Numerical investigation of cyclic wetting and drying of Boom clay based on the Barcelona Expansive Model

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Summary

Expansive soils are characterized by their unique structural morphology and drastic volume change. Cyclic wetting and drying cause significant deformation and rearrangement of soil structure which causes yield surface variations due to hydromechanical effects. Various laboratory investigations have been performed to study the behaviour of expansive soil structures under wetting and drying cycles. Several studies have also been conducted to simulate the elastoplastic deformation of expansive soil, which resulted in relevant constitutive models, one of the most acceptable of which is BExM model. In this study, the effect of wetting and drying cycles on the volume change and movement of the load–collapse yield surface of a column of Boom clay is investigated using the BExM constitutive model. Based on the results, a load called transition surcharge (p_t) was defined under which the soil has elastic deformation. The simulation results showed that under loads higher and lower than transition surcharge, the change of total porosity and saturated preconsolidation pressure have different trends in various soil depths.

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Introduction

Cyclic wetting and drying phenomena of the expansive clayey soils cause significant deformations, which may lead to differential settlement and damage in structures. These cycles cause considerable changes to the expansive soil's physicochemical properties, such as the fabric, water content, and porosity. Accordingly, swelling and shrinkage deformation is generated, which may cause ground heave or land subsidence, desiccation cracks, slopes, landfills, clay liners, embankments, infrastructure, and ground deformation (Wang and Wei, 2015; Xu et al., 2022). Several laboratory works have been performed, where different methods (e.g., SEM, CT scanning, MIP, NMR) have been used to investigate the change in soil structure and variation of triaxial shear strength parameters due to wetting and drying cycles (e.g. An et al., 2022; Hao et al., 2022; Wen et al., 2022). Based on the experimental works, a number of constitutive models have been developed for expansive unsaturated soils, such as the models developed by Gens and Alonso (1992), Alonso et al. (1999) and Cui et al. (2002). The elastoplastic model developed by Alonso *et al.* (1999), namely Barcelona Expansive Model (BExM), is the most widely used one in describing the mechanical behaviour of unsaturated expansive soils. While substantial element-volume investigation (experimental and numerical) has been reported in understanding the volumetric and plastic behaviour of expansive soil, behaviour in large-scale phenomena under specific hydromechanical conditions such as initial stress, water table elevation, suction distribution in the vadose zone, permeability, initial total porosity, and microstructure porosity remains less well understood.

The main objective of this study is to numerically investigate the effect of wetting and drying cycles on ground surface settlement and heave. The simulations have been performed using the finite-element code Code_Bright (Olivella et al., 1996). The constitutive modelling of the coupled hydromechanical response of the unsaturated Boom clay has been achieved using the Barcelona Expansive Model (BExM). In particular, much attention has been given to the volume changes and the movement of the yield curve LC (Loading Collapse). Saturated preconsolidation pressure, p_0^*, was also considered as a criterion for changing the plastic behaviour of Boom clay in different depths of the soil column.

Barcelona expansive model (BExM)

The BExM model is developed to handle the appearance of irreversible swelling deformation during soil wetting, the accumulation of compression or extension deformation under hydraulic cycles, and the dependence of the soil response to the stress paths under increasing monotonous variation of the degree of saturation. However, this model assumes that the microstructure level is mainly saturated, the effective stress concept holds, and its behaviour is elastic. The neutral line (NL) is the geometric locus of points where no microstructural strain occurs (Figure 1). Microstructural swelling affects the structural arrangement of the macrostructure, inducing an irreversible increase in the void ratio (*e*). Reciprocally, microstructural shrinkage causes an irreversible decrease in void ratio (Alonso et al., 1999). In the BExM, the swelling–shrinkage strain caused by wetting and drying is defined as

(1) $$d\varepsilon_{vM}^{p} = f_I d\varepsilon_{vm}^{e} \qquad if \quad d(p+s) \geq 0$$

(2) $$\varepsilon_{vM}^{p} = f_D d\varepsilon_{vm}^{e} \qquad if \quad d(p+s) < 0$$

where ε_{vM}^{p} is the plastic macrostructural volumetric strain; ε_{vm}^{e} is the microstructural volumetric strain; f_I and f_D are two coupling functions. In a *p*–*q*–*s* diagram, LC yield locus is expressed by:

(3) $$q^2 - M^2(p + k_s s)(p_0 - p) = 0$$

where M is the slope of the critical state line, k_s is a parameter describing the increase of cohesion with suction, p_0 is the preconsolidation pressure which is a function of suction and p_0^*, and defines the shape of the LC yield surface in the p–s plane.

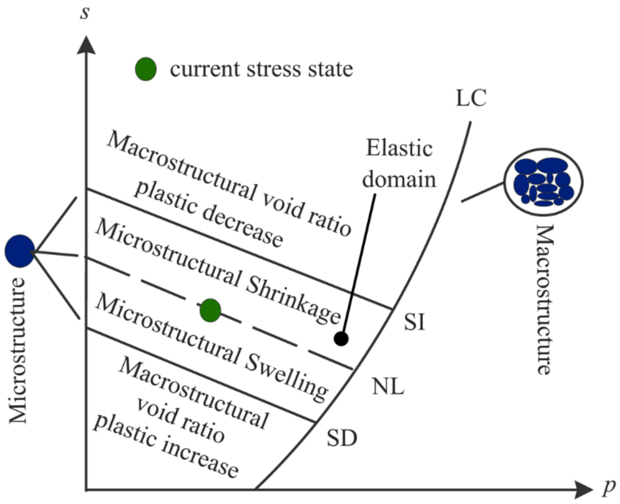

Figure 1 *BExM yield loci in p–s plane (after Alonso et al., 1999).*

Numerical simulation results

The finite element method was chosen to study the global hydromechanical processes governing the phenomena. The field equations consider the medium as a deformable three-phase material (i.e., an unsaturated medium) in which mass transfers occur. The added value of this contribution is to couple such hydromechanical field equations with a consistent soil BExM constitutive model. The formulation has been incorporated into a computer code, Code_Bright, capable of performing fully coupled THMC analyses to investigate the volumetric and plastic behaviour of expansive soils with application to ground surface settlement and heave. The dimensions of the model are 1 m × 10 m. The mesh contains 90 four-node quadrilateral elements; it has been refined near the top surface of the model domain in order to be able to deal with the high pore pressure gradients in this zone. Constitutive model parameters are reported by (Sánchez et al., 2005). Wetting and drying cycles were applied as a hydraulic boundary condition to the surface of the soil column. The main parameters involved in the simulation of the soil column were considered linearly variable in depth (Table 1).

In the first model, the initial soil stress value was considered 10 kPa, and a uniformly distributed surcharge load with a magnitude of 10 kPa was applied to the top surface of the model domain. The stress–suction paths were considered in such a way that first, the soil was subjected to the wetting path from its initial surface suction value (i.e., 20 MPa), and its suction reached 1 MPa, and then suction under the drying path reached 80 MPa. This process continued for six cycles in the suction range of 1 to 80 MPa. The first day was considered for equilibration, and each wetting and drying path lasted five days (61 days in total). The second model assumed that the soil column is subjected to a higher surcharge load with a magnitude of 30 kPa. Therefore, the initial load of 10 kPa increased to 30 kPa under a ramp loading within a day (62 days in total).

Table 1 *linearly variable parameters with depth.*

parameter	definition	value	
		top	bottom
P_l	Liquid pressure (MPa)	– 20	0
p_0^*	Saturated pre-consolidation pressure (MPa)	0.11	0.2
n_m	Microstructure porosity	0.18	0.26
n	Heterogeneous porosity	0.635	0.635

The variation of microstructure porosity (n_m) and heterogeneous porosity (n) due to wetting and drying cycles under two different surcharges in three depths is presented in Figure 2. Generally, the wetting and drying cycle trends fluctuate, which is shown in a simplified form here. The process starts from its initial state, goes through its maximum and minimum values along the way, and reaches its final state. The microstructure porosity (n_m) at the soil surface (y=0) under low surcharge first increases and then decreases continuously. At lower depths, the initial increase rate of microstructure porosity (n_m) decreased, until at a depth of 9 m, the trend is entirely decreasing (Figure 2(a)). Under high surcharge, the opposite trend happened, so the microstructure porosity (n_m) at the soil surface first decreased, then increased until the end of the last wetting path and decreased in the final drying path until it reached the final value. At lower depths, the initial reduction rate of microstructure porosity (n_m) increases, and the increase rate of the next stage decreases until no increase occurs at a depth of 9 m, and microstructure porosity (n_m) changes are almost reversible (Figure 2(b)). Generally, under the applied cycles, the microporosity decreased with increasing cycles compared to the initial state.

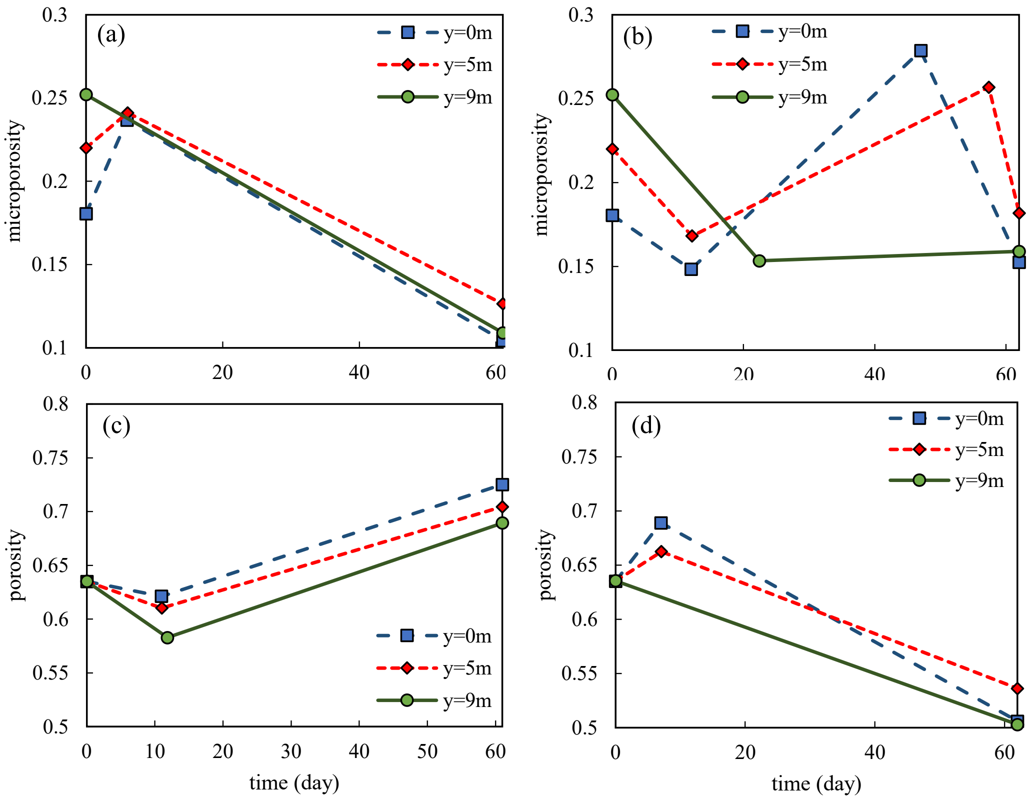

Figure 2 *Microporosity and porosity variation under (a and c) 10 kPa and (b and d) 30 kPa surchargs.*

Porosity on the topsoil surface under a low surcharge first decreased and then increased uniformly (Figure 2(c)), while under a high surcharge, it first increased and then decreased (Figure 2(d)). Therefore, it is possible to consider a surcharge that the soil plastic volumetric deformation due to wetting and drying cycles can be ignored, which we named it the transition surcharge (p_t). Variations of saturated preconsolidation pressure with suction as a criterion of plastic behaviour of expansive soils are presented in Figure 3. The results show that when $p < p_t$, the saturated preconsolidation pressure (p_0^*) decreases with increasing cycles (the starting point of the trend is marked). This reduction is higher at lower depths. However, when $p > p_t$, the saturated preconsolidation pressure (p_0^*) increases with increasing cycles, which is higher at depths close to the soil surface. In general, in all cases, wetting paths led to a decrease in saturated preconsolidation pressure (p_0^*) and drying paths led to an increase in p_0^*. Saturated preconsolidation pressure variation in depth showed that in high surcharge ($p > p_t$) and drying paths, the saturated preconsolidation pressure (p_0^*) has the highest value. In low surcharge ($p < p_t$) and wetting paths, the saturated pre-consolidation pressure (p_0^*) has the lowest value among all four cases.

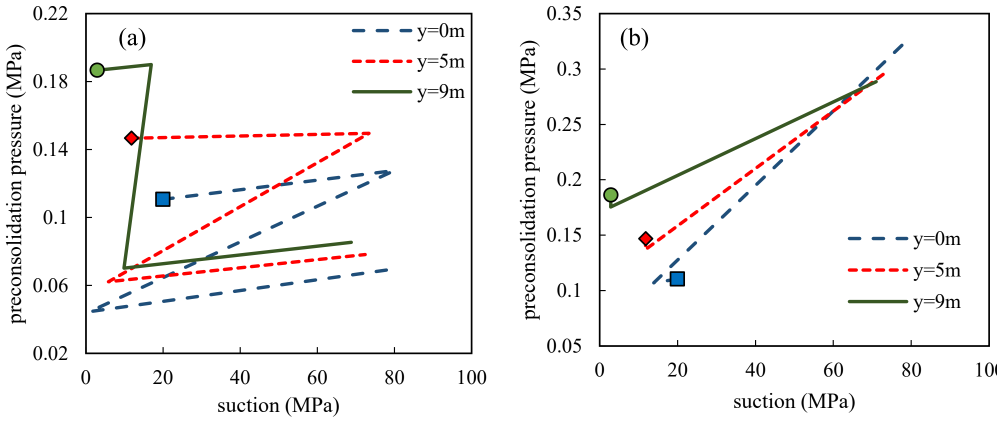

Figure 3 *Variation in saturated preconsolidation pressure under (a) 10 kPa and (b) 30 kPa surcharge.*

In the two other cases, the behaviour is similar to the second path, that is, in the case of a low surcharge ($p < p_t$) and drying paths, the p_0^* decreases with the continuation of the cycles (like the wetting path), and in the case of a high surcharge ($p > p_t$) and wetting paths, the p_0^* increases with the continuation of the cycles (like the drying path).

Conclusions

Numerical simulation employing the BExM model revealed that the soil's volumetric and plastic behaviour due to wetting and drying cycles depend on hydraulic conditions (i.e., applied suction distribution and flux) and mechanical conditions (i.e., initial stress, applied surcharge). According to the results, a surcharge was defined as a transition surcharge; in that case, the porosity under wetting and drying cycles changes reversibly. The reduction rate of microporosity decreased with increasing surcharge. The opposite behaviour between porosity and saturated preconsolidation pressure was also observed.

References

Alonso, E.E., Vaunat, J. and Gens, A. 1999. Modelling the mechanical behaviour of expansive clays. *Engineering geology*. **54**(1–2), pp.173–183.

An, R., Kong, L. and Li, C. 2022. Effects of Drying-Wetting Cycles on the Microstructure and Mechanical Properties of Granite Residual Soils. *Soil Mechanics and Foundation Engineering*. **58**(6), pp.474–481.

Cui, Y.J., Yahia-Aissa, M. and Delage, P. 2002. A model for the volume change behavior of heavily compacted swelling clays. *Engineering geology*. **64**(2–3), pp.233–250.

Gens, A. and Alonso, E.E. 1992. A framework for the behaviour of unsaturated expansive clays. *Canadian Geotechnical Journal*. **29**(6), pp.1013–1032.

Hao, R., Zhang, Z., Guo, Z., Huang, X., Lv, Q., Wang, J. and Liu, T. 2022. Investigation of Changes to Triaxial Shear Strength Parameters and Microstructure of Yili Loess with Drying–Wetting Cycles. *Materials*. **15**(1), p.255.

Olivella, S., Gens, A., Carrera, J. and Alonso, E.E. 1996. Numerical formulation for a simulator (CODE_BRIGHT) for the coupled analysis of saline media. *Engineering Computations*. **13**(7), pp.87.

Sánchez, M., Gens, A., do Nascimento Guimarães, L. and Olivella, S. 2005. A double structure generalized plasticity model for expansive materials. *International Journal for numerical and analytical methods in geomechanics*. **29**(8), pp.751–787.

Wang, G. and Wei, X. 2015. Modeling swelling–shrinkage behavior of compacted expansive soils during wetting–drying cycles. *Canadian Geotechnical Journal*. **52**(6), pp.783–794.

Wen, T., Chen, X. and Shao, L. 2022. Effect of multiple wetting and drying cycles on the macropore structure of granite residual soil. *Journal of Hydrology*. **614**, p.128583.

Xu, Xu-tang, Liu, D., Xian, Z., Yang, F., Jian, W., Xu, Xiang and Huang, J. 2022. Influence of Drying–Wetting Cycles on the Water Retention and Microstructure of Residual Soil. *Geofluids*. **2022**.