concrete targets concerned in the present paper, it is well known that the shear strength-pressure relationship is nonlinear [10], thus more actual nonlinear yield criterion should be utilized.

Besides, as for the EOS associated with the existing dynamic cavity expansion models, i.e., the relationship between the pressure and volumetric strain, was usually described by the bulk modulus of linear elastic deformation [2–3,6,7,9] or a locked one (material becomes incompressible beyond a critical value of volumetric strain) [1,5]. For high-speed projectiles penetration into concrete targets, the pressure around the projectile-target interface can reach a magnitude around 1-3 GPa, where the relationship of pressure-volumetric strain exhibits obvious nonlinear characteristics. Therefore, neither the linear nor locked EOS could well represent the actual situation. Feng et al. [4] and Shi et al. [8] used a three-stage and P-alpha EOS to consider the nonlinear pressure-volumetric strain relationships of the concrete and soil targets under projectile penetration, respectively. However, the yield criteria used in above works cannot describe the nonlinear shear strength-pressure relationship. It should be pointed out that, in all above-mentioned cavity expansion models, the shear and compaction behaviors of concrete material were treated separately, i.e., the shear behavior was described by the yield surface and compaction behavior was described by the EOS. The implied hypothesis is that J_2 flow rule (non-associative and no dilatancy during plastic flow) was adopted. In addition, strain hardening was not considered, thus the concrete material was assumed to be purely elastic until the yield surface was reached, and in other words, the concrete material was assumed to be elastic/perfectly plastic. Non-associated flow rule and arbitrary strain-hardening were comprehensively considered in previous cavity expansion models [11–13], in which the yield criteria was assumed to be linear Drucker-Prager [11] and Mises [12–13].

Considering the deficiencies of the yield criterion and EOS used in the existing dynamic cavity expansion models, an extended dynamic cavity expansion model is proposed in Section 2, where a hyperbolic yield criterion [14] and the nonlinear Murnaghan EOS [15] are

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introduced to describe the plastic behavior of concrete material under projectile penetration using J_2 flow rule. Then a unified one-dimensional resistance of concrete target with the consideration of projectile nose shape influences is presented in Section 3. Furthermore, in Sections 4 and 5, by combining with the Newton's second law and Alekseevskii-Tate equations, the rigid and eroding projectile penetration models are established, respectively, which are verified by comparing with the existing penetration tests data as well as the predicted results of previous model [2].

2. Extended dynamic cavity expansion model

Under the projectile penetration, a spherically symmetric cavity is expanded pointwise radially from the projectile surface, and the cavity radius increases from zero at a constant velocity V_r. As discussed by Forrestal and Tzou [2], shown in Fig. 1, cavity expansion produces four distinct zones in the target, where r, t, c, c_1 and c_d are the radial Eulerian coordinate, time, cracked-plastic boundary velocity, elastic-cracked boundary velocity and dilatational velocity, respectively. Previously, as introduced in Section 1, the linear yield criteria [1–5,7,8,11–13] and EOS [2–3,6,7,9] are used. An extended dynamic cavity expansion model has been introduced in Ref. [16] for metallic targets based on Mises yield criterion and Murnaghan EOS. In this paper, the yield criterion is replaced by a hyperbolic yield criterion for concrete material, the classic dynamic cavity expansion model is improved.

Similar to the previous studies [1–9], for the present dynamic cavity expansion model, the following assumptions are made. (i) The shear and compaction behaviors of concrete material are treated separately, described by the proposed hyperbolic yield criterion and Murnaghan EOS, respectively, and the J_2 flow rule is adopted. This is the most popular approach to describe the dynamic behavior of concrete material subjected to large strain and high pressure, such as the well-known HJC concrete material model [17]. (ii) Concrete material is assumed to be purely elastic until the hyperbolic yield surface is reached.

The hyperbolic yield criterion in Eulerian coordinates with spherical symmetry is described by

$$\sigma_r - \sigma_\theta = a_0 + \frac{P}{a_1 + a_2 P} \tag{1a}$$

$$P = (\sigma_r + \sigma_\theta + \sigma_\phi)/3,\ \sigma_\theta = \sigma_\phi \tag{1b}$$

where σ_r and σ_θ are the radial and hoop components of the stresses, and P is the pressure, which are measured positive in compression. a_0, a_1 and a_2 are the constants, which need to be determined from a suitable set of triaxial compression data. Specially, Eq. (1) reduces to Mohr-Coulomb (or Drucker-Prager) yield criterion when $a_2 = 0$.

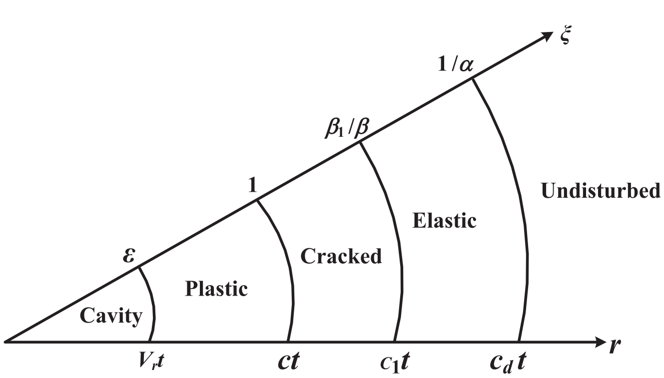

Fig. 1. Response regions of concrete target.

Murnaghan EOS is suitable to describe the adiabatic compression of solid materials in the pressure range of 0-50 GPa [15, 16] and is expressed as

$$P = \frac{K}{\gamma}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \tag{2}$$

where $K = \rho_0 C_0^2$ is the bulk modulus of target material with C_0 being the bulk sound speed. ρ_0 and ρ are densities of the undeformed and deformed target material, respectively. γ is related to the slope s of the linear Hugoniot relationship between the shock velocity and particle velocity

$$\gamma = 4s - 1 \tag{3}$$

In the following, the relationship between the cavity stress and cavity-expansion velocity are obtained numerically with the similarity transformation method, which is then used to formulate the unified one-dimensional resistance of concrete targets in Section 3.

2.1. Plastic region

The equations of momentum and mass conservation in Eulerian coordinates with spherical symmetry are [18]

$$\frac{\partial \sigma_r}{\partial r} + \frac{2(\sigma_r - \sigma_\theta)}{r} = -\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r}\right) \tag{4a}$$

$$\rho\left(\frac{\partial v}{\partial r} + \frac{2v}{r}\right) = -\left(\frac{\partial \rho}{\partial t} + v\frac{\partial \rho}{\partial r}\right) \tag{4b}$$

where v is the particle velocity measured positive for outward motion.

By introducing the non-dimensional variables and applying similarity transformation suggested by Forrestal and Tzou [2],

$$\xi = \frac{r}{ct};\ U = \frac{v}{c};\ \varepsilon = \frac{V_r}{c};\ F = \frac{f_t}{f_c};\ S = \frac{\sigma_r}{f_c};\ T = \frac{P}{f_c};\ \beta = \frac{c}{c_p};\ \beta_1 = \frac{c_1}{c_p};\ c_p = \sqrt{E/\rho_0} \tag{5}$$

the conservation equations in Eq. (4) can be transformed into the non-dimensional forms as

$$f(T) f_c \frac{dT}{d\xi} + \frac{2 \times g(T)}{\xi} = \beta^2 E\left(T f_c \frac{\gamma}{K} + 1\right)^{\frac{1}{\gamma}} \frac{dU}{d\xi}(\xi - U) \tag{6a}$$

$$\frac{dU}{d\xi} + 2\frac{U}{\xi} = \frac{f_c}{K + T f_c \gamma}(\xi - U)\frac{dT}{d\xi} \tag{6b}$$

where f_t, f_c and E are the uniaxial tensile strength, compressive strength and elastic modulus of concrete target, respectively. It should be pointed out that the one dimensional rod wave velocity $c_p = \sqrt{E/\rho_0}$ is used in Eq. (5) instead of the bulk wave speed $c_p = \sqrt{K/\rho_0}$ used in Ref. [2], which will affect the value of β_1. However, the solutions of Eq. (6) is not affected since β_1 is only used as an initial value, as shown in Section 2.4. $f(T)$ and $g(T)$ can be obtained with the use of Eq. (1).

$$f(T) = \frac{1}{3}\frac{3a_1 + 6a_2 T f_c + 2a_0 a_2 + 2}{a_1 + a_2 T f_c} - \frac{1}{3}\frac{\left(3T f_c a_1 + 3a_2 T^2 f_c^2 + 2a_0 a_1 + 2a_0 a_2 T f_c + 2T f_c\right) a_2}{\left(a_1 + a_2 T f_c\right)^2} \tag{7a}$$

$$g(T) = a_0 + \frac{T f_c}{a_1 + a_2 T f_c} \tag{7b}$$

By using Eq. (1), the non-dimensional relationship between the radial stress S and pressure T is derived as

$$S = \frac{1}{3f_c}\frac{3T f_c a_1 + 3a_2 T^2 f_c^2 + 2a_0 a_1 + 2a_0 a_2 T f_c + 2T f_c}{a_1 + a_2 T f_c} \tag{8}$$

The standard forms of Eq. (6) suitable for numerical solution with the Runge-Kutta method are