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An effective constitutive model for lime treated soils

V. Robin [a,b], A.A. Javadi [a,*], O. Cuisinier [b], F. Masrouri [b]

[a] Computational Geomechanics Group, Department of Engineering, University of Exeter, United Kingdom
[b] LEMTA – UMR 7563 CNRS, Laboratoire d'Energétique et de Mécanique Théorique et Appliquée, Université de Lorraine, France

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ABSTRACT

The effect of lime on the yield stress, and more generally the presence of structure in the soil, is usually not accounted for in the design of geotechnical structures. As a result the potential of lime treatment or of a structured soil has not been fully exploited. This paper presents a new formulation to account for the effect of structure on the mechanical behaviour for structured soils. A constitutive model is proposed in the framework of the Modified Cam Clay model to describe the behaviour of lime treated soils. The new formulation introduces a limited number of additional parameters, all of which have a physical meaning and can be obtained from an isotropic compression test. Due to similarity in behaviour of lime treated soils and naturally structured soils, the formulation can be applied to both types of soil. It is shown that the proposed model can successfully reproduce the main features of both structured soils such as maximum rate of dilation at softening and degradation at yield. The model can be applied for any structured material regardless of the origin of cementation.

1. Introduction

The use of on-site materials has become a central issue for civil engineering companies, but it is sometimes difficult to deal with all the resources available on site. For soils with low mechanical characteristics, lime treatment appears to be an efficient method to improve their mechanical properties and allow their use in geotechnical earth structures (e.g. [23]). The effects of the addition of lime on the soil parameters such as cohesion and friction angle have been extensively studied (e.g. [6]). Nevertheless, lime is still mostly used to dry soils with high water contents and increase the bearing capacity. However, it is also generally known that adding lime leads to a significant increase of the yield stress and modifies other mechanical parameters in compacted soils. In lime-treated soils, the modification of the mechanical behaviour results from several physico-chemical processes associated with the increase in calcium concentration and pH (i.e. cation exchange, pozzolanic reactions, etc.).

From an economical point of view, it is becoming increasingly important to account for the properties of treated materials in the design of the geotechnical structures. However, despite its proven efficacy, the use of treated materials suffers from several major drawbacks: there is no reliable method to account for the structure in the calculations. At yield, and for an increasing mechanical loading, treated materials experience what is called the "loss of structure", resulting in the degradation of the structure in different ways. To model the behaviour of these materials, a constitutive law describing the behaviour at yield is a requirement.

Some studies [26,3,22,25,16] have shown that naturally structured soils and artificially treated materials have common mechanical features; artificial treatment appears to create a "structure" in the soil. In this paper, "structure" refers to Burland's definition [7], and is seen as the combination of the fabric and the bonding of the soil skeleton. Fabric accounts for the arrangement of particles, which depends on the state of compaction and their geometry.

Several constitutive models have been proposed for structured materials. Most of these models use the destructured state as reference to describe the mechanical behaviour of structured soils. [24] proposed a constitutive model, based on the Modified Cam Clay model (MCC), by adding three additional parameters to the original MCC [36]. Since then, several enhancements (e.g. [18,40]) have been proposed. However, various modes of destructuration have been identified, and the original formulation fails to model some of them. A number of other formulations have been developed [19,42,30,5,38,29] and some of which give good agreement with experimental results. However, it often comes at the cost of a larger number of parameters, or high computational resources (e.g. mapping rule). Parameters do not always have a physical meaning, and some of them can be difficult to determine. All these limitations make these models difficult to be used in engineering practice.

* Corresponding author.

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The main objective of this paper is to propose a general and simple formulation capable of fulfilling some fundamentals criteria regarding the degradation of the structure. This model must be capable of modelling any kind of degradations, and require a limited number of parameters to account for the maximum number of features of structured materials. These parameters should be rapidly obtained from classic experimental tests, and they all must have a physical meaning. To this end, the paper will focus on two aspects:

- How can the key features of structured or lime treated materials be described?
- How can these features be efficiently accounted for in a constitutive model?

This paper is divided into four parts. The first part gives a review of the main characteristics of naturally and artificially structured materials that must be reproduced by the model. The second part introduces the theoretical framework chosen for the model for lime treated soils (MLTS) and the new formulation developed to model the degradation of the structure. In the third part, the developed formulation is used to calculate the compliance matrix and obtain the stress–strain relationship. Finally, in the last part, we assess the suitability of the model in predicting experimental results obtained from triaxial tests on artificially (i.e. lime treated) and naturally structured materials.

2. Features of structured soils

The mechanical behaviour of naturally and artificially structured material has been extensively studied [22,17,8,13,27,15,14,11,31,34] and some specific features have been identified. Several studies have pointed out that naturally and artificially structured soils have a similar mechanical behaviour. In this section, we identify the key features common to naturally and artificially structured soils that should be properly reproduced by a model.

2.1. Naturally structured soils

It has been shown that naturally structured soils have a higher yield stress compared to the destructured state [8], the latter being usually considered as the reference state. For the same stress state, a higher yield stress leads to a higher void ratio at yield compared to the destructured state, called the additional void ratio Δe. Once plastic deformations take place, one can observe that the additional void ratio decreases. Depending on the material, the additional void ratio can quickly or slowly decrease until the material reaches a normal compression line (ncl), which can correspond to the ncl of the reference state (ncl_d), or a different one, parallel to the reference ncl but vertically translated along the v axis (ncl_r) [5,10,40]. More generally, 4 modes of degradation can be identified (Fig. 1):

Mode 1: Destructuration takes place immediately at yield. The additional void ratio progressively decreases until it converges toward the destructured state [45,20].

Mode 2: Destructuration takes place immediately at yield, but it does not converge toward its destructured state. A different ncl appears parallel to the destructured state, but a residual additional void ratio still remains [8,32].

Mode 3: No significant destructuration is observed immediately after yield. The process of degradation is initiated later on for a higher effective mean stress and the additional void ratio completely disappears [10].

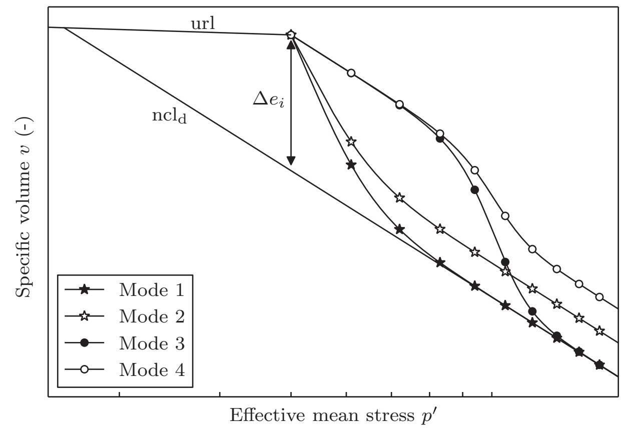

Fig. 1. The four different modes of destructuration in structured soils – ncl_d: Normal compression line of the destructured state, url: Unloading–reloading line.

Mode 4: No destructuration is observed immediately after yield. The process of degradation is initiated later on for a higher effective mean stress. However, a residual additional void ratio remains [37].

Additionally, the volumetric behaviour of naturally structured soils was compared with the destructured state by Leroueil and Vaughan [22] on heavily overconsolidated specimens from drained triaxial test results. They identified two different mechanisms taking place. While the maximum rate of dilation was measured before the peak of the deviatoric stress for the destructured soil, it was observed after the peak of the deviatoric stress for structured soils. This is due to the structure, which binds soil particles together. To allow the particles to move freely, the structure has to be degraded first to release particles [22].

2.2. Lime treated soils

Several studies have shown that addition of lime leads to an increase of the yield stress compared to the untreated state

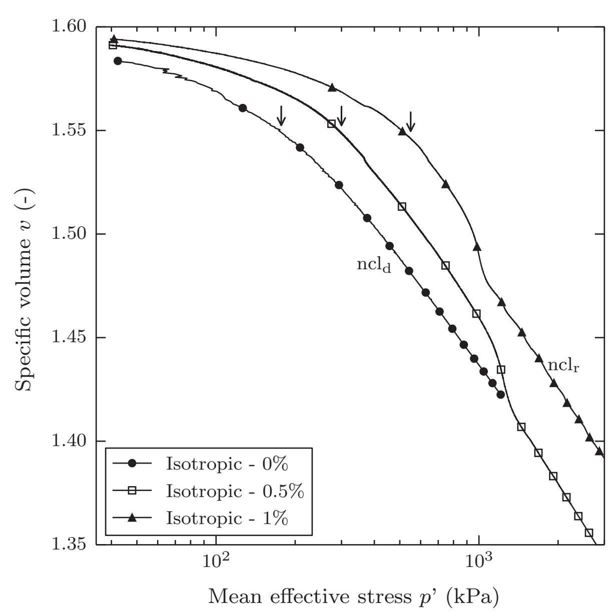

Fig. 2. Isotropic consolidation curves obtained from specimens of silt treat at 0.5% and 1% in lime – Arrows mark the yield stress p'_y, ncl_d: Normal compression line of the destructured state, ncl_r: Normal compression line of the residual state [34].