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Research Paper

A simplified approach to transient flow effects induced by rigid cylinder rotation in a porous medium

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ABSTRACT

Drainage conditions associated with loading rate effects during rotation of elements embedded in intermediate permeability soils are fundamental factors in the assessment and analysis of *in situ* measured properties and foundation design systems. In that context, a simplified model for poromechanical analysis of consolidation induced by rotation of a rigid cylinder embedded within a porous medium is formulated. The approach is closely connected with the concept of deformation plasticity and relies upon the equivalence between the local behavior of a poroplastic material under monotonic loading process and that of an appropriate non-linear fictitious poroelastic behavior. The non-linear poroelastic model is conceived to capture the transient flow effects on the poromechanical response of the soil surrounding the rotating cylinder. Semi-analytical solutions are derived for pore-fluid pressure, displacement and stress distributions, allowing for the evaluation of rate effects in silty soils, with specific application to purely cohesive and frictional materials. The accuracy of the approach is assessed by comparison of model predictions with poroplastic finite element solutions. The results correlating the degree of drainage to normalized rotation velocity derived from proposed model may be a useful support for a wide range of geotechnical applications, such as laterally loaded rigid piles with rotationally pile connections, offshore wind turbines shafts subjected to torque or torsional vibration, rotation of shaft drilling tools and *in situ* tests subjected to shear.

1. Introduction

Geotechnical design requires stress, displacement and pore fluid pressure fields to be assessed in order to support limit state calculations under different loading conditions. Based on the current state-of-knowledge the stress-strain analysis of soils subjected to shear and compressive stresses in continuum mechanics can be addressed within the general framework of poromechanics. In this context, the theory of poroelasticity Biot [2], offers a well-established engineering framework for studying the fluid flow process through porous materials assuming that the solid matrix deforms elastically. From a microscopic point of view, the theory originally developed by Biot [2] has been reformulated and extended within a rigorous mechanical setting for the analysis of coupled deformation-diffusion processes [35,11,5,44,12,40,18], to cite a few). The concepts of macroscopic poroelasticity have been revisited in light of micromechanics, allowing to link the overall poroelastic parameters to microstructure properties of the medium [17,18]. Due to the significant advances made in recent years, the field of applicability of this theory has been extended from soil and rock mechanics to concrete mechanics, biomechanics and geophysics.

In this paper, the Biot consolidation analysis is applied to the problem of an infinite long solid cylinder rotating in a porous isotropic elastic medium. Since the drainage condition in saturated soils generally depend on permeability, compressibility, shear strength and loading rate [41,24,22,38], a change in the rate of loading is expected to produce variations in the pore-fluid pressure profile, thus inducing changes in the strength and stiffness of the soil. In that respect, a key issue in geotechnical engineering is the possibility to evaluate the variations in the strength and stiffness of the soil and to assess the way they influence the design of problems such as piles, shafts, tunnels or *in situ* test. Previous solutions were essentially conceived to model cavity expansion problems [41,15]. For instance, Carter et al. [6] approached the disturbance of the soil due to pile driving by considering the stress and pore pressure changes in clay during and after the expansion of a cylindrical cavity. Silva et al. [41] presented a coupled finite element approach in which the rate of cavity expansion was linked to the penetration rate of a cone test considering a plane axisymmetric assumption for skeleton deformations in a Cam Clay-type material. Recently, Dienstmann et al. [15] introduced a theoretical analysis and finite element simulations for non-linear poroelastic behavior of

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cylinder expansion in infinite media under transient pore-fluid flow conditions.

The solution to the consolidation problem around a rotating cylinder presented in this paper aims at understanding these mechanisms and developing an approach capable of identifying the drainage conditions taking place around piles or *in situ* tests carried out at different loading rates. It can be viewed as an original analysis for rotating cylinder that complements to previous solutions developed for cavity expansion. Referring for instance to *in situ* vane tests, it is expect that no significant pore pressure dissipation occurs in soft clays during rotation of the vane. However, severe partial drainage effects can take place during shearing under standard rotation rates in intermediate permeability soils (silty soils). The consequences of overlooking this phenomenon may lead to errors in the assessment of undrained shear strength.

In the absence of published solutions or testing data that could be used as reference, the theoretical modeling developed in this paper seeks primarily to provide a simplified poromechanics-based tool for predicting pore pressure rate effects induced by rotation of a rigid cylinder within a porous medium. In particular, the analysis is able to identify the drainage conditions taking place around elements rotating at different loading rates. Evaluation of these drained effects is based on the normalization of rotation tests characterized by an analytical drainage characterization curve represented in the degree of drainage U versus a non-dimensional parameter $\overline{V}$ space (e.g. [32], where:

$$\overline{V} = \frac{Vd}{c_h} \tag{1}$$

being d the probe diameter, V the loading rate and c_h the horizontal coefficient of consolidation.

This framework has been extensively used recently to determining experimentally rate effects taking place during penetration and rotation of *in situ* tests [21,39,32,10,38,13]. Yet few attempts have been made to develop a structured theoretical framework to predict drained conditions in intermediate permeability soils [41,14,16], which is the aim of the present research. It should be emphasized that applicability of the modeling to piles and shafts will depend on the availability of either experimental data or theoretical/computational solutions regarding the initial poromechanical state induced by the installation process prior to rotation. In that respect, evaluation of initial stress and pore-fluid pressure fields is beyond the scope of the paper.

2. Problem statement and framework of analysis

This section describes the main features of the simplified poromechanics setting adopted for the analysis of consolidation induced by rotation of a rigid cylinder deeply embedded within an isotropic elastic medium of infinite extent. The cylinder is subjected to a prescribed rotation-like displacement and its geometry may be viewed as a simple conceptual model of a pile, shield, shaft or vane test, and the associated solution would then be relevant to the consolidation of soil around the cylinder induced by its rotation during related *in situ* shear.

The analysis presented in the sequel is based on the assumption of plane strain conditions in the cross-section of a system defined by the cylinder and surrounding porous medium, restricting displacements and flow to two-dimensions setting (Fig. 1). In addition, assumption of perfect bonding at the soil/rigid cylinder interface will be assumed throughout the analysis.

The soil surrounding the rotating cylinder is modeled as a fully saturated poroelastic material undergoing infinitesimal strains. At the macroscopic scale, the representative elementary volume is the superposition of both solid and fluid particles that are located at the same geometrical point [12,18]. The skeleton is the macroscopic perception of the solid phase.

The classical soil mechanics sign convention with compressive stresses and strains counted positive is adopted throughout the paper.

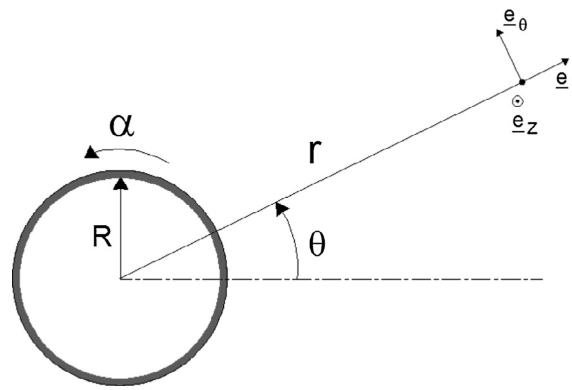

Fig. 1. Geometry model for consolidation around infinite rotating cylinder.

2.1. Governing equations for stress and displacement fields

Denoting by $\underline{\underline{\sigma}}_0$ and p_0 the initial fields of stress and pore-fluid pressure in the medium, the poroelastic state equations for an isotropic material can be expressed within the framework of infinitesimal strains as

$$\Delta\underline{\underline{\sigma}} = \lambda \mathrm{tr}\underline{\underline{\varepsilon}}\underline{\underline{1}} + 2G\underline{\underline{\varepsilon}} + b\Delta p\underline{\underline{1}} \tag{2}$$

$$\Delta\phi = -b\mathrm{tr}\underline{\underline{\varepsilon}} + \frac{1}{M}\Delta p \tag{3}$$

where λ and G are the Lamé constants, b and M are respectively the Biot coefficient and Biot modulus. The first poroelastic state equation relates the stress change $\Delta\underline{\underline{\sigma}} = \underline{\underline{\sigma}} - \underline{\underline{\sigma}}_0$ to the skeleton infinitesimal strain $\underline{\underline{\varepsilon}}$ and pore-fluid pressure change $\Delta p = p - p_0$, while the second state equation relates the Lagrangian porosity change $\Delta\phi = \phi - \phi_0$ to the skeleton volumetric strain and fluid pressure change.

The *in situ* stress, strain and fluid pressure fields induced by rotation of the rigid cylinder are in general significantly controlled by the non-linear behavior of the material. An approximate framework to capture some of these non-linear features consists in considering that the secant shear modulus G is evolving with the level of local shear strain and pore-fluid pressure induced by cylinder rotation. More precisely, we shall consider that the secant shear modulus depends on pore pressure p as well as on volumetric strain $\varepsilon_v = \mathrm{tr}\underline{\underline{\varepsilon}}$ and equivalent deviatoric strain $\varepsilon_d = \sqrt{(\underline{\underline{\varepsilon}} - \frac{1}{3}\mathrm{tr}\underline{\underline{\varepsilon}}) : (\underline{\underline{\varepsilon}} - \frac{1}{3}\mathrm{tr}\underline{\underline{\varepsilon}})}$. The idea consists basically in assuming that the local response of a plastic behavior under monotonic loading process can be conveniently simulated by means of a fictitious non-linear elastic behavior. The proposed approach is actually an extension to porous media of deformation (or Henky) plasticity concepts, originally formulated to approximate the material plastic response for problems involving the so-called proportional loading.

The starting point is the yield function characterizing the plasticity of the porous medium. In the present analysis, it is assumed that plasticity of the soil can be described by the following Drucker-Prager yield condition

$$F(\underline{\underline{\sigma}}') = \sigma_d - T(\sigma_m{}' + h) \leqslant 0 \tag{4}$$

where is the Terzaghi effective stress, $\sigma_d = \sqrt{(\underline{\underline{\sigma}} - \frac{1}{3}\mathrm{tr}\underline{\underline{\sigma}}) : (\underline{\underline{\sigma}} - \frac{1}{3}\mathrm{tr}\underline{\underline{\sigma}})}$ is the equivalent deviatoric stress and $\sigma_m' = \frac{1}{3}\mathrm{tr}\underline{\underline{\sigma}}' = \sigma_m - p$ is the mean Terzaghi effective stress. Material parameters h and T respectively refer to the tensile strength and the friction coefficient. The fictitious non-linear poroelastic material is then defined by imposing that the stress $\underline{\underline{\sigma}}$ associated with secant poroelastic behavior (2) meets asymptotically the above yield condition (4)

$$\lim_{\varepsilon_d/\varepsilon_{ref} \to \infty} F(\underline{\underline{\sigma}}' = \underline{\underline{\sigma}} - p\underline{\underline{1}}) = 0 \tag{5}$$

where ε_{ref} is a reference strain whose order of magnitude may evaluated from the elastic limit shear strain.