Computers and Geotechnics 48 (2013) 293–303

Contents lists available at SciVerse ScienceDirect

Computers and Geotechnics

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

Parameter identification for elasto-plastic modelling of unsaturated soils from pressuremeter tests by parallel modified particle swarm optimization

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ARTICLE INFO

Article history:
Received 8 June 2011
Received in revised form 12 May 2012
Accepted 15 August 2012
Available online 13 October 2012

Keywords:
Barcelona Basic Model (BBM)
Parameter identification
Hybrid moving boundary particle swarm optimization (hmPSO)
Pressuremeter test
Parallel computing

ABSTRACT

This paper presents a methodology for the identification of parameter values in the Barcelona Basic Model (BBM) by inverse analysis of the experimental cavity pressure–cavity strain curve from pressuremeter tests in unsaturated soils. This methodology involves a high-dimensional optimization process which is particularly challenging due to the existence of a large number of local minima caused by the nonlinearity of the BBM. A novel parallel modified particle swarm optimization algorithm is utilized to minimize the difference between measured and computed values on the cavity pressure–cavity strain curve. The computed cavity pressure–cavity strain curve is obtained by using a finite element model of an unsaturated soil whose mechanical behaviour is described by the BBM. An example is presented to validate the proposed methodology making use of artificial experimental results that had been calculated by a finite element simulation of pressuremeter tests. Finally, the application to a real case is presented by showing that the proposed methodology can safely identify the values of at least six BBM parameters via inverse analysis of pressuremeter tests at different suction levels.

1. Introduction

Research into the constitutive behaviour of unsaturated soils has traditionally focused on the interpretation of material behaviour rather than on the selection of parameter values inside specific constitutive models. Currently there are a number of constitutive models, which are able to capture the main features of unsaturated soil behaviour [1–6]. However, a major obstacle to the use of these models is the need to determine a relatively large number parameter values, requiring costly and time consuming laboratory tests on small scale undisturbed samples.

In situ testing provides an appealing alternative to small scale laboratory experiments because it is generally less expensive and allows faster material characterization. In particular, pressuremeter tests have been widely used to obtain in situ measurements of stiffness and strength in saturated soil deposits. A pressuremeter test consists of the application of an increasing pressure to the sidewalls of a section of a cylindrical borehole by an inflatable probe (the pressuremeter), previously lowered to the required depth. The pressure applied by the pressuremeter is plotted against the corresponding radial expansion of the borehole to give what is conventionally referred to as the "cavity pressure–cavity strain" curve (the cavity strain is the change in the borehole radius divided by the initial radius). Unlike laboratory tests, pressuremeter tests do not require coring of samples from the field, thus limiting soil disturbance prior to testing. This feature is especially advantageous for unsaturated soils, which are often characterized by an open soil fabric with large pores and a metastable structure held together by suction that makes sampling difficult. Pressuremeter tests are widely used for the determination of the engineering properties of saturated soils. However, they are still only tentatively employed for the characterization of unsaturated soil deposits because of the lack of recognized experimental standards and reliable interpretation methods.

Soil parameters can be obtained from pressuremeter tests by performing an inverse analysis of the cavity pressure–cavity strain relationship measured in the field. In order to achieve this, the pressuremeter test is usually simulated as the expansion of an infinitely long cylindrical cavity inside an unbounded uniform medium by using closed-form analytical solutions or approximate numerical models, such as finite elements [7–12]. Closed-form analytical solutions are normally preferred to numerical models because they reduce computational costs and offer greater accuracy. However, if the complexity of the soil constitutive model makes it difficult to obtain a closed-form solution, the use of approximate numerical models becomes the only viable alternative. Moreover, in most elasto-plastic models, a relatively large

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http://dx.doi.org/10.1016/j.compgeo.2012.08.004

number of parameter values needs to be defined, which makes empirical curve fitting impractical so that the use of optimization algorithms for matching simulations to experiments becomes a necessity.

The goal of the present work is to develop an effective and reliable procedure for the characterization of the engineering properties of unsaturated soils by interpreting results from pressuremeter tests. In particular, the paper presents a methodology for the identification of parameter values in the Barcelona Basic Model (BBM) [1] by inverse analysis of the experimental cavity pressure–cavity strain curve measured during pressuremeter tests in the field. BBM is arguably one of the most popular elasto-plastic constitutive models for unsaturated soils and has been widely used in the analysis of boundary value problems in geotechnical engineering due to its capability of providing a unified interpretation of plastic soil behaviour under both changes of load and suction.

In this research, the Nelder–Mead local search method [13] has been used in conjunction with a novel evolutionary global optimization algorithm [14] to match the cavity pressure–cavity strain curves calculated by finite element models to the field measurements. The proposed evolutionary global optimization algorithm has been formulated within the framework of Particle Swarm Optimization (PSO) [15–18] and has been implemented in a parallel form to improve computational efficiency.

In Section 2 of this paper, the BBM model is briefly introduced followed by a description of the proposed methodology for the identification of model parameters. Subsequently, an example is presented to validate the above methodology making use of artificial experimental results produced by finite element simulations. Finally, the identification of soil parameter values from real pressuremeter tests is demonstrated.

2. The Barcelona basic model for unsaturated soils

The BBM [1] is an elasto-plastic constitutive model that extends the framework of Modified Cam-clay to the case of unsaturated soils. The BBM is able to reproduce the main features of the mechanical response of an unsaturated soil, such as the increase of shear strength and preconsolidation pressure with suction, the development of reversible swelling strains during wetting at low confining stresses and the occurrence of irreversible collapse strains during wetting at high confining stresses [1,19].

The BBM is formulated in terms of two independent stress variables, namely the net stress tensor and the suction scalar. The net stress tensor, σ_{ij} is defined as $\sigma_{ij} = \sigma^*_{ij} - \delta_{ij} u_a$, where σ^*_{ij} is the total stress tensor, u_a is the pore air pressure and δ_{ij} is the Kronecker delta. The suction, indicated by the symbol s is defined as $s = u_a - u_w$, where u_w is the pore water pressure.

The yield locus is defined in terms of stress invariants by the equation:

$$F(p,q,s) = q^2 - M^2(p+ks)(p_0(s) - p) = 0 \tag{1}$$

which describes an ellipse in the (p, q) plane at constant suction s, where p is the net mean stress and q is the deviator stress. In Eq. (1), M is the slope of the critical state line in the (p, q) plane at constant suction, k is the parameter controlling the increase of apparent cohesion with suction and $p_0(s)$ is the isotropic preconsolidation stress, which depends on suction s according to:

$$p_0(s) = p^c \left\{ \frac{p_0(0)}{p^c} \right\}^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \tag{2}$$

Eq. (2) describes the relationship between the isotropic preconsolidation stress and suction in the (p, s) plane at $q = 0$ and is often referred to as the Loading-Collapse (LC) yield curve. In Eq. (2), $\lambda(s)$ and $\lambda(0)$ are the slopes of the normal compression lines at suctions equal to s and 0 respectively, κ is the elastic swelling index with respect to changes of mean net stress, $p_0(0)$ is the isotropic preconsolidation stress under saturated conditions and p^c is a reference pressure such that, when $p_0(0) = p^c$, the LC yield curve reduces to a straight line with equation $p_0(s) = p^c$.

Note that the version of the BBM model implemented in the FE code used in this work has been extended beyond the case of triaxial stress states, as contemplated in the original contribution by Alonso et al. [1], to any stress state. This is achieved by replacing the definition of deviator stress q for triaxial stresses with that for general stress states. Therefore, in the principal stress space, the cross section of the constant suction yield surface in the plane perpendicular to the hydrostatic axis (i.e. in the deviatoric plane) has the shape of a circle, similar to what is assumed for the saturated Modified Cam-clay model.

The normal compression lines at constant suction s are defined as:

$$v = N(s) - \lambda(s) \ln \frac{p}{p^c} \tag{3}$$

where v is the specific volume. The change of intercept $N(s)$ and slope $\lambda(s)$ of the normal compression lines with suction s is described as:

$$\begin{aligned} N(s) &= N(0) - \kappa_s \ln \tfrac{s+p_{atm}}{p_{atm}} \\ \lambda(s) &= \lambda(0)\left[\left(1-r\right)e^{-\beta s} + r\right] \end{aligned} \tag{3bis}$$

where κ_s is the elastic swelling index with respect to changes of suction, $N(0)$ and $\lambda(0)$ are the intercept and slope of the saturated normal compression line at zero suction, r is a parameter controlling the range of variation for the slopes of the constant suction normal compression lines, β is a parameter controlling the rate at which the slopes of normal compression lines change with suction and p_{atm} is the atmospheric pressure.

Isotropic plastic hardening is governed by the variation of the parameter $p_0(0)$, which regulates the change in size of the yield locus and depends on the plastic volumetric strain ε^p_v according to:

$$\frac{dp_0(0)}{p_0(0)} = \frac{1+e}{\lambda(0)-\kappa} d\varepsilon^p_v \tag{4}$$

where e is the void ratio.

A non-associative flow rule in the (p, q) plane relates increments of plastic deviatoric and volumetric strains:

$$\frac{d\varepsilon^p_s}{d\varepsilon^p_v} = \frac{2q\alpha}{M^2(2p + ks - p_0(s))} \tag{5}$$

where ε^p_s is the plastic deviatoric strain while α is the plastic flow constant that depends on the value of Jaky's coefficient of earth pressure at rest (according to the equation presented in the original contribution by Alonso et al. [1]) and has been introduced to improve prediction of soil behaviour during K_0 loading.

The elastic variation of volumetric and deviatoric strains, denoted by the symbols ε^e_v and ε^e_s respectively, is calculated as:

$$d\varepsilon^e_v = \frac{\kappa}{1+e}\frac{dp}{p} + \frac{\kappa_s}{1+e}\frac{ds}{s+p_{atm}} \tag{6}$$

$$d\varepsilon^e_s = \frac{G}{3} dq \tag{7}$$

where G is the elastic shear modulus.

The five BBM parameters $N(0)$, $\lambda(0)$, r, β and p^c, as well as the initial value of the hardening parameter $p_0(0)$, are therefore associated with the plastic behaviour of the soil under isotropic stress states. The values for such parameters are conventionally obtained from laboratory tests involving isotropic compression of unsatu-