Computers and Geotechnics 85 (2017) 59–70

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

An elastic-viscoplastic double-yield-surface model for coarse-grained soils considering particle breakage

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ARTICLE INFO

Article history:
Received 18 May 2016
Received in revised form 10 December 2016
Accepted 12 December 2016
Available online 27 December 2016

Keywords:
Constitutive model
Coarse-grained soil
Shear creep
Compression creep

ABSTRACT

The proper modelling of time-dependent behavior, such as creep and strain rate effects, of coarse-grained soils (e.g., rockfills) is important to predict the long-term deformation of high-fill projects. In this paper, the primary features of coarse-grained soil are discussed, and an elastic-viscoplastic model is proposed for simulating its time-dependent behaviors in both shear and compression. The stress-dependence of the strength, dilatancy/contractibility and creep is carefully considered based on recent experimental findings. Verifications with various experimental results demonstrate that the model is capable of predicting the creep behavior in various stress states satisfactorily.

1. Introduction

In recent years, high-fill engineering projects have become increasingly common due to the construction of dams or embankments for infrastructures (e.g., airports, highways, etc.) in mountainous regions. The construction of these projects always involves considerable amounts of geo-materials being excavated from high places and filled into valleys, forming a high-fill ground using broken rocks or gravels. For example, the maximum filled height of the *Jiuzhai Huanglong Airport* is more than 104 m [15].

In contrast to ordinary projects, where stress levels are low and the time-dependent behaviors of filled coarse-grained soils are negligible, the stress level is clearly high in high-fill projects, which may induce a significant instantaneous as well as time-dependent increase in deformation [1,32]. In fact, considerable post-construction settlements have been observed for some projects [37], which could influence the operation and even cause stability problems [10,21]. Thus, the long-term stability and deformation of high-fill projects must be considered carefully. To describe the time-dependent behaviors of the filling materials and predict the long-term behaviors of high-fills, it is necessary to establish a proper constitutive model for this type of material.

To model the deformation behavior of a material, one needs to know the mechanism of the deformation, which is quite complex, especially for the creep of rocks. In modelling the time-dependent deformation of sedimentary rocks (e.g., shales), Pietruszczak et al. [26] attributed the creep of these rocks to the propagation of micro-cracks as well as the progressive change in their microstructures and proposed a mathematical framework to describe the creep. To model the creep of water saturated chalks, Pietruszczak et al. [27] and Lydzba et al. [16] proposed that the creep of chalks is due to the time-dependent degradation of the intergranular interface, which is caused by the chemo-mechanical interaction, i.e., the dissolution/diffusion within the intergranular interface in the chalks. On that basis they introduced a multiscale framework to describe chalk creep. In these studies, the macroscopic models are established using the mechanism at a micro-level. The philosophy is quite reasonable, but extensive work is still required to determine the quantitative relationship between the macro-phenomenon and the micro-mechanism. Coarse-grained soil consists of broken rock particles, whose short-term and long-term deformations are closely related with the individual grains, and their interactions affected by the environment. The mechanism behind its creep is more complicated. The primary cause of coarse-grained soil creep is commonly recognized as the time-dependent breakage of the rockfill grains, especially those with a large size and angular shape [1,17]. There must be also time-dependent degradation of inter-grain contacts due to some chemo-mechanical process. Currently, it is still difficult to establish constitutive models intended for the analysis of practical problems directly on the micro-mechanism. Tapias and Alonso [32] and Zhou and Song [51] used DEM (Discrete Element Method) to simulate the time-dependent crack of particles and predict the creep deformation of rockfills. The method proposed may be suitable for

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http://dx.doi.org/10.1016/j.compgeo.2016.12.014
0266-352X/

research but is not yet applicable for practical analysis. Thus, the model here is proposed on the basis of macro-scale creep experiments, and the viscoplastic theory is used as a phenomenological description of creep while considering particle breakage.

Based on laboratory tests, it is observed that the mechanical characteristics of coarse-grained soils are prominently different from that of fine grained soils (e.g., clays and silts) due to particle crushing [11,14]. The following 4 features have been observed. (1) Non-linear strength. Its friction angle decreases with the confining pressure. (2) Dilatancy and contractibility. It demonstrates a more pronounced shear contractibility under high pressures and a shear dilatancy under low confining pressures [41]. (3) *Isotach* behavior. The behavior of this material in drained shearing fits the *Isotach* hypotheses. A faster loading strain rate corresponds to a higher shear stress and failure strength [2,34]. (4) Stress level dependence of the creep coefficient. It has been discovered through previous studies on crushable sands [6] and recent experiments on soil-rock mixtures and rockfills [42] that the creep coefficient (*coefficient of secondary compression*) for coarse-grained soils varies with the applied load.

The first two features have been considered in a few elasto-plastic models. For example, Xu and Song [41] and Cao [5] performed modifications to the Mohr-Coulomb failure envelope and Rowe's dilatancy using these considerations. Wang & Yao [40,48] considered the effects of particle breakage on the time-independent mechanical behaviors in the UH model with a single yield surface. However, there are few models thus far that have given sufficient consideration to reflect features 3 and 4 in describing the creep behavior of coarse-grained soils.

The currently available models simulating the time-dependent behavior of coarse-grained soils are mostly phenomenological, which can be primarily categorized into the following three types.

The first type is the single-yield-surface model. These models were originally proposed for soft soils based on oedometer tests or isotropic compression tests, and they are widely accepted nowadays, e.g., the Soft Soil Creep model [36] and the Hunter Clay model [43], for the deformation analysis of soft soils. Some researchers assumed that the creep behavior of coarse-grained soil is similar to that of soft soil. For instance, Wahls (1965) [37] and Parkin [22] once concluded from certain oedometer tests that the compression creep of coarse-grained soils fit a time-logarithm pattern similar to the secondary compression of soft soils. Based on this view, single-yield-surface creep models for soft soils were also applied in the coarse-grained soil calculation [23]. Although the viscoplastic framework is applicable to coarse-grained soils, the application above has at least two defects: (1) The loading rate dependence of the material strength, i.e., feature 3 of the coarse-grained soil mentioned above, cannot be reflected by the existing single-surface models. Indeed, they can simulate the creep and rate-dependent behavior in compression. However, for shear deformation, the drained shear strength simulated is irrelevant to the loading rates because the calculated effective stress of the soil at failure will lie on the critical state line, whose location does not change with time. (2) The stress dependence of the compression creep coefficient, i.e., feature 4 of the coarse-grained soil mentioned above, cannot be reflected. Most of the currently available models use the compression creep law of soft soils, where the creep coefficient is independent of the stress level. This is different from what has been observed from creep tests on coarse-grained soils, as previously mentioned. In the literature, there are a few creep models for soft soils formulated with double yield surfaces [20,38] that can overcome certain disadvantages of the current models and better describe the drained shear creep behavior using a yield surface different from that for compression creep.

The second type is the time-hardening model [13,44]. In time-hardening models, the creep strain calculated by the model for a given time merely depends on the current stress state and the time duration from the start to the current moment. Thus, the creep strain is irrelevant to any previous stress states in the time history, i.e., the effects of the loading path and loading history are neglected.

The third type is the component model. A component model uses a combination of springs, dampers and plastic elements to compose a mechanical model. Tatsuoka et al. (2006) [33] proposed an *Isotach* component model for granular materials, in which the strain-stress-time relationship in shearing was simulated using the combination of several components. It is a shear model which can represent the *Isotach* shear behavior of granular materials well, and is validated by several constant rate loading tests, varying rate tests and creep tests. However, consideration is not sufficiently given for such models to simulate the compression behaviors of soil, such as compression hardening and compression creep. Much work is needed to ensure such models suitably simulate the soil behaviors for both shearing and compression.

It can be seen from the above discussion that the currently available creep models are insufficient to describe the primary characteristics of coarse-grained soils, and improvements are required. Some of them considered the strength features but failed to suitably describe creep, and some other models considered creep behaviors but neglected the time effects on drained strength. In constructing a constitutive model for coarse-grained soils, the material's distinctive characteristics should be included so that better simulations of the deformation for high-fills can be achieved. Moreover, because soils in the high-filled ground may be subjected to various stress states, both shear creep and compression creep can be significant during the lifecycle of the filled body, which can be better described using double yield surfaces.

The aim of this paper is to present a practical model for the stress-strain-time behaviors of coarse-grained filling materials, especially *rockfills*, which are consistent with previous experiences and recent experimental observations. The proposed model is a double-yield-surface hardening model based on the *elastic-viscoplastic* (EVP) framework. The primary features that are different from the previous EVP models consider both shear creep and compression creep, suitability for creep behavior in various stress states, stress dependence and the effects of particle crushing on the material parameters relative to strength and deformation. The model is established using available experimental findings from literature as well as the authors' group. Even though the underlying physico-chemical mechanisms are not directly considered in the model, the phenomena induced by the time-dependent breakage of grains are properly considered. Then, the proposed model is implemented into a finite element program and validated with various experimental results.

2. Model description

The proposed model is based on the elastic-viscoplastic (EVP) framework. In the EVP framework [24,25], the total strain rate tensor $\{\dot{\varepsilon}\}$ can be decomposed into an elastic strain rate tensor $\{\dot{\varepsilon}^{e}\}$ and a time-dependent viscoplastic strain rate tensor $\{\dot{\varepsilon}^{cr}\}$ as follows:

$$\{\dot{\varepsilon}\} = \{\dot{\varepsilon}^{e}\} + \{\dot{\varepsilon}^{cr}\} \tag{1}$$

where $\{\dot{\varepsilon}^{e}\}$ is calculated based on the generalized Hook's law, and the elastic modulus takes the value of the unloading-reloading modulus [50], which is dependent on the minor principal effective stress $E_{ur} = E_{ur}^{ref}(\sigma_3'/p^{ref})^{m}$. In the following sections, the direction and magnitude of tensor $\{\dot{\varepsilon}^{cr}\}$ will be derived from the strain-stress-time relationships observed in relevant experiments.