Applied Clay Science 153 (2018) 9–15

Contents lists available at ScienceDirect

Applied Clay Science

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

Research paper

A semi-analytical solution for one-dimensional elasto-viscoplastic consolidation of layered soft clay

Sheng-Feng Zou[a,b,c], Jin-Zhu Li[b,*], Xin-Yu Xie[a,b,c]

[a] Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310058, China
[b] Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, China
[c] MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou 310058, China

ARTICLE INFO

Keywords:
Threshold yield stress
Soft clay
Rheological consolidation
Elasto-viscoplastic model
Semi-analytical method

ABSTRACT

The threshold yield stress plays a key role in controlling the rheological consolidation behaviour of soft clay. A semi-analytical theory combining numerical and analytical methods is introduced that excludes the effects of clay self-weight. The governing equations assume the clay is an elasto-viscoplastic material. Approximate solutions as well as computational programme to surface loading for two drainage boundary conditions are obtained, while the clay profile is separated into material which is overconsolidated and normally consolidated. The effects of threshold yield stress and time-dependent loading on the rheological behaviour of soft clays are explored using the solutions developed.

1. Introduction

Consolidation theories for soft clay have been frequently discussed for nearly a century since Terzaghi first presented the one-dimensional consolidation theory in 1923. With the advancement of constitutive research, especially since Taylor and Merchant (1940) first proposed the rheological consolidation theory, a number of rheological constitutive models of soft clay have been proposed (Šuklje, 1957; Gibson and Lo, 1961; Bjerrum, 1967; Singh and Mitchell, 1968; Mesri and Godlewski, 1977; Mesri et al., 1981). However, very few models exist that can provide quantitative assessment of the impacts of the elasto-viscoplastic characteristics of clay.

A suitable constitutive model to describe the rheological behaviour of soft clay should simultaneously consider natural characteristics including the viscosity, elasticity and plasticity. Frequently used rheological constitutive models include linear models and nonlinear models composed of empirical models, component models, yield surface models and endochronic models (Yuan et al., 2001). Taylor and Merchant (1940) first conducted research on consolidation theories considering the creep behaviour of clay. Tjongkie (1958) argued that the deformation of clay can be divided into viscous volumetric creep deformation and viscous shearing creep deformation, and the Hooke body and Maxwell body were adopted to compute these two kinds of deformation, respectively. Gibson and Lo (1961) proposed a four-element viscoelastic model to study one-dimensional consolidation. Bjerrum (1972) developed a semi-empirical model based on the Singh-Mitchell empirical rheological model in which the rheological deformation was computed by the Taylor equation. Yin and Graham (1989, 1996) developed a one dimensional elasto-viscoplastic (EVP) model to study the long term characteristics of clay based on the isotache theory. Fodil et al. (1997) combined the critical state concept and viscoplasticity theory, and deduced a constitutive model to quantify delayed settlements of the Le Flumet dam, which was proved validated along different stress-strain paths according to experimental results. Yin et al. (2008) developed a rheological model, based on the framework of Perzyna's overstress theory and the Modified Cam Clay model, that could satisfactorily describe the time-dependent characteristics of normally consolidated or slightly overconsolidated clay along various loading paths. Hinchberger and Rowe (2005); Hinchberger and Qu (2009); Hinchberger et al. (2010); Qu et al. (2009) raised a constitutive equation with a scalable elliptical yield surface and evaluated two elastic-viscoplastic formulations by case study of an embankment founded on Sackville soft clay. Deng et al. (2012) considered the unloading progress and investigated the long-term deformation behaviour of plastic Boom clay. Li et al. (2014) proposed a three-dimensional rheological model and coded a user material subroutine of the model on an ABAQUS platform, declaring that with an increase in the confining pressure, the elastic deformation, viscoelastic deformation and viscoplastic deformation decreased to some extent. Madaschi and Gajo (2016) proposed a multi-axial model assuming that plastic deformation is due to two mechanisms relevant to rate dependencies, in which the first is an approximated instantaneous and the second is a viscous. For

* Corresponding author.
E-mail address: jinzhu_lee@nit.zju.edu.cn (J.-Z. Li).

https://doi.org/10.1016/j.clay.2017.11.042
Received 23 June 2017; Received in revised form 28 November 2017; Accepted 29 November 2017

clays, plastic strains due to short-term and long-term mechanisms have approximately the same magnitude, and the experimental results were found by Madaschi and Gajo (2015) on fine-grained materials.

How to solve the formulations of the models introduced above is another key topic. Gray (1944) first devised the consolidation analytical solution of double-layered ground under instantaneous loading. Olson (1977) presented solutions to both purely radial flow and combined vertical and radial flow in the linear loading consolidation process. Xie (1994) considered double-layered ground and gave a general analytical solution to the problem of one-dimensional consolidation. Based on this framework, analytical solutions considering time-dependent loading were then obtained (Xie and Pan, 1995). Furthermore, after Lan (2003) introduced a semi-analytical method into the computing of rheological consolidation theories, Ma et al. (2013, 2014) discussed the ageing effects occurring in clay. Xie et al. (2016) investigated the compression behaviours of double-layered structured clay, and the approximated solutions for time-dependent loading were provided.

This paper expresses the Nishihara rheological model to simulate the elasto-viscoplastic characteristics of soft clay. Then, the approximate theoretical solutions as well as the numerical model of soft clay subjected to surface loading for two types of boundary conditions are obtained. Finally, the effects of the critical yield stress and time-dependent loading of rheological models on rheological consolidation behaviours are analysed.

2. Rheological model

2.1. Mathematical model

Fig. 1 depicts the schematic diagram of the Nishihara model adopted in this paper. As the figure shows, the Nishihara model is composed of a Hooke elastic body, a Kelvin viscoelastic body and a Bingham viscoplastic body, which makes it possible for the model to describe simultaneously the elastic, viscous and plastic behaviours exhibited in natural clays.

When a constant load q is applied, the stress-strain relationships for this model can be expressed by the following equations, namely,

$$q + \frac{\eta_1}{E_0 + E_1}\dot{q} = \frac{E_0 E_1}{E_0 + E_1}\varepsilon + \frac{E_0 \eta_1}{E_0 + E_1}\dot{\varepsilon} \quad q < \sigma_s \tag{1a}$$

$$(q - \sigma_s) + \left(\frac{\eta_2}{E_0} + \frac{\eta_1 + \eta_2}{E_1}\right)\dot{q} + \frac{\eta_1 \eta_2}{E_0 E_1}\ddot{q} = \eta_2 \dot{\varepsilon} + \frac{\eta_1 \eta_2}{E_1}\ddot{\varepsilon} \quad q \geq \sigma_s \tag{1b}$$

where E_0 denotes the elastic modulus of the Hooke elastic body, E_1 and η_1 represent the elastic modulus and viscosity parameter of the Kelvin viscoelastic body, while E_2 and σ_s indicate the viscosity parameter and plastic yielding limit of the Bingham viscoplastic body, respectively. When the applied load q is less than σ_s, the Nishihara model behaves with viscoelastic characteristics; otherwise, elasto-viscoplastic responses can be found.

Mathematical modelling of the rheological consolidation considering the elasto-viscoplastic behaviour of soft clay layers in this study is shown in Fig. 2. The thickness of the single layer is H, the top surface is regarded as pervious, while the bottom is assumed to be pervious or impervious in different situations, and an instantaneously uniformly distributed load q is applied on the surface of the clay. With

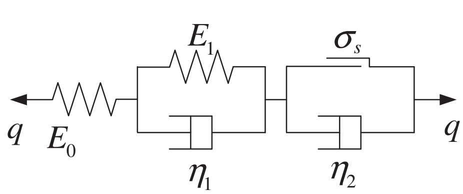

Fig. 1. Sketch of Nishihara model

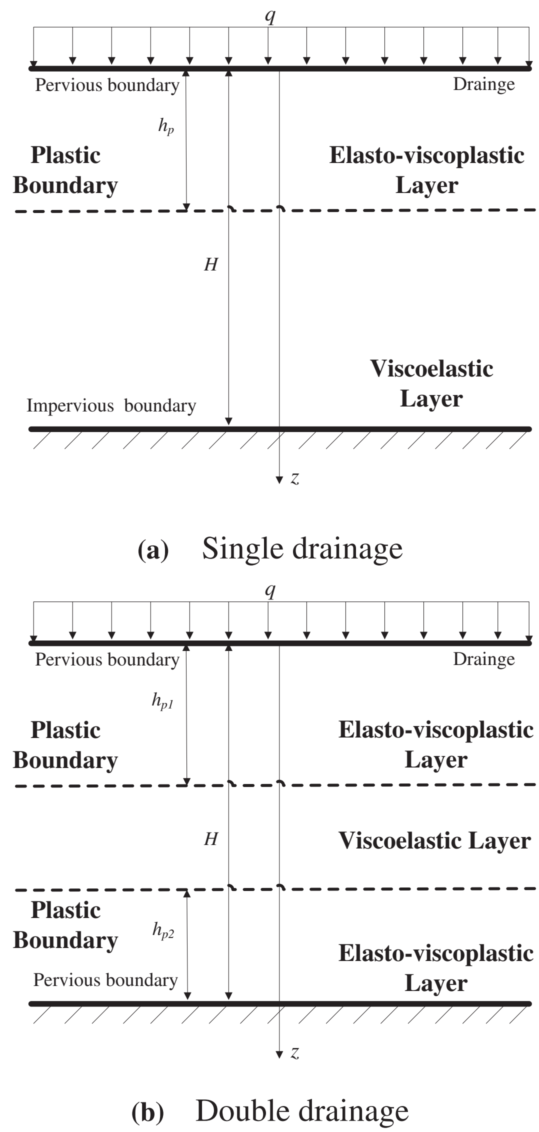

Fig. 2. Mathematical modelling of the soft soil layer.

the assumption that the effects of self-gravity of clay are disregarded in this research, the total pressure throughout the clay layer is thought to be q in the meantime, while the effective pressure grows from zero to q progressively between the top surface and bottom boundary, that is, the plastic yielding boundary moves from the top side to the boundary during the consolidation process. According to Terzaghi's assumption, the effective pressure of the clay is given by

$$\sigma_z' = q - u \tag{2}$$

where u is the excess pore water pressure.

2.2. Governing equations

During the consolidation phases, according to the rheological model raised by Nishihara in 1961, the elasto-viscoplastic behaviour of soft clay is accounted for by either considering or not considering the Bingham viscoplastic body in the Nishihara model before and after the effective stress has reached the plastic yielding limit. Accordingly, the vertical strain of the clay layer ε_z can be derived by the following equations: