

# Expansive Soils: Examining the Critical Parameters Influencing Swelling and Shrinkage

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## RESUME

Expansive soils; characterized by high clay mineral content, especially montmorillonite, pose significant challenges in geotechnical engineering due to their large volume changes in response to moisture fluctuations. Prevalent in regions with extreme climates, these soils swell when wet and shrink when dry, creating structural risks for infrastructure. Analysing the shrink-swell behaviour of expansive soils reveals critical factors driving these volume changes and their impacts, particularly in areas where climate variability exacerbates moisture extremes. Examining soil suction, water retention characteristics, and pore size distribution (PSD) uncovers mechanisms influencing swelling-shrinkage cycles. The Water Retention Curve (WRC) illustrates how unsaturated soils manage moisture and demonstrates the influence of soil texture, density, and mineral composition on water retention. Additionally, the effects of compaction and consolidation on PSD reveal how pore structure modifications amplify or mitigate expansive tendencies. Geotechnical parameters, including plasticity index, water content, and dry density, are highlighted as central to understanding soil swelling behaviours. Given the numerous factors influencing soil swelling, it is crucial to conduct studies that identify and evaluate the most significant parameters to improve predictive models and advance the understanding of swelling behaviour in expansive soils.

**Mots-clefs** Expansive soils, Shrink-swell behaviour, Water retention curves, pore size distribution, Geotechnical parameters

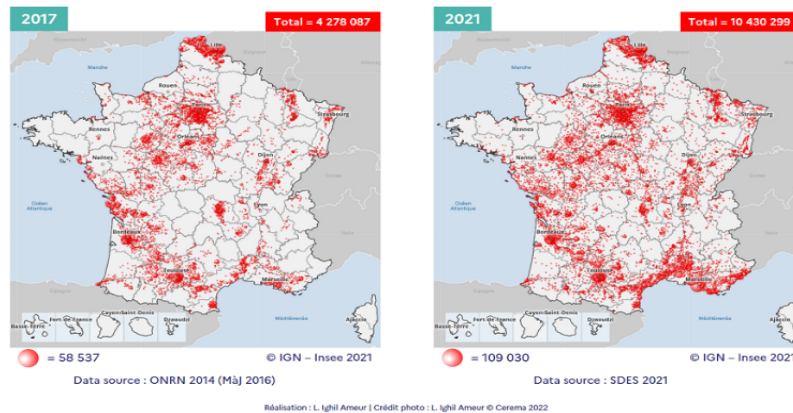
## I. INTRODUCTION

Expansive soils, composed mainly of reactive clay minerals like montmorillonite, exhibit significant volume changes due to moisture variations, causing major geotechnical challenges. These soils, prevalent in arid and semi-arid regions, absorb water and swell, leading to issues such as foundation cracking and pavement failure, necessitating robust engineering solutions (Assadollahi and Nowamooz, 2019; Nelson and Miller, 1997). Seasonal moisture fluctuations exacerbate shrink-swell cycles, causing vertical ground movements that compromise infrastructure stability and result in substantial maintenance costs (Lytton et al., 2004).

In France, shrink-swell behaviour ranks second to floods in damage costs, particularly affecting lightweight residential buildings. Damages surpassed €3.3 billion in 2002, highlighting these soils' economic and durability concerns (Vincelas et al., 2020; Zemeny et al., 2009). By June 2021, over 10.4 million houses were identified as exposed to clay soil shrinkage and swelling hazards (RGA), nearly half of which were built after 1976. Strong or moderate exposure affects 48% of metropolitan areas, and three-quarters of communes have over 50% of houses at risk, as

illustrated in Figure 1. Expansive soils also accounted for 77% of insured natural disaster damage costs in 2020 (Caisse Centrale de Réassurance, 2021; CEREMA Web Resource., 2022).

Climate change intensifies the swelling-shrinkage phenomenon due to increased rainfall and prolonged droughts. Engineers must prioritize soil stabilization techniques and improved soil mechanics to mitigate risks and ensure infrastructure stability in affected regions (Lytton et al., 2004; Nelson and Miller, 1997).



**Figure 1** Evolution of the number of single-family homes exposed to the "strong or medium" RGA hazard between 2017 and 2021, "(CEREMA Web Resource., 2022)"

Given the threat expansive clays pose to infrastructure, it is vital to understand the factors influencing their swelling. Understanding these factors is essential for predicting and mitigating the risks associated with expansive soils. Therefore, this study will include a comprehensive state-of-the-art review of research on expansive soils to provide context and understanding of the topic. The state-of-the-art review will specifically focus on exploring the parameters that affect the swelling behaviour of these soils. Additionally, a detailed experimental investigation using oedometric cells will be conducted to explore and quantify the swelling behaviour of these soils under varying conditions. The oedometric tests will be designed to examine the impact of some of the identified parameters on swelling behaviour, enabling a better understanding of their influence and interactions.

## II. Swelling and Suction in Expansive Clays

Expansive clays like smectite and montmorillonite swell due to their 2:1 layered structure, which allows water and cations to enter interlayer spaces, driven by high cation exchange capacity (CEC). This process is enhanced by the diffuse double layer (DDL), a charged zone around clay particles composed of a fixed and a diffuse layer, that attracts water and cations (Banganayi and Nyembwe, 2020; Olarte and Cavalcante, 2023).

Two primary mechanisms govern swelling: osmotic swelling, caused by repulsion between DDLs, leading to significant volumetric changes, and crystalline swelling, caused by water infiltrating interlayer spaces and hydrating exchangeable cations, resulting in moderate expansion limited by the clay's structural constraints (Massat et al., 2016). For example, sodium montmorillonite swells more than calcium montmorillonite due to higher hydration energy, highlighting the influence of mineralogy and water chemistry on swelling behaviour (Rahman and Grasley, 2023).

The relationship between swelling behaviour and the soil's structural properties is closely linked to suction, the state variable used for unsaturated soils which affects moisture balance and drives changes in the microstructure. Suction, defined as the difference between pore air and pore water pressure, regulates water retention and swelling in unsaturated soils. High suction reduces water infiltration, limiting swelling, while low suction increases water absorption, intensifying swelling (Delage, 2002). This regulation of water movement and particle interactions by suction directly affects the internal forces within the soil, which can be captured through the concept of effective stress. The effective stress equation incorporates suction through the parameter  $\chi$ :

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad \text{Equation 1}$$

Where  $\sigma$  is total stress,  $u_a$  is pore-air pressure,  $u_w$  is pore-water pressure, and  $\chi$  accounts for suction's influence.

Higher suction enhances soil cohesion and stiffness, but excessive wetting induces a decrease in suction that can lead to failure, particularly in clayey soils with high water absorption capacity. These effects, coupled with wetting-drying cycles, underscore suction's critical role in geotechnical stability, making tools like the Water Retention Curve (WRC) essential for understanding and managing expansive soils (Fleureau and Kheirbek-Saoud, 2001). It is therefore, important to explore the WRC in detail and examine how it is influenced by soil parameter.

### III. Water Retention curve

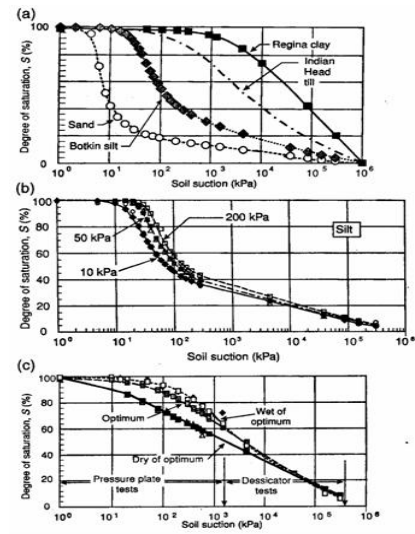
The Water Retention Curve (WRC) describes the variation of suction in unsaturated soils with the variation of water content or saturation degree. Soil texture and particle size distribution are key factors, with sands inducing lower suction due to larger pores, while clays, with smaller pores and larger surface areas, can develop very high suction. Poorly graded sands retain more water than well-graded sands, and clay particles enhance retention through specific surface area and cation exchange capacity (Delage, 2002).

Higher void ratios allow greater water retention until the air-entry value is reached, but at higher suctions, microstructure plays a larger role. Compaction affects retention, with wet-compacted soils forming dense microstructures that retain more water, while dry-compacted soils have larger pores and reduced retention (Gao and Sun, 2017).

Mineralogical composition, particularly hydrophilic minerals like smectite and illite, further enhances water retention Boom Clay, rich in these minerals, maintains strong retention at high suctions, unlike soils with non-swelling minerals that show greater WRC changes (Delage, 2002).

Consolidation collapses larger pores, increasing water retention by creating finer pores. Techniques like SEM and MIP highlight how consolidation, temperature and stress alter soil microstructure and saturation levels (Delage, 2002; Gao and Sun, 2017).

The impact of soil texture, consolidation, and compaction on the WRC can be visualized in Figure 2 (Delage, 2002) and Table 1. This figure illustrates the influence of these parameters on the water retention properties of soils.



**Figure 2** Influence of a) soil texture, b) consolidation and c) compaction on the water retention properties of soils (from Barbour (1998) and Vanapalli et al. (1999)).

**Table 1** Influence of soil texture, consolidation and compaction under different conditions on the water retention properties of soils

Parameter	Variable Condition	Observation
Effect of Texture	Sand	Coarser texture, low water retention capacity
	Bodin Silt	Intermediate behavior between sand and clay
	Regina Clay	Finer texture, high water retention capacity
Effect of Consolidation Pressure	Silt (10 kPa)	Low applied pressure limits the soil's capacity to retain water
	Silt (50 kPa)	Increased pressure enhances water retention compared to 10 kPa
	Silt (200 kPa)	Highest pressure results in the greatest water retention
Effect of Compaction	Optimum Condition	Balanced capacity to retain water between wet and dry conditions
	Dry of Optimum	Lower capacity to retain water compared to optimum and wet conditions
	Wet of Optimum	Higher capacity to retain water due to better water-holding capacity in wet soils

Understanding how pore size distribution changes at the microstructural level when properties like compaction, mineral composition, and consolidation are altered is important, as these factors are critical for linking the Water Retention Curve (WRC) to unsaturated soil behavior.

#### IV. Pore Size Distribution

Pore size distribution (PSD) describes the variation in void sizes within a soil matrix, ranging from nanometers to millimeters. Based on their diameter, these voids are categorized into micropores, mesopores, and macropores. PSD significantly influences soil properties and behaviour, determining factors like permeability, strength, and swelling capacity. Understanding PSD provides essential insights into the structural characteristics of soils and their responses to environmental and mechanical stresses.

##### A. Impact of pore size distribution on the swelling behaviour

Pore size distribution significantly influences the swelling behaviour of expansive clays. (Pedarla et al., 2016) found that soils compacted at the maximum dry unit weight (MDUW) swelled more than those at 95% MDUW due to denser particle packing, enhancing water-particle interactions despite smaller pores. MIP data confirms MDUW compacts shift toward micropores, boosting retention and swelling.

Table 2 highlights the relationship between plasticity index (PI), compaction, and confining pressure on swell strain. Soils with higher PI swelled more but showed reduced strain under higher pressures. For example, Grayson soil (PI 49) had the highest strain, while Keller soil (PI 11) had the least.

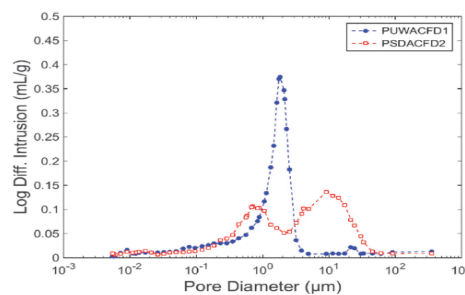
**Table 2** Comparison of vertical and volumetric swell strain properties of the 8 types of soil at different dry unit weight and confining pressures

Soil	PI	Vertical swell strain %		Volumetric strain at 95% MDUW (%)		
		MD UW	95% MDUW	7 kPa	50 kPa	100 kPa
Grayson	49	14.2	9.8	11.65	8.76	7.67
San Antonio	43	10.2	7.3	9.13	7.4	5.74
Colorado	42	12	8.2	9.29	7.55	6.3
Burleson	37	8.8	5.5	8.03	6.45	4.69
San Diego	28	4.4	3.4	4.52	3.43	2.13
Anthem	27	5.8	4.5	4.8	4.3	2.87
Oklahoma	21	4.8	3.8	5.03	3.69	2.69
Keller	11	7.9	5.6	6.84	5.73	3.71

### B. Effect of Compaction on pore size distribution

Compaction moisture content significantly influences pore size distribution (PSD), affecting soil microstructure and mechanical behaviour. Dry-side (SD) compaction yields bimodal PSD (micro and macro pores)—stable under saturation, especially in silty soils (Oualmakran et al., 2016). Figure 6 illustrates this, with the red dashed line representing SD soils' bimodal PSD.

Conversely, wet-side (UW) compaction gives unimodal PSD, a more uniform, dense matrix under stress. This uniformity creates a denser, more predictable soil matrix under external stress, as shown by the blue solid line in Figure 3 (Oualmakran et al., 2016).



**Figure 3** Comparison of pore-size distributions for dry-side (SD) and wet-side (UW) compacted soils (Oualmakran et al., 2016)

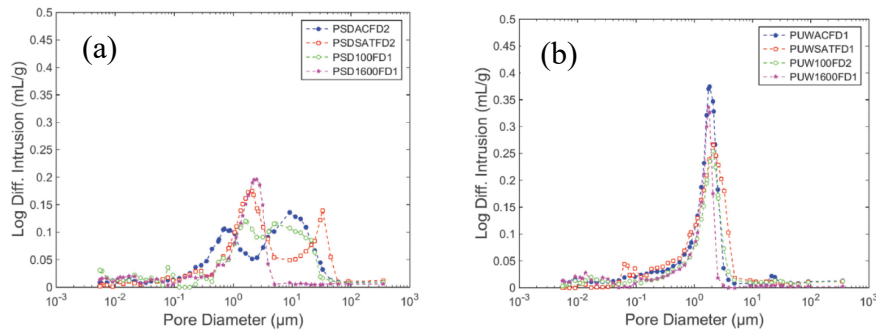
### C. Effect of Consolidation on pore size distribution

Consolidation impacts PSD based on a soil's initial structure and mineral composition. Mechanical loading, particularly in saturated conditions, significantly affects PSD in SD soils. (Oualmakran et al., 2016) observed that SD soils, which initially exhibit a bimodal PSD, transition to a unimodal distribution under high pressures, as illustrated in Figure 4(a). This change reflects the collapse of the porous network and the development of a denser and more uniform microstructure as pressures exceed the soil's pre-consolidation limit.

In contrast, UW soils, which begin with a unimodal PSD, experience densification without significant structural transformation under loading. Figure 4(b) highlights their inherent stability

due to their already compact structure, making them less susceptible to major changes compared to SD soils (Oualmakran et al., 2016).

While SD soils initially demonstrate resistance and flexibility due to higher pre-consolidation pressures, extreme stresses eventually cause their structure to collapse, resembling the uniformly compacted behaviour of UW soils. This distinction underscores the differing responses of SD and UW soils to mechanical loading and consolidation(Oualmakran et al., 2016).

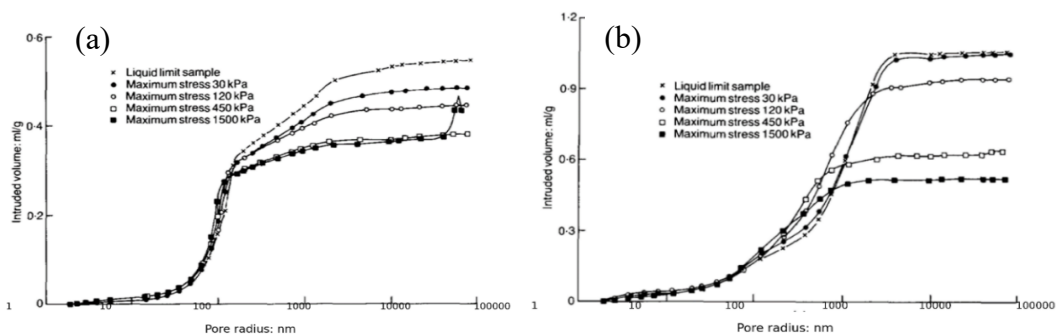


**Figure 4** Changes in pore size distribution under different loading conditions for soil compacted on, (a): the dry side of the optimum and (b): the wet side of the optimum (Oualmakran et al., 2016)

*D. Effect of Mineral composition pore size distribution*

Consolidation pressure in clay soils reveals complex interactions between soil composition and mechanical behavior. Mercury Intrusion Porosimetry (MIP) studies by (Griffiths and Joshi, 1989) show that higher pressures reduce larger pores (>0.8 µm) while increasing smaller ones (0.1–0.8 µm), indicating pore redistribution rather than uniform compaction.

Mineralogy significantly affects this response. Soil 2, primarily kaolinite, has a liquid limit of 45.1% and plastic limit of 28%, reflecting its rigidity and low expansiveness. In contrast, Soil 4, with both kaolinite and montmorillonite, shows a higher liquid limit (100%) and slightly higher plastic limit (30.4%). Montmorillonite contributes to expansive behavior and interlayer swelling, leading to substantial shifts in larger pores. Soil 2 shows more uniform pore size reduction under pressure, consistent with kaolinite’s stable structure. Figures 5 (a) and (b) illustrate that Soil 2 experiences steady pore size reduction, while Soil 4 undergoes significant pore redistribution due to montmorillonite’s expansive and compressible nature (Griffiths and Joshi, 1989).



**Figure 5** Pore size distribution of a: soil 2 and b: soil 4(Griffiths and Joshi, 1989)

## V. Geotechnical Parameters and swelling

The study of soil behaviour, particularly in expansive soils, has been a significant focus in geotechnical engineering due to the challenges posed by soil volume changes under varying moisture conditions. In this context, several key studies have provided insights into the variability of soil responses, emphasizing the importance of parameters such as soil suction, plasticity index, water content, dry density, and mineral composition. These studies, with their methodologies, findings, and implications, have introduced various equations to predict the swelling behaviour of soil, some of which are summarized in Table 3.

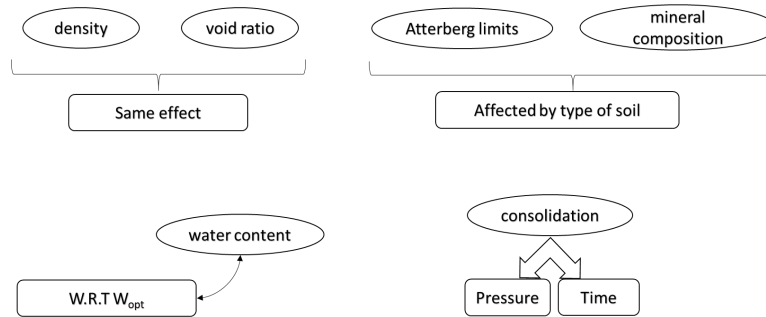
**Table 3** Different studies predictions of swelling from different parameters (Sp: Swell Percent, PS: Swelling Pressure)

Model	Reference	Equation	Parameters Explained
Models dependent on Plasticity Index (PI) Alone	Seed et al. (1962)	$Sp = 2.16 \times 10^{-3} (PI)^{2.44}$	PI = Plasticity Index
	Chen (1974)	$Sp = 0.2558e^{(0.08381PI)}$	PI = Plasticity Index
	Popescu (1974)	$PS = 0.5735PI - 10.9196$	PI = Plasticity Index
Models dependent on Plasticity Index (PI) and Other parameters	Nayak & Christensen (1971)	$Sp = 0.00229(PI)^{2.67} (1.45C)/Wi + 6.38$ and $PS = [(3.58 \times 10^{-2})PI^{1.12} C^2/Wi^2] + 3.79$	PI = Plasticity Index, C = Clay Content, Wi = Initial Water Content
	Schneider & Poor (1974)	$Sp = 0.66 \times 10^{(0.9PI/Wi-1.19)}$	PI = Plasticity Index, Wi = Initial Water Content
	Brackley (1975)	$\log PS = 5.3[(147e)/PI]$	PI = Plasticity Index, w = Water Content, P = Applied Load in kPa
	Zumrawi (2012)	$Sp = 24.5(P)^{-0.26} (PI \times C)^{1.26} [Fi - 7.1(P)^{0.22} \times (PI \times C)^{0.78}]$ and $PS = 249 \times (PI \times C)^{1.18} [Fi - 0.84 \times (PI \times C)^{-0.96}]$	Fi = Initial State Factor, PI = Plasticity Index, C = Clay Content, P = Surcharge Pressure
Models dependent on Liquid Limit (LL) and other parameters	Weston (1980)	$Sp = 0.000195WL^{(4.17)} * Wi^{-2.33}$	LL = Liquid Limit, w = Water Content
	Vijayvergiva & Ghazzaly (1973)	$Sp = 1/12[0.4WL - Wi + 5.55]$	LL = Liquid Limit, wi = Water Content
	Komorinik & David (1969)	$\log PS = 2.13 + 0.021WL + 0.000665cd - 0.027Wi$	WL = Liquid Limit, cd = Dry Density, Wi = Initial Water Content
	Elsharief (1987)	$\log PS = 2.6386cd + 1.3922 + 10^{-2}WL - 2.4775$	cd = Dry Density, WL = Liquid Limit
	Zacharias & Ranganathan (1972)	$Sp = -225 + 290(WL - W100)/SI + SI/S$ and $PS = (-225/6.4) + (1.2/6.4) \times (SI/S) + (229/6.4) \times (WL - W100)/SI$	WL = Liquid Limit, W100 = Water Content at 100% Saturation, SI = Shrinkage Index, S = Degree of Saturation
Models dependent on Clay Content (C)	Didier et al. (1983)	$\log PS \text{ (kg/cm}^2\text{)} = 0.0294C - 1.923$	C = Clay Content
	El Sohby & Rabbaa (1981)	For sand-clay: $\log PS = 2.17(cd + 8.4 \times 10^{-3}C - 1.8)$ For silt-clay: $\log PS = 2.5(cd + 6 \times 10^{-3}C - 1.6)$	cd = Dry Density, C = Clay Content

## VI. Methodology

This methodology studies the swelling behaviour of various soils by selecting samples with different mineral compositions, plasticity levels, and pore size distributions. This diverse selection allows a better understanding of how soil properties influence swelling. Based on the literature review, Figure 6 summarizes the key factors identified as influencing swelling behaviour. These factors will therefore be the focus of the planned experimental tests.

Key factors affecting swelling, such as density and void ratio, are tested to assess the role of compaction. Water content is adjusted to levels below, at, and above the optimum moisture level ( $W_{opt}$ ), including saturation, to study its effect on water retention and swelling potential. Consolidation is examined under different pressures and durations to understand its impact on soil stability and swelling. Other properties, such as Atterberg limits, Specific Surface Area (SSA), Cation Exchange Capacity (CEC), and mineral content, are also studied due to their strong influence on swelling behaviour. These properties are analysed across different soil types, as changes in soil type naturally alter these characteristics, providing deeper insights into their effects.



**Figure 6** Summary of Key Factors Influencing Swelling Behaviour in Expansive Soils

Thus, Table 4 outlines the methodology to study the different parameters found to affect swelling behaviour, using a range of values for each parameter.

To study the effect of different soil types on swelling behaviour, two main soils were selected as the base materials: Argile Aulnat Allier, a natural low-plasticity clay, and Artificial Clay, which is highly expansive and composed of over 91% sodium montmorillonites. These two soils serve as reference points for further experimentation and are used to create new mixtures that reflect more complex, naturally expansive soils. Their geotechnical properties are presented in Table 5.

To simulate naturally expansive soils and examine the effects of varying swelling clay content, soil-clay mixtures were prepared using Argile Aulnat Allier and Artificial Clay. The proportions varied from 97:3 to 92:8 clay-to-soil ratios. These mixtures help to reflect the interaction of swelling and non-swelling components in real soils and assess how microstructural arrangements influence swelling behaviour. This methodological inclusion ensures a more realistic and representative investigation of expansive soil conditions.

The Oedometer test measures swelling under controlled conditions. Soil samples are subjected to pressure and gradually saturated to observe their swelling response. After data collection, regression analysis is performed to develop predictive models based on factors like liquid limit, plasticity, and consolidation conditions.

**Table 4** parameters to be under study for different soils

Parameter	Notes
Density or void ratio	90%, 95%, and 100% of maximum dry density (MDD)
Water content	Two values below $W_{opt}$ , at $W_{opt}$ and two values above $W_{opt}$
Consolidation pressure	76.5, 127.5, and 178.5 kPa
Time	90 minutes per layer, 5 hours per sample, 24 hours per sample

**Table 5** Geotechnical Characteristics of Argile Aulnat Allier and Artificial Clay

Property	Argile Aulnat Allier	Artificial Clay
Plastic Limit (wP) (%)	22	85.5
Liquid Limit (wL) (%)	43	540
Plasticity Index (PI) (%)	21	454.5
VBS	4.55	28
Particles < 2 $\mu\text{m}$ (%)	43.5	100
Particles < 80 $\mu\text{m}$ (%)	94.7	100
Mineral Composition	-	>91% Sodium Montmorillonites

## VII. Results and discussions

### A. Consolidation Effect on Swelling of Argile Aulnat Allier

#### 1. Effect of Consolidation Time

The influence of consolidation time on the swelling strain of Argile Aulnat Allier soil was studied by subjecting samples to durations of 5 hours, 90 minutes per layer, and 24 hours, all at a consolidation pressure of 127.5 kPa. The results in Figure 7 demonstrate that longer consolidation times lead to more significant swelling strains. Shorter durations (e.g., 5 hours) result in a gradual swelling increase, while longer durations (e.g., 24 hours) show a sharper rise, suggesting structural rearrangements that enhance the soil's capacity to absorb water during saturation.

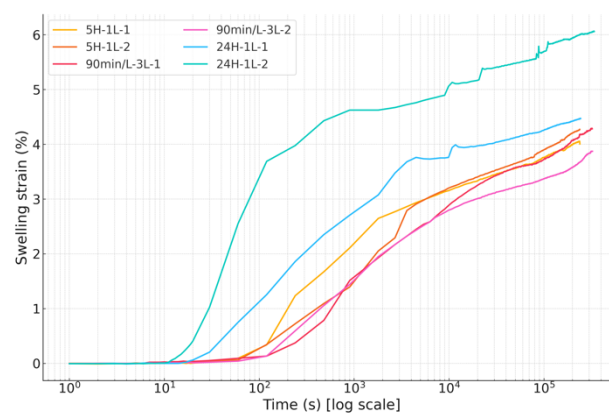
These results indicate that prolonged consolidation modifies the soil structure, densifying the particle arrangement and increasing water-particle interactions. This effect is supported by void ratio and saturation data from Table 6.

From a microstructural perspective, this behaviour may be explained by the realignment of clay particles under extended loading time, leading to a more ordered structure that enables higher water intake during subsequent saturation phases.

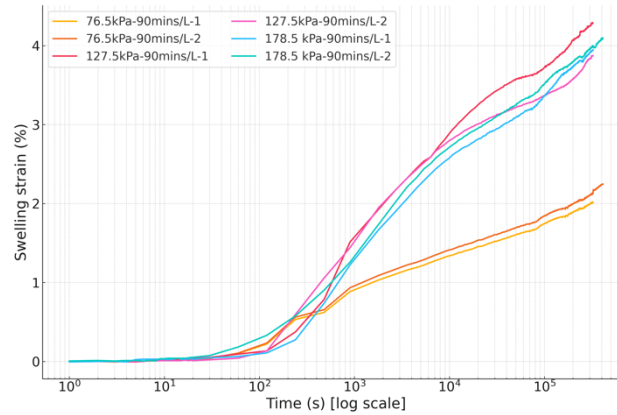
#### 2. Effect of Consolidation Pressure

The effect of consolidation pressure was evaluated at 76.5, 127.5, and 178.5 kPa, with a uniform consolidation time of 90 minutes per layer. As shown in Figure 8, higher pressures result in significantly greater swelling strains. For example, soils consolidated at 178.5 kPa exhibited higher swelling than those at 76.5 kPa, indicating that increased pressure alters the soil structure. These results are again corroborated by Table 6, where changes in void ratio and saturation reflect the structural densification and water retention resulting from increased pressure. This behaviour aligns with previous studies' findings, highlighting consolidation time's critical role in influencing soil swelling.

Minor differences in swelling strain were observed for samples subjected to the same pressure, likely due to variations in soil heterogeneity or sample preparation. This emphasizes the importance of consistency in experimental procedures to minimize variability.



**Figure 7** Comparison of swelling strain of different consolidation time and at same consolidation pressure (127.5kPa) of Argile Aulnat Allier soil, 5H-1L: 1layer soil for 5 hours consolidation, 90mins/L-3L: 3Layers of soils for 90mins consolidation/layer and 24H



**Figure 8** Comparison of swelling strain of different consolidation pressure and same consolidation time (90 mins/Layer) of Argile Aulnat Allier soil

**Table 6** Summary of Void Ratio and Saturation Under Various Consolidation Conditions

Test Condition	Initial Void Ratio	Final Void Ratio	Initial Saturation	Final Saturation
5H-1L-1	0.82	0.9	0.61	0.99
5H-1L-24	0.82	0.9	0.61	1
90min/L-3L-1	0.82	0.91	0.61	0.93
90min/L-3L-2	0.82	0.9	0.61	0.92
24H-1L-1	1.02	1.11	0.49	0.9
24H-1L-2	0.72	0.78	0.7	1.11
76.5Kpa-90min/L-1	0.82	0.86	0.61	0.99
76.5Kpa-90min/L-2	0.87	0.91	0.58	0.93
127.5Kpa-90min/L-1	0.82	0.91	0.61	0.93
127.5Kpa-90min/L-2	0.82	0.9	0.61	0.92
178.5Kpa-90min/L-1	0.77	0.84	0.65	0.95
178.5Kpa-90min/L-2	0.77	0.84	0.65	0.95

#### A. Swelling Behaviour of Artificial Clay

Artificial clay, known for its high swelling potential due to its montmorillonite content, was tested to evaluate its expansive behaviour. The results, shown in Figure 9, indicate that the pure clay exhibited a swelling strain of approximately 325%, reflecting its expansive nature. A 75:25 sand-to-clay mixture was prepared to mitigate this excessive swelling, which significantly reduced the swelling strain to 60%, as also illustrated in the same figure.

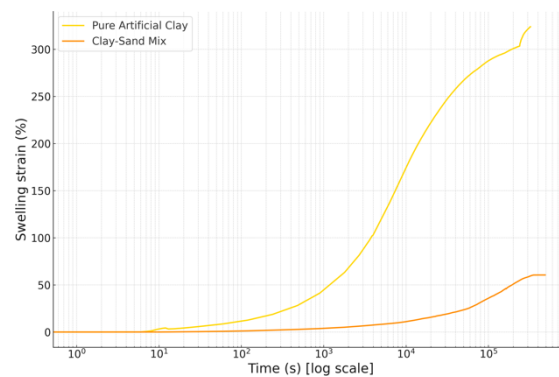
Mixing sand with artificial montmorillonite clay was not the right solution since it still exhibited very high swelling, and no natural soil consists solely of clay and sand, making it dissimilar to natural soils.

This pronounced swelling highlights the critical influence of mineralogy. The high sodium montmorillonite content in the artificial clay is responsible for its enormous water absorption capacity and resulting expansion. However, the binary clay-sand mixture, although mitigating swelling, still presented values far beyond what would be acceptable in practical engineering contexts. This suggests that sand is not an effective mitigating agent on its own and that binary mixtures oversimplify the behaviour of natural soils.

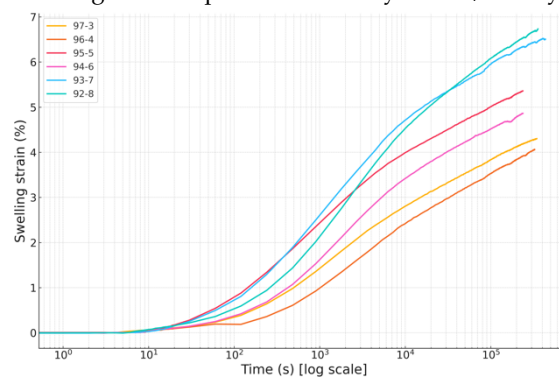
### B. Swelling Behaviour of Mixed Soils

The results of mixing Argile Aulnat Allier soil with varying percentages of artificial clay, ranging from 97:3 to 92:8 clay-to-soil ratios, are illustrated in Figure 10. The results reveal that smaller percentages of artificial clay, such as the 97:3 mix, sometimes exhibit slightly higher swelling than larger percentages like the 94:6 mix. This indicates that swelling behaviour depends on the clay content and on the microstructural arrangement of soil particles. Furthermore, the relationship between clay content and swelling strain is nonlinear; an increase in clay percentage does not translate proportionally to an increase in swelling. For instance, increasing clay from 97:3 to 92:8 does not replicate pure artificial clay's 325% swelling strain. These findings suggest that the distribution and interaction of clay and non-clay particles significantly influence the swelling potential, highlighting the complexity of mixed soil behaviour at the microstructural level.

These findings emphasize the complexity of particle interactions in mixed soils. The unexpected result that a 97:3 mix exhibited more swelling than a 94:6 mix suggests that flocculation, dispersion, and particle fabric play dominant roles in governing the swelling potential. This further supports the conclusion that clay percentage alone is not a reliable predictor of swelling behaviour. Instead, particle arrangement, connectivity, and contact points significantly modulate how expansive minerals behave in real soil matrices.



**Figure 9** Swelling strain of pure artificial clay and 25/75 Clay/sand mix



**Figure 10** Swelling strain of different mixes of Argile Aulnat Allier soil and artificial clay

## VIII. Conclusion

Expansive soils, particularly those rich in montmorillonite, present serious geotechnical challenges due to their pronounced sensitivity to moisture-induced volume changes. Suction, a

central parameter in unsaturated soil mechanics, significantly affects water retention, particle interaction, and overall soil stability. Key indicators such as the Water Retention Curve (WRC) and pore size distribution (PSD) reveal that micropores enhance swelling by retaining more water, while macropores mitigate it. Processes like compaction and consolidation directly influence PSD, altering the way soils absorb and retain water. This study has identified that swelling behaviour is governed not only by factors like plasticity index, water content, dry density, and mineral composition, but also by their complex interactions at the microstructural level.

The experimental investigation into the swelling behaviour of both natural and artificial clays has revealed several significant findings that underscore the complexity of expansive soils. For Argile Aulnat Allier, the results demonstrate that both consolidation time and pressure have a marked impact on swelling potential. Longer consolidation times and higher pressures, rather than suppressing swelling, tend to increase it, likely due to microstructural rearrangement and enhanced water-particle interaction. This behaviour emphasizes the importance of considering time-dependent consolidation effects in engineering applications involving clayey soils. In contrast, the artificial clay, rich in sodium montmorillonite, exhibited extremely high swelling (325%), reaffirming the dominant role of mineralogical composition in soil expansiveness. Attempts to reduce this swelling through sand admixture were only partially effective, resulting in still excessive strains, highlighting that such binary mixtures do not replicate the behaviour of more complex, natural soil systems.

The study of mixed soils, combining Argile Aulnat Allier with varying proportions of artificial clay, revealed a non-linear swelling response. The results showed that small increases in clay content did not lead to proportional increases in swelling. In some cases, lower clay percentages produced higher swelling, suggesting that microstructural arrangement, particle fabric, and interparticle forces govern swelling more than clay content alone.

Moving forward, the preparation of soil mixtures will allow simultaneous geotechnical characterization and swelling behaviour analysis, validating the influence of various parameters and aiding in the development of equations that link swelling behaviour to specific geotechnical properties. Future research will complete swelling tests for the outlined parameters, focusing on their individual effects to identify the most impactful factors. Additionally, new soil mixes using Argile Aulnat Allier soil combined with varying artificial clay contents will be studied to comprehensively explore the relationship between soil composition and behaviour. By refining predictive models and linking geotechnical characteristics to swelling behaviour, this research aims to improve the accuracy of predictions and develop effective strategies for managing the challenges posed by expansive soils in geotechnical engineering.

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