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Benchmarking selection of parameter values for the Barcelona basic model

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ABSTRACT

Seven teams took part in a benchmarking exercise on selection of parameter values for the Barcelona Basic Model (BBM) from experimental data on an unsaturated soil. All teams were provided with experimental results from 9 tests performed on a compacted soil in order to determine values for the ten BBM soil constants and an initial value for the hardening parameter. The coordinating team then performed simulations (at stress point level) with the 7 different sets of parameter values, in order to explore the implications of the differences in parameter values and hence to investigate the robustness of existing BBM parameter value selection procedures. The major challenge was found to be selection of values for the constants $\lambda(0)$, r, β, $N(0)$ and p^c and an initial value for the hardening parameter $\overline{p}_0(0)$, with the various teams proposing significantly different values for some of these key parameters. A key lesson emerging from the exercise is the importance of choosing a method for selecting values for the parameters β and p^c which places the main emphasis on attempting to optimise the match to the experimental spacing of normal compression lines at different values of suction.

1. Introduction

This paper describes a benchmarking exercise on selection of parameter values for the Barcelona Basic Model (a widely used elasto-plastic constitutive model for the mechanical behaviour of unsaturated soils) from experimental data. This benchmarking exercise was organised within a 'Marie Curie' Research Training Network on 'Mechanics of Unsaturated Soils for Engineering' (MUSE) (Gallipoli et al., 2006; Toll et al., 2009), which was supported financially by the European Commission. The activities undertaken by the MUSE Network included a variety of benchmarking exercises relating to experimental techniques, constitutive modelling and numerical modelling (see, for example, Tarantino et al. (2011) and D'Onza et al. (2011)).

The Barcelona Basic Model (BBM), developed by Alonso et al. (1990) is the earliest and most widely used elasto-plastic constitutive model for unsaturated soils. It has been implemented in a number of finite element codes and has been applied in the numerical analysis of real boundary value problems, including earthworks (e.g. Alonso et al.,

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2005), field tests (e.g. Costa et al., 2008) and underground disposal of nuclear waste (e.g. Gens et al., 2009). Dissemination and use of the BBM outside the unsaturated soils research community have however been relatively limited, and possible contributory factors in this have been uncertainty in how best to select BBM model parameter values from laboratory test data and concerns on the robustness of such parameter value selection procedures. The benchmarking exercise was designed to investigate these issues.

7 teams took part in the benchmarking exercise: the University of Glasgow, UK (GU); the University of Durham, UK (DU); the Università degli Studi di Trento, Italy (UNITN), the École Nationale des Ponts et Chaussées, France (ENPC); the Università degli Studi di Napoli Federico II, Italy (UNINA); the Universität Innsbruck, Austria (UNINN); and the University of Strathclyde, UK (USTRAT). The first 5 of these were members of the MUSE Network and the last 2 were external participants. The exercise was coordinated from the University of Glasgow (GU).

All 7 teams were provided with the same set of experimental data from a programme of laboratory tests on a single compacted soil. Each team then used the laboratory test data to select BBM parameter values for the soil, with complete freedom on the methodology they employed for selection of parameter values. Each team returned to GU their selected BBM parameter values, together with details of the procedure they had employed in selection of parameter values. The team at GU then performed simulations with the 7 different sets of parameter values. These simulations were performed at stress point level (rather than for boundary value problems), and they included simulations of the full set of laboratory tests that the teams had used in the selection of parameter values, but also several fictitious stress paths and various other features of model performance. Comparisons between the simulation results with the 7 different parameter value sets were used to explore the implications of the differences in parameter values and hence to investigate the robustness of BBM parameter value selection procedures.

2. Barcelona Basic Model

The Barcelona Basic Model (BBM), developed by Alonso et al. (1990), uses mean net stress $\overline{p}$, deviator stress q and matric suction s as stress state variables, where $\overline{p}$ is the excess of mean total stress over pore air pressure and s is the difference between pore air pressure and pore water pressure. The model implicitly assumes that saturated conditions are achieved whenever s is zero, and only when s is zero, and at this limit the BBM converges with the Modified Cam Clay model for saturated soils (Roscoe and Burland, 1968). The BBM is intended for use with unsaturated fine-grained soils, but excluding those containing highly expansive clay minerals.

In the formulation of BBM, elastic volumetric strain increments are given by:

$$d\varepsilon_v^e = \kappa \frac{d\overline{p}}{v\overline{p}} + \kappa_s \frac{ds}{v(s+p_{at})} \tag{1}$$

where v is the specific volume, p_{at} is atmospheric pressure and κ and κ_s are two elastic soil constants. The term involving κ represents elastic volume changes caused by variation of $\overline{p}$, giving elastic unloading/reloading lines of gradient κ in the v:ln $\overline{p}$ plot, whereas the term involving κ_s represents elastic volume changes caused by variation of s (swelling on wetting and shrinkage on drying), giving shrink/swell lines of gradient κ_s in the v:ln$(s + p_{at})$ plot. Atmospheric pressure p_{at} is (rather arbitrarily) included within Eq. (1) in order to avoid infinite elastic volumetric strains as suction tends to zero.

Elastic shear strain increments are given by:

$$d\varepsilon_s^e = \frac{dq}{3G} \tag{2}$$

where G is the elastic shear modulus (a soil constant).

Isotropic normal compression lines for different values of suction are all assumed to be straight lines in the v:ln $\overline{p}$ plot, defined by:

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

where p^c is a reference pressure (a soil constant) and the intercept $N(s)$ (defined at the reference pressure p^c) and gradient $\lambda(s)$ are both functions of suction s.

The variation of $N(s)$ with suction is assumed as:

$$N(s) = N(0) - \kappa_s \ln\left(\frac{s+p_{at}}{p_{at}}\right) \tag{4}$$

where $N(0)$ (a soil constant) is the value of $N(s)$ at zero suction (the intercept of the saturated normal compression line). The assumption that there exists a single value of $\overline{p}$ (the reference pressure p^c) at which the spacing between the saturated normal compression line and the normal compression lines for all non-zero values of s is given by Eq. (4), is a major assumption within the BBM, which was made by Alonso et al. (1990) in order to produce subsequently a relatively simple expression for the LC yield curve (Eq. (6)). This assumption within the model has significant implications for both the positions of the normal compression lines for different values of suction and the development of the shape of the LC yield curve as it expands.

The variation of $\lambda(s)$ with suction is assumed as:

$$\lambda(s) = \lambda(0)[r + (1-r)\exp(-\beta s)] \tag{5}$$

where $\lambda(0)$ (a soil constant) is the value of $\lambda(s)$ at zero suction (the gradient of the saturated normal compression line) and r and β are two further soil constants. Inspection of Eq. (5) shows that $\lambda(s)$ varies monotonically with increasing suction, from a value $\lambda(0)$ at zero suction to a limiting value $r\lambda(0)$ as suction tends to infinity, with the soil constant β controlling the rate of exponential approach to this limiting value. If the value of r is less than 1 then $\lambda(s)$ decreases with increasing suction (collapse potential increasing with increasing $\overline{p}$), whereas if the value of r is greater than 1 then $\lambda(s)$ increases with increasing suction (collapse potential decreasing with increasing $\overline{p}$). In the former case, the value of the reference pressure p^c will need to be very low (much lower than the range of $\overline{p}$ over which the model is to be applied), whereas in the latter case, the value of p^c will need to be very high (much higher than the range of $\overline{p}$ over which the model is to be applied) (see Wheeler et al., 2002).

For isotropic stress states, the BBM includes a Loading–Collapse (LC) yield curve, defined in the s:$\overline{p}$ plane, which corresponds to the onset of plastic volumetric strain during either isotropic loading (increase of $\overline{p}$) or wetting (reduction of s). Stress states on the LC yield curve also correspond to points on the isotropic normal compression lines defined by Eq. (3), and hence combination of Eqs. (1), (3) and (4), leads to the following expression for the shape of the LC yield curve in the BBM:

$$\left(\frac{\overline{p}_0}{p^c}\right) = \left(\frac{\overline{p}_0(0)}{p^c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \tag{6}$$

where $\overline{p}_0$ is the yield value of $\overline{p}$ at a suction s and $\overline{p}_0(0)$ is the corresponding value of $\overline{p}_0$ at zero suction. Eq. (6) defines the developing shape of the LC yield curve as it expands during plastic straining (as the value of the hardening parameter $\overline{p}_0(0)$ increases). The relatively simple form of Eq. (6) is a consequence of the assumption within the BBM that there exists a single reference pressure p^c at which the spacings of all the normal compression lines for different values of suction are given by Eq. (4). Inspection of Eq. (6) indicates that a consequence of this assumption is that the LC yield curve is a vertical straight line in the s:$\overline{p}$ plane when $\overline{p}_0(0) = p^c$, and the developing shape of the LC yield curve as it expands can be traced back to this assumption.