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Physicomechanical Analysis of Swelling Clay Formations in the Southern Region of Urmia Lake, Iran

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***Abstract*:** The swelling potential of fine-grained soils is a critical factor influencing the engineering and agricultural design of foundations, as it can cause significant expansion-related issues. This study investigates the swelling potential of clayey soils in the southern region of Urmia Lake, located in East Azerbaijan Province, NW Iran. A comprehensive set of laboratory tests was conducted on 125 soil samples collected from 25 distinct locations. The analyses included assessments of physicochemical properties, soil classification according to the USDA system, and clay mineralogical composition. Regression analysis was employed to develop predictive formulas for swelling potential based on laboratory indices, including water absorption, porosity, density, specific gravity (G_s), sulfate (SO_4^-) and chloride (Cl^-) concentrations, pH, Casagrande limits, unconfined compressive strength (UCS), X-ray diffraction (XRD) patterns, and clay content. The results revealed that the studied soils, classified as clay, clay loam, and silty clay, exhibit swelling potentials ranging from moderate to high. This research provides valuable insights for designing stable structures and optimizing land use in the region.

Keywords: Swelling clay, Urmia Lake, Physicomechanical properties, Soil stability, Land-use.

I. INTRODUCTION

Clayey soils are among the most common types of soil found in various regions around the world. These soils are primarily composed of fine particles, specifically clay minerals, which have unique physical and chemical properties that distinguish them from coarser-grained soils such as sand and silt (Smaida et al., 2021). Clay particles are incredibly small and can retain water in amounts much higher than other soil types, which significantly affects their behavior when subjected to changes in moisture content (Misra et al., 2005). This characteristic makes clayey soils particularly sensitive to environmental conditions, leading to challenges in construction, agriculture, and land management (Nikbakht et al., 2022). Clay classification is a process that categorizes soils based on their particle size distribution, mineral composition, and other defining characteristics (Marat et al., 2022). The United States Department of Agriculture (USDA) soil classification system is commonly used, which divides soil into categories such as clay, silt, sand, and combinations thereof. Within this system, soils are further classified into subgroups based on their texture and plasticity, which are determined by the amount of water the soil can absorb and how easily it deforms when moist (Moreno-Maroto & Alonso-Azcarate, 2022). The classification helps to understand the soil's ability to retain water, its shrink-swell capacity, and its suitability for various uses such as agriculture, construction, or infrastructure development (Brubaker et al., 1992). One of the most critical properties of clayey soils is their swelling potential, which refers to the ability of these soils to expand or contract with changes in moisture content. This swelling is a result of the absorption of water by clay particles, which causes them to increase in volume (Anderson et al., 2010). The degree of swelling can vary depending on the type of clay mineral present, as well as the amount of water available. Clayey soils with a high swelling potential can pose significant challenges in construction and land-use planning, as they can lead to the deformation of foundations, roads, and other structures (Franzmeier & Ross, 1968). The consequences of swelling in clayey soils are widespread and can lead to serious structural problems. When these soils expand, they exert pressure on foundations, pavements, and other structures built on or within them. This pressure can cause cracks, shifts, and even complete structural failure in some cases. In agricultural settings, swelling soils can lead to uneven land surfaces, waterlogging, or root damage, which can reduce crop yields and complicate land management practices (Yong, 1999). The unpredictability of clayey soils makes them particularly difficult to work with, requiring careful analysis and planning to mitigate the risks associated with swelling (Smiles, 2000).

Understanding and analyzing the swelling potential of clayey soils is essential to managing the risks they pose. Geotechnical engineers and soil scientists use various methods, including laboratory tests and field studies, to assess the swelling behavior of soils in different environments (Rimmer & Greenland, 1976). These tests measure parameters such as water absorption, plasticity, porosity, and mineral composition to predict how the soil will behave under different moisture conditions. By understanding the swelling potential, engineers can design foundations and structures that are better equipped to withstand the pressure exerted by swelling soils, ensuring long-term stability (Ghalamzan et al., 2022). In addition to engineering applications, understanding the swelling potential of clayey soils is also critical in land-use planning (Smiles, 2000). For instance, areas with high swelling potential may not be suitable for large-scale infrastructure projects without significant modifications, such as soil stabilization or the use of specialized foundation techniques (Basma, 1996). In agricultural settings, recognizing the swelling potential allows for the development of irrigation and drainage systems that can manage excess water and prevent damage to crops. Proper land-use planning can prevent costly mistakes and optimize the use of land for various purposes, from urban development to agriculture (Low & Margheim, 1979).

Swelling clayey soils also have implications for environmental sustainability. In regions where these soils are prevalent, poor land-use practices or inadequate construction techniques can lead to long-term environmental damage (Fattah et al., 2021). For example, building on highly expansive soils without considering their behavior can result in land degradation, which can lead to erosion, reduced agricultural productivity, and the displacement of communities (Reddy et al., 2020). Understanding the swelling potential of these soils and implementing appropriate mitigation strategies can help protect the environment and ensure sustainable land management practices (Fattah et al., 2021). The study of clayey soils, particularly their swelling potential, is important not only for practical reasons but also for advancing our understanding of soil science (Assadollahi & Nowamooz, 2020). Clay minerals, with their ability to absorb water and expand, offer unique insights into the behavior of soils under changing environmental conditions (Hozatlıoğlu & Yılmaz, 2021). By studying the mineralogy and physical properties of clayey soils, researchers can develop better predictive models for soil behavior, improving construction methods, agricultural practices, and environmental management strategies. In the context of climate change, the study of swelling clayey soils becomes even more crucial. As global weather patterns shift, extreme weather events such as heavy rainfall or droughts may become more common (Fondjo et al., 2021). These fluctuations in moisture levels can exacerbate the swelling and shrinkage of clayey soils, increasing the likelihood of structural damage and land-use conflicts. Researchers and engineers are now more focused on understanding how clayey soils will respond to these changing conditions and how best to adapt infrastructure and land-use practices accordingly (Fernandez et al., 2021).

The study and analysis of clayey soils, particularly their swelling potential, are critical for safe and sustainable land use. Whether for construction, agriculture, or environmental protection, understanding how these soils behave under various conditions allows for better planning, design, and mitigation strategies. By conducting thorough investigations into the properties and behavior of clayey soils, engineers, land planners, and scientists can contribute to more resilient and sustainable infrastructure, reducing risks and ensuring long-term land productivity.

II. SWELLING CLAYEY SOIL

Swelling clays are a group of soils characterized by their ability to expand significantly when exposed to water and contract upon drying. This unique behavior is primarily due to their mineral composition, which enables the adsorption of water between the layers of clay minerals (Anderson et al., 2010). Among swelling clays, montmorillonite is the most prominent and widely studied mineral. It belongs to the smectite group of clay minerals and is known for its high swelling capacity. Montmorillonite's structure allows for significant water absorption, leading to volume changes that can pose challenges in construction, agriculture, and land management (Low, 1980). The structures of clays have been illustrated in Fig. 1. Clays are typically classified based on their mineralogical composition, particle size, and plasticity. The primary types of clays include kaolinite, illite, and smectite, each with distinct properties. Kaolinite has a stable structure with low swelling potential and is commonly used in ceramics and industrial applications. Illite, a non-expanding clay, has intermediate properties and is frequently found in sedimentary rocks. Smectite, which includes montmorillonite, is highly expansive due to its ability to absorb large amounts of water between its layers. These classifications help in understanding the behavior of clays under varying environmental and mechanical conditions (Nesse, 2000; Środoń, 2006).

Expansive clays are a subset of clays, primarily dominated by smectite minerals such as montmorillonite, which exhibit significant volume changes with moisture fluctuations (Gromko, 1974). These clays are highly sensitive to environmental conditions and can expand several times their original volume when saturated with water (Gaspar et al., 2022). This expansion generates substantial pressure on structures and soils in their vicinity. Expansive clays are often considered problematic due to their potential to cause damage to foundations, pavements, pipelines, and other infrastructure (Petry & Little, 2002). The swelling potential of expansive clays can lead to several issues in construction and land use (Puppala et al., 2013). When these clays expand, they exert upward pressure on structures, leading to cracking, deformation, and even failure of foundations and pavements. During dry conditions, these clays shrink, causing subsidence and uneven surfaces. These cyclic volume changes can significantly increase maintenance costs and complicate land management. Identifying and mitigating the effects of expansive clays are critical to ensuring the stability and longevity of structures (Kaczyński & Grabowska-Olszewska, 1997).

Montmorillonite, the most well-known swelling clay mineral, has a layered structure with a high cation exchange capacity (CEC). This structure consists of two tetrahedral silica sheets sandwiching an octahedral alumina sheet, forming a crystalline framework (Katti et al., 2015). The space between these layers can hold water molecules and exchangeable cations, making montmorillonite highly reactive to changes in moisture content. This property gives it a wide range of applications, from use in drilling muds and absorbents to challenges in construction due to its expansive nature (Pedarla et al., 2016). While their expansive nature of montmorillonite can pose challenges, understanding their classification, properties, and impacts allows for effective management and mitigation strategies

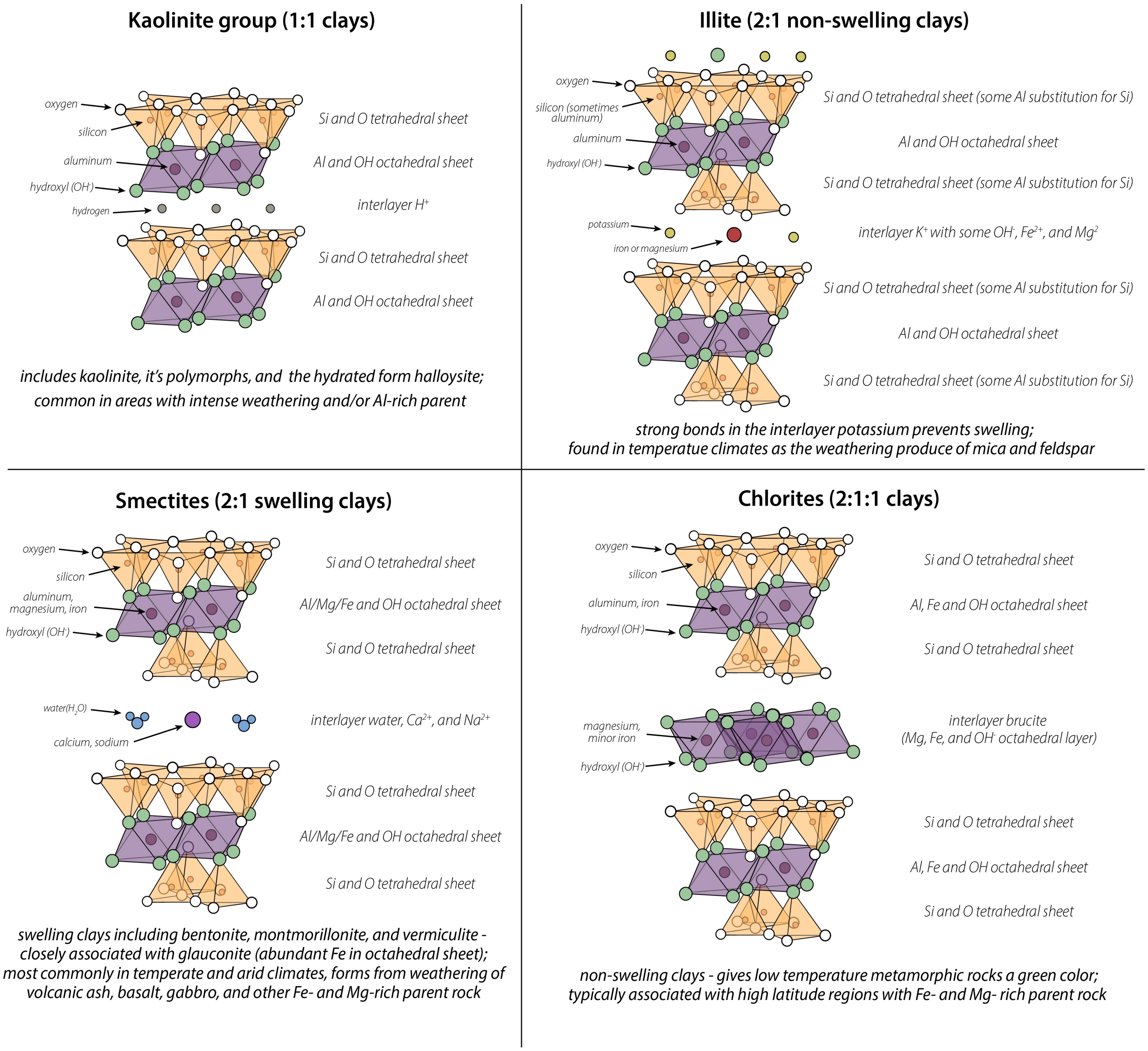

Fig. 1 A scheme of various clays' structures (Nesse, 2000; Środoń, 2006)

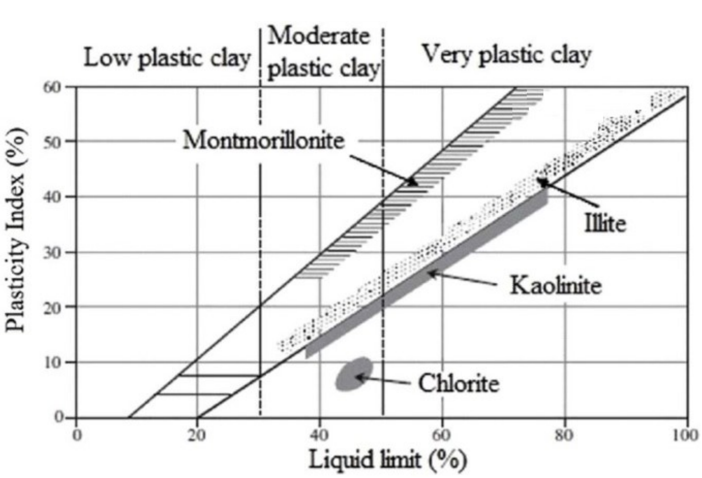

Fig. 2 Clay minerals position on the Holtz & Kovacs (1981) diagram

Classifying and analyzing clays is essential for understanding their behavior and mitigating potential risks. Engineers and geologists use various methods to classify clays, such as mineralogical analysis, Atterberg limits, and soil classification systems like the USDA and Unified Soil Classification System (USCS). Figure 2 illustrated an empirical method that used Atterberg limits to classify the clays in different groups. These methods help in predicting the behavior of clays under different environmental conditions (Holtz & Kovacs, 1981). Proper classification enables the selection of suitable foundation designs, soil stabilization techniques, and construction materials for projects involving expansive clays (Azam, 2007; Smaida et al., 2021).

III. MATERIALS AND METHODS

A. Region Geological Setting

The southern region of Urmia Lake, located in northwestern Iran, is a distinctive area characterized by its unique geomorphology, geology, and climate (Eimanifar & Mohebbi, 2007). Situated within the expansive Urmia Lake basin, this region has experienced significant environmental changes over recent decades, notably the substantial reduction in the lake's surface area. This transformation has had profound effects on the surrounding landscape and ecosystems (Kelts & Shahrabi, 1986). Geomorphologically, the southern part of Urmia Lake features a combination of plains and gentle slopes, shaped by both fluvial and lacustrine processes. The terrain is primarily composed of alluvial deposits from rivers such as the Zarrineh Rud and Simineh Rud, which flow into the lake from the south. These rivers have historically contributed to the formation of fertile plains, supporting agriculture and human settlements. However, the desiccation of the lake has led to the exposure of vast salt flats, altering the natural geomorphology and posing challenges to land use (Feizizadeh et al., 2013). Figure 3 is provided the geomorphologic features identified in Urmia Lake region. In according to this figure, the main composition of the soil in southern region of Urmia Lake are clay, clayey loam and clayey soils (Alkhayer et al., 2019). Climatically, the southern region of Urmia Lake experiences a semi-arid climate, characterized by hot, dry summers and cold winters. Precipitation is relatively low, with most rainfall occurring during the spring and autumn months. In recent years, climate change has exacerbated the aridity, leading to prolonged droughts and increased evaporation rates (Lak et al., 2021). These climatic shifts have significantly impacted the hydrological balance of Urmia Lake, contributing to its shrinkage and the consequent environmental challenges.

Geologically, the region encompasses a diverse array of formations. Studies indicate the presence of Eocene deposits in the southern areas, alongside igneous formations to the east and northwest, and metamorphic formations in the northern, southwestern, southern, and southeastern areas (Feizizadeh et al., 2013). Figure 4 is providing geological map of the region. This geological diversity has influenced soil characteristics, hydrology, and the distribution of natural resources. The interplay between these geological formations and surface processes has been pivotal in shaping the current landscape (Azad et al., 2021). The southern part of Urmia Lake is characterized by diverse Quaternary sediments that have formed due to a combination of fluvial, lacustrine, and aeolian processes (Lak et al., 2021). These sediments include alluvial deposits, lacustrine clays, silts, and sands, as well as evaporite minerals such as halite and gypsum, which have accumulated as the lake has undergone periodic drying (Alkhayer et al., 2019). The alluvial deposits are primarily derived from rivers like the Zarrineh Rud and Simineh Rud, which transport materials from the surrounding highlands. These deposits are crucial for agriculture and human settlement in the region, but they are also subject to salinization due to the lake's retreat (Feizizadeh et al., 2013). The southern region of Urmia Lake is influenced by its position within a tectonically active zone. The area's bedrock consists of a mix of Eocene volcanic rocks, sedimentary formations, and Quaternary deposits (Lak et al., 2021). To the south and southeast, older formations such as limestones, shales, and marls are overlaid by more recent Quaternary sediments. The presence of volcanic rocks, particularly andesite and basalt, contributes to the mineralogical diversity of the region's soils. These geological formations have a direct impact on the hydrology, soil properties, and the behavior of sediments under varying environmental conditions. The Quaternary deposits in the region also reflect climatic fluctuations over thousands of years, marked by alternating wet and dry periods. During wetter phases, lacustrine sediments were deposited as the lake expanded, while drier periods led to the formation of evaporites and increased aeolian activity. These cyclical processes have shaped the geomorphology and sediment composition of the southern part of the lake. Understanding these geological formations and their interactions with the environment is crucial for managing the challenges associated with soil salinity, land use, and the lake's ongoing desiccation.

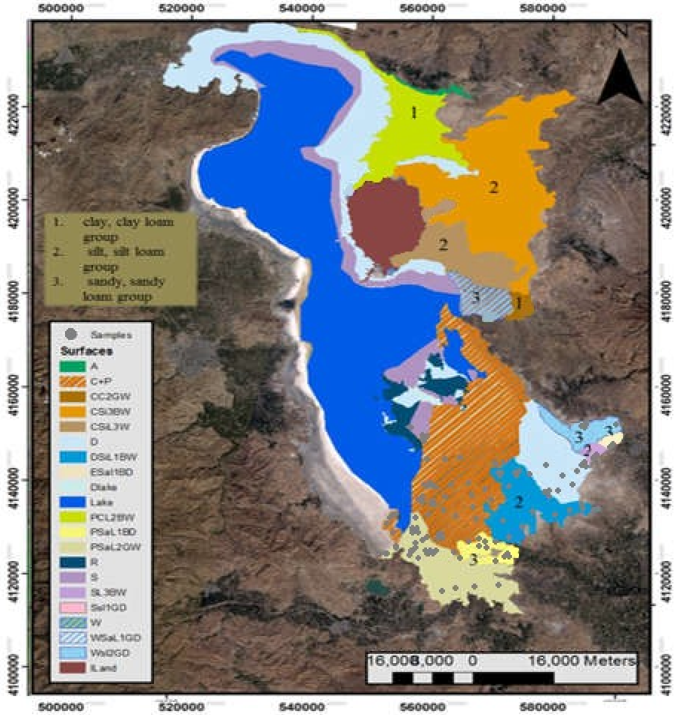

Fig. 3 Geomorphic feature Map of Urmia Lake region (Alkhayer et al., 2019)

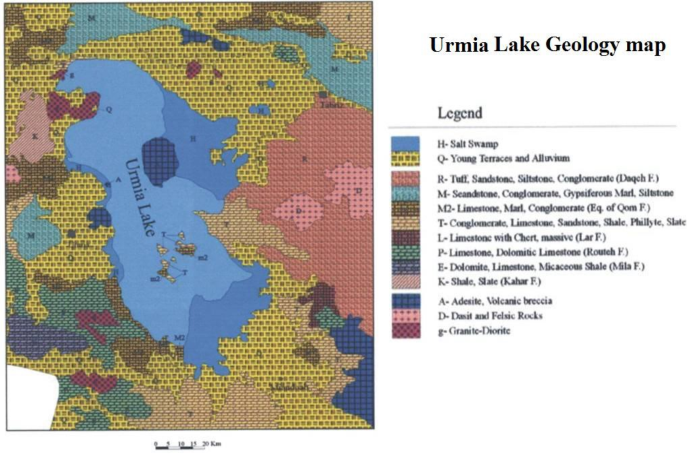

Fig. 4 Geological Map of Urmia Lake region (Azarafza & Mokhtari, 2013)

B. Laboratory Assessments

The following sections outline the principles and methodology implemented to conduct various laboratory experiments on the collected soil samples. The sampling process was meticulously planned and executed during the summer of 2022, ensuring that all samples were representative of the southern region of Urmia Lake. A total of 125 soil samples were collected from 25 distinct locations, carefully chosen to capture the variability in soil characteristics across the study area. The sampling locations are detailed in Fig. 3. Field sampling involved the use of standard equipment to extract undisturbed and disturbed soil samples, depending on the specific tests required. Undisturbed samples were taken using core samplers to preserve the soil's natural structure and moisture content, essential for tests like density, porosity, and unconfined compressive strength (UCS). Disturbed samples, used for chemical and mineralogical analyses such as pH, sulfate, chloride concentrations, and X-ray diffraction (XRD), were obtained from shallow pits or boreholes at varying depths.

Once collected, the samples were promptly sealed in airtight, moisture-resistant containers to prevent contamination and moisture loss during transportation. Each container was labeled with detailed information, including the sample location, depth, and date of collection, to maintain traceability and accuracy in subsequent analyses. The samples were carefully transported to the laboratory under controlled conditions to ensure their integrity. Upon arrival, they were cataloged, and the necessary preparations were made for testing. The author took full responsibility for overseeing the testing procedures and ensuring that all results were accurately recorded and controlled in compliance with established standards. By following this rigorous process, the study ensured that the collected data was reliable and representative, forming the foundation for the comprehensive analysis of the swelling potential of clayey soils in the study area.

Porosity test: Porosity is the measure of the void spaces within a soil sample, expressed as a percentage of the total volume. It is determined by analyzing the soil's bulk and particle density to calculate the void ratio. Porosity significantly influences the swelling potential of clayey soils as it determines the soil's capacity to absorb and retain water. Higher porosity often correlates with greater swelling, making this parameter essential for assessing the behavior of clay soils under varying moisture conditions. This test has been taken under ASTM D7263 instruction.

Density test: Density refers to the mass of soil per unit volume and is typically measured in two forms as bulk density and dry density. Bulk density includes the weight of the soil and its water content, while dry density measures only the soil solids. Density impacts the swelling behavior because denser soils tend to exhibit less expansion due to their compact structure. It helps in understanding the packing of soil particles and their behavior during wetting and drying cycles. This test has been taken under ASTM D7263 instruction.

Specific Gravity (G_s): G_s is the ratio of the density of soil solids to the density of water. It is measured using a pycnometer or other specialized apparatus. For clay swelling analysis, G_s provide insights into the mineralogical composition of the soil, as different minerals have distinct specific gravities. Montmorillonite, for example, has a lower G_s compared to other minerals, which can indicate the presence of highly expansive clays. This test has been taken under ASTM D854 instruction.

Sulfate (SO_4^-) and Chloride (Cl^-) concentrations in soil are measured using chemical analysis methods such as ion chromatography or titration. These ions influence the chemical interactions within the soil, particularly with clay minerals. High concentrations of sulfate can lead to expansive reactions in the presence of water, while chloride can affect soil salinity and water retention. Understanding these concentrations helps in assessing the chemical factors contributing to soil swelling. This test has been taken under ASTM D516 and ASTM D4327 instructions.

pH test: Soil pH is determined using a pH meter and reflects the acidity or alkalinity of the soil. It affects the chemical stability of clay minerals and their interaction with water. Alkaline soils are more likely to exhibit higher swelling due to increased ion exchange between clay particles and water. Measuring pH helps in understanding the chemical environment of the soil and its influence on swelling potential. This test has been taken under ASTM D4972 instruction.

Casagrande limits: Casagrande limits, which include the liquid limit (LL) plastic limit (PL) and plastic index (PI), are measured using Atterberg limit tests. These parameters describe the soil's consistency and its behavior under varying moisture conditions. High liquid limits often indicate a higher swelling potential, as the soil can hold more water before transitioning from a plastic to a liquid state. These limits are crucial for classifying soil and predicting its response to moisture changes. This test has been taken under ASTM D4318 instruction.

UCS is tested by applying axial load to a cylindrical soil sample until failure. It measures the soil's strength without lateral confinement. In the context of swelling clays, UCS helps evaluate the soil's resistance to deformation when subjected to moisture-induced expansion. Lower UCS values in expansive clays indicate their susceptibility to structural failure under load. This test has been taken under ASTM D2166/D2166M instruction.

X-Ray Diffraction (XRD) analysis identifies the mineralogical composition of the soil by analyzing the diffraction patterns of X-rays passing through the soil sample. This technique is particularly useful for detecting swelling clay minerals like montmorillonite. Understanding the mineral composition allows researchers to correlate specific minerals with swelling behavior, providing critical insights for soil classification and management. This test has been taken under ASTM D5979 instruction.

Clay content is determined using particle size analysis methods, such as the hydrometer or sieve analysis. It represents the percentage of fine-grained particles in the soil. Higher clay content generally correlates with increased swelling potential, as clay particles have a higher capacity to absorb water. Measuring clay content is fundamental for classifying soils and predicting their swelling behavior under different environmental conditions. These tests have been taken under ASTM D422 and ASTM D7928 instructions.

IV. RESULTS AND DISCUSSION

As mentioned perviously, the laboratory analysis of the 125 soil samples collected from the southern region of Urmia Lake revealed significant variability in soil properties, which directly influence the swelling potential. Table 1 summarizes the statesical assessment of physical and chemical characteristics for the analyzed samples, including porosity, density, G$_s$, SO$_4^-$, Cl$^-$, pH, and UCS values. The results indicate that the majority of the soils in the study area are classified as clay, clay loam, silty clayey loam, to loamy sand, with a moderate to high clay content ranging between 20% and 60% as per described in USDA classification system. Figure 5 illustrates the USDA soil classification system applied to the studied samples, providing a detailed understanding of their texture and composition. This classification helped categorize the soils into groups such as clay, clay loam, and silty clay, which are critical for assessing their swelling potential. The results, plotted on the USDA soil texture triangle, reflect the dominance of fine-grained materials, particularly clay, in the study area.

Additionally, the clay minerals' characteristics for the analyzed samples are presented using the chart developed by Holtz & Kovacs (1981). This chart offers a comprehensive visualization of the clay minerals, focusing on their specific properties, including plasticity and swelling potential were presented in Fig. 6. High liquid limits and plasticity indices as Casagrande limits further highlight the expansive nature of these soils, with liquid limits exceeding 50% in some samples which is illustrated in Table 2. As shown in Figure 6, the primary mineralogical composition of the clays in the southern region of Urmia Lake is classified as montmorillonite, which is the key contributor to the swelling behavior of the soils in this area.

Table 1 Statistical description of physicomechanical for studied samples

Properties	Maximum	Minimum	Mean	Standard deviation	Variance	Skewness
Porosity, n (-)	77.4	28.8	63.1	21.88	47.91	-1.171
Density, γ (kN/m^3)	22.8	18.3	20.5	1.644	2.704	0.316
G$_s$ (-)	2.71	2.43	2.55	0.095	0.093	0.486
LL (%)	56	36	44.4	5.88	34.66	0.840
PL (%)	28	15	18.9	3.18	10.16	1.018
PI (%)	40	16	25.4	6.02	36.26	0.662
Clay content (%)	61	35	51.6	8.16	66.61	-0.556
pH	7.7	7.3	7.55	0.15	0.023	-1.135
SO$_4^-$	0.18	0.06	0.12	0.46	0.028	-0.353
Cl$^-$	0.12	0.08	0.13	0.04	0.018	-0.234
UCS (kPa)	120	75	97.1	1.61	26.08	0.308
Clay activity (-)	3	1	2.18	0.87	0.763	-0.408

Table 2 Casagrande limits estimated for studied samples (average value)

Parameter	LL (%)	PL (%)	PI (%)
Station 1	42	15	27
Station 2	42	16	26
Station 3	56	16	40
Station 4	55	18	37
Station 5	54	18	36
Station 6	56	28	28
Station 7	50	22	28
Station 8	49	22	27
Station 9	48	22	26
Station 10	45	16	29
Station 11	45	17	28
Station 12	45	18	27
Station 13	43	16	27
Station 14	42	15	27
Station 15	42	16	26
Station 16	41	20	21
Station 17	41	18	23
Station 18	41	18	23
Station 19	39	17	22
Station 20	42	23	19
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Station 22	40	22	18
Station 23	37	18	19
Station 24	38	22	16
Station 25	36	18	18

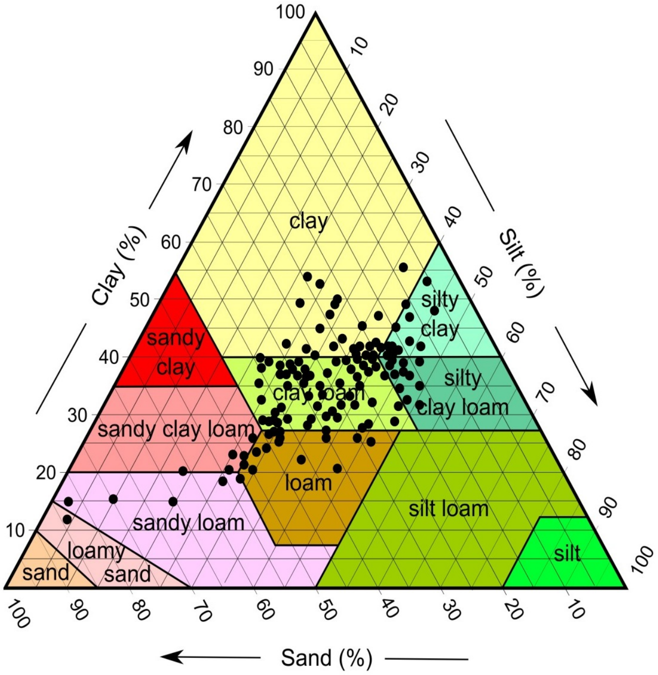

Fig. 5 The USDA plotting diagram for studied samples

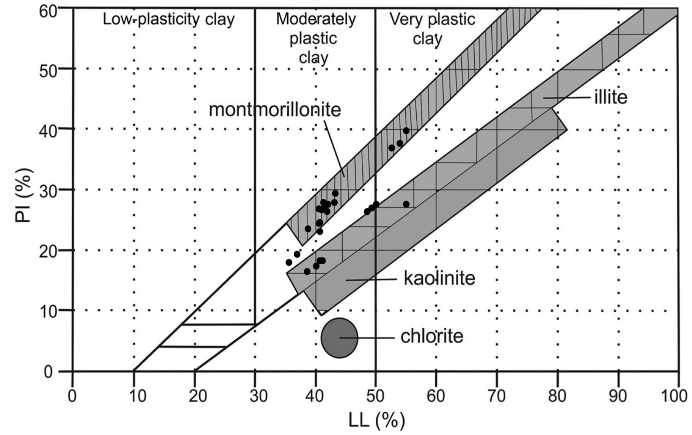

Fig. 6 The clay minerals positioning on the Holtz & Kovacs diagram for studied samples

According to Yilmaz (2006), the Holtz and Kovacs diagram is a valuable tool for anticipating the swelling potential of soils. Yilmaz emphasized that the use of plasticity charts and LL values provides sufficient and reliable information for evaluating swelling behavior. In the present study, as illustrated in Figure 6, the analysis indicates that the clayey materials in the study area exhibit moderate to very high swelling potential. This classification highlights the importance of using such methods for accurate assessment and effective planning in regions with expansive soils.

The findings of this study highlight the significant swelling potential of the clayey soils in the southern region of Urmia Lake, attributed primarily to the dominance of montmorillonite in their mineralogical composition. This expansive clay mineral, known for its high water absorption capacity and subsequent volume changes, poses substantial challenges for engineering and agricultural activities in the area. The moderate to high swelling potential observed across the studied samples necessitates careful consideration in the design and implementation of structures and land-use practices. The physical and chemical properties of the soils, as revealed through laboratory analyses, further reinforce their expansive nature. High liquid limits, plasticity indices, and clay content observed in most samples align with the characteristics of soils prone to swelling. Moreover, the variations in sulfate and chloride concentrations, coupled with the relatively high porosity and low density of some samples, underline the heterogeneity of the soil properties in this region. Such variability emphasizes the importance of site-specific evaluations rather than generalized assumptions for construction and development projects. From a geotechnical perspective, the UCS values recorded for the soils indicate a moderate resistance to deformation under load. However, the presence of expansive minerals like montmorillonite significantly reduces this resistance during wetting and swelling cycles. This behavior could lead to structural instability, cracking, and damage to foundations, roads, and other infrastructure if proper mitigation measures are not adopted. These risks are further compounded by the climatic conditions of the region, where seasonal rainfall and fluctuating groundwater levels exacerbate the swelling and shrinkage cycles.

The study also highlights the role of soil chemistry in influencing swelling behavior. Elevated sulfate concentrations in certain locations may contribute to secondary expansive reactions, particularly when in contact with calcium-rich soils or water. Similarly, chloride levels affect the soil's salinity and its interaction with clay minerals, altering the extent of swelling. These findings underscore the need to incorporate chemical testing as a standard practice in evaluating expansive soils for engineering applications. In terms of agricultural land use, the swelling and shrinkage of soils can disrupt root systems, damage irrigation infrastructure, and affect crop yields. Farmers in the region may face challenges in maintaining consistent soil conditions, especially in clay-rich areas. Strategies such as soil amendment, drainage management, and crop rotation can help mitigate these impacts, but they require comprehensive planning and resource allocation. Overall, this study emphasizes the critical importance of understanding the geotechnical and mineralogical properties of soils in regions with expansive clays. By integrating field sampling, laboratory testing, and mineralogical analysis, this research provides valuable insights for engineers, planners, and policymakers tasked with addressing the challenges posed by swelling soils. Future studies could explore advanced stabilization techniques or the application of modern soil reinforcement methods to further enhance the safety and sustainability of development in the southern region of Urmia Lake.

V. CONCLUSION

This study provides a comprehensive evaluation of the swelling potential of clayey soils in the southern region of Urmia Lake, focusing on their geotechnical, mineralogical, and chemical characteristics. The results reveal that the dominant clay mineral in the area is montmorillonite, a highly expansive mineral responsible for the significant swelling behavior observed in the studied soils. The classification of soils as clay, clay loam, and silty clay, coupled with high liquid limits, plasticity indices, and moderate to high clay content, further highlights their susceptibility to volumetric changes under varying moisture conditions. The variability in sulfate and chloride concentrations and the measured porosity, density, and UCS values emphasize the heterogeneity of the soils across the region. This variability underscores the necessity for site-specific soil evaluations to inform the design and construction of infrastructure and agricultural practices. The study also identifies the significant impact of swelling soils on structural stability, irrigation systems, and agricultural productivity, stressing the need for proper mitigation and soil management strategies. By combining field sampling, laboratory testing, and mineralogical analysis, this research provides a robust framework for understanding and addressing the challenges associated with expansive soils in the region. Future efforts should focus on the application of soil stabilization techniques, drainage improvements, and long-term monitoring to mitigate the risks posed by swelling soils. These findings are critical for engineers, planners, and policymakers in developing sustainable solutions for infrastructure and land-use practices in areas with expansive clay soils.

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Authors' contributions

Maryam Golnezhad conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, methodology, validation checks, conceptual guidance, and was responsible for drafting the initial and 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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