Computers and Geotechnics 100 (2018) 135–143

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Model updating and uncertainty analysis for creep behavior of soft soil

Wan-Huan Zhou[a], Fang Tan[b,a], Ka-Veng Yuen[a,*]

[a] Department of Civil and Environmental Engineering, Faculty of Science and Technology, University of Macau, Macau, China
[b] School of Civil Engineering, Shandong Jianzhu University, Jinan City, Shandong, China

ARTICLE INFO

Keywords:
Bayesian model class selection
Creep
Elastic viscoplastic models
TMCMC method
Uncertainty evaluation

ABSTRACT

Of late, various constitutive models have been proposed in the literature for the purpose of capturing the various complex physical mechanisms governing the creep behavior of soft soil. However, the more complex the model, the greater the number of associated uncertain parameters it has, and the less robustness it is. In this study, the Bayesian model class selection approach is applied to select the most plausible/suitable model describing the creep behavior of soft soil using laboratory measurements. In total, one elastic plastic (EP) model and eight elastic viscoplastic (EVP) models are investigated. To assess the performance of the different models in the prediction of creep behavior of soft soils, Bayesian model class selection is respectively performed using the oedometer test data from the intact samples of Vanttila clay and reconstituted samples of Hong Kong Marine Clay collected from the literature. All unknown model parameters are identified simultaneously by adopting the transitional Markov Chain Monte Carlo (TMCMC) method, and their uncertainty is quantified through the obtained posterior probability density functions (PDFs). The result shows that the proposed method is an excellent candidate for identifying the most plausible model and its associated parameters for different kinds of soft soils. The approach also provides uncertainty evaluation of the model prediction based on the given data.

1. Introduction

Over the past few decades, researchers have conducted numerous laboratory studies to investigate the time-dependent stress-strain behavior for soft soils [1–9]. To describe the viscous features of soft soils, the strain rates were used in the models [5,10–12]. Based on laboratory observations, mathematical models have been proposed to consider the creep behavior of soft soil under one-dimensional (1-D) straining [1,5,10,13–17] triaxial stress states, and general stress states [18–21]. Advanced elastic viscoplastic (EVP) models have also been developed to incorporate the anisotropy and destructuration effects [22,23]. Due to different physical, chemical and biological processes over time, soils from different places can perform very differently under loading. The main physical mechanism controlling the creep behaviors may be very different for different soft soils. It is a difficult decision for engineers or researchers to select the most suitable model in the analysis of creep behavior for a certain soil.

When analyzing the creep behavior of soft soil using an EVP model, the associated model parameters should be determined in advance. Traditionally, curve-fitting techniques are commonly adopted for separate parts of the experimental data to determine the model parameters [13,24,25]. Yin and Graham [13] used such a technique to delineate the model parameters, which were separated based on the experimental data at different consolidation stages. The studies by Yin [24] and Yin et al. [25] suggested that the reference equivalent time (t_0) can be approximately calculated by referring to the time at which the excess pore water pressure has dissipated completely, while the other two parameters, *i.e.*, creep coefficient and creep strain limit, are obtained by fitting the measured data after the primary consolidation stage. However, this procedure actually violates the mathematical theory. The measured total strain includes the elastic and viscoplastic strain, although the elastic and plastic parameters are determined using the data on total strain. On the other hand, certain parameters are determined subjectively, such as reference equivalent time (t_0). To overcome the limitation of the traditional curve-fitting technique, Le et al. [26] adopted the trust-region reflective least square method to simultaneously obtain all model parameters based on the test data under different loading, while the time parameter t_0 was assumed to be the unit minute. The recent studies [27,28] also used said optimization method to conduct the analysis with the same assumption on the time parameter. Additionally, certain researchers [29–31] used the enhanced genetic algorithm to identify the model parameters, and Jin

* Corresponding author at: Room E11-3023, Department of Civil and Environmental Engineering, Faculty of Science and Technology, University of Macau, Avenida da Universidade, Taipa, Macau.
E-mail addresses: hannahzhou@umac.mo (W.-H. Zhou), kvyuen@umac.mo (K.-V. Yuen).
URL: http://www.cis.umac.mo/~kvyuen (K.-V. Yuen).

https://doi.org/10.1016/j.compgeo.2018.04.006
Received 22 November 2017; Received in revised form 2 March 2018; Accepted 3 April 2018

Nomenclature

t_0	reference equivalent time
t	elapsed time
e_0	initial void ratio
γ_w	unit weight of water
k	hydraulic conductivity
u	pore water pressure
σ'_{zr}	reference effective stress
σ'_u	unit effective stress
σ'_z	effective vertical stress
σ'_p	preconsolidation pressure
σ'^{r}_{p0}	initial reference preconsolidation pressure
$\dot{\sigma}'_z$	effective vertical stress rate
$\dot{\varepsilon}^e_z$	elastic strain rate
$\dot{\varepsilon}^{vp}_z$	viscoplastic strain rate
$\dot{\varepsilon}_z$	total vertical strain rate
ε_z	total vertical strain
ε^r_z	elastic-plastic strain
ε^r_{z0}	vertical strain at $\sigma'_z = \sigma'_{zr}$
ε^{vp}_{lm}	creep strain limit
ε_{oi}	intercept of the line in the $\log(\sigma'_z/\sigma'_{p0})-\varepsilon^{vp}_z$ plane
κ	defines unloading-reloading behavior
λ	defines the elastic-plastic behavior
λ_i	intrinsic slope of the compression line
λ^*_i	compression coefficient obtained at large strain where the state of soil structure stabilizes under ongoing normal consolidation stress paths
ψ	creep parameter
ψ'_0	creep coefficient
$C_{\alpha e}$	secondary compression coefficient
C_ε	compression index
C_p	preconsolidation index
τ	reference time in Vermeer model
Γ	value of $\log\sigma'_{p0}$ in a constant rate-of-strain test with a strain rate $\dot{\varepsilon}^{vp}_z = 1\ \mathrm{s}^{-1}$
χ_0 and ρ (χ^*_0 and ρ^*)	two structure parameters
C	denotes the model class
D	denotes the data
$\bar{\varepsilon}_z(\Theta_m;C)$	predicted vertical strains given model class C
ε	zero-mean Gaussian random variable
σ^2_ε	prediction error variance
Θ_m	model parameter vector
Θ	uncertain parameter vector, *i.e.*, $\Theta = [\Theta^T_m, \sigma^2_\varepsilon]^T$
Θ_m	optimal parameter vector
f	denotes the probability density function (PDF)
P	denotes probability value
N	number of measured data
s	denotes the stage number
N_s	total number of stage
p_s	random value used to decide the intermediate PDF
S	evidence of model class
m	denotes the different model classes
w	plausibility weight
$\sum_s$	covariance matrix
$\Theta_{s,l}$	sample of parameter vector in TMCMC simulation
H_0	height of soil sample
$MAPE$	mean absolute percentage error
$RMSE$	root mean square error

et al. [29] even conducted selection work on the sand models. In order to get the most reliable simulations during mechanized tunneling, Hölter et al. [32] adopted the optimal measurement design method to determine the optimal positions of getting measured settlements, and conducted the model parameter identification using the least-square-based method based on the corresponding measured data.

It should be mentioned that all these authors adopted the deterministic method to determine the model parameters. The best fitting between the predictions and the observations is the only concern in said determination. This method ignores the uncertainties associated with statistical uncertainty, measurement error, and model uncertainty and its effect on the model predictions. Recently, the probabilistic methods for back analysis have been widely conducted in geotechnical engineering, *e.g.* maximum likelihood method and Bayesian probabilistic method [33]. The Bayesian probabilistic method is considered to be more effective for updating the soil parameters [34–37], and it can quantify the uncertainty of soil parameters by the obtained posterior probabilistic distributions. It has been successfully applied to various geotechnical problems [38–46].

In this study, we propose to investigate the efficiency of several well-known time-dependent models in the predictions of long-term 1-D straining behavior of soft soils. The model updating is realized using the Bayesian method and the transitional Markov Chain Monte Carlo (TMCMC) method. Two groups of 1-D oedometer test data from intact and reconstituted soft soil samples are employed for the model updating. A total of nine models and their associated model class selections are conducted respectively. The analysis results indicate that the most suitable model should be selected to capture the different characteristics of deformation for different soil samples. The proposed method can evaluate the corresponding uncertainty during the model updating and hence the prediction with 95% credibility interval (CI) can be computed.

2. Review of time-dependent models for soft soils

Many researchers have proposed models to describe the viscoplastic strain rate for modeling the time-dependent behavior of soft soils. The total strain rate is composed of the elastic strain rate $\dot{\varepsilon}^e_z$ and viscoplastic strain rate $\dot{\varepsilon}^{vp}_z$:

$$\dot{\varepsilon}_z = \dot{\varepsilon}^e_z + \dot{\varepsilon}^{vp}_z \tag{1}$$

The elastic strain rate can be written as follows:

$$\dot{\varepsilon}^e_z = \frac{\kappa}{1+e_0}\frac{\dot{\sigma}'_z}{\sigma'_z} \tag{2}$$

where e_0 is the initial void ratio, κ is used to denote the elastic behavior of soil, and σ'_z is the effective vertical stress. In the following, several well-known time-dependent 1-D compression models for soft soils are briefly reviewed. We will assess their performance in the simulation of different soft soil samples, using probabilistic approach, in the later sections.

(1) Yin and Graham [10,13] developed the idea of "equivalent time", and deduced a general EVP constitutive model for the 1-D straining condition. This model uses a logarithmic function with a constant creep coefficient to describe the creep compression:

$$\dot{\varepsilon}^{vp}_z = \frac{\psi}{(1+e_0)t_0} \times \exp\left[-(\varepsilon_z - \varepsilon^r_{z0})\frac{1+e_0}{\psi}\right]\left(\frac{\sigma'_z}{\sigma'_{zr}}\right)^{\lambda/\psi} \tag{3}$$

where λ is used to denote the elastic-plastic behavior of soil; ψ is a creep parameter; t_0 is the reference equivalent time, which is different from the real test time; ε_z is the current total vertical strain; and ε^r_{z0} is the vertical strain at $\sigma'_z = \sigma'_{zr}$.

(2) Yin [24] further proposed a non-linear function to model the creep strain, which contains the creep coefficient ψ'_0 and creep strain limit