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Technical Analysis of Swelling Soils and Engineering Control Solutions

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***Abstract*:** This study focuses on the swelling potential and damage capacity of buildings and foundations constructed on expansive soils. The geotechnical properties of such soils are mainly controlled by moisture absorption and clay content, particularly the presence of montmorillonite. As moisture and clay minerals increase, so does the soil's swelling potential and ability to cause damage. Laboratory tests on disturbed and undisturbed samples reveal that swelling percentage, swelling pressure, and free swell are critical properties. These are measured using tests like free swell and one-dimensional oedometer tests. The study shows that free swell ranges from 100% to 150%, and swelling pressure is around 45 kPa. The linear swelling coefficient (COLE) for these soils, analyzed using Plaxis software, ranges from 0.09 to 0.14. The findings emphasize the need for soil stabilization, with drainage and water control proving most effective. Numerical modeling enhances accuracy in predicting uplift behavior in these soils.

Keywords: Swelling soils, Geotechnical analysis, Soil behavior, Engineering solutions, Soil control methods.

I. Introduction

Swelling soils, also known as expansive soils, are types of clay-rich soils that undergo significant volume changes when exposed to variations in moisture content (Kalantari, 2012). These soils expand when they absorb water and shrink when they lose moisture. The primary reason for this behavior is the presence of certain clay minerals, such as montmorillonite, which have a high affinity for water molecules (Smiles, 2000). Swollen soils are commonly found in arid and semi-arid regions but can pose challenges in any location where moisture conditions fluctuate (Kalantari, 2012).

The behavior of swelling soil is primarily influenced by two geotechnical properties including moisture absorption and clay mineral content (Nayak & Christensen, 1971). The amount of water the soil can absorb and retain, and the type of clay present, determine how much the soil will swell or shrink. Montmorillonite is the most expensive of these minerals, contributing to significant swelling potential when water is absorbed (Al-Yaqoub et al., 2017). This property makes such soils highly problematic for construction, as the expansion can lead to ground heaving, cracking, and foundation damage (Nagaraj et al., 2010).

From a geotechnical perspective, understanding swelling soils is critical in the planning and design of buildings, roads, and other infrastructure (Liu & Vanapalli, 2017). When foundations are placed on expansive soils, they are at risk of structural failure due to the forces exerted by soil expansion. This can result in uneven settlement, foundation cracks, and even structural collapse in severe cases (Cherif et al., 2018). Geotechnical engineers must assess the swelling potential of soils before construction begins to implement mitigation measures that can prevent damage (Liu & Vanapalli, 2017). Several laboratory and field tests are used to evaluate the swelling potential of soils. Common tests include the free swell test and the one-dimensional oedometer test. These tests help determine key parameters such as swelling percentage, swelling pressure, and the coefficient of linear expansion. The results of these tests allow engineers to predict the behavior of swelling soils under varying moisture conditions. Numerical modeling, using software like Plaxis, is also employed to simulate soil behavior and improve the accuracy of geotechnical assessments (Zamin et al., 2021).

Constructing swelling soils presents a variety of challenges. The constant expansion and contraction of these soils can exert tremendous force on foundations and structures (Nagaraj et al., 2010). Even minor changes in moisture content, such as those caused by seasonal rainfall or underground water flow, can lead to significant soil movement. As a result, buildings, pavements, and utilities may suffer from uneven settlement, cracking, and differential movement, making repairs costly and complicated (Kalantari, 2012).

To manage the risks associated with swelling soils, engineers use several mitigation techniques. One common approach is soil stabilization, which involves mixing expansive soils with materials like lime or cement to reduce their swelling potential.

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II. Role of Clay Minerals in Swelling Soils

The behavior of swelling soils is largely dictated by the type and amount of clay present in the soil matrix (Smiles, 2000). Clays are fine-grained materials composed of microscopic mineral particles that possess unique properties, particularly in their ability to absorb water (Zumrawi, 2015). The presence of expansive clay minerals, such as montmorillonite, is a key factor in the swelling behavior of soils. These minerals exhibit a high capacity for moisture absorption due to their layered crystalline structure, which allows water molecules to enter between layers, causing the soil to expand (Fattah et al., 2021). Among the various clay minerals, montmorillonite is the most expansive and, therefore, the most problematic for geotechnical applications (Ito & Azam, 2010). Other clay minerals like illite and kaolinite also exist in soils, but they do not exhibit the same level of expansiveness as montmorillonite (Dominijanni & Manassero, 2012). Montmorillonite's ability to expand several times its original volume when wet makes it a significant contributor to soil instability. Its swelling potential can lead to ground heaving and foundation movement, posing risks for any structures built on these soils (Kirby et al., 2003).

Clay content is a critical factor in determining the behavior of swelling soils, which are notorious for their capacity to expand and contract in response to moisture changes. The higher the clay content in soil, the more likely it is to experience significant swelling when wet and shrinking when dry. This is because clay particles are very small and have a large surface area, which allows them to absorb substantial amounts of water. The degree of expansion or contraction can cause major problems for buildings and infrastructure built on such soils, leading to structural damage and instability (Ghalamzan et al., 2022). Montmorillonite is the most expansive clay mineral and plays a key role in swelling soils. It belongs to the smectite group of clays, which are characterized by their ability to absorb water between their layers. This mineral has a unique layered structure that can expand dramatically when exposed to water, causing the surrounding soil to swell. Montmorillonite can absorb up to several times its own weight in water, which makes it highly susceptible to swelling, particularly in areas where soil moisture fluctuates, such as during rainy and dry seasons (Reddy et al., 2020). Montmorillonite is a phyllosilicate, meaning it is composed of sheets of silicon-oxygen tetrahedra and aluminum-oxygen octahedra. These sheets are arranged in layers with weak bonds between them, allowing water molecules to easily penetrate and separate the layers (Tong et al., 2021). This layered structure is what gives montmorillonite its swelling properties. When dry, the layers are tightly packed, but as water enters, the layers expand, sometimes doubling or tripling in thickness. This ability to absorb and retain water makes montmorillonite one of the most problematic clay minerals in geotechnical engineering (Pérez et al., 2021). The chemical composition of montmorillonite includes silica (SiO_2), alumina (Al_2O_3), and small amounts of other elements like magnesium, iron, and potassium. The presence of these elements affects its swelling potential. The charge imbalance created by substitutions within the crystal structure (such as magnesium replacing aluminum) allows water and other cations (like sodium or calcium) to enter the gaps between the layers. Figure 1 is illustrated the structures of montmorillonite clay (Davidovic et al., 2011).

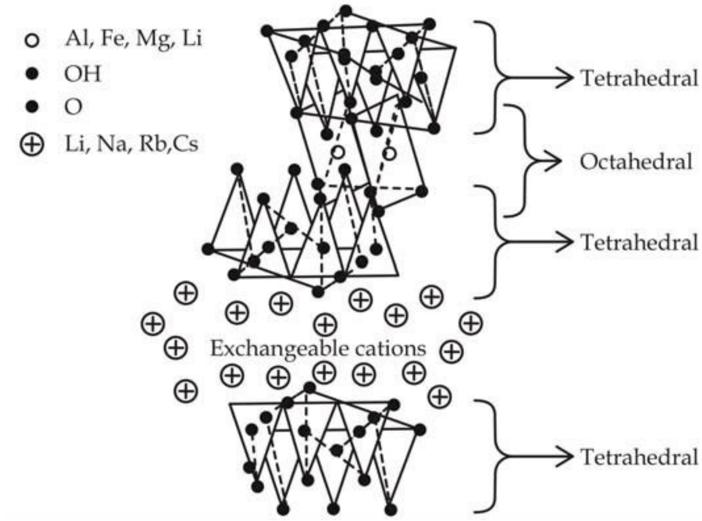

Fig. 1 A structure diagram of montmorillonite clay (Davidovic et al., 2011)

The type of cations presents influences swelling behavior; for instance, sodium montmorillonite tends to swell more than calcium montmorillonite (Pérez et al. 2021). The presence of montmorillonite in swelling soils is the primary reason these soils can cause such severe damage to structures. Its ability to expand when wet and contract when dry leads to significant changes in the volume of the soil. This creates upward pressure on foundations during wet conditions and downward movement during dry conditions, causing uneven settlement, cracks in foundations, walls, and even structural failure. The higher the montmorillonite content in a soil, the greater its swelling potential, making it essential for engineers to accurately assess clay mineralogy when designing foundations in such areas (Davidovic et al., 2011).

Clay content is closely associated with two important geotechnical properties including moisture sensitivity and plasticity (Tong et al., 2021). High clay content in soils results in increased plasticity, meaning the soil can be easily molded or shaped when wet but retains its form when dry. Plasticity is measured using indices such as the plasticity index (PI) and liquid limit (LL), which describe how much the soil can deform without cracking (Kalantari 2012). High plasticity clays are more prone to swelling and shrinking as moisture levels change. This behavior makes expansive clays unpredictable and difficult to manage in construction projects, especially when moisture conditions are not controlled (Cherif et al., 2018). The volume change characteristics of clays are a direct result of their mineral composition. In swelling soils, the change in volume is a function of the clay's ability to absorb and release water. The more expensive the clay, the larger the volume changes, which leads to problems like soil heaving, cracking, and settlement. These volume changes can be exacerbated by seasonal variations, such as rainfall or drought, leading to cyclic soil movement that can destabilize foundations, roads, and other infrastructure (Al-Naje et al., 2020).

Swelling pressure is another critical aspect of the engineering behavior of clay in expansive soils. As clay absorbs water, it exerts outward pressure on its surroundings, including any structures built on or within it (Devkota et al., 2022). The magnitude of this swelling pressure depends on the clay content, its mineral composition, and the moisture conditions (Ermias & Vishal, 2020). High-swelling soils with significant montmorillonite content can produce pressures high enough to cause uplift and damage to foundations, floor slabs, and pavements. This makes it essential for engineers to account for swelling pressure in their design and foundation strategies (Reddy et al., 2020). The presence of expansive clay in soils presents significant challenges for structural foundations. As the clay expands, it can cause upward movement of the soil, known as heaving, which can crack foundations, tilt walls, and displace other structures (Silvani et al., 2020). Conversely, during dry conditions, the soil may shrink, leading to settlement and subsidence. This combination of expansion and contraction creates differential movement, which is particularly damaging to rigid structures like concrete foundations. Without proper mitigation, structures built on expansive clay soils can experience long-term performance issues and require frequent repairs (Kayabaşı, 2020).

Due to the problems posed by montmorillonite-rich soils, it is vital to consider clay content in construction projects. Geotechnical engineers conduct detailed soil analyses to determine the proportion of montmorillonite and other clays present (Silvani et al., 2020). This helps them predict the swelling potential and design appropriate mitigation strategies, such as soil stabilization, drainage control, or the use of deep foundations that bypass the expansive soil layers (Reddy et al., 2020). Understanding the clay content and mineralogy of the soil is crucial to preventing costly structural damage and ensuring the longevity of buildings and infrastructure. To mitigate the effects of swelling clay content, geotechnical engineers employ several strategies (Kalantari, 2012). Soil stabilization techniques, such as mixing lime or cement into the soil, can reduce its expansiveness by altering the chemical properties of the clay minerals (Ghalamzan et al., 2022). Improved drainage systems are also implemented to control moisture levels, preventing excessive water from reaching the clay. In some cases, deep foundations, such as piles or piers, are used to transfer the structural load beyond the depth of expansive clay layers, minimizing the impact of swelling and shrinking on the building. Proper assessment and understanding of clay content are crucial for these engineering solutions to be effective (Ikechukwu & Mostafa, 2022). Figures 2 and 3 show cases of foundation that damaged with swelling soils.

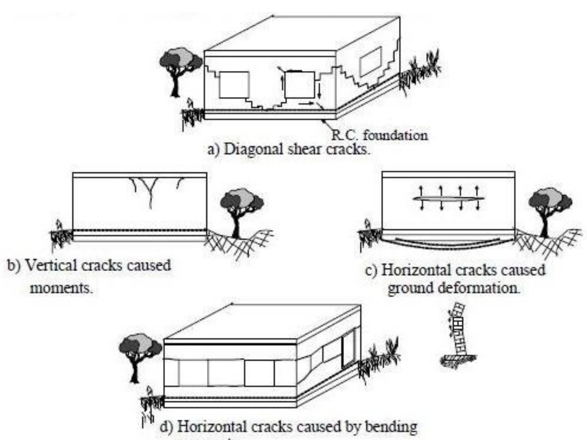

Fig. 2 Typical cracks indicating swelling soils (Hamza, 2016)

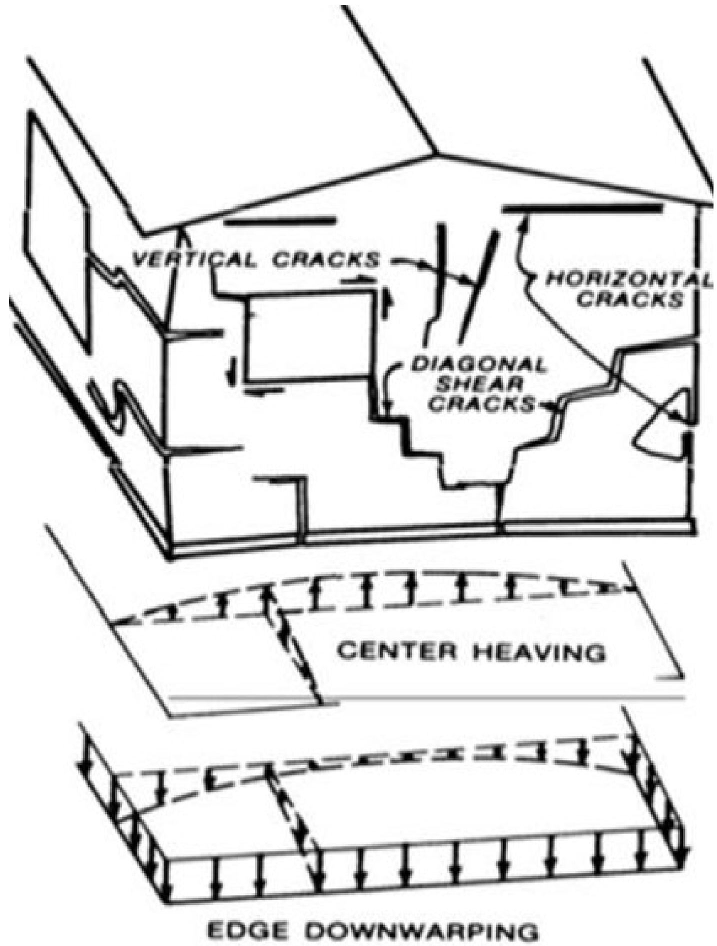

Fig. 3 A schematic example of foundation damage caused by swelling soils (Zumrawi et al., 2017)

III. Materials and Methods

Swelling soils, also known as expansive soils, can cause serious problems for building foundations (Ghalamzan et al., 2022). These soils contain clay that expands when it absorbs water, leading to shifts in the ground. When a foundation is built on this type of soil, the pressure from the swelling can push upwards on the structure, causing it to move or settle unevenly (Zumrawi et al., 2017). This becomes particularly problematic when the soil expands more in some areas than others, creating stress on the foundation that it wasn't designed to handle (Silvani et al., 2020). One of the most common issues is cracking in foundation walls and floors. As the soil swells, it pushes against the foundation; causing stress that leads to cracks (see Figure 2 and 3). These cracks can start small but grow over time, weakening the structure. In addition, cracks allow water to seep in, which can worsen the damage by further weakening materials and even lead to mold growth or rusting of steel components (Hamza, 2016). Another issue caused by swelling soils is differential movement, where different parts of the foundation move at different rates. When this happens, it can cause parts of the building to rise while others settle, leading to sloping floors, doors and windows that don't close properly, and visible gaps in walls or ceilings (Kalantari, 2012).

The presented study attempted to analysis the swelling soil's behavior by using numerical modeling in this regard, the following stages are implemented:

- The first step in the methodology involves collecting both disturbed and undisturbed soil samples from sites known for expansive soil conditions. Disturbed samples are used for index property tests, while undisturbed samples are critical for understanding in-situ soil behavior.
- Free swell tests and one-dimensional oedometer tests will be performed to measure the swelling potential, swelling pressure, and free swell percentage. The free swell test was conducted by fully saturating of soil and recording the increase in volume, while the oedometer test will be used to determine the vertical pressure needed to maintain constant soil volume as moisture content changes.
- The swelling percentage was calculated by comparing the initial and final volumes of the soil in the free swell test. Swelling pressure will be measured in the oedometer test by applying vertical pressure to the soil sample until further swelling is prevented.
- The linear swelling coefficient (COLE) will be calculated to quantify the extent of volumetric changes in the soil. COLE will be determined using the results of the oedometer tests, with values ranging from 0.09 to 0.14, as indicated in previous studies. This coefficient will be a critical parameter for understanding the extent of potential soil uplift and shrinkage.
- Numerical modeling will be conducted using Plaxis software to simulate the behavior of expansive soils under various environmental conditions. The model will incorporate the geotechnical properties measured in the laboratory, such as swelling percentage, swelling pressure, and COLE.

Based on the test results and numerical modeling, soil stabilization techniques will be explored to mitigate the damage caused by swelling soils. Stabilization methods, such as adding lime or cement to the soil, will be tested in the laboratory to determine their effectiveness in reducing swelling potential. Drainage control systems will also be evaluated as a practical solution for managing moisture levels in expansive soils. By comparing the performance of treated versus untreated soils in both laboratory tests and numerical models, the study will propose optimal strategies for preventing structural damage caused by expansive soils.

The first step in the modeling of shallow foundation which is considered in this research on swelling soils involves selecting a site known for its expansive soil conditions, preferably rich in clay minerals such as montmorillonite. The general arrangement was considered in modeling with Plaxis software and finite element modeling (FEM). Such consideration is necessary for advanced testing to in-situ conditions. Moisture content, soil density, and clay content was documented based on Table 1, as these factors are crucial for modeling swelling behavior.

Once the soil properties have been established, the design parameters for the shallow foundation will be determined. This includes calculating the bearing capacity of the soil, which is essential for ensuring that the foundation can support the load without excessive settlement. Figure 4 is presented as the basic model that provided for this analysis. Swelling pressure and uplift forces will also be calculated based on the results of the laboratory tests. The depth and width of the foundation will be chosen according to standard geotechnical design guidelines, ensuring that it can accommodate the soil's expansive nature while minimizing structural damage.

Numerical modeling of shallow foundation will be carried out using Finite Element Analysis (FEA) software, such as Plaxis. The geotechnical data obtained from laboratory testing will be used to simulate the interaction between the foundation and the expansive soil that were illustrated in Table 1. The model will incorporate key parameters such as swelling pressure, soil stiffness, and moisture content changes. The results will provide insights into potential differential settlement, heave, and structural deformation. To validate the numerical model, results will be compared with case studies of actual shallow foundations built on expansive soils. The model will be adjusted based on any discrepancies between predicted and observed behavior. Once validated, the model will be used to optimize the foundation design by testing various mitigation strategies. These may include soil stabilization techniques, drainage control, or the use of flexible or deep foundations to mitigate swelling effects. The optimized design will aim to reduce the risks of foundation heaves and structural damage while ensuring long-term stability.

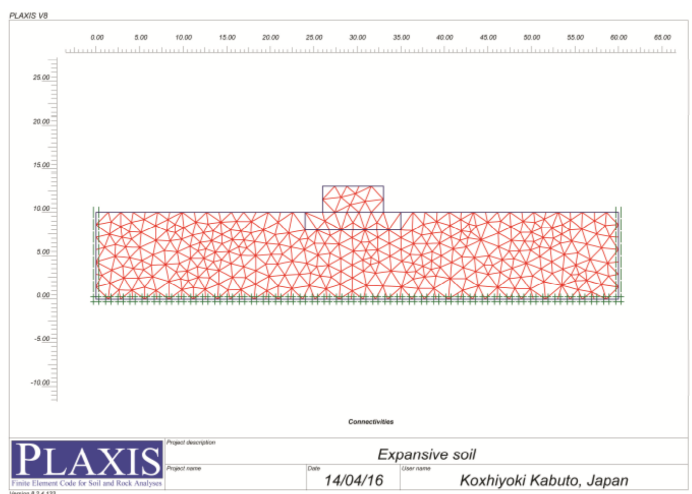

Fig. 4 Geometric model used in this study

Table 1 Input geotechnical parameters for ground properties

Element	Parameter	Unit	Value
Concrete	γ_{unsat}	kN/m^3	19.00
	γ_{sat}	kN/m^3	19.00
	E_{ref}	kN/m^2	10000000
	υ	-	0.2
	C_{ref}	kN/m^2	712
	ϕ	Degree	54.9
	ψ	Degree	0.00
Soil	γ_{unsat}	kN/m^3	17.20
	γ_{sat}	kN/m^3	19.00
	E_{ref}	kN/m^2	20000
	υ	-	0.35
	C_{ref}	kN/m^2	255
	ϕ	Degree	0.00
	ψ	Degree	0.00

IV. Results and Discussion

Numerical modeling using FEM analysis provided deeper insights into how shallow foundations respond to swelling soils over time. The model simulated various moisture conditions, from dry to fully saturated, to observe how these changes affect foundation stability. Results showed that under high-moisture conditions, the foundations experienced significant uplifts, with vertical displacements as high as 20 mm in some scenarios. Differential settlement was also observed in areas where moisture was unevenly distributed, leading to tilting and potential cracking of the foundation. Also, the study shows that free swell ranges from 100% to 150%, and swelling pressure is around 45 kPa. The linear COLE for these soils, analyzed using Plaxis software, ranges from 0.09 to 0.14. The findings emphasize the need for soil stabilization, with drainage and water control proving most effective. Figures 5 to 9 are provided the modeling output from Plaxis modeling.

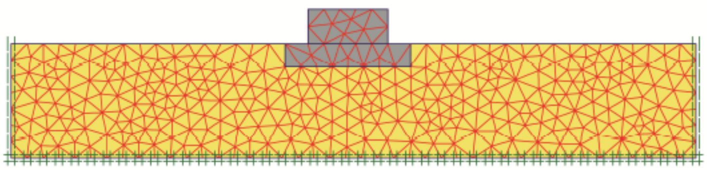

Fig. 5 A generic behavioral model that provided for this study

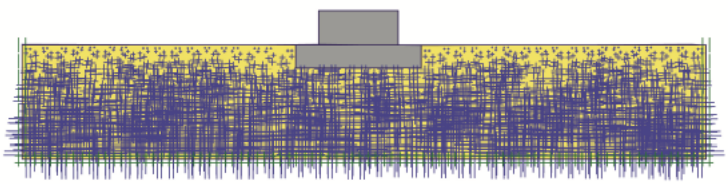

Fig. 6 Pore-water pressure calculated for the swelling soil

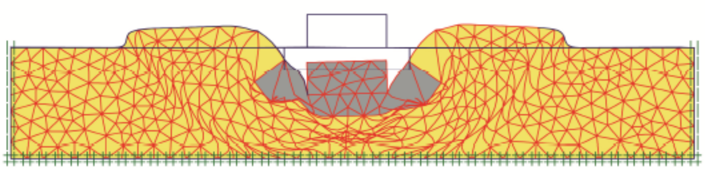

Fig. 7 A ground deformation was calculated for the swelling soil

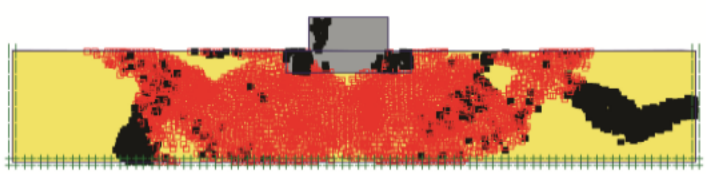

Fig. 8 A plastic displacement was calculated for the swelling soil

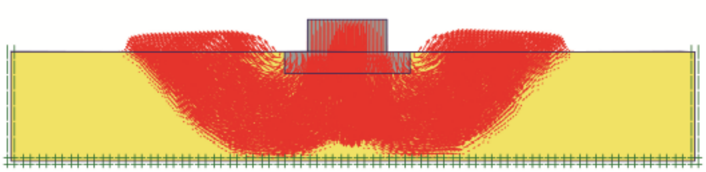

Fig. 9 A plastic displacement was calculated for the swelling soil

The geotechnical analysis showed a strong correlation between clay content and the swelling potential of the soils. Soils with higher percentages of montmorillonite displayed the most extreme swelling behavior, especially when exposed to moisture variations. The study also indicated that soil moisture content had a significant effect on the swelling pressure. As moisture levels increased, so did the expansion potential and pressure exerted on the foundation. The results highlighted the need for moisture control as a critical factor in managing swelling soils under shallow foundations. The results of the numerical model were further analyzed to simulate seasonal moisture fluctuations, mimicking real-world conditions. During the wet season, swelling pressures increased significantly, leading to heaving of foundation. Conversely, during dry seasons, shrinkage occurred, which caused subsidence. The cyclical nature of this movement creates challenges for the long-term stability of structures built on swelling soils. The model showed that without proper mitigation, structures could experience cumulative damage over multiple seasons, such as cracking in walls, misalignment of doors and windows, and uneven floors.

One of the primary stabilization strategies explored in the study was lime treatment. Lime works by reducing the plasticity and swell potential of expansive soils through chemical reactions that bind the soil particles and reduce their ability to absorb water. Laboratory tests on lime-treated samples showed a reduction in swelling pressure by as much as 50%. The free swell percentages dropped to below 70%, and the swelling pressure in oedometer tests decreased to less than 25 kPa. These results indicate that lime treatment can be a highly effective solution for stabilizing expansive soils under shallow foundations.

Cement stabilization was also evaluated as a potential strategy. Cement, like lime, alters the chemical and physical properties of expansive soils, making them more stable and less susceptible to swelling. Laboratory tests revealed that cement-treated soils showed a decrease in swelling pressure to around 20 kPa, and the volumetric expansion dropped significantly, reaching free swell percentages of less than 60%. While cement stabilization was effective, it also increased soil stiffness, which could lead to brittleness under certain loading conditions. Therefore, the suitability of cement stabilization depends on the specific project requirements and soil conditions.

The study also assessed the impact of drainage control systems on mitigating swelling pressures. Proper drainage systems can prevent water from accumulating around the foundation, thereby reducing moisture fluctuations that cause soil expansion and contraction. Numerical modeling incorporated the effect of subsurface drainage systems, and the results showed that controlled moisture levels led to a reduction in swelling pressure by 30%. Additionally, foundations with good drainage systems experienced less differential movement, which significantly minimized the risk of structural damage due to soil swelling.

Geosynthetic materials, such as moisture barriers or geomembranes, were tested as an additional strategy to limit the ingress of water into the swelling soil beneath foundations. These materials were placed beneath the foundation in the model to create a physical barrier that prevented moisture from reaching the expansive soil. The results demonstrated a significant reduction in the swelling potential, with free swell percentages dropping by 40% compared to untreated soils. Geosynthetics can be a practical solution, especially in regions with unpredictable rainfall or where deep foundation systems are not feasible.

Based on the study's findings, addressing the challenges posed by swelling soils requires a combination of stabilization techniques and moisture control strategies. For projects involving shallow foundations on expansive soils, lime or cement stabilization, coupled with an effective drainage system, can significantly reduce the risks associated with soil swelling. In high-risk areas, geosynthetic barriers and deep foundations may provide additional protection. It is recommended that future projects conduct thorough geotechnical investigations to assess the soil's swelling potential and apply the appropriate stabilization methods to ensure long-term foundation stability.

V. Conclusion

This study emphasizes the significant challenges posed by swelling soils to shallow foundations, especially in areas with high clay content and varying moisture levels. Laboratory tests and numerical modeling show that expansive soils, particularly those containing montmorillonite, can exert substantial swelling pressure and cause considerable ground movement. Seasonal changes in moisture, like rainfall or drought, worsen the risk of foundation heave, uneven settlement, and structural damage. Several methods were examined to address these issues. Lime and cement stabilization proved effective in lowering swelling pressures and reducing soil expansion. Installing drainage systems and moisture barriers also helped control soil moisture, which is essential in minimizing swelling. For more severe conditions, deep foundations such as piles and piers provided a stable solution by bypassing the problematic soil layer. In summary, using a mix of soil stabilization techniques, moisture management, and thoughtful foundation design is crucial to ensuring long-term structural stability on expansive soils. Careful geotechnical evaluations and the right interventions can prevent damage and ensure safe, durable construction in areas with swelling soils.

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Authors' contributions

Javad Nasirfam conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and was responsible for drafting the initial manuscript. Masood Purbaba and Dariush Ahadi-Ravoshti assisted in the development of the methodology and performed validation checks, provided supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors have not disclosed any competing interests.

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