International Journal of Plasticity 65 (2015) 1–21

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Numerical optimisation to obtain elastic viscoplastic model parameters for soft clay

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ARTICLE INFO

Article history:
Received 22 April 2014
Received in final revised form 7 August 2014
Available online 1 September 2014

Keywords:
Elastic viscoplastic
Finite difference solution
A. Creep
C. Soft soils

ABSTRACT

In this paper, a numerical optimisation procedure is presented to obtain non-linear elastic viscoplastic (EVP) model parameters adopting the available consolidation data. The Crank–Nicolson finite difference scheme is applied to solve the combination of coupled partial differential equations of the EVP model and the consolidation theory. Then, the model parameters are determined applying the trust-region reflective optimisation algorithm in conjunction with the finite difference solution. The proposed solution for the model parameter determination can utilise all available consolidation data during the dissipation of the excess pore water pressure to determine the required model parameters. Moreover, in order to include creep in the numerical predictions explicitly from the very first time steps, the reference time in the elastic viscoplastic model can readily be adopted as a unit of time. Results obtained from two sets of laboratory experiments adopting hydraulic consolidation (Rowe cells) on a soft soil are reported and discussed. The proposed numerical optimisation procedure is utilised to obtain the viscoplastic model parameters adopting the experimental results, while the settlement and pore water pressure predictions are compared with experimental results to evaluate the accuracy and reliability of the proposed numerical procedure. The predictions are in good agreement with the measurements, supporting the proposed numerical method as a practical tool to analyse the stress–strain behaviour of soft clay.

1. Introduction

Soft soil creep has remained one of inspiring research topics in geotechnical engineering for the last few decades. The long term settlement prediction is one of the key challenges for soft soil analysis, and the elastoplastic constitutive models excluding the viscous behaviour cannot describe the time dependent behaviour of soft soils properly. According to Scheidler and Wright (2001) and Voyiadjis and Kim (2003), the viscoplasticity should be included in the constitutive models in order to predict the long-term time dependent behaviour of soils accurately. The viscoplastic deformation has been considered to occur in various materials such as asphalt concrete (Abu Al-Rub et al., 2012; Darabi et al., 2012), frozen soils (Lai et al., 2000), and soft rocks (Abou-Chakra Guery et al., 2008; Zhou et al., 2008). The prediction of total settlement in general and particularly the settlement induced by creep of a soft soil deposit under structural loads is an ongoing challenge, due to the lack of a unique theory or a computational method to predict the deformation (Fatahi et al., 2013; Le et al., 2012). Clay,

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http://dx.doi.org/10.1016/j.ijplas.2014.08.008
0749-6419/

the major composition of soft soils, has sophisticated mineralogical composition and structure, which causes significant influences on the mechanical response of soft soils such as inelastic behaviour under loading (Shen et al., 2012). Various studies have been conducted to investigate cyclic loading and temperature effects (heating and cooling cycles) on the structure of clayey soils (e.g. Li et al., 2011; Tsutsumi and Tanaka, 2012), which in long term may induce fatigue similar to some metals (e.g. Ghodrat et al., 2013a, 2013b) and change the inelastic behaviour.

The widely accepted assumption in the study of the soft soil creep is that the compression induced by the creep is a deformation process occurring concurrently with the excess pore water pressure dissipation (e.g. Degago et al., 2009; Watabe et al., 2012). For the sake of simplicity, practising engineers may compute the creep settlement based on a constant creep coefficient (C_α) for a particular soil (e.g. Nash, 2001; Vermeer and Neher, 1999). However, many researchers have reported that the long term relation between the strain and logarithm of time may not be linear (Berre and Iversen, 1972; Yin, 1999). In order to overcome the limitation of the linear logarithmic creep function, Yin (1999) proposed a non-linear creep function substituting for the linear creep function to describe the creep deformation more accurately. Although the non-linear creep function proposed by Yin (1999) is one step closer to the real behaviour of soils, the determination of the parameters is a challenging task. More creep data points are required for curve fitting to define the creep strain limit.

In brief, this paper presents a new method adopting all the consolidation test data points (during and after the dissipation of the excess pore water pressures) to determine the model parameters in order to overcome the limitations of the conventional procedure. The proposed method advances the process of model parameter determination by introducing an optimisation procedure incorporating the elastic viscoplastic model. The proposed method allows the model parameters to be obtained simultaneously. Various optimisation methods to define single or several model parameters have been applied widely in other types of materials such as metals (e.g. Cooreman et al., 2007; Yoshida et al., 2003; Yun and Shang, 2011), while it has been rarely employed to estimate soil parameters. Additionally, the proposed approach implements the time parameter t_o as a unit of time to avoid the difficulty of determining the end of the primary consolidation in the conventional method. Thus, the proposed solution in this study is to strengthen the merits of the non-linear creep model by providing a set of unique model parameters for a particular soil irrespective of the size of the sample tested. In this paper, a multiple-stage consolidation test result on a thin clay sample is used to determine the EVP model parameters adopting the developed numerical solution. Then, the obtained model parameters are implemented to predict the settlement and the excess pore water pressure variations of a thicker soil sample of the same material in the laboratory. Analyses of results and discussions are presented to examine and validate the developed numerical solution.

2. Numerical analysis

2.1. Viscoplastic strain rate

Yin and Graham (1989) introduced an elastic viscoplastic model adopting the time line concept. The time line concept includes an instant time line, a reference time line, a limit time line, and a series of equivalent time lines. The detailed explanation of the time line concept was presented by Yin and Graham (1989).

In the original EVP model developed by Yin and Graham (1989), the linear logarithmic creep function with a constant creep coefficient ψ/V results in the unrealistic infinite creep strain, when the equivalent time (t_e) approaches infinity. Thus, the non-linear creep function as presented in Eq. (1) was proposed by Yin (1999) as the solution for this limitation. The non-linear creep function includes a creep strain limit (ε_{lm}^{vp}), the initial creep coefficient (ψ'_o) at equivalent time $t_e = 0$, and a time parameter t_o. Based on Eq. (1), when $t_e = 0$, $\varepsilon_z^{vp} = 0$; and, as t_e approaches infinity, $\varepsilon_z^{vp} = \varepsilon_{lm}^{vp}$. In other words, the creep strain approaches the creep strain limit, when time approaches infinity.

$$\varepsilon_z^{vp} = \frac{\psi'_o}{1 + \frac{\psi'_o}{\varepsilon_{lm}^{vp}} \ln \frac{t_e + t_o}{t_o}} \ln \frac{t_e + t_o}{t_o} \tag{1}$$

where ε_z^{vp} is the vertical creep strain under a constant effective stress, t_e is the equivalent time determined based on the reference time line, ψ'_o is the initial creep coefficient at $t_e = 0$, and ε_{lm}^{vp} is defined as the creep strain limit.

Moreover, the creep strain rate, which is obtained by differentiating Eq. (1) with respect to time (t), decreases with time, while the effective stress is kept constant as observed in Eq. (2).

$$\dot{\varepsilon}_{vp} = \frac{\psi'_o}{(t_o + t_e)} \frac{1}{\left(1 + \frac{\psi'_o}{\varepsilon_{lm}^{vp}} \ln \frac{t_e + t_o}{t_o}\right)^2} \tag{2}$$

As reported by Yin (1999), the values of creep strain limit (ε_{lm}^{vp}) and the creep coefficient (ψ'_o) decrease linearly with the increase of logarithm of the effective stress for the case of Hong Kong marine clay. Yin (1999) suggested the linear logarithmic functions to correlate these model parameters to the vertical effective stress, as follows:

$$\varepsilon_{lm}^{vp} = a - b \ln\left(\frac{\sigma'_z}{\sigma'_u}\right) \tag{3}$$