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Fully coupled solution for the consolidation of poroelastic soil around geosynthetic encased stone columns

Boštjan Pulko*, Janko Logar

University of Ljubljana, Faculty of Civil and Geodetic Engineering, Jamova 2, 1000 Ljubljana, Slovenia

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ABSTRACT

The paper presents an extension of a recently developed fully coupled elastoplastic method (Pulko and Logar, 2016) for the analysis of a poroelastic thick-walled soil cylinder around an elastoplastic end-bearing stone column to account for the influence of an elastic geosynthetic encasement. The method was developed in the framework of Biot's consolidation theory (Biot, 1941) and is based on a unit cell concept, wherein the column encasement is modeled as a thin elastic membrane, which can only sustain tension and acts in the radial direction. Analytical closed-form expressions for excess pore pressures, stresses, strains, displacements and encasement forces were derived in the Laplace domain. The final elastoplastic solution in time domain was obtained numerically by using efficient numerical scheme for the inverse Laplace transform. The validity of the solution was checked against finite element analyses and compared with previously developed analytical methods. The results showing the influence of column encasement on transient state of settlements, strains, excess pore pressures and encasement forces under instantaneous or time dependent load are presented and discussed.

1. Introduction

Stone columns (SC) or granular piles are a technique frequently used for the improvement of soft ground beneath embankments, storage tanks, bridge abutments and other structures that can tolerate some settlements. The beneficial effects of stone column installation include increased bearing capacity, reduction of settlements, acceleration of settlements and reduction of the liquefaction risk. However, the installation of ordinary stone columns (OSC) in very soft soils often yields unsatisfactory results due to insufficient lateral resistance of the soil and excessive bulging and consequent failure of the columns (Mckenna et al., 1975). This can be significantly improved by encapsulation of the stone column into geosynthetic sleeve to form what is called geosynthetic encased columns (GEC). Although the effects of encasement are generally well understood, the issue of ground improvement using GEC represents an area of active research aimed at improving the design methods and prediction of ground behavior (Tandel, 2012; Najjar, 2013; Abhishek et al., 2016).

The efforts to improve the understanding of the behavior of GEC improved soft soils are made through extensive laboratory tests (Gniel and Bouazza, 2009; Murugesan and Rajagopal, 2009; Wu and Hong, 2009; Dash and Bora, 2013; Ghazavi and Nazari Afshar, 2013; Ali et al., 2014; Miranda et al., 2015, 2017; Miranda and Da Costa, 2016; Hasan and Samadhiya, 2017) and also trough field tests and in-situ data, as reported by several researchers (Raithel et al., 2005; Tandel et al., 2014; Alexiew and Raithel, 2015; Almeida et al., 2015; Hosseinpour et al., 2015; Schnaid et al., 2017). Although the results obtained by means of laboratory, field tests and in-situ data usually do not serve as general design methods, they provide indispensable insight into the actual behavior of GEC improved ground and serve for the evaluation of the developed design methods. These methods can be classified as general numerical methods, usually based on advanced numerical modelling extensively used by several researchers (Murugesan and Rajagopal, 2006; Yoo and Kim, 2009; Khabbazian et al., 2010, 2015; Lo et al., 2010; Hong, 2012; Almeida et al., 2013; Ou Yang et al., 2016; Rajesh, 2017), or approximate analytical methods, based on certain simplifying assumptions.

The majority of analytical methods for the design of raft foundations on soft soil improved by a large number of regularly spaced end-bearing GEC are developed on the basis of previously developed methods for ordinary non-encased columns (OSC), which are based on well-known unit cell concept and assume elastic behavior

* Corresponding author.
E-mail addresses: bostjan.pulko@fgg.uni-lj.si (B. Pulko), janko.logar@fgg.uni-lj.si (J. Logar).

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of the soil and rigid plastic or elasto-plastic behavior of the column (Priebe, 1976, 1995; Balaam and Booker, 1981, 1985; Van Impe and Madhav, 1992; Pulko and Majes, 2006; Castro and Sagaseta, 2009). Raithel and Kempfert (2000) presented an analytical method for predicting of load-settlement response of a unit cell of elastic clay with GEC, considered as non-dilating rigid-plastic material encased in elastic membrane. Similar approach was used by Pulko et al. (2011), except that the stone column is considered as an elasto-plastic non-associative Mohr-Coulomb material with a constant dilatancy angle. Both methods describe long-term drained conditions and allow the calculation of final settlements, encasement hoop forces and stresses. Castro and Sagaseta (2011a, 2013) presented more advanced closed-form analytical solutions, where undrained loading is followed by a consolidation process based on Barron's solution (Barron, 1948) to account for the ability of the GEC to take greater proportion of the load. Although not fully coupled, the solutions exhibit satisfactory behavior, but for low degrees of consolidation (Castro and Sagaseta, 2011b), if compared to finite element (FE) calculations.

This paper presents an extension of a recent fully coupled semi-analytical solution for OSC (Pulko and Logar, 2016), developed within Biot's theory of poroelasticity (Biot, 1941), to account for geotextile encasement. The method is based on a general solution for axisymmetric poroelastic thick-walled hollow cylinder (Jourine et al., 2004) coupled with permeable stone column with geotextile casing. The geosynthetic encasement does not affect the groundwater flow in radial direction. The analytical solutions for elastic and yielding behavior of the stone column were obtained in the Laplace domain. A fully coupled elastoplastic solution in time domain giving the transient states of settlements, strains, stresses, excess pore pressures and encasement hoop forces under time dependent load, were then calculated by numerical inverse Laplace transform.

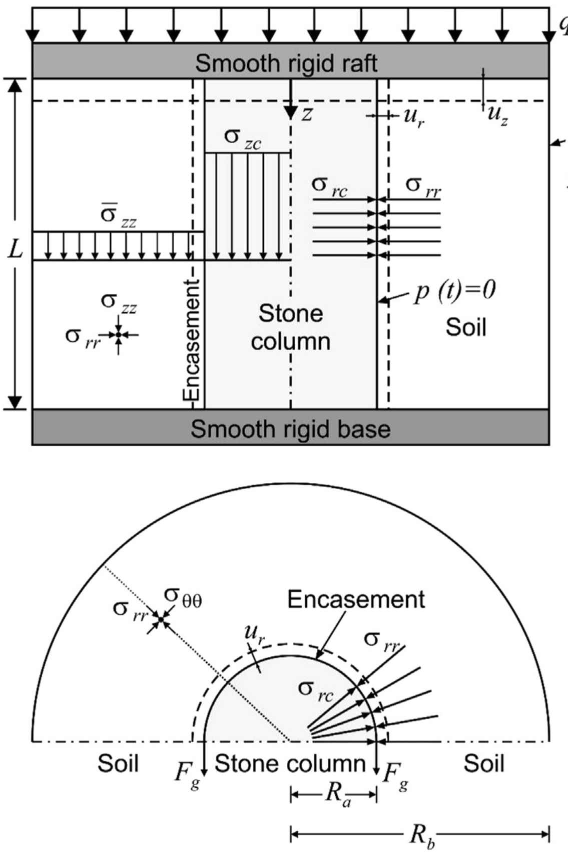

Fig. 1. Unit-cell axisymmetric representation.

2. Model basics

In terms of geometry, the widely adopted unit cell concept, which is used to represent a single end-bearing encased stone column, and its equivalent circular influence zone, both located on the interior of an infinitely large group of stone columns and loaded with rigid load, is adopted for the analysis (Fig. 1). In order to develop an elasto-plastic solution, we will first consider a saturated thick-walled poroelastic cylinder of constant permeability with inner radius R_a and outer radius R_b The stone column is assumed to behave as a permeable non-associative elasto-plastic Mohr-Coulomb material with constant dilatancy angle. The geosynthetic column encasement is considered as a permeable elastic membrane that can only take tension and acts only in the radial direction, without any influence on the vertical direction. Only radial flow is considered in the soil. The possible stress dependency of the material properties is beyond the scope of the method.

The basics of the model are shown in Fig. 1. The standard cylindrical coordinates are adopted (r, θ, z) with z axis along the symmetry axis of the unit cell. Compression negative notation is adopted for stresses and strains. Excess pore water pressures are assumed to be positive.

2.1. Basic equations for a poroelastic thick-walled cylinder

The basic equations for poroelastic thick-walled cylinder were presented by Jourine et al. (2004). For the sake of completeness, the basic equations covering the behavior of a poroelastic thick-walled cylinder are repeated below:

Stress-strain relationships:

$$\begin{aligned} \sigma_{rr} &= 2G\varepsilon_{rr} + \lambda\varepsilon - \alpha p \\ \sigma_{\theta\theta} &= 2G\varepsilon_{\theta\theta} + \lambda\varepsilon - \alpha p \\ \sigma_{zz} &= 2G\varepsilon_{zz} + \lambda\varepsilon - \alpha p \\ \varepsilon &= \varepsilon_{rr} + \varepsilon_{\theta\theta} + \varepsilon_{zz} \end{aligned} \tag{1}$$

Excess pore pressure-volumetric strain relationship:

$$p = M(\zeta - \alpha\varepsilon) \tag{2}$$

Strain-displacement relationships:

$$\varepsilon_{rr} = \frac{\partial u_r}{\partial r}, \quad \varepsilon_{\theta\theta} = \frac{u_r}{r}, \quad \varepsilon_{zz} = \frac{\partial u_z}{\partial z} \tag{3}$$

Equilibrium equation:

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} = 0 \tag{4}$$

Equations for fluid content variation:

$$\frac{\partial \zeta}{\partial t} - c\left(\frac{\partial^2 \zeta}{\partial r^2} + \frac{1}{r}\frac{\partial \zeta}{\partial r}\right) = 0 \tag{5}$$

$$\left(\frac{\partial^2 \zeta}{\partial r^2} + \frac{1}{r}\frac{\partial \zeta}{\partial r}\right)\left(\zeta - \frac{GS}{\eta}\varepsilon\right) = 0 \tag{6}$$

Poroelastic soil material constants, such as Biot's coefficient α, diffusivity coefficient c, Biot's modulus M, poroelastic stress coefficient η, storage coefficient S and Lamé parameter λ, are expressed by material property equations (Detournay and Cheng, 1993):

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