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Research Paper

Non-coaxial soil model with an anisotropic yield criterion and its application to the analysis of strip footing problems

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ABSTRACT

This paper presents numerical applications of a non-coaxial soil model, in which an anisotropic yield criterion is incorporated, to analyze two-dimensional strip-footing problems. Semi-analytical solutions of the bearing capacity for a strip footing that rests on anisotropic, weightless, cohesive-frictional soils are developed based on the slip line method. The degrees of influences of soil anisotropy and non-coaxiality on the bearing capacity of the strip footing are examined. From the viewpoint of strength and stiffness, it is necessary to incorporate both the strength anisotropy and non-coaxiality into numerical simulations and practical designs of geotechnical problems.

1. Introduction

Extensive experimental (e.g., [1–6]) and micromechanics-based (e.g., [7–11]) evidence has demonstrated that non-coaxiality, which refers to the non-coincidence of the principal axes of the stress and plastic strain rate tensors, is an intrinsic characteristic of granular materials. These fundamental insights have guided the development of numerous realistic continuum soil models. Approaches for constitutive modelling can be broadly classified into the phenomenological approach and the multi-scale approach for rate-independent elasto-plastic behaviors of granular materials under a quasi-static loading. The phenomenological approach directly describes the observed phenomena using an approximate and sophisticated mathematical formulation. In recent decades, a number of phenomenological models have been developed that consider the non-coaxial behavior of soils, and examples include the hypo-plastic models [12], the generalized sub-loading surface model [13]; among others ([14–16]). On the other hand, multi-scale approaches have been proposed to describe non-coaxial behavior of soils based on micro-mechanics. The macroscopic mechanical behavior of granular materials is then directly related to the evolution of the internal structure. One popular category within this framework can be classified as elasto-plastic models with fabric tensors (e.g., [17–19]).

However, analysis of practical geotechnical problems that consider the non-coaxial plasticity of granular soils is rare. Although phenomenological models have demonstrated their ability to capture many of the most salient features, e.g., dilatancy, soil anisotropy, hardening and strain localization, they often introduce too many parameters without physical meaning and are difficult to be calibrated. Indeed, the mathematical formulations for most of the current models based on phenomenological approaches are complex; hence, it is difficult for those non-coaxial models to be implemented into non-linear numerical codes for the solution of boundary value problems. With respect to the models that use multi-scale approaches, information on the evolution of the internal structure is difficult to define using the laboratory work. These reasons might explain why these non-coaxial constitutive models have not been widely applied to investigate boundary value problems.

Many real engineering problems subjected to proportional loading, e.g., tidal waves, earthquakes and footing-penetration, demonstrate obvious principal stress rotations [20,21]. It is accepted that the soil mass underneath a footing, especially in the vicinity of the footing edges, experiences a large amount of stress rotations under loading [22]. Yu and other authors [22,23] numerically applied non-coaxial constitutive models to investigate shallow foundations. In these researchers' work, the application of non-coaxial models predicted a larger settlement prior to collapse compared with the conventional coaxial models. The conclusions drawn from this study clearly stated that without considering the non-coaxial behavior of soil, a high chance

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of unsafe design exists in shallow foundations. Nevertheless, work of the above researchers is restricted to soil strength isotropy. The natural characteristic of soils is anisotropic, and recent experimental observations have demonstrated that non-coaxiality is a significant aspect of soil anisotropy (e.g., [4]). As concluded by Tsutsumi and Hashiguchi [24], both the tangent effect (non-coaxiality) and the anisotropy in the yield condition must be incorporated into constitutive equations for a description of the general non-proportional loading behavior of soils. Assuming non-coaxiality in the context of soil isotropy might result in poor predictions of stability and serviceability problems in geotechnical engineering. Hence, it remains a key issue to gain insight into the different aspects that might be introduced into footing problems modeled by non-coaxial plasticity in the context of soil strength anisotropy compared with those that are modeled using coaxial plasticity.

In this paper, a plane-strain, elastic/perfectly plastic non-coaxial soil model with an anisotropic yield criterion is applied to simulate strip footing problems. The anisotropic yield criterion is generalized from the conventional isotropic Mohr-Coulomb yield criterion to account for the effects of initial strength anisotropy, which is characterized by the variation of internal friction angles (angles of shearing resistance) with the direction of the principal stresses. Based on the slip line method, a semi-analytical solution of the bearing capacity is presented for a strip footing that rests on an anisotropic, weightless, cohesive-frictional soil. Comparison between the numerical predictions and semi-analytical results of the bearing capacity are performed. The influences of degrees of soil anisotropy and non-coaxiality on the bearing capacity of strip footings are also discussed.

2. A non-coaxial model: development and implementation

The plane strain non-coaxial soil model used in this paper emphasizes on two ingredients: the anisotropic yield function and the non-coaxial plastic flow rule. The signs of the stress (rate) are chosen as positive for compression.

2.1. The anisotropic yield criterion

Following Booker and Davis [25], the anisotropic yield function in the stress space of $(\frac{\sigma_x-\sigma_y}{2}, \sigma_{xy})$ is a known function of the mean pressure p and the direction of principal stresses Θ. As shown in Fig. 1 and in line with the experimental evidence that the internal friction angle varies with the direction of principal stresses (e.g.,[4]), the yield criterion can be written as follows:

$$f(\sigma_x,\sigma_y,\sigma_{xy}) = R + F(p,\Theta) = 0 \tag{1}$$

where

$$F(p,\Theta) = (p - c\cdot\cot\phi_{\max})\cdot\sin\phi(\Theta) \tag{2}$$

$$\sin\phi(\Theta) = \frac{n\cdot\sin\phi_{\max}}{\sqrt{n^2\cos^2(2\Theta-2\beta) + \sin^2(2\Theta-2\beta)}} \tag{3}$$

and where $R = \frac{1}{2}[(\sigma_x-\sigma_y)^2 + 4\sigma_{xy}^2]^{1/2}$, $p = \frac{1}{2}(\sigma_x+\sigma_y)$, $\tan(2\Theta_p) = 2\sigma_{xy}/(\sigma_x-\sigma_y)$, c denotes cohesion. The expression of Eq. (3) is derived by geometric considerations.

As indicated in Fig. 1b, the cross-section of the anisotropic yield criterion is assumed to be a rotational ellipse. The centre of the anisotropic ellipse is assumed to be located at the original point O, and ϕ_{max} and ϕ_{min} are defined as the maximum and minimum peak internal friction angles, respectively along all possible major principal stress directions. The major and minor lengths of the ellipse depend on the maximum magnitudes of the peak internal friction angle, respectively. Two shape parameters n and β, as shown in Eq. (3), are added to those material properties of the conventional isotropic Mohr-Coulomb yield criterion in order to define the anisotropic yield criterion:

- $n = \sin\phi_{min}/\sin\phi_{max}$, where the range of n is between 0 and 1. In particular, the isotropic Mohr-Coulomb yield criterion is recovered when $n = 1.0$.
- β refers to an angle when the major principal stress (corresponding to the case of the maximum peak internal friction angle) is inclined to the deposition direction; and β ranges from 0 to $\frac{\pi}{4}$.

The two shape parameters can be obtained via tests using the hollow cylinder apparatus (HCA). Experimental investigations from the laboratory [4] can aid in testing the accuracy of the proposed anisotropic yield criterion, as illustrated in Fig. 2. The non-dimensional parameter b is the intermediate stress ratio defined as $b = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. For a plane strain condition, $b \approx 0.2$–0.4.

2.2. The non-coaxial plastic flow rule

As indicated in Fig. 3, the general form of the plastic strain rate $\dot{\varepsilon}^p$ consists of the conventional component $\dot{\varepsilon}^{pc} = \dot{\lambda}\frac{\partial g}{\partial \sigma}$ and the non-coaxial component $\dot{\varepsilon}^{pt} = k\cdot\dot{\boldsymbol{T}}$. The conventional component is normal to the yield surface derived from the classical plastic potential theory. The non-coaxial component is tangential to the yield surface induced by the deviatoric stress-rate component. The general form of the plastic strain rate $\dot{\varepsilon}^p$ is shown as follows:

$$\dot{\varepsilon}^p = \dot{\lambda}\frac{\partial g}{\partial \boldsymbol{\sigma}} + k\cdot\dot{\boldsymbol{T}} \quad \text{if } f = 0 \text{ and } \dot{f} = 0 \tag{4}$$

where $\dot{\lambda}$ denotes a positive scalar, g denotes the plastic potential, f represents the yield surface, k is a dimensionless scalar (known as the non-coaxial coefficient in this paper), and $\dot{\boldsymbol{T}}$ denotes the material derivative, which can be displayed in the form of principal stress increments:

$$\dot{\boldsymbol{T}} = \frac{1}{k}\cdot\boldsymbol{N}\cdot\boldsymbol{\sigma} \tag{5}$$

$\boldsymbol{N}$ is defined in Appendix A.

If $g = f$, then the associativity in the conventional plastic flow rule (abbreviated to asso) is used, and otherwise, the non-associativity in the

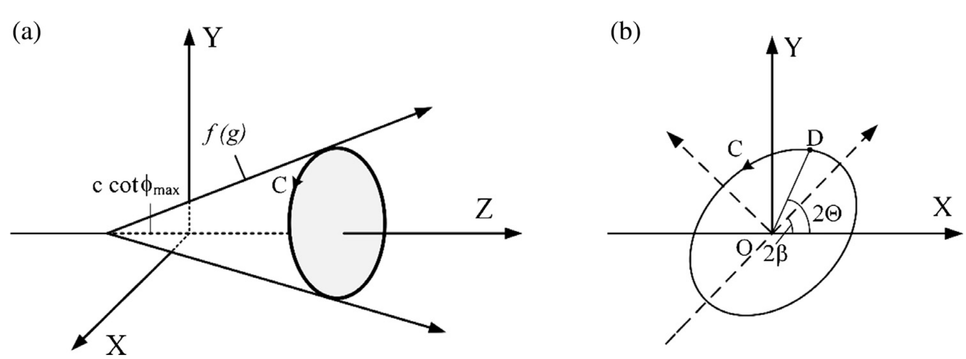

Fig. 1. Anisotropic yield surface in: (a) ($X = \frac{\sigma_x-\sigma_y}{2}$, $Y = \sigma_{xy}$, $Z = \frac{\sigma_x+\sigma_y}{2}$) space; (b) ($X = \frac{\sigma_x-\sigma_y}{2}$, $Y = \sigma_{xy}$) space.

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