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Research Paper

Long-term Non-linear creep and swelling behavior of Hong Kong marine deposits in oedometer condition

Wei-Qiang Feng [a], Borana Lalit [a], Zhen-Yu Yin [b,c], Jian-Hua Yin [a,*]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China
[b] Department of Civil Engineering, Tongji University, Shanghai 200240, PR China
[c] Research Institute in Civil and Mechanical Engineering, GeM UMR CNRS 6183, Ecole Centrale de Nantes, BP 92101, 44321 Nantes Cedex 3, France

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ABSTRACT

The time-dependent stress-strain behavior of clayey soil is a great concern for predicting long-term settlement especially for large-scale land reclamation projects. In this paper, long-term time-dependent behavior of Hong Kong Marine Deposits (HKMD) under the loading stage and unloading stage is investigated by multi-staged loading oedometer test. Special emphasis has been given to study creep and swelling behavior. It is found that the clayey soil demonstrates the creep behavior during the loading stage, whereas it shows the swelling behavior during the unloading stage. The analysis of the creep behavior shows that there exists a linear trend between creep strain and time (in log-scale) within a certain period, whereas a nonlinear relationship in a long term view. Similar result is found for the swelling behavior. A nonlinear function is found to be suitable to predict the long-term creep and swelling behavior. The creep strain limit and swelling strain limit can be obtained if the nonlinear function is adopted to fit the experimental data. In addition, a new modified Elastic Visco-Plastic model considering Swelling (EVPS model) is proposed and presented, which considers the nonlinear creep and swelling behavior. In this modified EVPS model, the final creep and swelling equilibrium stress-strain state can also be obtained when the time is infinite.

1. Introduction

The time-dependent stress-strain behavior of soft clayey soils has been normally examined by one-dimensional (1D) tests. The viscous behavior of clayey soil during the loading stage, which is named as "creep", has been studied by several researchers [1–6], whereas few attempts have been made by researchers to study the viscous behavior during the unloading stage, termed as "swelling" [7,8].

The creep mechanism seems to be related to several factors, such as internal soil structure rearrangement [9], particle sliding and compression [10], delayed water that transfers and aggregates soil macro-pores [11]. Other factors that influence creep behavior are jumping of molecule bonds [12], adsorbed water flow in double layers of clay particles [13] and viscous adjustments of clay structure [14]. Based on scanning electronic microscope (SEM) and mercury intrusion porosimetry (MIP) measurements of clayey soils, there are two types of fabric elements in clayey soils, namely (a) particle clusters and (b) particle assemblages [15]. The particle clusters are related to clay mineral surface and physical-chemical interaction between clay minerals and the adsorbed water. The particle assemblages are controlled by the structure of particle clusters, forming the soil skeleton. Interaction of particle clusters and particle assemblages will transfer the loading and fluid water within the clay-water system [12,15].

The swelling behavior of unsaturated or expansive soils has gained considerable attention [16–18]. This is because that expansive soil usually results in differential settlement which may cause serious damage to the overall safety and stability of structural element of buildings and other structures. Mitchell and Soga [13] used the concept of osmotic pressure and double layer theory to reasonably explain the swelling behavior of compacted clays. The time-dependent swelling behavior is also observed in sand-bentonite mixtures [19–21], particularly in clayey soils after the dissipation of excess pore water pressure during the unloading stage [22,23]. Mesri et al. [7] explained that the swelling mechanism is related to clay permeability, particle rearrangement, diagenetic bonds breakdown, structural adjustment and chemical changes. Both creep and swelling mechanisms are explained by the particle rear-

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* Corresponding author.
E-mail addresses: 11901182r@connect.polyu.hk (W.-Q. Feng), lalitborana@gmail.com (B. Lalit), zhenyu.yin@gmail.com (Z.-Y. Yin), cejhyin@polyu.edu.hk (J.-H. Yin).

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rangement and double layer concept, whereas some soils such as sand-bentonite mixtures (SMB) exhibit both creep and swelling behavior in the loading and unloading/reloading stages [8,24].

The typical in-situ soils in Hong Kong are completely decomposed granite (CDG) and Hong Kong Marine Deposites (HKMD). CDG is one of the largely used fill materials in Hong Kong and numerous studies have been conducted to investigate its behavior [25,26]. With the rapid growth of infrastructure and urbanization in Hong Kong, there are many civil structures and foundations that need to be constructed in offshore and onshore, which requires massive land area [27]. One method of fulfilling land requirement is through reclamation and building of artificial islands in sea. Some of the large scale reclamation projects in Hong Kong are similar to one-dimensional straining condition, where the time-dependent soil behavior is a great concern [28,29]. Construction of artificial island requires a great deal of ground improve planning, which includes ground treatments like stone column, deep cement mixing, soil mixing etc. These ground improvement techniques often change the in-situ properties of HKMD and it often exists in the remolded state. As a typical soft soil, HKMD have been extensively examined [3,30–33], and it is articulated that creep behavior is an important factor in the long-term settlement prediction. However, swelling behavior is usually neglected.

This paper investigates the creep and swelling behavior of the remolded HKMD in the loading and unloading stages and demonstrates the characteristics of long-term creep and swelling behavior. A nonlinear function proposed by Yin [34] is employed to predict the long-term creep and swelling behavior. The Elastic Visco-Plastic model considering Swelling (EVPS model), proposed by Yin and Tong [35], is improved by adopting the nonlinear function for both creep and swelling behavior.

2. Time-dependent creep and swelling behavior of soil

The result of an oedometer test could be effectively utilized to evaluate of time-dependent behavior under constant loading conditions [36]. In order to interpret the oedometer result, compression parameter (λ/V) is defined as the slope of vertical strain versus vertical effective stress (ln scale) in normal loading conditions:

$$\frac{\lambda}{V}=\frac{\Delta\varepsilon_z}{\Delta\ln(\sigma_z')}=\frac{\varepsilon_{z2}-\varepsilon_{z1}}{\ln(\sigma_{z2}'/\sigma_{z1}')} \tag{1}$$

where $\Delta\varepsilon_z$ is the strain increment, $\Delta\varepsilon_z=\varepsilon_{z2}-\varepsilon_{z1}$, $\Delta\ln(\sigma_z')$ is the corresponding vertical stress difference, $\Delta\ln(\sigma_z')=\ln(\sigma_{z2}'/\sigma_{z1}')$, V is the specific volume, $V=1+e_o$. Similarly, rebounding parameter (κ/V) is also defined as the slope of over-consolidated loading condition. Compression index (C_c/V) and rebounding index (C_r/V) are also used to analyze the oedometer results, and can be obtained from the relationships with compression parameter and rebounding parameter. The relationship is illustrated as follows:

$$\begin{aligned}\tfrac{C_c}{V}&=\ln(10)\tfrac{\lambda}{V}=2.3\tfrac{\lambda}{V}\\ \tfrac{C_r}{V}&=\ln(10)\tfrac{\kappa}{V}=2.3\tfrac{\kappa}{V}\end{aligned} \tag{2}$$

The creep coefficient (ψ^c/V) is usually defined to describe a linear relationship of vertical strain and time (ln scale) [37,38]:

$$\varepsilon_z=\varepsilon_{zo}+\frac{\psi^c}{V}\ln\left(\frac{t_o^c+t_e^c}{t_o^c}\right) \tag{3}$$

where t_e^c is equivalent time related to creep, which was defined by Yin and Graham [37,38], t_o^c is the time parameter to account the beginning of creep time, which is directly related to the strain rate on reference time line. ε_{zo} is the strain at the time $t=t_o^c$, ψ^c/V is creep coefficient and it is a constant in this equation, and the superscript "*c*" indicates the creep. The relationship between creep coefficient and "secondary consolidation" coefficient is defined as Eq. (4):

$$\frac{\psi^c}{V}=\ln(10)\frac{C_{\alpha e}}{V}=2.3\frac{C_{\alpha e}}{V} \tag{4}$$

Regarding the swelling behavior as a reverse of the creep, the swelling coefficient (ψ^s/V) is also defined as the rate of vertical strain and time [35]:

$$\varepsilon_z=\varepsilon_{zo}-\frac{\psi^s}{V}\ln\left(\frac{t_o^s+t_e^s}{t_o^s}\right) \tag{5}$$

Yin [34] proposed a nonlinear function to describe the long-term creep strain considering the creep strain limit when time is infinite. This function is expressed as Eq. (6):

$$\varepsilon_z^c=\frac{\psi_o^c/V}{1+\frac{\psi_o^c}{\varepsilon_z^{cl}V}\ln\left(\frac{t_o^c+t_e^c}{t_o^c}\right)}\ln\left(\frac{t_o^c+t_e^c}{t_o^c}\right) \tag{6}$$

where t_o^c, ψ_o^c/V and ε_z^{cl} are three constant parameters related to creep. ψ_o^c/V is similar to the creep coefficient, ε_z^{cl} is the creep strain limit when the creep time is infinite, the value of ε_z^{cl} is the vertical distance between the reference time line and limit time line for creep. This nonlinear function has been adopted by researchers to analyze the nonlinear creep behavior for different types of soils [8,39,40].

Similarly, Eq. (6) is also proposed in this paper to consider the nonlinear swelling behavior, illustrated as Eq. (7):

$$\varepsilon_z^s=-\frac{\psi_o^s/V}{1-\frac{\psi_o^s}{\varepsilon_z^{sl}V}\ln\left(\frac{t_o^s+t_e^s}{t_o^s}\right)}\ln\left(\frac{t_o^s+t_e^s}{t_o^s}\right) \tag{7}$$

where t_o^s, ψ_o^s/V and ε_z^{sl} are three constant parameters related to swelling, and the superscript "*s*" indicates the swelling. t_o^s defines the beginning of the swelling behavior under saturated condition, t_e^s is the equivalent time for the swelling behavior, which will be explained later, ψ_o^s/V and ε_z^{sl} are also obtained from the experimental swelling strain. Eq. (7) can be written as:

$$-\frac{1}{\varepsilon_z^s}\ln\left(\frac{t_o^s+t_e^s}{t_o^s}\right)=\frac{V}{\psi_o^s}-\frac{1}{\varepsilon_z^{sl}}\ln\left(\frac{t_o^s+t_e^s}{t_o^s}\right) \tag{8}$$

If $\ln\left(\frac{t_o^s+t_e^s}{t_o^s}\right)$ is considered as one variable, and $-\frac{1}{\varepsilon_z^s}\ln\left(\frac{t_o^s+t_e^s}{t_o^s}\right)$ is taken as another variable, Eq. (8) is a straight line of the format: $y=a-bx$. Values of ψ_o^s/V and ε_z^{sl} can be obtained by fitting the experimental data.

The compositional and environmental factors, including the physical interactions, fabric and structures, stress history, stress path, temperature, affect the soil compression and swelling behavior [13]. Elastic Visco-Plastic (EVP) model is developed and accepted to describe the time-dependent stress-strain behavior based on the "equivalent time" concept in past decades. Recently, Tong and Yin [8] observed both the creep and swelling phenomenon for sand mixed bentonite (SMB) under one-dimensional (1D) oedometric conditions. Based on this observation and Eqs. (3) and (5), the Elastic Visco-Plastic model considering swelling (EVPS) was proposed by Yin and Tong [35] to consider both the creep and swelling behavior in 1D condition. However, when the time is infinite, the creep or swelling strain is also infinite for Eqs. (3) and (5). This is not logically correct, as there must be a final stress-strain state for both the creep and swelling equilibrium when the time is infinite. Yin [41] drew a conceptual model, including the swelling equilibrium line (SEL) and creep equilibrium line (CEL), and stated that there should be a neutral zone between the swelling equilibrium state and creep equilibrium state. In this study, it is intent to adopt the Eqs. (6) and (7) to improve the Elas-