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Technical note

Creep analysis of an earth embankment on soft soil deposit with and without PVD improvement

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ABSTRACT

In this paper, an anisotropic creep constitutive model, namely Creep-SCLAY1S is employed to study the installation effects of prefabricated vertical drains (PVDs) on the behavior of a full scale test embankment, namely Haarajoki embankment in Finland. The embankment was constructed on a natural soft soil with PVD installed to improve the drainage under one half of it. The Creep constitutive model used in this study, incorporates the effects of fabric anisotropy, structure and time within a critical state based framework. For comparison, the isotropic modified Cam clay (MCC) model and the rate-independent anisotropic S-CLAY1S model are also used for the analyses. The numerical predictions are compared with field measurements and the results indicate that the creep model provides an improved approximation of field settlements, and excess pore pressure build-up and dissipations. In addition, the application of two commonly used permeability matching techniques for two dimensional (2D) plane-strain analysis of the PVD problem is studied and the results are discussed highlighting their limitations and advantages.

1. Introduction

In order to tackle the delayed consolidation settlement problem typical of soft soils, installation of prefabricated vertical drains (PVDs), combined with preloading, has become popular in the industry as an effective ground improvement solution (e.g. Abuel-Naga et al., 2015; Lam et al., 2015; Wang et al., 2016). Preloading is an old way of dealing with the problem of long-term consolidation in soft soils; however, in practice, this procedure on its own can be considerably time consuming. For the excess pore water pressure (PWP) to be dissipated quickly, the drainage paths need to be shortened. PVDs are geosynthetic slender elements made of corrugated plastic cores that their installation can effectively reduce the consolidation time as they provide short horizontal drainage paths in thick soft soil deposits that need improvement (Rowe and Taechakumthorn, 2008).

Some aspects of PVD installation e.g., well resistance, smear effect and the overlapping of smear zones have been widely studied (e.g. Kim and Lee, 1997; Zhu and Yin, 2000; Cascone and Biondi, 2013; Deng et al., 2013; Xue et al., 2014; Chen et al., 2016; Nguyen and Indraratna, 2017). However, very few studies exist regarding the long-term effects of PVD installation on the response of the soft soil layer (e.g. Kim, 2012; Lo et al., 2013; Hu et al., 2014), this deemed to be in part due to the unavailability of appropriate soil models. Many soil constitutive models, which are commonly used for the analysis and design of geotechnical engineering problems, assume that the behavior of soil is simply isotropic. Application of such simplified models in practice often provide solutions that are overly conservative and costly, and in some cases result in uncertainties regarding long-term performances. In reality, the behavior of natural soils is highly anisotropic. Natural clays also have an inherent structural property that gives them an undisturbed shear strength in excess of their remolded strength. Furthermore, clayey soils are known to be the most susceptible to time effects on their strength and deformation characteristics. An accurate prediction of soft soil response, either improved or unimproved, requires that these aspects of their behavior are

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considered by the employed constitutive model.

Because of considerable computational cost of three dimensional (3D) finite element (FE) analysis, the boundary value problems related to PVD ground improvement are commonly modeled in the representative 2D plane-strain condition. As water flow into the PVD is an axisymmetric problem; therefore, for the representative 2D analysis, a number of so-called mathematical matching techniques have been proposed (e.g. Hird et al., 1992; Lin et al., 2000; Indraratna et al., 2005). These matching methods are used for the conversion of permeability coefficient from axisymmetric state into plane-strain condition.

The focus of this paper is, to assess the long-term behavior of an embankment on soft clay deposit with and without PVD improvement, and to examine the applicability of a recently developed creep constitutive model in predicting ground deformations at a practical level. For this study, Haarajoki test embankment (Finnish National Road Administration, 1997) is numerically simulated using an advanced creep constitutive model, namely Creep-SCLAY1S (Sivasithamparam et al., 2015). This test embankment is constructed on deep soft soil deposit improved with PVDs for one half of its length. The results from the newly developed creep model are compared with those obtained by using a time-independent anisotropic model, S-CLAY1S (Karstunen et al., 2005), and the MCC model (Roscoe and Burland, 1968). In addition, a simple comparative study is carried out in order to examine the sensitivity of the results to the adopted matching technique.

2. Creep-SCLAY1S model

The Creep-SCLAY1 (Sivasithamparam et al., 2015) is an extension of S-CLAY1 (Wheeler et al., 2003) to incorporate rate-dependent response of clays. In this model the elliptical surface of the S-CLAY1 model is adopted as the normal consolidation surface (NCS), i.e. the boundary between small and large irreversible (creep) strains; furthermore, creep is formulated using the concept of a constant rate of visco-plastic multiplier (Grimstad et al., 2010). The new creep model incorporates the same rotational hardening law as that of the S-CLAY1 and S-CLAY1S models. Moreover, the Creep-SCLAY1 model has been further extended by incorporating the destructuration hardening law of the S-CLAY1S model to take into account the effect of the initial inter-particle bonding in the soil response. Despite assuming anisotropy of plastic behavior, the S-CLAY1 class of models assume isotropy of elastic behavior which is a reasonable assumption for modeling the behavior of soft and sensitive clays (Rezania et al., 2016). In addition to the soil parameters required for modeling with SCLAY1S (as detailed in Karstunen et al., 2005), the use of Creep-SCLAY1S requires three viscous parameters namely, the reference time, τ, the modified creep index, μ^*, and the intrinsic value of the modified creep index, μ_i^*. Note that μ^* is related to the one-dimensional secondary compression index, C_α, as

$$\mu^* = \frac{C_\alpha}{[\ln 10\,(1+e_0)]} \tag{1}$$

The extended Creep-SCLAY1S model has recently been successfully applied for modeling pile installation effects in a soft clay deposit (Rezania et al., 2017).

3. Numerical modeling of PVD improved ground

For planning a PVD ground improvement work, penetration depth, installation pattern and spacing of PVDs are the important factors that need to be taken into consideration. For the Haarajoki embankment the length of the PVDs used was 15 m and for simplicity they were installed in a square pattern (Fig. 1a) with spacing, $S = 1\,m$ and equivalent diameter, $D = 1.13\,m$. For modeling purposes, the diameter of installation induced smear zone, D_s (see Fig. 1b), is often considered to be in the range of 3–5 times the diameter of the mandrel, D_m, or 5–8 times the equivalent drain diameter, D_w (Xiao, 2001).

Ideally the study of PVD ground improvement is a 3D problem, requiring a 3D FE analysis. This is due to the fact that the seepage and consolidation around vertical drains are in reality 3D. However, such a model would be computationally very expensive and time consuming, mainly due to the need for discretely modeling each vertical drain and its associated influence zone (Yildiz, 2009) that can result in mesh complexity and therefore increased convergence time and required computer memory. Therefore, often a 2D plane-strain FE model is used and a matching technique is employed to convert the general permeability of the medium into an equivalent plane-strain value. In practice, the axisymmetric unit cell representing a drain is simplified into a plane-strain unit cell, assuming an equivalent half width, B, for the cell.

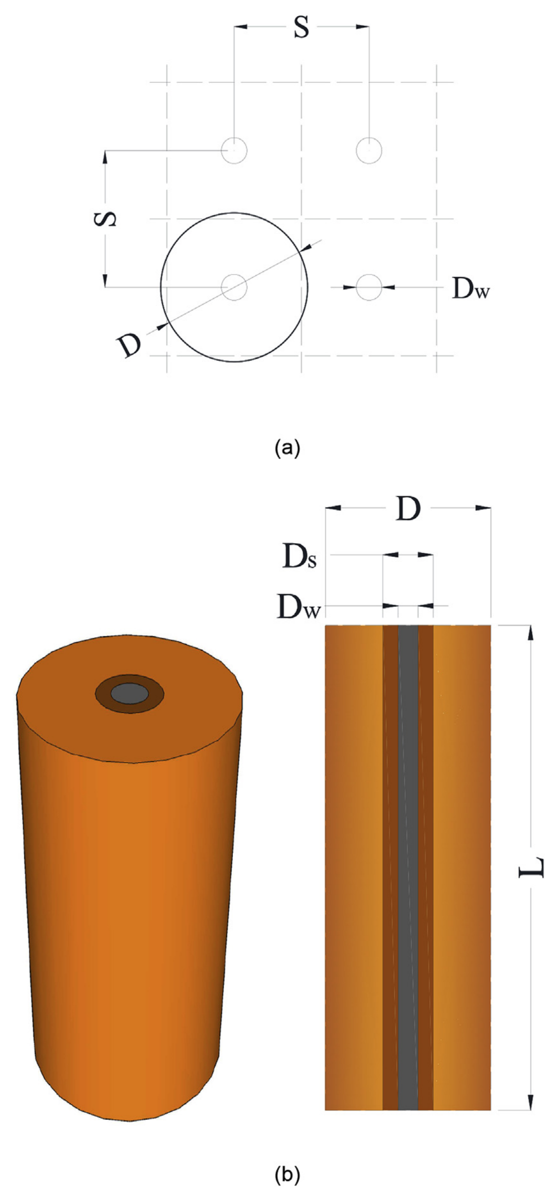

Fig. 1. PVD pattern: (a) square pattern; (b) drain with smear zone.