CALIBRATION METHODS OF A CONSTITUTIVE MODEL FOR PARTIALLY SATURATED SOILS: A BENCHMARKING EXERCISE WITHIN THE MUSE NETWORK

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Francesca D'Onza (donza@civil.gla.ac.uk)
University of Glasgow, Glasgow, United Kingdom

ABSTRACT. The paper presents a benchmarking exercise comparing different procedures, adopted by seven different teams of constitutive modellers, for the determination of parameter values in the Barcelona Basic Model, which is an elasto-plastic model for unsaturated soils. Each team is asked to determine a set of parameter values based on the same laboratory test data. The different set of parameters are then employed to simulate soil behaviour along a variety of stress paths. The results are finally compared to assess the implications of the different choices and draw conclusions on the validity of current methodologies for determining parameter values in BBM. This research is carried out in the context of the Research Training Network "Mechanics of Unsaturated Soils for Engineering"- MUSE (http://muse.dur.ac.uk) funded by the European Commission under the 6th Framework Programme. In particular, the work is undertaken within a wider research benchmarking programme on experimental techniques, constitutive and numerical models in unsaturated soil mechanics carried out by the MUSE Network together with some external partners.

1. Objectives and methodologies

The objective of this collaborative research is to benchmark procedures for establishing model parameter values of the Barcelona Basic Model of Alonso et al. (1990), which is an elasto-plastic constitutive model for unsaturated soils. The benchmarking exercise is based on the experimental data produced by Mauricio Barrera Bucio during his Ph.D. at the Universitat Politécnica de Catalunya in 2002. The research undertaken within the context of the MUSE "Marie Curie" Research Training Network by seven universities across Europe (University of Durham (DU), United Kingdom; Università degli Studi di Trento (UNITN), Italy; Ecole Nationale des Ponts et Chaussées (ENPC), France; University of Glasgow (GU), United Kingdom; Università degli Studi di Napoli Federico II (UNINA), Italy; University of Strathclyde (USTRAT), United Kingdom and Die Universität Innsbruck (UNINN), Austria). Each team has therefore been asked to determine parameter values of the same model (i.e. BBM) based on the same set of experimental data (Barrera Bucio, 2002).

Each team has been provided with:

- a Word file containing the specifications of the benchmarking exercise and general information on the laboratory tests to be used for the parameter determination;
- a series of Excel spreadsheets containing the experimental data;
- a return form to be completed with the list of parameter values and a short description of the procedure used for estimating them.

The University of Glasgow coordinated the benchmarking exercise and was responsible for:

- selection of experimental data including nine laboratory tests from Barrera Bucio (2002);
- circulation of benchmark specifications, experimental data and return forms;
- collection of returns and interpretation of different parameter values sets;
- simulation of the nine laboratory tests using parameter values by each team;
- additional simulation of fictitious stress paths under triaxial and oedometric conditions to demonstrate the significance of the difference between parameters sets;
- discussion of results, extraction of conclusions and drafting of a final report document.

2. Experimental data used

The soil used in the tests reported in Barrera Bucio (2002) has been sampled in the city of Barcelona, Spain during the excavation works for the construction of the library "Rector Gabriel Ferraté" in the North Campus of the Technical University of Catalunya (UPC).

The soil is made of a 39.4% fraction of sand, a 44.5% of silt and a (mainly illitic) clay fraction of 16.1%. The soil has a specific gravity, Gs, equal to 2.71 and a plasticity index of 16%.

The samples used in the tests employed for this benchmarking exercise have been prepared by static compaction at a water content, w, of 11±0.2% by applying an isotropic confining pressure of 600 kPa. The measured total suction after compaction is equal to 800 kPa. Given the negligible volumetric strains during initial equalization at 800 kPa of matric suction, the total suction is supposed to be equal to the matric suction. A total of nine tests have been selected as experimental evidence for the determination of parameter values. They include:

- two isotropic tests: one saturated and one carried out in suction controlled condition including multiple loading/unloading at different levels of suction (800, 150, 20 kPa) and multiple wetting/drying paths at a mean net stress of 600 kPa;
- six triaxial tests including a combination of compression at 800kPa of suction, unloading, wetting and/or drying before final shear. All the shear stages have been carried out at a suction of 800 kPa except for one performed at a suction of 20 kPa;
- one oedometric test including multiple loading/unloading at different levels of suction (800, 300, 50 kPa) and multiple wetting/drying paths at constant vertical net stress of 600 kPa.

3. Model

The model used for this benchmarking exercise is an elasto-plastic model for unsaturated soils, namely the Barcelona Basic Model (Alonso et al. 1990). The model is expressed in terms of net stresses and suction as constitutive variables and reverts to the Modified Cam Clay model at the saturated limit (s=0). Among other predicting capabilities, the BBM makes sense of plastic collapse on wetting by appreciating that onset of collapse corresponds to yielding. Moreover, it unifies the interpretation of plastic straining regardless of whether is caused by loading or wetting/drying and predicts volume changes during wetting/drying within a coherent overall constitutive model capable of providing quantitative predictions. In addition, the model incorporates the influence of suction on yielding under any combination of stresses and on shear strength. It also links volume changes and shearing within a single elasto-plastic model, distinguishing between reversible and irreversible strains along any stress path (equivalent to Modified Cam Clay for saturated soils).

BBM has however some limitations due to either its specific formulation and the use of net stresses and suction as constitutive variables or, more generally, to the classical isotropic hardening elasto-plastic framework in which it has been formulated.

In spite of these shortcomings, the model has been chosen for this benchmarking exercise because is one of the first elasto-plastic constitutive models for unsaturated soils and is widely implemented in finite element codes. BBM has had a pioneering role as modelling of unsaturated soil behaviour prior to BBM tended to assume non-linear elastic constitutive relationships (e.g. state surface approach for volumetric strains and hyperbolic relationship for shear strains) incurring in deficiencies such as the lack of a link between volume change and shearing, no distinction between loading and unloading and poor representation of volume changes during wetting/drying.

4. Results

Table 1 presents the parameters sets selected by all teams involved in the benchmarking exercise and shows quite a wide variation of values between different teams. It should be first noted that there is not right or wrong solution to this benchmarking exercise as it is certainly clear that no selection of parameter values is going to give a perfect match to a real set of experimental data. Inevitably, there are differences depending on how each team has chosen to optimize model calibration and to which aspect of experimental evidence they gave more weight to.

As a general comment, it is possible to say that all the teams tended to use a specific aspect of soil behaviour to determine the initial value of each parameter but, after a first calibration, they went back to adjust some values to match other aspects. The only exception to this approach was given by UNINN that used a different calibration procedure from all the rest performing a free optimization of all parameters by minimizing a given error function. As a consequence, all parameter values were selected together as the result of one blind optimization exercise rather than separate optimizations for each parameter to match a physical aspect of the experimentally observed behaviour. The danger, in this kind of approach, is that a false minimum of the objective function can be obtained depending on the starting point.

We can distinguish three main groups of parameters corresponding to the elastic (κ, κ_s, G), plastic ($\lambda(0)$, β, r, N(0), p^c) and strength (M, k) behaviour respectively. The initial value of the isotropic pre-consolidation stress at null suction (po*) defines the initial soil condition.

The elastic parameters have a relatively minor importance because of their limited influence on many of the other aspects of soil behavior predicted by the model. Moreover, given that elastic strains are usually very small compared to plastic ones, they do not affect significantly the overall deformation.

	DU	UNITN	ENPC	GU	UNINA	UNINN	USTRAT
κ	0.012	0.0104	0.007	0.0097	0.007	0.0098	0.0076
κ_s	0.001	0.0021	0.002	0.0045	0.002	0.0035	0.0005
G (MPa)	150	140	122	167	200	80	120
λ(0)	0.074	0.097	0.072	0.078	0.072	0.072	0.08
β (kPa^{-1})	0.125	0.0144	0.0017	0.0396	0.095	0.0222	0.008
r	0.8	0.8293	0.8	1.0567	0.875	1.814	0.87
N(0) (at s=0; $p=p^c$)	2	2.0375	2.17	-1.4786	2.59	1.158	1.85
p^c (kPa)	0.5	4	0.07	2E+19	0.0001	29673	7
M	1.14	1.1333	1.13	1.1784	1.119	1.16	1.165
k	0.46	0.449	0.45	0.4208	0.495	0.41	0.3
Initial value of **p*(0)** (kPa)	85	291	170	70	69	41.866	120

Table 1. Parameters sets values determined by all the teams involved in the benchmarking exercise.

All the teams, except UNINN, used the same procedure for fitting the experimental data relative to elastic paths in the isotropic (for κ and κ_s) or deviatoric plane (for G). The scatter of values in Table 1 is predominantly due to the way the fitting process was performed by each team rather than to the choice of different sub-sets of experimental data used for the calibration of elastic parameter.

Conversely, the scatter of plastic parameter values between different teams in Table 1, is primarily due to dissimilarity in the calibration approach. All teams adopted a sort of iterative procedure, tending to fit in turn one or another of the various aspects of soil behaviour to which each parameter is related but eventually coming back to adjust determined values to match other characteristics. As an example, some Universities fixed the λ(0) value using data of compression stages in saturated conditions or at low suctions. Values of r and β were subsequently fixed trying to interpolate the slopes of the normal compression lines at different suctions, λ(s), and the values of the yield stress at different suctions (depending also on the parameter pc). These values were finally adjusted by some universities to match the spacing between normal compression lines and, consequently, the collapse during wetting. It is worth to note that using a calibration approach where each aspect of soil behaviour is associated to a number of different parameters, leads to the possibility of having several equally accurate combinations of parameter values. Unlike other teams, GU adopted a procedure where the value of β was uniquely linked to the relative spacing between normal compression lines. In the case of GU, values of λ(0) and r were subsequently determined to match the slopes of the normal compression lines for each suction while the value of pc was selected to fix the absolute spacing. Subsequently, by choosing an appropriate value for N(0), the star of normal compression lines at different suctions was shifted in the position that minimizes the deviation from experimental data.

This procedure avoids the association of several parameter values to a single aspect of behaviour, which would inevitably lead to several possible combinations of parameter values that provide, in turn, a better match to one or another aspect of behaviour.

It is also worth noting that the particular choice of plastic parameters by each team produces radically different evolutions of the yield locus beyond the explored stress range. In the application of BBM to boundary value problems, there is therefore a risk in extrapolating the prediction of soil behaviour far from the experimentally explored stress range

The critical state is well defined by the available triaxial tests as experimental points are unambiguous and consistent. Therefore all groups end up with very similar critical state surfaces in the q : (p-ua) : (ua-uw) space, i.e. with very similar values of M and k.

The oedometric tests, despite their experimental simplicity compared to triaxial tests, are seldom used as experimental evidence to determine model parameters because of the uncertainties of the stress path resulting from the imposed radial constraint. In reality, by making some simplifying assumptions in BBM, some information can be used from the oedometric experimental data (for example, the slope of the oedometric virgin compression lines at constant suction can be assimilated to the slopes of the normal compression lines at the same levels of suction).

Nevertheless, none of the teams used experimental data from the oedometric test, except for GU that used the slopes of the virgin compression lines at suctions of 50 and 300 kPa as evidence of the slopes of normal compression lines at the same suction levels. As the oedometric test has not been used in the parameter determination process (with a minor exception for GU), the predictions of this test by the different teams can be regarded as Class A predictions. As a general trend, the behaviour during the oedometric test is not well predicted by any team.

Part of the reason for such misprediction is attributable to the limitations of BBM such as: a) the inaccuracy of the flow rule, as observed also for the predicted volumetric evolution during the shear stage of the triaxial tests, b) the incorrect prediction of the position of the oedometric virgin compression lines at constant suction, if calibration of the model is based on results from triaxial tests and c) the inaccurate prediction of the elastic stress path due to the model assumption of constant G.

An additional reason for the poor prediction of the oedometric behaviour is due to the limitations of the testing procedure. In particular, it is generally assumed that, in an oedometric test, only a vertical stress acts on the top and bottom surfaces of the sample while only a horizontal stress acts on the lateral surface. In reality, some friction (i.e. tangential stresses) could develop on the sample surfaces and this will change the direction of principal stresses in the soil. As a consequence, part of the mismatch in the model prediction might be simply due to the fact that the actual stress path followed during the test is not consistent with the assumed one.

Note that, as a consequence of the poor prediction of the elastic stress path (due to a constant G value) together with an inaccurate prediction of the yield locus, the yield stress during the first loading of the oedometer test is not correctly calculated by any team. Moreover, all teams, except for DU and USTRAT, yield on the dry side of the yield locus, which amplifies discrepancies between simulations and experimental observations because, as it is well known, the BBM produces unrealistic predictions in this region of the stress space.

5. Conclusions

The paper has presented a benchmarking exercise comparing different procedures for the determination of parameter values in the Barcelona Basic Model, which is an elasto-plastic model for unsaturated soils. Seven different teams of experienced constitutive modelers have produced seven different sets of BBM parameter values based on the same laboratory test data. Rather surprisingly, widely different parameter value sets have been calculated by each team resulting in significant divergences in the predictions along a variety of stress paths. Radically different evolutions of the yield locus beyond the explored stress range are also predicted by using the different sets of parameter values. This highlights the risk of extrapolating predictions far from the experimentally explored stress range (e.g. during application to boundary value problems).

Another interesting aspect resulting from this study is the importance of considering the secondary effects of each parameter in BBM. The parameter β is a classical example as it controls the variation of the slopes of the normal compression lines with suction as well as the relative positions of the normal compression lines at different values of suction and the shape of the LC yield curve. It is therefore clear the necessity of looking at all aspects of soil behaviour, which are controlled by each particular parameter, to avoid mispredictions of important features.

Regardless of the model calibration procedure adopted by each team, it is not possible to identify a set of parameter values giving a perfect match to experimental data mainly because of the general limitations of every constitutive model in reproducing soil behaviour. During determination of parameter values, particular aspects of soil behaviour should be given more weight than others depending on the particular application in a similar way as the choice of the model itself is led by the physical process to simulate.

6. References

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