# UNSATURATED SWELLING CLAYS BEHAVIOUR MODELLING

# MODÉLISATION DE COMPORTEMENT DES ARGILES GONFLANTES NON SATURÉES

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**Abstract-** Lightweight constructions resting on unsaturated expansive clays often undergo serious damage as any significant moisture content occurs. Indeed, a geometric model that consists of an unsaturated expansive marly clay layer with a phreatic level located at −3.50 m depth, used to support a four-storey building and underlain by a natural substratum of gravely sand, is selected in this study. Due to the support soil type, a stiffened raft foundation design with basement walls is adopted. To assess the mechanical behaviour of this unsaturated clay under increasing vertical loadings, three-dimensional finite element analysis (3DFEA) is carried out using PLAXIS$^{3D}$ code. It is performed according to two material models, viz. Soft Soil (SSM) and Hardening Soil (HSM). However, it mainly focuses on swelling, settlement, and soil suction states within the medium during the project construction stages. According to the main results, SSM exhibits significant swelling and settlements compared to the HSM one, but in terms of the soil suction, closed values are roughly reported for both models. Although they show swelling and settlement at the middle and edges' excavation, soil suction is only observed under its middle zone. Even though, SSM shows higher parameter values in most cases, the highest soil suction history values are registered under the foundation middle for the HSM case. This leads to a surface tension that constrains the air-water interface to behave as a membrane, preventing, therefore, such swelling development.

**Keywords :** Unsaturated expansive clays, 3DFEA, SSM, HSM, Soil suction.

**Résumé -** Les constructions légères reposant sur des argiles gonflantes non saturées subissent souvent des dommages importants dès qu'un changement d'humidité survient. En effet, un modèle géométrique composé d'une couche d'argile marneuse surmontant un substratum naturel de sable graveleux sur lesquelles repose un bâtiment R+4 en présence d'une nappe phréatique située à -3.50 m est adopté dans cette étude. Compte tenu de la nature du sol de fondation, un radier général avec voiles périphériques en soubassement est adopté comme système de fondation de cet immeuble. Pour évaluer le comportement mécanique de cette argile non saturée sous l'effet de l'accroissement significatif des chargements verticaux, une analyse tridimensionnelle en éléments finis (3DFEA) est menée via le code de calcul PLAXIS$^{3D}$. Cette analyse est effectuée selon deux modèles de comportement, à savoir : le modèle des sols mous (SSM) et le modèle élastoplastique avec écrouissage (HSM). Cette étude s'est principalement penchée sur l'état de gonflement, de tassement et de succion à l'intérieur de la masse du sol de fondation durant les phases de construction du projet. Selon les principaux résultats des analyses, le SSM affiche des gonflements et tassements plus importants que ceux établis par le HSM. Alors qu'en termes de succion, des valeurs étroitement proches sont données par les deux modèles. Bien qu'ils affichent un gonflement et un tassement au milieu et aux bords de l'excavation, la succion n'est observée qu'au milieu. Même si le SSM donne des valeurs élevées dans la plupart des cas, des valeurs historiques plus élevées de la succion sont affichées au-dessous de la zone médiane par le HSM. Ceci amène à une surface de tension contraignant l'interface air-eau de se comporter comme une membrane, empêchant par conséquent tout développement de gonflement.

**Mots - clé :** Argiles gonflantes non-saturées, 3DFEA, SSM, HSM, Succion des sols.



## 1-Introduction

The mechanical behaviour controlling of the unsaturated expansive clays remains one of the challenging issues frequently encountered in geotechnical engineering practice. Constructions built on unsaturated swelling clays without any treatments often require specific foundation systems. For instance, pile foundations are strongly recommended, but they are not cost-effective for low-rise buildings [1-2]. However, using shallow foundations in unsaturated expansive clays showing soil suction and settlement can significantly threaten its stability [2-5] Thereby, stiffened raft foundations are often considered a suitable foundation system for small structures resting on the swelling clay.

Since all methods developed to predict and assess the swelling capacity of expansive soils use empirical relationships of some basic soil parameters, analytical or numerical methods remain heavily preferred [6-8]. Unlike using analytical methods to describe the complex expansive clays' behaviour in terms of swelling, settlement, or soil suction, under loadings seems difficult, even impossible. Therefore, for these complex expansive clay models in the presence of moisture and applied loads, numerical methods using implemented specific algorithm programs prove a suitable tool to solve unsaturated expansive clay problems. In addition, numerical methods, such as finite difference (FDM) or finite element (FEM) methods, have been used to overcome difficulties noted during the prediction behaviour of unsaturated expansive clays [9-12]. In addition, few 3D finite element analysis attempts for simulating constructions built on unsaturated swelling clays, using the elastic perfectly plastic constitutive model of Mohr-Coulomb in pair with other advanced material models available in the PLAXIS$^{3D}$ program, have been found in geotechnical engineering practice [13-15]. For further extended studies to understand the behaviour of the unsaturated expansive clays under vertical loadings, using the improved nonlinear elastoplastic models seems vital.

In this context, this paper tends to find out the most differences in terms of swelling, settlement, and suction states of unsaturated expansive marly clay supporting a four-story building, given by 3DFEA via PLAXIS$^{3D}$ code using the advanced material models HSM and SSM.

## 2-Problem description and finite element modelling process

The selected 3D geometric model shown in Fig. 1 consists of unsaturated expansive marly clay as an upper layer, on which a four-storey building rests at a 3.0 m excavation depth and a lower one of a gravely sand is used as a substratum of the model. The phreatic level is located at -3.50 m from the ground surface. The building is 16.0 m wide, 24.0 m long, and 15.0 m high. Owing to the foundation soil type, a stiffened raft foundation design with basement walls is adopted.

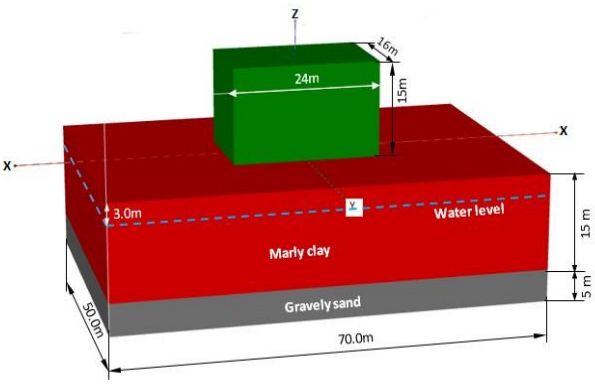



**Figure 1**:3D Geometric model established by PLAXIS$^{3D}$ code

**Figure 1** : Modèle géométrique tridimensionnel établi par le code PLAXIS$^{3D}$

On the other hand, PLAXIS$^{3D}$ is conducted to establish a 3D discretised model, during which a transformation of the input data from a geometric model to the finite element mesh is made. Basic tetrahedral elements of 10 and 12 nodes are respectively used to generate soil body volume and soil-structure interaction behaviour. Moreover, PLAXIS$^{3D}$ automatically applies boundary conditions. Hence, they are restricted on the vertical limits in both X and Y directions, whereas they are fully blocked at the bottom and obviously free on the ground surface. In addition, SSM and HSM material models are successively adopted to describe the marly clay layer response, while the substratum is modelled according to the Mohr-Coulomb (MC) constitutive model. Likewise, structural elements are assumed to follow the isotropic elastic model. The average input parameters of soils used in this simulation are summarised in Tab. 1.

**Table 1**: Average geomechanical properties used in the 3DFEA

**Tableau 1** : Propriétés géomécaniques moyennes utilisées dans 3DFEA

| Parameter | Marly clay | | Gravely sand | Unit |
|---|---|---|---|---|
| Material model | HS | SS | M-C | (−) |
| Material behaviour type | Undrained | Undrained | Drained | (−) |
| Unsaturated soil unit weight ($\gamma_{unsat}$) | 17.80 | 17.80 | 18.20 | kN/m³ |
| Saturated soil unit weight ($\gamma_{sat}$) | 19.60 | 19.60 | 20.30 | kN/m³ |
| Secant modulus $E_{50}^{ref}$ | 4800 | − | 5800 | kN/m² |
| Tangent modulus $E_{oed}^{ref}$ | 6461 | − | − | kN/m² |
| $E_{ur}^{ref} = 3E_{50}^{ref}$ | 14400 | − | − | kN/m² |
| m | 1.0 | − | − | (−) |
| Pref | 100 | − | − | (−) |
| Poisson's ratio ($\nu$) | 0.33 | − | 0.30 | (−) |
| Modified compression index ($\lambda^*$) | − | 0.1014 | − | (−) |
| Modified swelling index ($k^*$) | − | 0.04 | − | (−) |
| $\nu_{ur}$ | 0.15 | 0.15 | − | (−) |
| $k_0^{nc}$ | 0.708 | 0.708 | − | (−) |
| Effective Cohesion ($C_{ref}$) | 35 | 35 | 10 | kN/m² |
| Effective Friction angle ($\varphi_{ref}$) | 10 | 10 | 30 | (°) |
| Angle of dilatancy ($\psi$) | 0.00 | 0.00 | 0.00 | (°) |
| X-direction permeability ($k_X$) | 1E − 04 | 1E − 04 | 1.0 | (m/day) |
| Y-direction permeability ($k_Y$) | 1E − 04 | 1E − 04 | 1.0 | (m/day) |
| Z-direction permeability ($k_Z$) | 1E − 04 | 1E − 04 | 1.0 | (m/day) |
| Swelling index ($C_s$) | − | 0.069 | − | (−) |
| Compression index ($C_c$) | − | 0.35 | − | (−) |

However, raft foundation and basement walls have, respectively, 0.5 and 0.25 m as thickness and other similar concrete parameters (i.e., a Young modulus of 3x$10^3$ kPa, a Poisson's ratio of 0.15, and a unit weight of 25 kN/m³).

As illustrated in Fig. 2, the 3D numerical model corresponding to the 3D geometric one shown in Fig. 1 consists of 37357 tetrahedral elements of 1.811 m as the average element size and 58613 nodes.

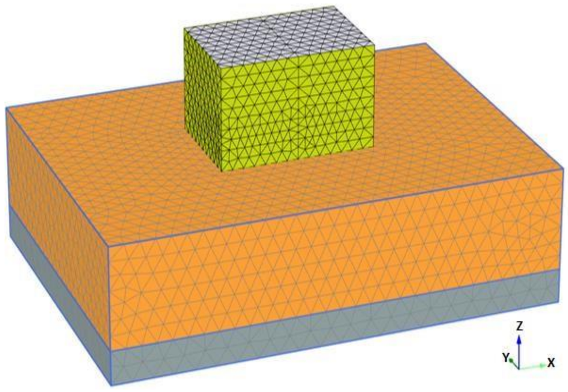



**Figure 2**: 3D finite element model mesh generated by PLAXIS$^{3D}$ code

**Figure 2** : Modèle 3D éléments finis établis génération de maillage par le code PLAXIS$^{3D}$

To follow heave, settlement, and soil suction histories during the calculation process, three monitoring points, A, B, and C, are selected. They are respectively located at the left edge, the middle, and the right of the stiffened raft foundation.

Once the numerical model is established, initial conditions are generated, in which the soils' self-weight is fully applied. To easily run the model; the building shown in Fig. 1 is replaced by a uniform accumulated vertical load, directly applied over the raft foundation surface, as shown in Fig. 3. Then the staged construction technique is used with a plastic calculation mode to perfectly simulate, three successive project phases.

1) : excavation stage;

2) : stiffened foundation implementation;

3) : building weight applications of 15, 25 and 35 kN⁄m3 on the raft foundation.

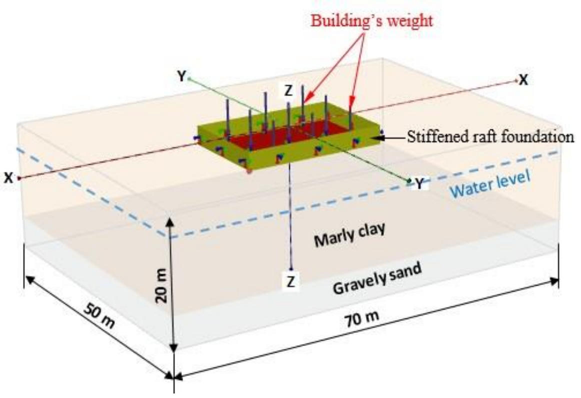



**Figure 3**: 3D equivalent model used in finite element analysis

**Figure 3** : Modèle équivalent 3D utilisé dans l'analyse d'éléments finis

## 3-Results and discussions

Owing to the aim of this study, analysis results have mainly referred to maximum swelling, settlement, and suction values within the soil body during the project construction stages and under different vertical loadings applied in ascending order. Likewise, heave histories under the raft middle zone were only considered. As shown in Fig. 4, the unsaturated SSM shows swelling values higher than the HSM one during construction stages and under vertical loadings. It can be seen that swelling decreases in the intermediate phase for both models, SSM and HSM.

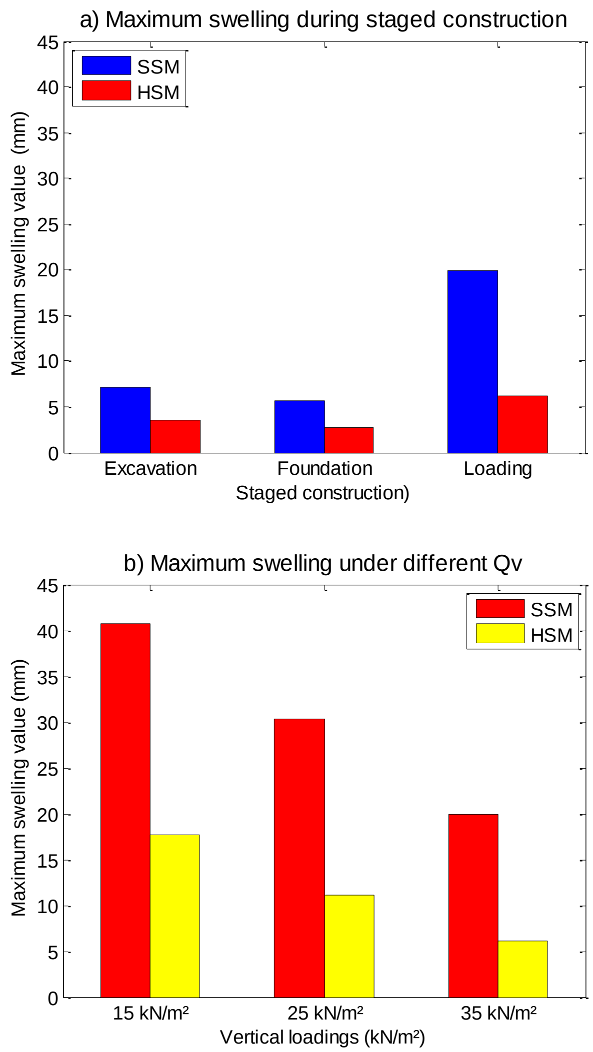



**Figure 4**: Maximum swelling values during the project achievement and under different vertical loading Qv values

**Figure 4** : Valeurs maximales des gonflements durant la réalisation du projet et sous différents chargements verticaux Qv

Hence, the implemented foundation phase sensibly decreases the swell of soil by creating a tension surface that behaves as a membrane, preventing the swelling evolution at the soil-structure interface (Fig. 4a). As regards the applied vertical loading effect, it is proved when they take up an ascending order. Using the HSM, in which soil improvements are considered, amply decreases the swelling clay behaviour (Fig. 4b). The gap between the two models increases from 47% for lightweight constructions (15 kN/m²) to 70% for the heavy ones (35 kN/m²). It means that, in such an unsaturated clay state, the HSM is more efficient when higher compressive forces are applied. In this case, the SSM significantly reduces the swelling evolution of the clay under the foundation more than the Soft Soil one, but it cannot eliminate it. Unlike significant settlement values, which are reported during the project stages in the SSM case than the HSM one (Fig. 5a). It is directly proportional to vertical loadings and develops with the Qv increase in ascending linear rate around 6 and 3 mm for both SSM and HSM cases, respectively, as illustrated in Fig. 5b.

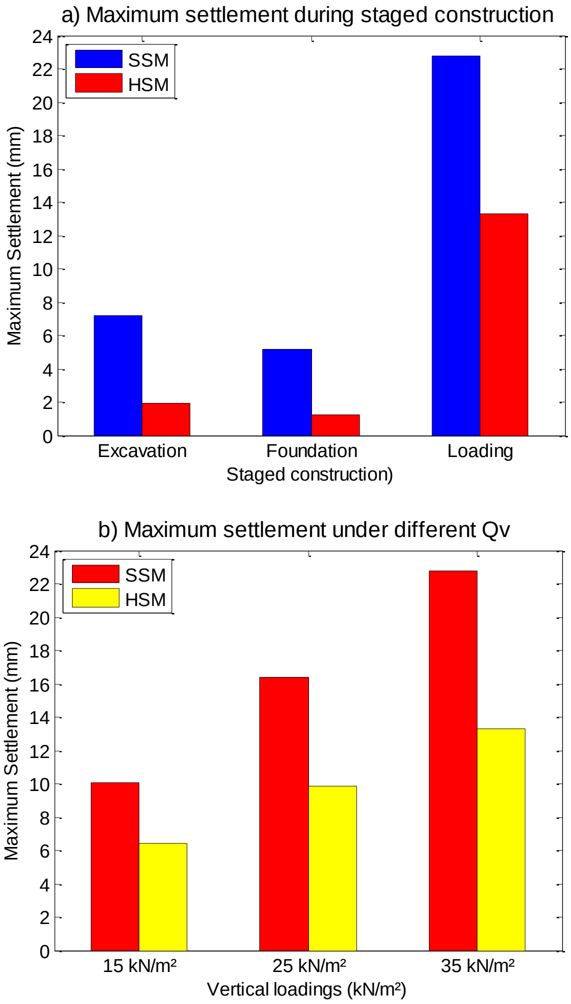



**Figure 5**: Maximum settlement values during the project achievement and under different vertical loading Qv value

**Figure 5** : Valeurs maximales des tassements durant la réalisation du projet et sous différents chargements verticaux Qv

Furthermore, closed soil suction values are reported for both models during the achievement project stages and after applying different increasing compressive loads (Fig. 6). Hence, these material models can produce significant negative pore water pressures spread through the extended vadose zone of the unsaturated clay that is located above the phreatic level and exerted by clays to equalize the soil moisture in the soil body.

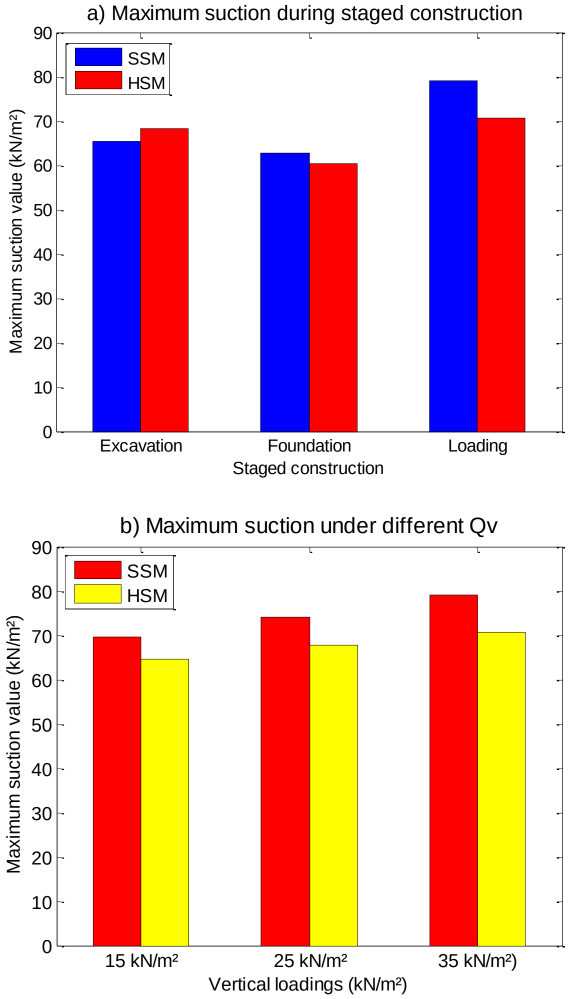
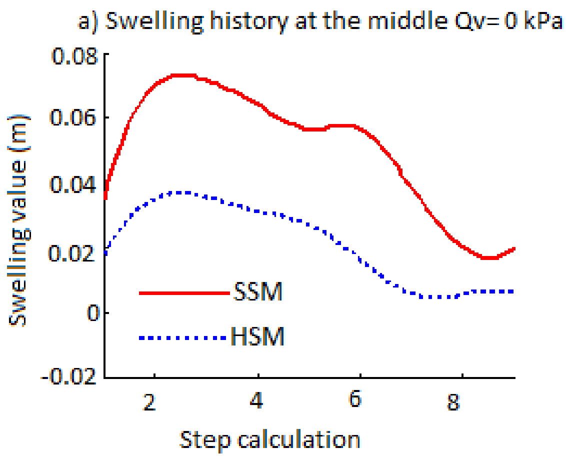
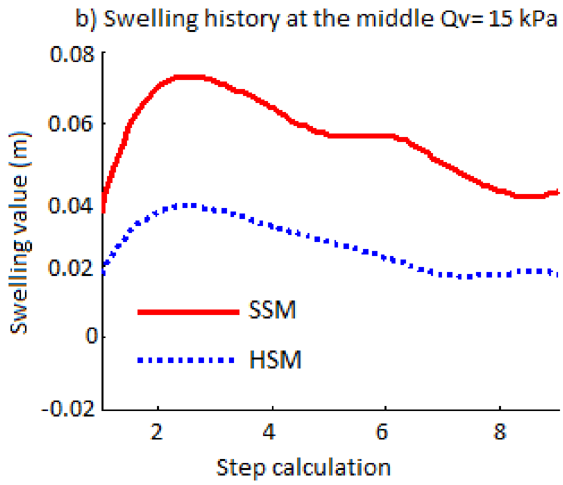


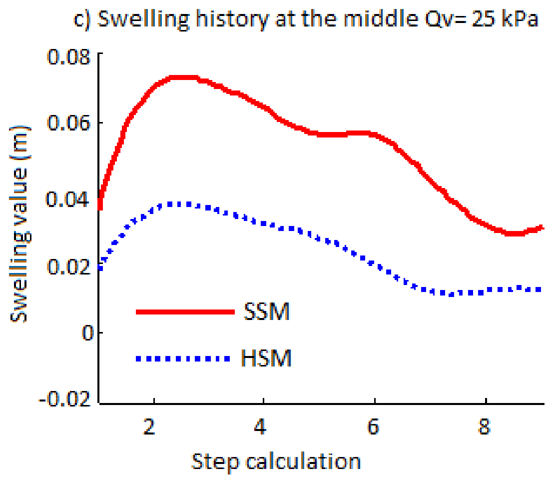

**Figure 6**: Maximum soil suction values during the project achievement and under different vertical loading Qv values

**Figure 6** : Valeurs maximales des succions des sols durant la réalisation du projet et sous différents chargements verticaux Qv

On the other hand, swelling curve histories of the soil foundation under the middle raft zone show similar patterns but with a significant gap between the two models. They also have nearest amplitudes along most parts of the computation process, whereas, in the end, they tend to exhibit a compressive behaviour (settlement) under increasing vertical loadings than the heave one (Fig. 7). Although the significant gap among them, all curves converge at the end of the calculation procedure, showing therefore a significant construction weight effect on the heave behaviour.



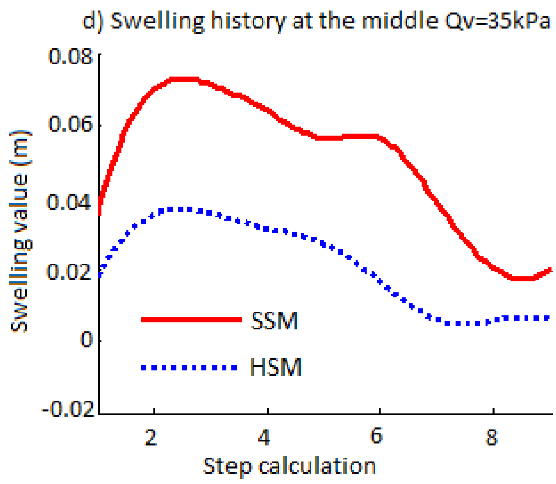




**Figure 7**: Swelling curve histories at the middle of the raft foundation during the construction period under different Qv values

**Figure 7** : Courbes de l'évolution du gonflement au milieu du radier durant la période de construction sous différents chargements verticaux Qv

## 4- Conclusions

These are the main findings that can be derived from this work.

- Through a 3DFEA as a promising tool, it becomes easy to solve swelling, settlement, and suction problems of the unsaturated heave clays.
- The behaviour of these clays in terms of swelling or settlement is often presented in reciprocal patterns, but in terms of soil suction, tightened values are exhibited by both material models SS and HS. In this case, significant suction matric can be produced over the saturated zone, inducing a tension surface to behave as a membrane, therefore reducing significantly the heave behaviour.
- Another important issue is that under low compressive loads, unsaturated expansive clays retain their heave state and hence can induce serious damage to the construction built over them. Nevertheless, if these loadings are significant, they tend to settle regardless of their swelling amplitude.
- This study shows that the use of advanced material models leads easily to understanding the unsaturated heave clay behaviour.

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