Computers and Geotechnics 80 (2016) 215–225

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Modeling the compression behavior of remolded clay mixtures

X.S. Shi *, I. Herle

Institute of Geotechnical Engineering, Technische Universität Dresden, D-01062 Dresden, Germany

ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form 23 June 2016
Accepted 13 July 2016

Keywords:
Open-pit mining
Clay mixture
Compression model
Homogenization
Yield stress

ABSTRACT

Clay mixture is a waste material in open pit mining from the excavation of various soil layers. In the present study, a general constitutive framework is proposed for the prediction of compressibility of remolded clay mixtures. First, the resulting structure of a clay mixture is simplified as a composite structure, in which the elements of the constituents are randomly distributed in a representative elementary volume. Afterwards, the initial water contents of the constituents are estimated based on a simplified model for the undrained shear strength of the clay mixture. Then, the representative elementary volume of the mixed soil is divided into separate individual parts and the volume fractions of the constituents are formulated as functions of the overall porosity and those of the constituents. Finally, a homogenization law is proposed based on the analysis of the randomly arranged structure together with a simple compression model for clay mixtures. Parameters required by the model correspond only to the constituents, which are simple to calibrate based on standard laboratory tests. By making comparisons of the predictions with test data, it is shown that the proposed model can well represent the compression behavior of the clay mixtures.

1. Introduction

After an excavation cuts different soil layers in an open pit mine, the excavation waste is displaced from the original site to a deposition place via a conveyor belt which can be several kilometers long. Two possible soils may result from this process. The first one is a lumpy soil with a granular structure [4,14,20,24]. The other one is a clay mixture which is homogeneous in a macroscopic point of view [25]. The structure of the resulted material depends on the mixing intensity (the length of the conveyor belt) and the strength of the original soils. If the original clay has a relatively high strength, the excavated lumps can keep their original structure during a relatively short distance of transportation, thus a granular structure prevails. However, if the original soil has a low strength or a long transportation takes place, the material may disintegrate into small lumps and soils from different layers can be thoroughly mixed. The pore fluids in the constituents are assumed to be the same after being mixed. A new clay composite structure arises in this way.

The deposited clayfills may reach depths of several tens of meters without compaction (see Fig. 1, right). The initial water content may be relatively high, thus a large settlement can be expected. A deformation at a constant total stress level and the accompanying transient behavior (including primary and secondary consolidation) are important for the design of landfills. In this work, the authors deal with the compression behavior which is a basis for the transient analysis.

To give a theoretical estimation for the compressibility of clayfills from clay mixtures, the following questions need clarification:

(1) As mentioned above, a clay mixture seems homogeneous on a macro-scale. Actually, each of the constituents follow its own regime from a microscopic point of view and the overall behavior of the clay mixtures is a combination effects of the constituents. Hence, a reasonable description for the representative elementary volume of a clay mixture is needed.
(2) The constituents of the clay mixture can not keep their original (natural) water contents due to different water holding capacities of the clay minerals [23,19], i.e. a redistribution of the water contents for the constituents may happen. Note that chemical effect may also change the pore fluid chemistry in the clay mixtures, leading to a water content redistribution in the constituents. For simplicity, this effect was not included in this work.
(3) The structure of the clay mixtures is highly complex. Therefore, we need to simplify it of the clay mixtures and to obtain a homogenization law considering the overall stiffness and those of the constituents.

* Corresponding author.
E-mail addresses: Xiusong.Shi@mailbox.tu-dresden.de (X.S. Shi), Ivo.Herle@tu-dresden.de (I. Herle).

http://dx.doi.org/10.1016/j.compgeo.2016.07.007
0266-352X/

Fig. 1. Excavation of the soil layers (left) and deposition of the mixed clays (right) in the open-pit mining.

Shi and Herle [25] have performed a series of oedometer and fall cone tests to investigate the compression and undrained shear strength of clay mixtures. The considered soils were a high plasticity clay and a silty clay (desidas Clay1 and Clay2, respectively, in this paper). The tests included a wide range of initial water contents (between 0.8 and 1.5 times the liquid limit) and 6 different dry mass fractions of the Clay1 (5%, 10%, 20%, 40%, 60% and 78%, respectively). In the following, a few conclusions from the above mentioned test results are summarized.

(1) Similarly to the constituents, the undrained shear strength of a clay mixture can be well normalized by the liquid limit. Its magnitude follows from a combination of the constituents in an appropriate proportion.
(2) Both the initial water contents and the volume fractions of the constituents have a significant influence on the compression behavior of a clay mixture. More specifically, the compressibility of a clay mixture increases with the initial water content and the volume fraction of the constituent with a higher compressibility.
(3) The compression curves of the clay mixtures can be divided into two regimes according to the compressibility. Similar to the natural soils, the stiffness of clay mixtures in oedometer tests changes significantly in the vicinity of a stress level, which corresponds to the pore water suction [22,19].

2. Initial water content distribution

A simple model was proposed by Shi and Herle [26] for the undrained shear strength and initial water content distribution of a clay mixture. In the model, the structure of a clay mixture was simplified as a composite structure, in which the elements of the constituents are randomly distributed in a representative elementary volume (see Fig. 2).

The model proposed by Shi and Herle [26] is based on two constituents. In this paper, a clay mixture with N constituents will be analyzed. The water content ratios are defined as

$$k_i = \frac{w_i}{w_N}; \quad (i = 1, \ldots, N) \tag{1}$$

The overall water content of the mixture w_m can be derived from its definition:

$$w_m = \sum_{i=1}^{N} f_i w_i \tag{2}$$

where f_i is the dry mass fraction of the ith ($i = 1, \ldots, N$) constituent, defined as the ratio between the dry mass of the constituent and the total dry mass of the mixture;w_i is the water content of the ith ($i = 1, \ldots, N$) constituent. Combing Eqs. (1) and (2), the water content of the Nth constituent can be calculated as

$$w_N = \frac{w_m}{\sum_{i=1}^{N} f_i k_i} \tag{3}$$

Considering Eqs. (1) and (3), the water content of the constituents can be derived as

$$w_i = k_i \xi w_m (i = 1, \ldots, N); \quad \xi = \frac{1}{\sum_{i=1}^{N} k_i f_i} \tag{4}$$

If one assumes for each constituent that it local elements (Fig. 2) reach their limit stress at the same time when the overall stress is at its limit stress state,[1] the undrained shear strength of the clay mixture $c_{u,m}$ can be estimated as

$$c_{u,m} = \sum_{i=1}^{N} \phi_i * c_{u,i} \tag{5}$$

where ϕ_i denotes the volume fraction of the ith constituent. Note that the definition of water content (Eq. (2)) is based on the masses, thus mass fractions are used; However, the undrained shear strength is defined within the homogenization framework, therefore the volume average definition is adopted. $c_{u,i}$ is the corresponding undrained shear strength which can be estimated after Hong et al. [9]:

$$c_{u,i} = 1.40 \left(\frac{w_i}{w_{L,i}} \right)^{-4.5} p_0 \quad (i = 1, \ldots, N) \tag{6}$$

where $p_0 = 1$ kPa is the reference stress (the above conclusion is based on analysis of 115 different soils), $w_{L,i}$ ($i = 1, \ldots, N$) is the liquid limit of the ith constituent. Eq. (6) was experimentally validated by Shi and Herle [25] for the investigated soils. The undrained shear strength of a clay mixture thus follows from Eqs. (1), (4)–(6). The water content ratios k_i ($i = 1, \ldots, N$) can be calibrated by trial and error attempt. After experiments and model analysis by Shi and Herle [25,26], the water content ratio of the constituents can be approximated by the ratio between the corresponding liquid limits for different mass fractions of the constituents.

$$k_i = \frac{w_{L,i}}{w_{L,N}}; \quad (i = 1, \ldots, N) \tag{7}$$

From Eqs. (1)–(7), the undrained shear strength of a clay mixture can be estimated. The comparison between the test data and the model is shown in Fig. 3 (test data from [25]). The consistence between the model and the experimental data indicates that the water content ratio of the constituents equals the ratio between the corresponding liquid limits in a wide range of water contents of the clay mixtures. Note that the undrained shear strength of the clay mixtures were tested in completely remolded state. Hence, the water content distribution can be regarded as a initial state for

[1] This assumption was also used by Wang et al. [29] for mixed materials.