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Simplifying calibration of bonded elasto-plastic models

Sara Rios [a,*], Matteo Ciantia [b], Nubia Gonzalez [c], Marcos Arroyo [b], António Viana da Fonseca [a]

[a] CONSTRUCT-GEO, Faculty of Engineering (FEUP), University of Porto, Portugal
[b] Departamento de Ingeniería del Terreno, Universidad Politécnica de Cataluña, Barcelona, Spain
[c] REPSOL I+D, Madrid, Spain

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ABSTRACT

Using realistic constitutive models for artificially cemented soils is advantageous in design. However, the price of that increased realism is often a more elaborate model, which is difficult to calibrate. A database of high quality triaxial tests on compacted cemented silty sand is used to calibrate and validate a generalized critical state bonded soil model. The exercise highlights the staged calibration procedure that is convenient in this kind of application. The calibration results have shown a direct relation between added yield strength and a well-established soil–cement mixture ratio, which facilitates the application of the model in design. It is shown that such relation can be also deduced from the analysis of unconfined compressive strength tests.

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1. Introduction

Artificially cemented soils are extensively used in a variety of geotechnical engineering applications. Cement improved soils are generally stronger and stiffer but more brittle than the parent soil. The effects of stress level and strain history on stiffness and strength are modified by the presence of cement. Broadly speaking, strain-hardening soils are transformed into strain-softening materials. Densification, which is generally positive for non-cemented soils, might become undesirable after treatment.

Accurate modelling of the mechanical behavior of improved soil is important, either because they directly have some structural role (e.g. soil–cement columns beneath an embankment) or because mechanical integrity is a prerequisite for its function (e.g. an isolating barrier for a contaminated zone). Many practical rules and approximate solutions are available for design of structures incorporating improved soils (e.g. [1]). However, when some circumstance makes those rules inapplicable or uneconomical, numerical analysis will be typically required.

How to represent the mechanical behavior of the improved soil in numerical analysis is subject to some debate. Treated soils are intermediate materials between soils and rocks and several analogies are possible. For instance, elasto-plastic Mohr–Coulomb models incorporating residual strength such as those used for rocks (e.g. [2]) have been applied to model cement treated clay [3]. Similarly, and because improved soils have analogies with concrete, cemented soils have been represented adapting models originally developed for concrete [4]. Taking a different perspective, a number of researchers have successfully extended elasto-plastic models for soils of the critical state tradition to represent artificially cemented clays [5] and silts [6]. This approach is directly inspired by a long line of constitutive models originally developed for naturally structured soils and soft rocks [7–10].

Despite all those developments it is fair to say that simplified, elastic perfectly plastic models (with either a Mohr–Coulomb or Tresca failure criterion) still dominate numerical applications (e.g. [11,12]). It is accepted that this type of model may neglect many important features of cemented soil behavior, but it appears easy to calibrate. Alternative material models, which may represent with more accuracy the target behavior, are perceived as difficult to calibrate, particularly when the practical constraints of treated soil investigation are noted (limited “in situ” testing; dominance of simple tests like UCS – Unconfined Compressive Strength).

Indeed, if calibration procedures remain difficult, there will be very limited use of advanced constitutive models in practice. That may be disadvantageous, because several examples [5,3] show that structure-scale responses predicted numerically are strongly

* Corresponding author at: Department of Civil Engineering, Faculty of Engineering of the University of Porto, R. Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal. Tel.: +351 225081728.

E-mail addresses: sara.rios@fe.up.pt (S. Rios), matteo.ciantia@upc.edu (M. Ciantia), nubiaaurora.gonzalez@repsol.com (N. Gonzalez), marcos.arroyo@upc.edu (M. Arroyo), viana@fe.up.pt (A.V. da Fonseca).

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dependent on the constitutive model and that elastic-perfectly plastic models may not capture all relevant failure modes.

To address this problem, models that are not just accurate but also as simple to calibrate as possible are necessary. The purpose of this work is to contribute to that goal of simplified calibration. A bonded elasto-plastic constitutive model, previously used to simulate cemented Bangkok clay [5] behavior, is here used for a very different cemented soil, namely compacted cemented silty sand. While the Bangkok clay case was representative of products obtained by deep mixing "in situ", the case presented here is representative of the cemented soils used within engineered fills. In what follows, after introducing the constitutive model and the target material, the calibration process is described, extracting general lessons that will facilitate further application of bonded elasto-plastic models.

2. Case description

2.1. Constitutive model

The constitutive model formulation is based on the original model for clays and sands (CASM) developed by [13]. CASM is an elasto-plastic single surface model of the critical state tradition that has been used as a starting point to develop more advanced soil models by several researchers [6,14,15]. The model applied in this work, called herein "Cemented CASM" (C-CASM) is part of a suite of advanced models based on CASM that are described in [16]. This model has already been successfully applied to clays, both naturally structured [17,18], and artificially cemented [5]. However, it is the first time a cemented granular soil is calibrated with this model.

C-CASM extends CASM introducing a new basic state variable, b, to represent the intact amount of intergranular bonding as defined by [19]. The shape of the yield surface is assumed to be the same in uncemented and cemented conditions. Bonding (b) modifies the yield surface, enlarging it with increasing amount of cementation. The way the yield surface is affected by bonding (b) is expressed using two separate intermediate or derived state variables, p'_c and p'_t, which control respectively the isotropic compression yield and the tensile yield of the soil (Fig. 1). These intermediate variables are:

$$p'_c = p'_s(1 + b) \tag{1}$$

$$p'_t = \alpha p'_s b \tag{2}$$

where p'_s is the equivalent preconsolidation pressure, and α is a model parameter, controlling the tensile strength derived from cementation (see Fig. 1).

The yield surface is given by Eq. (3),

$$f = \left(\frac{q}{M(p' + p'_t)}\right)^{\bar{n}} + \frac{1}{\ln r}\left(\frac{p' + p'_t}{p'_c + p'_t}\right) \tag{3}$$

where M is the stress-ratio (q/p') at critical state. Several flow rules can be implemented in C-CASM. Rowe stress-dilatancy relationship is used here,

$$d = \frac{\dot{\varepsilon}^p_v}{\dot{\varepsilon}^p_q} = \frac{9(M - \eta)}{9 + 3M - 2M\eta} \tag{4}$$

where $\dot{\varepsilon}^p_v$ is the incremental plastic volumetric strain and $\dot{\varepsilon}^p_q$ the incremental plastic shear strain.

The equivalent preconsolidation pressure evolves following the classical critical state hardening rule,

$$\frac{\dot{p}'_s}{p'_s} = \frac{\dot{v}}{\lambda - \kappa} \tag{5}$$

λ and κ are compressibility parameters of the reference material (Fig. 1).

Following [19] bonding b is degraded exponentially with accumulated plastic damage h,

$$b = b_0 e^{-h} \tag{6}$$

$$\dot{h} = h_1 \dot{\varepsilon}^p_v + h_2 \dot{\varepsilon}^p_q \tag{7}$$

where b_0 is the initial bonding and h_1 and h_2 are two material parameters. The elastic stiffness for cemented materials is made dependent on bonding [15],

$$\kappa_c = \frac{\kappa}{1 + \sqrt{\frac{p'_s b}{p}}} \tag{8}$$

The model requires specification of 10 parameters, seven of which describe the reference uncemented material, and initialization of two state variables, apart from effective stress.

A version of C-CASM valid for general stress paths and requiring no further parameters was coded into the finite element code PLAXIS, which has a facility to implement user-defined (UD) soil models. Further details can be found in [16].

2.2. Compacted cemented silty sand

Several cemented granular materials were created by mixing cement, water and a silty sand, weathering product of Porto granite. This is a well characterized soil and extensive geotechnical data has been gathered both for the parent soil alone [20] and for its mixtures with cement [21–24].

The calibration presented here uses a series of 38 triaxial tests on soil–cement mixtures The series includes isotropic, undrained and drained triaxial compression tests performed on soil–cement mixtures obtained using percentages of Portland cement (CEM I 52.5 R) between 0% and 7% of the soil dry weight. Two separate ranges of isotropic confining pressures were applied: in the low pressures 30, 80, 100 and 250 kPa were used while for the high pressures the specimens were submitted to 10 and 20 MPa. Specimens for testing were obtained by static compaction immediately after mixing covering a range of initial void ratios between 0.58 and 0.78. Initial void ratio and cement content were selected so that mixture ratio parameter ($n/C_{iv}^{0.21}$) values were clustered in two groups, around 30 and 40. The test conditions of every test are tabulated within the supplementary material to this paper; more detail on the experimental procedures and results can be found in [21]. Here it is just recalled that two different laboratories were involved, (one for low pressure tests, another for high pressure tests), and that all cemented samples showed clear signs of shear localization after dismounting.

3. Calibration process

3.1. Introduction

Because of the relatively large database that is available here different strategies for calibration may be adopted. A staged approach is applied, as follows:

1. Definition of a procedure for initialization of the CASM state variable, p'_s.
2. Calibration of the basic CASM parameters for the uncemented, reference material (ν, κ, N, λ and M).
3. Calibration of the advanced CASM parameters for the uncemented, reference material. These are the two parameters controlling the shape of yield surface (r and $\bar{n}$).

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