

Impact of climate change on the hydromechanical behavior of clayey soils: contribution of a coupled experimental and numerical approach.

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ABSTRACT: The management of expansive soils remains a significant challenge for the durability of structures, particularly in the context of climate change. In order, to develop preventive and remedial solutions, the mechanisms governing the behavior of structures founded on clayey soils need to be investigated. So, the present study analyzed the desiccation phenomenon of a clayey soil through a combined experimental and numerical approach. A new bearing capacity test was designed to study the drying and shrinkage of a soil under controlled laboratory conditions. The 2D evolution of the water content profiles near and under the foundation simulated in the test device was related with the volumetric variations of the soil. In parallel, a numerical model was carried out using a Multiphysics modelling software (i.e. COMSOL Multiphysics®), integrating the Richards equation to describe the water transfer in soil as well as the shrinkage curve obtained experimentally. The numerical results were compared with the experimental measurements to validate hypotheses and to better understand the mechanisms governing the behavior of clayey soils under foundations. Finally, both the stress and strain repartition under the foundation was observed, which remains a crucial step to develop preventive and remedial solutions and highlights the importance of considering coupled hydromechanical processes in order to model accurately the swelling-shrinkage behavior. This work represents a first step towards understanding the effects of wetting-drying cycles and foundation loading on soil behavior.

KEYWORDS: Climate change, swelling-shrinkage, clayey soils, numerical modeling, new bearing capacity test, foundation.

1 INTRODUCTION

In temperate regions, especially in France (Figure 1), clayey soils induce growing damages on the built constructions and roads, particularly under climate change impact.

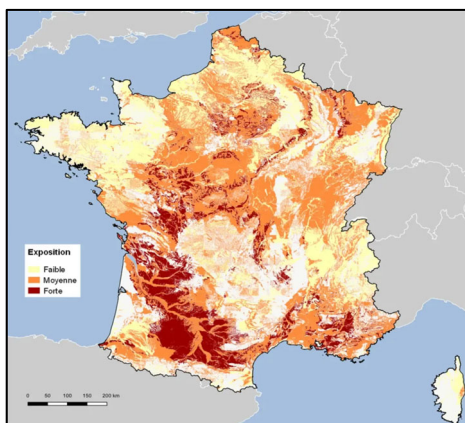


Figure 1. The mapping of French soils exposed to the swelling-shrinkage phenomena © BRGM (2020): white, yellow, orange and red colors correspond respectively to zero, low, medium and high water sensitivity of soils.

Indeed, such soils undergo significant volumetric variations in response to fluctuations in water content, leading to cyclic shrinkage during dry periods and swelling upon rehydration. This behavior, inherited from the mineralogical composition of clays, especially smectitic phyllosilicates such as montmorillonite (Shackelford, 2005) can compromise the serviceability of shallow foundations and generate structural damage.

The phenomenon, known as the clays swelling-shrinkage is responsible for huge and expansive damages. In France, damages costs were estimated more than €3.5 billion after the only 2022 drought event according to CCR (2023) while shrinkage-induced ground movements affect many other regions across the globe with documented cases in countries such as United Kingdom (MacQueen and al., 2023), United States (Mostafiz and al., 2021) or Italy (Meisina and al., 2006).

Numerous studies have investigated the swelling and shrinkage behavior of soils under mechanical loading. For example, Mrad and al, (2007) used the Barcelona Expansive Model (BExM) (Alonso and al, 1999) to simulate the effects of hydric solicitations (evaporation and rainfall) on the displacements of clayey soils under load. Their results confirmed that fluctuations in water content strongly influence the mechanical behavior, and that hydromechanical coupling is essential to accurately represent this phenomenon. However, their approach was limited to a specific set of parameters (soil type, climatic conditions, loading configuration) and relied on a simplified representation of soil-atmosphere exchanges, without experimental validation at the laboratory scale.

In parallel, several authors have explored remediation techniques. Qadad (2009) showed that adding surface protection (sidewalk) around a house can shift the transition zone between the dry and the wet soil, thereby reducing the total settlement. However later studies such as Béchade (2022) revealed that such measures can also have unintended consequences, including trapping water near the house, increasing infiltration and ultimately weakening the soil under the foundation. These findings illustrate both the potential and the limitations of individual mitigation techniques when considered in isolation.

Overall, these studies underline that given the multiplicity of parameters influencing shrink-swell behavior and the complexity of real situations (soil-foundation-environment interactions), it is necessary to develop and apply numerical modeling to explore a wide range of configurations. Such modelling not only makes possible to virtually investigate the effects of different climatic and geotechnical conditions, but also to assess the potential effectiveness of remediation measures. The present study was conducted in this perspective. The first step consisted in designing a new laboratory bearing capacity test and replicate it numerically using the COMSOL Multiphysics® software. The model integrated Richards equation (Richards, 1931) to describe the water flow in unsaturated soil. This approach provided both original experimental data and a reliable simulation tool to better understand, predict, and manage the behavior of expansive clayey soils in a climate change context.

2 EXPERIMENTAL SET-UP

2.1 Materials

The Romainville green clay (one of the main clay geological formations in Parisian Basin), known for its high content of fine particles, characteristic of a predominantly clayey soil, was chosen in this study.

Table 1. The tested soil properties.

Parameter	standards	Value	Unit
Fines fraction (% < 63 μm)	NF EN ISO 17892-4	96	%
Clay fraction (% < 2 μm)	NF EN ISO 17892-4	67	%
Plasticity index (PI)	NF EN ISO 17892-12	56	-
Methylen Blue value (VBS)	NF EN 17542-3	6.2	g/100g
Density (ρ)	-	1948	kg/m ³
Young's modulus (E)	NF EN ISO 17892-9	20	MN/m ²
Poisson's ratio (ν)	NF EN ISO 17892-9	0.3	-

The geotechnical characterization of the tested soil summarized in Table 1, revealed high plasticity index (PI) and methylene blue value (V_{BS}) reaching 56 and 6.2 g/100g, respectively. Both values indicated a high swelling/shrinkage potential under hydric variations. The tested soil was classified respectively as F3 based on the GTR (Guide des Terrassements routiers) (IDRRIM, 2024) and A3 based on the French standard (NF P11-300, 2025), which both corresponds to the category of highly plastic clays, with a strong sensitive to moisture changes.

To assess the soil mechanical behavior, especially its stiffness and deformation capacity, the Young's modulus (E) and Poisson's ratio (ν) were determined using the conventional consolidated drained triaxial tests (CD tests according to NF EN ISO 17892-9 standard (2018)) performed on intact soil specimens and corresponded to 20 MN/m² and 0.3 respectively. These values constituted essential input parameters for modeling the soil hydromechanical response under various environmental and mechanical loading conditions.

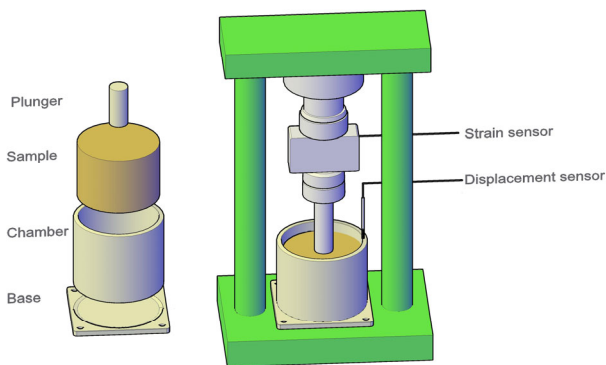


Figure 2. The experimental setup for new bearing capacity test (NBC test).

2.2 Setup and protocol for new bearing capacity test

The tested soil was first conditioned at optimum moisture content w_{omc} (21%) determined by the Standard Proctor compaction test (AFNOR, 2014). In first approximation, a remolded clayey soil was tested instead of intact soils as met under foundations, while previous E and ν parameters were measured on intact soil. The natural density (1908 kg/m³) was relatively close to the previously compacted one (1948 kg/m³), favorizing good reliability. Once the target moisture content

was reached, the soil was compacted into a 15x15cm cylindrical test mold using energy levels consistent with standard Proctor requirements to ensure uniform density ($\gamma_{d,max}$) and a satisfactory reproducibility in the mechanical measurements. After compaction, the sample was hermetically sealed to prevent any premature drying or uncontrolled evaporation. This isolation step during 24h ensured that the initial moisture conditions remained constant before the beginning of the test. The specimen was then installed within the chamber of the hydromechanical test apparatus (Figure 2), designed to simulate foundation loading under controlled drying conditions.

The experimental protocol of the NBC test involved the application of a constant vertical stress via a 3 cm cylindrical steel piston, centered on the compacted sample. An initial stabilization phase lasting 4h was applied in order to allow short-term settlement coming from solely mechanical loading. After this phase, the hydraulic isolation surrounding the soil was removed to initiate drying by natural evaporation from the top surface, while maintaining the vertical stress constant throughout the remainder of the test.

The setup was equipped with high-precision displacement sensors and stress transducers, enabling continuous data acquisition at 1s intervals. For the present study, a maximum vertical stress of 350 kPa was applied during both the mechanical stabilization phase and the subsequent drying phase in order to simulate maximum realistic stress conditions beneath shallow foundations.

3 NUMERICAL MODEL DESCRIPTION

In this study, the finite element modeling software COMSOL Multiphysics® was employed to simulate the hydromechanical behavior of the soil subjected to drying under loading. This multiphysics platform offers a flexible environment for coupling multiple physical phenomena such as unsaturated soil mechanical behavior and water flow within a single time-dependent framework.

To reproduce the behavior of the experimental setup described previously, a 2D axisymmetric model was developed. The geometry included two primary domains: the soil specimen and the loading steel piston. The vertical load was applied on the top of the piston, which in turn transmitted the stress uniformly to the soil surface, inducing vertical deformation (settlement) within the soil domain (Figure 3).

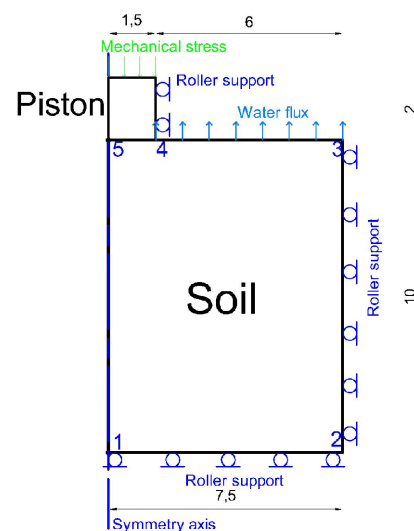


Figure 3. Geometry introduced in the model associated to the new bearing capacity test chamber and imposed boundary conditions (dimensions in cm).

The simulation was structured in two successive phases:

- Phase 1 - Mechanical loading (stabilization phase): a vertical load (350 kPa) was applied to the soil as during the four hours corresponding to the experimental plateau under constant loading and hydraulically isolated conditions. During this phase, only the mechanical settlement of the soil was calculated, allowing the system to reach a stabilized state.
- Phase 2 - Coupled hydro-mechanical loading (drying phase): this phase began using the final state of the first phase as initial conditions. While the mechanical load remained constant, evaporation was introduced at the soil surface, initiating the decrease of the water content. The model then calculated the additional settlement due to shrinkage associated with drying, capturing the coupled effect of mechanical stress and desaturation.

The numerical model assumed a linear poroelastic behavior coupled with hydraulic changes described by the Richards equation (Richards, 1931) using a van Genuchten formulation as detailed in Equation (1).

To describe the water-soil interaction and shrinkage behavior, the soil shrinkage curve (time-dependent volumetric variation or void ratio e versus the water content w) was experimentally determined and used as input for the model. Especially, the van Genuchten (van Genuchten, 1980) parameters were assessed from the water retention curve: α , which controls the inverse of the air-entry suction and reflects how easily the soil starts to desaturate; n , a shape parameter related to the pore-size distribution, influencing the steepness of the retention curve; θ_r , the residual water content, representing the water still retained in the soil matrix and that is no longer available for flow; θ_s , the saturated water content, which corresponds to the porosity when the soil is fully saturated.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha \times h)^n]^m} \quad (1)$$

where h is the hydraulic pressure head, representing the energy potential of water in the soil, i.e., the equivalent height of a water column generating the same pressure.

4 RESULTS

4.1 Experimental results

The NBC test successfully reproduced the coupled effects of sustained vertical loading and progressive desiccation on an expansive clay.

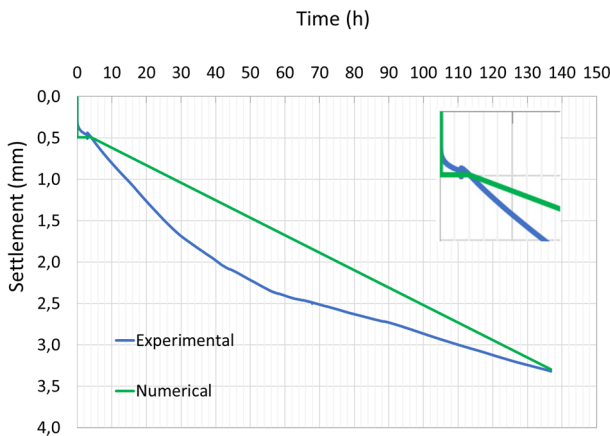


Figure 4. Numerical and experimental time dependent settlement

4.2 Numerical results

In this section, results appear in the form of 2D contour plots illustrating the distribution of displacements throughout the geometry. A blue point exhibited where maximum displacement was precisely located in each plot. These visual outputs generated by the software, also provided insight into the deformation distribution of soil under applied loading.

The results corresponding to the first phase which involved only mechanical loading (without any hydraulic effect) are shown in Figure 5. The maximum displacement distribution revealed a pronounced concentration near the edge of the contact zone between the piston and the soil surface, which was consistent with usual stress concentration patterns observed in confined loading scenarios.

Similarly to the mechanical phase, the simulation during the second phase revealed a significant concentration of maximum displacements near the edge of the foundation. At the end of this hydromechanical phase, the maximum resulting settlement of 3.3 mm (Figure 6) reflected the cumulative effect of the mechanical loading from the first step and the additional 2.8 mm deformation caused by soil shrinkage due to desiccation.

The settlement was clearly larger during the drying phase (Figure 6) compared to the first phase (Figure 5), with vertical displacements extending over a wider area, even in areas where mechanical stress levels remained relatively low. As expected, the highest settlement values reaching 0.5 mm and 3.3 mm were still located near the plunger, emphasizing both mechanical loading and drying.

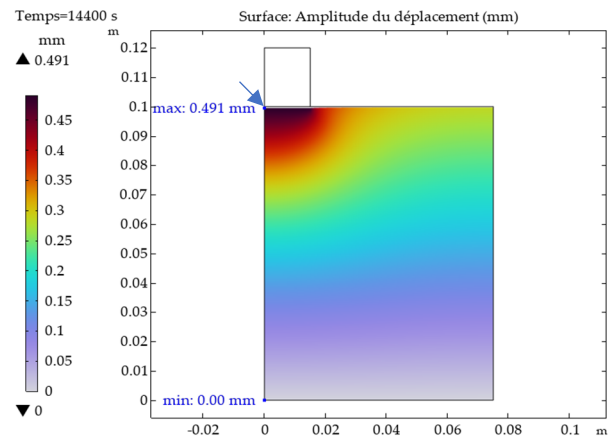


Figure 5. Mechanical phase: Settlement.

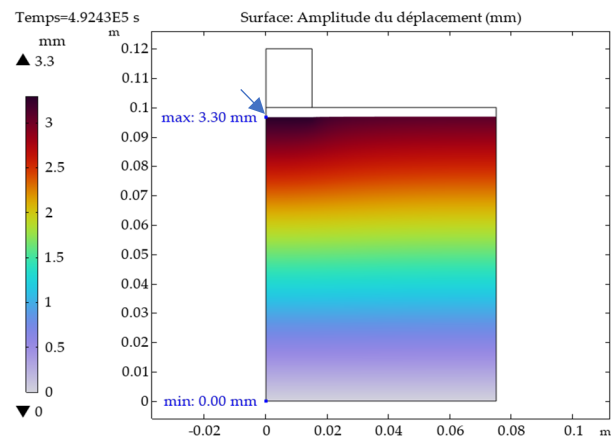


Figure 6. Hydromechanical phase: Settlement.

4.3 Comparison of the results

Figure 4 shows the numerical and experimental settlement-time evolution for both the mechanical phase (constant load, hydraulic isolation) and the hydromechanical phase (constant load, drying).

By comparing the settlement time-dependant evolution from experimental measurements and numerical simulations at a point located at the interface between soil and the piston surface, a good agreement was observed between both approaches at initial and final state for both steps in the NBC test. However, a noticeable discrepancy appeared between the two approaches between the beginning and the end point of drying. Numerically, the material followed a quasi-linear drying path, leading to gradual volumetric shrinkage as the water content decreased from the optimum moisture content ($w_{omc} = 21\%$) to the final state at the end of the test. The numerical model captured the overall trend but underestimated the deformation rate compared to the experimental observations during the drying process.

5 CONCLUSION

This study presented the first step of an integrated experimental and numerical investigation of the hydromechanical behavior of an expansive clay rich soil subjected to drying under mechanical load. Such phenomenon appeared as relevant in the context of climate change and impacts on the shallow foundations.

A new laboratory device was developed to simulate the coupled effects of drying and loading on the soil bearing capacity. The experimental results, especially the settlement behavior, were successfully reproduced using a finite element model implemented in COMSOL Multiphysics®. The model incorporated the water flow in unsaturated soil and an experimentally derived shrinkage curve, enabling a realistic simulation of soil response under hydromechanical cycling.

Overall, the results confirm that moisture variation is the dominant factor driving long-term settlement in clayey soils under foundations, and also that coupling experimental observations with numerical modeling provides a robust framework for understanding and mitigating these effects. In the mechanical phase, the agreement between measured and simulated settlements was very good. In the hydromechanical phase, the model captured the general deformation pattern but underestimated the settlement rate during intermediates stages of drying, suggesting to refine the shrinkage curve implementation to better match intermediate settlement rates. The vertical displacement field indicated that, during drying, deformation extended well beyond the directly loaded zone, highlighting the far-field influence of water content variation on settlement. Nevertheless, the ability of the model to replicate both the magnitude and special distribution of displacements confirms its potential as a predictive tool for expansive soil behavior under coupled climatic and mechanical loading.

This study represents an initial contribution to the development of predictive tools and remediation strategies in order to enhance the resilience of structures built on expansive clay soils. In future work, the numerical approach validated through experimental test should be refined and extended to simulate cyclic wetting-drying conditions over longer time periods. These simulations should then be applied to real-world case studies involving shallow foundations, in order to improve the proposed mitigation measures for practical implementation.

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7 REFERENCES

- NF P11-300, 2025. Terrassements - Classification complémentaire des matériaux de terrassement. AFNOR French standard.
- NF P94-093, 2014. Soils : investigation and testing - Determination of the compaction reference values of a soil type - Standard proctor test - Modified proctor test. AFNOR French standard.
- Alonso, E.E., Vaunat, J. and Gens, A., 1999. Modelling the mechanical behaviour of expansive clays. *Engineering Geology*, 54(1), 173–183.
- NF EN 1997-1 2005. Eurocode 7: geotechnical design - Part 1 : general rules, AFNOR French standard.
- Béché, A.-F., 2022. La pathologie des fondations superficielles : Diagnostic, réparations et prévention - Expertiser et prévenir les mouvements des sols sensibles - Maisons individuelles et bâtiments assimilés Ed. 2. CSTB. Available at: <<https://international.scholarvox.com/catalog/book/88929702>> [Accessed 8th July 2025].
- BRGM, 2025. Retrait-gonflement des argiles : accompagnement de la Direction Générale de la Prévention des Risques dans l'application de la loi ELAN | BRGM. [online] Available at: <<https://www.brgm.fr/fr/reference-projet-acheve/retrait-gonflement-argiles-accompagnement-direction-generale-prevention>> [Accessed 8th July 2025].
- CCR, 2023. Rapport financier, Caisse Centrale de Réassurance. Available at: https://www.ccr.fr/documents/35794/1416184/20240417_RAPPORT_FINANCIER_CCR_SECURISE.pdf/433685fa-f1b9-7f7e-bd55-28cad503565c?t=1713441752231 [Accessed 8th July 2025].
- Van Genuchten, M.Th., 1980. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*, 44(5), 892–898.
- IDRRIM 2024. Guide des terrassements des remblais et des couches de forme: Fascicule n°1 - Principes généraux / Fascicule n° 2 - Annexes techniques – Éd. 2024. Les références, 216 p. Available at: <<https://doc.cerema.fr/Default/doc/SYRACUSE/595090/guide-des-terrassements-des-remblais-et-des-couches-de-forme-fascicule-n-1-principes-generaux-fascic>> [Accessed 8th July 2025].
- MacQueen, M., Lawson, M. and Ding, W.-N., 2023. The 2018–2019 UK residential dwellings clay shrinkage subsidence event. *International Journal of Building Pathology and Adaptation*, 43(5), 1012–1029.
- Meisina, C., Zucca, F., Fossati, D., Ceriani, M. and Allievi, J., 2006. Ground deformation monitoring by using the Permanent Scatterers Technique: The example of the Oltrepo Pavese (Lombardia, Italy). *Engineering Geology*, 88(3), 240–259.
- Mostafiz, R.B., Friedland, C.J., Rohli, R.V., Bushra, N. and Held, C.L., 2021. Property Risk Assessment for Expansive Soils in Louisiana. *Frontiers in Built Environment*, 7.
- Mrad, M., Abdallah, A. and Masroui, F., 2007. Modélisation numérique du comportement d'un sol gonflant chargé soumis à des variations hydriques. *Revue Française de Géotechnique*, 120–121, 121–130.
- Qadad, A.A., 2009. Influence de la sécheresse sur les structures : modélisation de l'interaction sol-atmosphère-structure. PhD thesis from University Lille 1, France.
- Richards, L., 1931. Capillary conduction of liquids in porous mediums. *Physics*, 1, 318–333.
- Shackelford, C., 2005. James K. Mitchell and Kenichi Soga, Fundamentals of Soil Behavior (third ed.), John Wiley & Sons Inc., 577 p., *Journal of Hazardous materials - J HAZARD MATER*, 125, 275-276.