Computers and Geotechnics 77 (2016) 134–155

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

An isotach elastoplastic constitutive model for natural soft clays

Chao Yang *, John P. Carter, Daichao Sheng, Scott W. Sloan

Centre of Excellence for Geotechnical Science and Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia

ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form 15 April 2016
Accepted 16 April 2016
Available online 7 May 2016

Keywords:
Elastoplasticity
Strain rate
Time
Plastic anisotropy
Cementation
Constitutive relations

ABSTRACT

The time and strain rate dependency observed in natural soft clays is formulated within the framework of conventional elastoplasticity. Creep of soft clays is essentially like the response of an overdamped oscillatory system, i.e., the strain rate decays in an exponential manner. A characteristic strain rate and time relationship is presented based on data from creep tests on a large number of different soft clays. The evolutionary change of strain rate is found to affect the mechanical response of soft clays in an isotach manner. Taking strain rate as another stress-like variable, a loading–isotach (LI) yield curve is proposed, which describes the combined hardening mechanisms of loading and variation of strain rate. Incorporation of this LI yield curve into critical state soil mechanics results in an isotach elastoplastic (IEP) model in triaxial stress–strain–strain rate space, which has been dubbed 'Hunter Clay'. The effects of fabric anisotropy and inter-particle cementation, which are typical features of natural soft clays, are also introduced to produce an advanced hierarchical constitutive model for soft clay. Qualitative predictions are first described and compared with the characteristic behaviour of natural soft clays. Experimental validations using test data for two soft clays are then carried out, and comparisons of the model predictions and experimental data demonstrate the capability of the model in reproducing realistic behaviour of natural soft clays. This work confirms that the complex mechanical behaviour of natural soft clays can be reproduced satisfactorily within the general framework of classical plasticity theory.

1. Introduction

Creep, which describes the continuous deformation of soft clays under constant effective stress conditions, has been actively investigated for decades (e.g., [4,32,69,26,23,72]). Increasing experimental observations tend to reveal that creep, as well as some other related engineering phenomena like relaxation, the effects of variable strain rate and undrained creep failure ('tertiary' creep), should be consistently attributed to the viscosity of the clay skeleton, and can be properly described via the dependence of its compressibility on time and strain rate [4,50,32,28,30]. Various constitutive models, for instance, empirical models (e.g., [50,55]), rheological models (e.g., [12,41]), and elastic viscoplastic (EVP) models (e.g., [1,49,67,16,71,6,51]), have been proposed to explain the time and strain rate-dependent mechanical behaviour of soft clay. Application of these constitutive models in engineering practice can result in significant improvements in predicting the long-term deformation of projects involving soft clays (e.g., [49,2,36,24,22]). It should be noted that the time and strain rate effects discussed in this paper only relate to the material viscosity of a single representative element of soil. They are not concerned with the time-dependent dissipation of excess pore water pressure in an initial or boundary value problem.

This paper attempts to clarify some issues with previous constitutive modelling of the time and strain rate dependence of soft clays, and proposes an alternative critical state model based on the classical theory of elastoplasticity. The description of the time and strain rate dependent stress–strain behaviour of soft clays has been closely linked with efforts to isolate the relevant strain variables describing soil behaviour. In critical state soil mechanics (e.g., [42]), the total strain variable consists of elastic and plastic components, both of which are assumed to be independent of time and strain rate. However, the majority of recent work in this field has opted for the viscoplastic strains to replace the original plastic strains in order to describe the time and strain rate effects observed in soft clays. Note that elastic strain is commonly assumed to be time and strain rate-independent for simplicity of the formulation. The experimental observation that the yield surface is not unique and varies with time and possibly strain rate, and the conjecture that the stress state can therefore lie "outside" the yield surface, led to the development of the popular overstress

* Corresponding author. Tel.: +61 2 49854996; fax: +61 2 49215500.
E-mail address: chao.yang@newcastle.edu.au (C. Yang).

http://dx.doi.org/10.1016/j.compgeo.2016.04.011

theory proposed by Perzyna [43]. One distinctive feature of this overstress theory is the correlation of the viscoplastic strain to the stress state, rather than the stress rate, as adopted in conventional elastoplasticity. Thus the rigorousness of classical plasticity theory, particularly in terms of the consistency condition and hardening laws, had to be sacrificed, although it was found that improved predictions could be provided by models based on Perzyna's overstress theory. Apart from this point, most EVP models of the overstress type inherit the other important components of classical elastoplasticity theory, e.g., the notion of yield and plastic potential surfaces, the plastic flow rule, incorporation of the effects of soil structure (cementation) and fabric anisotropy, and others.

There is another class of hybrid models (e.g., [7,20,69,16,64]), which assume that plastic straining in soils can occur instantaneously as well as in a delayed manner. In this case the total strain is correspondingly composed of a pair of time-independent elastic and plastic strain variables and another plastic (or viscoplastic) creep strain. It is noted that often the straining of geomaterials takes time to occur and it is therefore desirable to formulate within the same framework of classical elastoplasticity a time and/or strain rate-dependent constitutive model for natural soft clays.

By definition, the study of time and strain rate effects in soft soils has been commonly conducted considering two major aspects of their compression behaviour: (1) the effect of time and (2) the effect of strain rate. Representative studies of the time effects can be found in Bjerrum [4] and Yin and Graham [69,65,67]. Bjerrum [4] introduced a conceptual time line model for clays, where parallel normal compression lines were proposed to represent the effect of creep during a period of thousands of years after first sedimentation of the clay. The time lines defined by Bjerrum [4] correspond to constant durations of loading on normally consolidated clays. Yin and Graham [69,65] introduced the concept of equivalent time lines to extend Bjerrum's time line model to cover both normally consolidated and overconsolidated clays. Various time lines, e.g., the instant time line, instant normal compression line (or null creep time line), reference time line, equivalent time line and limit time line, were all proposed by Yin and his co-workers [69,65,67,70,74,64,73]. However, the time line concept appears to be difficult to implement in practice, as it might be impossible to determine these normal compression lines even for the life-time of an engineering project (i.e., typically up to a century). On the other hand, time, t, has been included explicitly to describe the change of volume (in terms of void ratio, e, or volumetric strain, ε_p) in creep tests in some models (e.g., [7,69,66]). One major difficulty for models that incorporate time effects in this way is the definition of an origin of time and its experimental determination, particularly when the applied load varies over time [30].

It appears that greater effort has been spent on examining the effects of strain rate on the compression behaviour of soft clays. Suklje [53] proposed the isotach model in which the compressibility of clays is considered to be strain rate dependent. The isotach concept has been experimentally validated for various types of clay by a number of researchers [55,33,34,32,31,28,25,38,30,57]. For example, Leroueil et al. [32] conducted a series of constant rate of strain (CRS) oedometer tests on Batiscan clay and some typical results are presented in Fig. 1. It can be seen that the stress–strain curves at different strain rates seem parallel to each other (Fig. 1a), and the yield stress tends to increase with increasing CRS (Fig. 1b). Leroueil et al. [32] then concluded that a unique stress–strain–strain rate (σ–ε–$\dot{\varepsilon}$) relationship could be proposed to describe the strain rate dependency of soft clays. This concept has been successfully extended to some other types of clay (e.g., [19,25,38,72,57]). However, Leroueil et al. [32] stated that this unique σ–ε–$\dot{\varepsilon}$ relationship obtained from CRS tests cannot explain relaxation tests, which have constant total strain and thus 'zero' strain rate. As such,

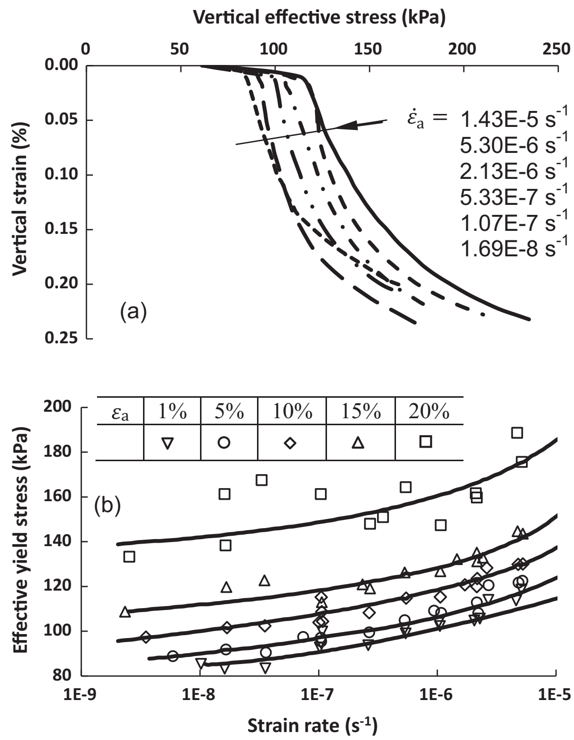

Fig. 1. Constant rate of strain (CRS) compression tests on Batiscan clay (data after [32]).

a plastic strain rate ($\dot{\varepsilon}^p$) was suggested to replace the total strain rate ($\dot{\varepsilon}$) and the modified σ–ε–$\dot{\varepsilon}^p$ relationship was applied by Kim and Leroueil [25], Marques et al. [38], and Watabe et al. [57]. The fact that experimental data are basically presented in terms of total (vertical) strain makes information on the plastic strain rate $\dot{\varepsilon}^p$ difficult to evaluate directly, in turn making it difficult for this σ–ε–$\dot{\varepsilon}^p$ relationship to solve 'real' problems [40]. As acknowledged by Leroueil et al. [32], the σ–ε–$\dot{\varepsilon}^p$ relationship, which was initially proposed based on experimental data for normally consolidated or lightly overconsolidated clays, might not be suitable to simulate creep and relaxation tests on heavily overconsolidated clay samples, for which the strain rate effect is generally small. Additionally, the information about the change of strain rate $\dot{\varepsilon}$ (or plastic strain rate $\dot{\varepsilon}^p$) is missing in the proposed stress–strain–strain rate relationship, and thus is unable to provide a direct prediction of creep and relaxation. Kim and Leroueil [25] resorted to the consolidation equation (a combination of mass conservation and Darcy's law) to describe the evolution of strain rate, which may intuitively solve the time effect of clay during primary compression (involving dissipation of excess pore water pressure) but is not sufficient to simulate secondary compression where creep dominates. The isotach approach first presented by Suklje [53] and subsequently developed by Leroueil and his co-workers, though a prominent methodology, still requires further clarification and development.

As well as being characterised by time and strain rate effects, natural soft clays are also often characterised by the effects of soil structure. Soil structure, as defined by Mitchell [41], commonly means the combined effects of fabric anisotropy (the arrangement of the solid particles or aggregates) and the inter-particle cementation (or bonding). A cross-anisotropic fabric, where the mechanical properties differ significantly between the vertical and horizontal directions, is inherent to many naturally deposited soft clays [15]. Conventional triaxial stress path experiments showed that