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Numerical modeling of pile penetration in silica sands considering the effect of grain breakage

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ABSTRACT

Current numerical platforms rarely consider the effect of grain breakage in the design of sandy soil foundations. This paper presents an enhanced platform for large deformation analyses which considers the effect of grain breakage during pile penetration in silica sand. For this purpose, a model based on critical state theory has been developed within the framework of multisurface plasticity to account in the same constitutive platform the effect of stress dilatancy and particle fragmentation. Furthermore, to implement the underlying constitutive equations into a finite element code, a stress integration scheme has been adopted by extending a cutting plane algorithm to the model with multiple yielding mechanisms. A laboratory model test and a series of centrifuge tests of pile penetration are simulated to verify the performance of the selected constitutive approach in terms of pile resistance and grain breakage distribution, with the parameters of sand calibrated through a set of drained triaxial compression tests from low to very high confining pressure. Some extra features of the enhanced platform are also discussed, such as: i) the effect of sand crushability on pile resistance and ii) the nonlinear relation of pile resistance to sand density. The proposed findings demonstrate the capability of this numerical platform to proper design of pile foundation in sandy soils and highlight the interplay between stress dilatancy and grain breakage mechanisms during pile penetration processes.

1. Introduction

Pile penetration is a common geotechnical engineering problem having to do with the improvement of a foundation, and it plays an important role in non-excavation construction. Besides of the conventional design methods employing the model test or in-situ test, numerical methods are more and more adopted in order to reduce the economic and time costs. Among numerous approaches, the finite element method (FEM) is considered a beneficial tool in engineering design (e.g., Kouretzis et al. [1], Sheng et al. [2], Zhang et al. [3,4], Shen and Xu [5]; Wu et al. [6]), when compared with meshfree methods [7], discrete element method (DEM) [8,9]. Accordingly, a numerical platform based on FEM adopting an appropriate constitutive model would be helpful for analyzing the pile penetration considering large deformation and further estimating the pile resistance.

During the process of pile penetration, sand along the pile always undergoes a high level of stress caused by the squeezing effect, causing lateral deformation (e.g., Shen et al. [10,11]). This high level of stress can result in grain breakage, even for silica sand. The importance of this grain breakage in silica sand during pile penetration has been highlighted from a practical standpoint [3,4,12–18]. Numerous studies have shown that the pile resistance in crushable sand is overestimated in comparison with that expected by a conventional simulation platform without considering grain breakage [1,3,19–21]. Accordingly, the degrading effect of grain breakage on pile resistance should be considered for practical design, which poses a requirement that the constitutive model accounting for grain breakage should be employed in the numerical platform.

In past decades, pile penetration in sand has been simulated by employing different constitutive models, such as Drucker-Prager [22] and Mohr-Coulomb [22], critical-based [1], and hyperplastic [23,24] models. However, these simulations did not consider the effect of grain breakage on pile resistance, resulting in an inaccurate prediction of pile resistance. More recently, the simulations performed by Zhang et al. [3,4, 19] adopted a simple breakage model. However, the nonlinear elasticity, dilatancy, and contraction with the soil density effect were not properly considered in this model, and its parameters were not fully calibrated

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against laboratory tests on the same silica sand before the simulation [3, 19].

Therefore, this paper aims to develop an enhanced numerical platform for large deformation analysis by considering the effect of grain breakage, nonlinear elasticity, and stress dilatancy with the density effect of sand during the pile penetration process. To achieve this purpose, a critical-state-based sand model within the framework of multi-surface plasticity accounting for the effects of stress dilatancy and particle crushing is first developed. Then, for the finite element implementation, the conventional cutting plane algorithm is extended for the model with multiple yielding mechanisms. Next, the proposed platform is verified by simulating a laboratory model test and a series of centrifuge tests of pile penetration in Fontainebleau sand, in which the model parameters are calibrated from various drained triaxial tests under low to high confining pressures. Finally, some extra features of the enhanced platform are discussed, such as the effect of sand crushability on pile resistance and the nonlinear relation between pile resistance and sand density.

2. Constitutive equations: multisurface plasticity for particle breakage

The double-yield-surface model originally developed by Hu et al. [25] and Yin et al. [26] is adopted to enhance the numerical platform for pile penetration analysis. Consistently with the elastoplastic theory, the total strain rate is composed of the elastic and plastic strain rates:

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{pl} \tag{1}$$

where $\dot{\varepsilon}_{ij}$ denotes the (i, j) the total strain rate tensor, and the superscripts *el* and *pl* represent the elastic and plastic components, respectively.

The nonlinear elastic behavior is assumed to be isotropic with the bulk modulus K characterized by the same expression of the shear modulus G, both defined by Richart et al. [27]:

$$\dot{\varepsilon}_{ij}^{el} = \frac{1+\upsilon}{E}\dot{\sigma}'_{ij} - \dot{\sigma}'_{kk}\delta_{ij} \tag{2}$$

where υ and E are Poisson's ratio and Young's modulus, $\dot{\sigma}'_{ij}$ is the effective stress rate tensor, and δ_{ij} is the Kronecker's delta. E is calculated by using the isotropic elastic bulk modulus K (i.e., $E = 3K(1\text{-}2\upsilon)$), which for sand is defined as:

$$K = K_0 p_{at}\frac{(2.97-e)^2}{(1+e)}\left(\frac{p'}{p_{at}}\right)^n \tag{3}$$

where K_0 and n are elastic parameters, p' is the mean effective stress, and p_{at} is the atmospheric pressure ($p_{at} = 101.3$ kPa).

To model in the same constitutive framework stress dilatancy and plastic compaction, the adopted model uses two yield surfaces and two potential surfaces, for shear sliding (f_S, g_S) and for normal compression (f_N, g_N), respectively. As a result, the plastic strain rate can be expressed as:

$$\dot{\varepsilon}_{ij}^{pl} = \left(\dot{\varepsilon}_{ij}^{pl}\right)_S + \left(\dot{\varepsilon}_{ij}^{pl}\right)_N = d\lambda_S\frac{\partial g_S}{\partial \sigma'_{ij}} + d\lambda_N\frac{\partial g_N}{\partial \sigma'_{ij}} \tag{4}$$

where the subscripts '*S*' and '*N*' indicate the components of the shear sliding and normal compression, respectively. The two yield surfaces in the *p*'-*q* and *e*-*p*' planes are shown in Fig. 1, which remarks the elastic region between the shear sliding surface and normal compression surface.

The yield surface for shear sliding can be expressed as,

$$f_S = \frac{q}{p'} - \frac{M_p\varepsilon_d^{pl}}{k_p+\varepsilon_d^{pl}} = 0 \tag{5}$$

where p' is the mean effective stress, q is the deviatoric stress, k_p is related to the plastic shear modulus, M_p is the stress ratio corresponding to the peak strength calculated by using the peak friction angle ϕ_p (i.e., $M_p = 6\sin(\phi_p)/(3\text{-}\sin(\phi_p))$ in compression), and ε_d^{pl} is the deviatoric plastic strain.

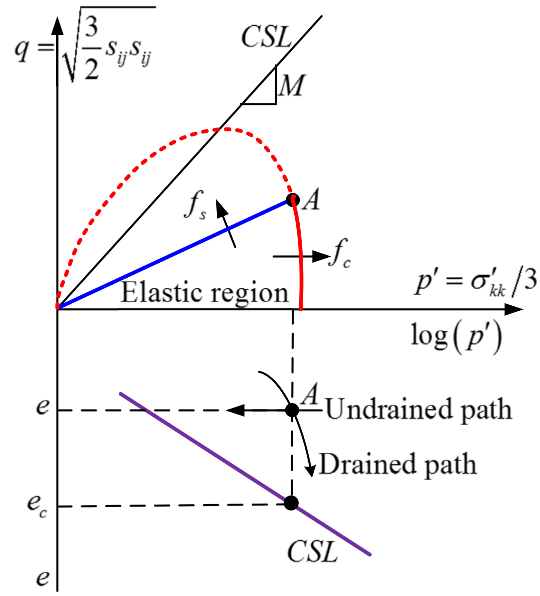

Fig. 1. Schematic representation of critical state based double-yield-surface model for crushable sand.

The gradient of the plastic potential surface for stress-dilatancy g_S can be expressed as:

$$\frac{\partial g_S}{\partial \sigma_{ij}} = \frac{\partial g_S}{\partial p'}\frac{\partial p'}{\partial \sigma_{ij}} + \frac{\partial g_S}{\partial q}\frac{\partial q}{\partial \sigma_{ij}} \text{ with } \frac{\partial g_S}{\partial p'} = A_d\left(M_{pt} - \frac{q}{p'}\right);\ \frac{\partial g_S}{\partial q} = 1 \tag{6}$$

It is worth noting that the frictional/sliding part of the model is non-associated as the functions f_S and g_S are different. A_d is the stress-dilatancy parameter, and M_{pt} can be calculated from the phase transformation friction angle ϕ_{pt} ($M_{pt} = 6\sin(\phi_{pt})/(3\text{-}\sin(\phi_{pt}))$ in compression).

The nonlinear critical state line (CSL) formulation proposed by Li and Wang [28] was well suited to sand modeling.

$$e_c = e_{ref} - \lambda\left(\frac{p'}{p_{at}}\right)^{\xi} \tag{7}$$

where e_c is the critical void ratio, e_{ref} is the initial critical void ratio at $p' = 0$, and λ and ξ are the parameters controlling the shape of CSL in the *e*-log*p*' plane. However, for high levels of stress, this equation cannot guarantee the positiveness of the critical void ratio. Therefore, a modified version of this equation is employed by using a logarithmic scale for the void ratio:

$$\log e_c = \log e_{ref} - \lambda\left(\frac{p'}{p_{at}}\right)^{\xi} \Rightarrow e_c = e_{ref}\exp\left[-\lambda\left(\frac{p'}{p_{at}}\right)^{\xi}\right] \tag{8}$$

Soil density and interlocking grains effects are introduced through the expression of the friction angle as:

$$\tan\phi_p = \left(\frac{e_c}{e}\right)^{n_p}\tan\phi_u;\ \tan\phi_{pt} = \left(\frac{e_c}{e}\right)^{-n_d}\tan\phi_\mu \tag{9}$$

where the parameters n_p and n_d are material constants, and ϕ_μ is the friction angle at critical state. The Lode angle dependent strength and stress-dilatancy are introduced as described in Sheng et al. [29], but could also be incorporated by using the transformed stress method of Yao et al. [30–33].

To describe the compression behavior resulting from particle frag-