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Semi-analytical model for rigid and erosive long rods penetration into sand with consideration of compressibility

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ABSTRACT

Sand is a granular, porous material with high compressibility, which influences the penetration process. According to the sand responses at different penetration velocities, the P-alpha equation of state and Mohr-Coulomb Tresca-limit yield criterion are used to describe the constitutive behavior. In the plastic region, the spherical cavity-expansion model is applied, and in the fluid-like region the hydrodynamic model with compressibility considered is applied based on the Alekseevskii-Tate model. Comparison with experimental results shows that the model is suitable for calculating sand penetration depths for rigid and erosive projectiles. Initial sand density affects penetration dissimilarly for different striking velocities, and a critical striking velocity exists. The compressibility should be considered with P-alpha equation of state below this critical striking velocity, and otherwise the fully compacted density can directly be used to calculate the penetration depth. Projectile dynamic yield strength influences penetration strongly. For an erosive projectile, the penetration depth and change in residual projectile length vary with the projectile dynamic yield strength.

1. Introduction

Sand is applied in protective engineering construction and battle defense as the typical protective material. Under dynamic loading, sand mechanical characteristics are determined by pore compaction, grain size, grains sliding and redistributing, grains crushing, and thus show high compressibility. Many institutes and researchers from different countries have paid intensive attention to sand penetration. Omidvar et al. [1] systematically reviewed the granular material penetration research including the analytical, experimental and numerical. Allen et al. [2,3] carried out sand penetration experiments with high velocity 4340 steel projectiles, and obtained the dimensionless hydrodynamic drag coefficients by experimental data fitting. Hakala [4] also derived similar formulas by dimensional analysis. Savvateev et al. [5] used the experimental results of tungsten and steel long rods penetrating into sand at 1–3 km/s striking velocities to get an empirical penetration depth formula. However these formulas are only suitable for specific experimental conditions and cannot predict penetration depths for others. Therefore, it is necessary to develop a generalized analytical model for sand penetration.

Cavity-expansion theory is an effective method of solving problems for projectiles penetrating various media. Analytical methods have been obtained with cavity-expansion theory for sand and soil penetration [6–11], however the models derived by Carter et al. [6], Yu and Houlsby [7], Salgado et al. [9], and Salgado and Prezzi [10] are mainly applied to cone penetration tests at low penetration velocities. Forrestal and Luk [8] advanced the hydrostatic locked model with compressibility considered, in which the sand densities throughout the plastic and elastic regions are taken as the locked density, which is the density beyond which the sand cannot be further compressed, and the initial density ρ_0, respectively. But this simplification does not reflect the whole compaction process. Shi et al. [11] employed the P-alpha equation of state to describe sand compressibility and obtained sand penetration depth calculation method. However, density change brings on the difficulty of solving differential equations, and numerical calculation must be used for the whole velocity range [11]. The calculation process is very complicated, and the model is only suitable for the

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rigid projectile penetration, but not for the erosive one. And, a fluid-like region appears in high velocity penetration, which allows the Bernoulli equation to be used and the calculation process can be efficiently simplified. Therefore, it is desirable to advance a simpler sand penetration model with compressibility considered which is suitable for a wide velocity range with the erosive projectile penetration included.

In this paper, the P-alpha equation of state and Mohr-Coulomb Tresca-limit yield criterion are employed, and different responses in sand penetration are taken into account. Then the hydrodynamic model for penetration depth is put forward and the model's validity is demonstrated with experimental results of rigid [2,3] and erosive [12] projectiles. In addition, the influences of initial sand density and projectile dynamic yield strength on penetration are also discussed.

2. The pressure on the projectile

Sand has different responses for different penetration velocities. The elastic, plastic and fluid-like regions appear at high enough penetration velocity. The pressure on the projectile is related to these three regions. In the elastic region, Hooke's law is satisfied. In the plastic region, the Mohr-Coulomb-Tresca yield criterion and P-alpha equation of state can be used to describe the response. In the fluid-like region, sand can be considered incompressible.

2.1. Sand responses in penetration

For low-velocity penetration, as Fig. 1 shows, there are elastic and plastic regions in the semi-infinite sand target. In the plastic region, sand grain sliding and pore compaction appear, and even grain crushing happens. A spherically symmetric cavity expands from a zero initial radius at constant velocity V in the target. As Fig. 2 shows, when the penetration velocity u is higher than some critical penetration velocity u_c, a fluid-like region appears in the target.

For linearly compressible elastic–plastic materials with Tresca yield criterion, Walker [13] pointed out that if $V > 0.2c_v$ (c_v is the speed of sound) is satisfied, the elastic–plastic interface velocity approaches the speed of sound and the material response is fluid-like. Qian and Wang [14] found if $V > 0.2c_d$ (c_d is the elastic, dilatation speed) for rocks, the target material transforms to a fluid-like state. In dry sand experiments, as the stress wave passes a given point near the penetration region, significant amounts of energy and momentum are imparted to the sand grains [1]. The formation of a cavity behind the penetrating projectile has been attributed to the afterflow resulting from this momentum transfer, as Borg et al.'s experiment shows [15]. And the afterflow is particularly evident in sand with high porosity [16]. Thompson's [17] experiments with 20–40 m/s showed that the resistance on the projectile increased near the end of penetration. The frictional resistance exceeds the hydrodynamic one (also inertial resistance, i.e., velocity-squared [18]) as Omidvar et al. [1] explained is the reason of above. In fact, the hydrodynamic resistance is the characteristic of fluid, which means that the sand response is fluid-like. Although sand is different from rock and other linearly compressible elastic–plastic materials, according to the calculation results [11], if $u \approx 0.2c_d$, the elastic–plastic interface velocity c is almost the same as c_v and the fluid-like region emerges in sand. Therefore, it is reasonable to analyze the fluid-like response in sand penetration calculation research.

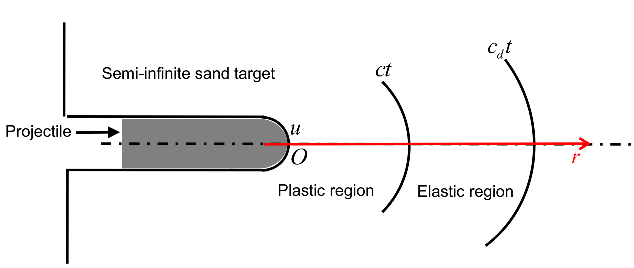

Fig. 1. Sand target responses at low penetration velocity.

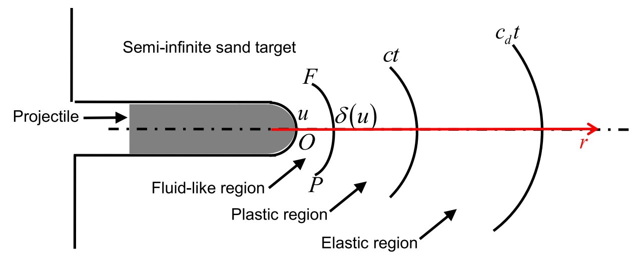

Fig. 2. Sand target responses at high penetration velocity.

2.2. The pressure in plastic region

If $u < u_c$, there is no fluid-like region and the spherical cavity-expansion theory can be used. However, as a typical granular material with pores, sand compressibility should be taken into account. The P-alpha equation of state advanced by Herrmann [19] describes sand compressibility well as Fig. 3 shows. Brown et al. [20] put forward a slightly modified P-alpha equation of state based on flat-plate tests as follows

$$\alpha = \begin{cases} \alpha_0 & p \le p_e \\ 1 + (\alpha_0 - 1)\left(\dfrac{p_s - p}{p_s - p_e}\right)^{\chi} & p_e < p \le p_s \\ 1 & p > p_s \end{cases} \tag{1a}$$

$$\alpha \equiv \frac{\rho_s}{\rho} \tag{1b}$$

where p is the pressure; ρ_s and ρ are the fully compacted and current sand densities, respectively; α_0 and α are the initial and current sand porosities, respectively; p_s is the sand fully compacted pressure and p_e is the sand elastic limit pressure at which irreversible compaction begins; χ is the parameter from experimental data fitting, here according to Borg [15] χ=2.

According to Fig. 3, the porosity decreases with pressure increase until $p = p_s$. In fact, in the elastic region ($p \le p_e$), the sand

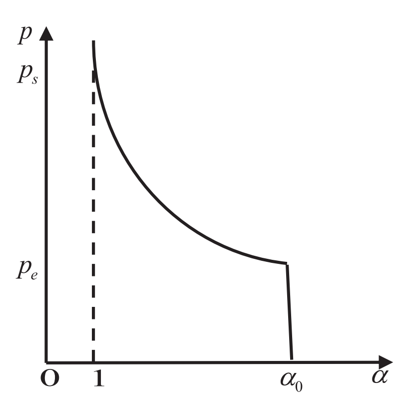

Fig. 3. Schematic of the postulated compaction behavior of a porous material [19].