New Methods for Characterizing and Modeling the Engineering Behavior of Expansive Soils

Maki Ito[1], Shahid Azam[2*], and Wayne Clifton[3]

[1]Water Security Agency, Regina, Canada
[2]University of Regina, Regina, Canada
[3]Clifton Engineering Group Inc., Regina, Canada

(*Corresponding E-mail: shahid.azam@uregina.ca)

Abstract: Expansive soils experience alternating swelling and shrinkage due to variations in soil suction, thereby creating long-term challenges for the integrity of civil infrastructure. Conventional design approaches typically rely on constant soil parameters and do not account for transient and cyclical changes in soil suction and variable hydraulic conductivity. This keynote lecture presents a new conceptual framework for characterizing expansive clays (Ito et al., 2022a) and a suction-based predictive model for estimating volumetric deformations (Ito et al., 2022b). The new framework integrates the water retention curve, the swell–shrink curve, and the hydraulic conductivity curve to develop a soil property function. The numerical modeling simulations closely matched ten years of field monitoring data, demonstrating the validity of the new approach for predicting periodic movements at and near ground level.

Keywords: ***Expansive Soils, Volumetric Deformations, Laboratory Characterization, Numerical Modeling.***

Introduction

Expansive soils at and near ground surface pose significant engineering challenges due to their inherent tendency to undergo cyclical swelling and shrinkage. These alternating deformations originate from variations in soil suction and, as such, are driven by seasonal climatic changes responsible for infiltration and evaporation. In semi-arid regions with pronounced wet–dry cycles, these movements can be substantial enough to damage residential buildings, surface pavements, shallow foundations, retaining structures, and underground utilities. Despite decades of research, commonly used design methods still depend on conventional laboratory testing, assuming constant values for parameters such as swelling pressure, swelling potential, and coefficient of consolidation. As a result, the cyclical and transient nature of suction-induced soil behavior is seldom incorporated into the design process.

This keynote lecture presents a scientific advancement that addresses these gaps. Building on our recent publications (Ito et al., 2022a; Ito et al., 2022b), we introduce (i) a conceptual framework for an improved characterization of expansive clays and (ii) a suction-based numerical model that allows prediction of total, cyclic, and transient ground deformations.

Limitations of traditional approaches

Conventional expansive soil assessments generally compute total heave and total settlement using simplified relationships derived from oedometer tests with free swell followed by stepwise loading. These methods assume constant soil properties, uniform moisture change, and steady-state hydraulic behavior. However, actual field response is far more complex, where soil suction fluctuates continuously with climatic variables such as rainfall, air temperature, relative humidity, wind speed, and solar radiation. Furthermore, hydraulic conductivity varies by several orders of magnitude between saturated and unsaturated states, influencing the rate and movement of wetting and drying fronts. Relying solely on fixed parameters ignores the cumulative effects of transient suction fluctuations and, as such, fails to capture the true deformation patterns observed in practice. Recognizing these limitations, our work sought to develop a framework that capture soil properties, climate-induced suction, and volume-change mechanisms. Next, we utilized this conceptual framework to develop a numerical model that could be validated using actual field data.

Conceptual framework for soil characterization

Our first contribution is a comprehensive conceptual framework integrating key soil properties relevant to the behavior of expansive clays (Ito et al., 2022a). The framework focuses on three fundamental curves:

The water retention curve (WRC) describes the relationship between water content and soil suction. In our study, the WRC was initially expressed with water content on the y-axis. Through iterative optimization, we derived a modified WRC using void ratio on the y-axis, enabling direct linkage to volumetric strains.

The swell-shrink curve (SSC) represents the relationship between void ratio and water content during wet-dry cycles. Laboratory observations revealed that the SSC follows an S-shaped trend with low volume changes near saturation and close to dry conditions and most deformation occurring between these extremes.

The hydraulic conductivity curve (HCC) quantifies hydraulic conductivity variations with soil suction. For the investigated expansive clay, saturated hydraulic conductivity was measured as 8 X 10^{-9} m/s. The conductivity dropped significantly under unsaturated conditions, influencing wetting and drying rates.

Instead of using a constant coefficient of consolidation, we defined a new soil property function that combines the effects of the above-mentioned curves. This function varies with suction, thereby enabling representation of time-related soil behavior. Both the WRC and SSC were fitted with sigmoidal equations, ensuring smooth transitions across the entire suction range. This allows the soil property function to capture the continuous evolution of soil state during seasonal weather cycles.

Suction-based numerical model

Our second contribution is to develop a numerical model for predicting volume changes in expansive soils using the new conceptual framework (Ito et al., 2022b) extended. The model includes two major components:

Atmospheric variables of rainfall and evaporation (dependent on air temperature, relative humidity, wind speed, and solar radiation) were applied at the ground surface to create the boundary conditions. These parameters generate transient suction variations within the soil profile as the climate varies. The combination of the WRC, SSC, HCC allowed calculation of the variable velocity of a moving mesh, representing deformation across depths.

Volumetric deformations were calculated using a governing differential equation incorporating the soil property function. Because the soil property function changes continuously with suction, the model successfully simulates both phases of expansion and contraction depending on climate-driven moisture movement.

The numerical model was validated using historical field monitoring data collected over a decade. The predicted heave–settlement cycles closely matched measured values, confirming that the framework accurately captures the temporal nature of expansive soil behavior.

Conclusions

The combined conceptual framework and suction-based numerical model address long-standing shortcomings in expansive soil analysis. The methods are straightforward to apply, grounded in fundamental soil behavior, and capable of representing total, cyclic, and transient movements with high accuracy.

Incorporating soil suction and variable hydraulic conductivity offers a realistic and predictive approach essential for designing and maintaining infrastructure on expansive soil formations.

Acknowledgement

The authors acknowledge the financial support provided by MITACS and Clifton Engineering Group Inc. Thanks to the University of Regina for providing laboratory space and computational facilities and to Mr. Allan Kelly for his assistance in providing soil samples.

References

Ito M., Azam S., and Clifton W. (2022a). Conceptual framework for determination of volume changes in expansive clays. Proceedings, 20th International Conference on Soil Mechanics and Geotechnical Engineering, Sydney, Australia. 1423-1426.

Ito M, Azam S, and Clifton W (2022b). Suction-based model for predicting cyclic and transient volume changes in expansive clays using a material property function. Engineering Geology. 296(106491):1-18. https://doi.org/10.1016/j.enggeo.2021.106491