

Article

Effect of KI Solution Concentration on Nuclear Magnetic Resonance T_2 Relaxation Characteristics of Pore Water in Expansive Soils

Jingjing Li ¹, Lei Jin ¹ and Xinming Li ^{2,3,*}

¹ College of Civil Engineering, Jiangsu Open University, Nanjing 210036, China; lijingjing@jsou.edu.cn (J.L.); jinl@jsou.edu.cn (L.J.)

² School of Civil Engineering and Architecture, Zhongyuan University of Technology, Zhengzhou 450007, China

³ State Key Laboratory of Geomechanics and Geotechnical Engineering Safety, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China

* Correspondence: xmli@zut.edu.cn

Abstract

The interaction between salt solutions and expansive soils is critical for engineering in chemically aggressive environments. However, the effect of iodide salts on pore water distribution in expansive soils remains poorly understood. This study investigated the transverse relaxation time (T_2) characteristics of pore water in expansive soils under varying KI concentrations (0–20%), moisture content (8.7–26.0%), and dry density (1.26–1.79 g/cm³) using nuclear magnetic resonance (NMR). All T_2 curves exhibited a single peak. Increasing moisture content from 8.7% to 26.0% resulted in increases of approximately 63% in T_2 at peak and 408–439% in peak area. Increasing KI concentration decreased both T_2 at peak by up to 33.3% and peak area by up to 44.0% within the tested range, attributed to diffuse double-layer compression and signal loss. Increasing moisture content broadened the T_2 distribution and linearly increased T_2 at peak and peak area, indicating water gradually occupied larger pore spaces as moisture content rose. T_2 at peak was independent of dry density, while the peak area showed a linear relationship with dry density, consistent with mass balance. The observed systematic linear relationships among T_2 at peak, peak area, and the three experimental variables suggest that NMR is a promising tool for the quantitative assessment of salt solution effects on pore water in expansive soils. These findings provide a theoretical basis for evaluating salt-affected expansive soils in coastal and arid regions.

Keywords: expansive soil; pore water distribution; nuclear magnetic resonance; KI solution; salt solution effect

Academic Editor: William Frederick Ritter

Received: 29 May 2026

Revised: 29 June 2026

Accepted: 2 July 2026

Published: 3 July 2026

Copyright: © 2026 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Expansive soils are widely recognized as a common and challenging engineering problem due to their distinct swelling and shrinkage behavior, which pose significant geotechnical hazards, such as slope instability and ground damage [1–10]. Those soils are characterized by an abundance of hydrophilic clay minerals, which exhibit high sensitivity to variations in moisture content and in the chemical composition of their pore solution [11,12]. The fundamental mechanism lies in the fact that the properties of the pore fluid

can alter the thickness of the diffuse double layers (DDLs) on clay particle surfaces [13]. Consequently, changes in the concentration and ionic constituents of the pore fluid can significantly influence the mechanical behavior of expansive soils, rendering this area of study essential for geotechnical engineering practice.

To this end, extensive research has been conducted worldwide on how salt solutions affect the physical and mechanical properties of expansive soils. Rao et al. [14] examined the impact of salt diffusion on the time–swell behavior of compacted expansive clays, focusing on osmotic suction differences between soil water and reservoir salt solution. Rao and Thyagaraj [15] investigated the effect of sodium chloride (NaCl) solutions infiltration on the swell–compression behavior of compacted expansive clays under various external loads. Thyagaraj et al. [16] analyzed the influence of physico-chemical factors on shrinkage behavior when the compacted expansive clay specimens were inundated with distilled water, NaCl, and CaCl_2 solutions. Sakr et al. [17] analyzed the influence of ferric chloride (FeCl_3) on the geotechnical properties and swelling potential of expansive soils. Zhang et al. [18] investigated the effect of salt-lake salt solution on the strength of expansive soil. Furthermore, studies have explored chemical stabilization techniques, such as the precipitation of lime through the sequential mixing of calcium chloride (CaCl_2) and sodium hydroxide (NaOH) solutions [19], and the performance of calcium carbonate stabilization by adding CaCl_2 and sodium carbonate (Na_2CO_3) solutions to expansive soils [20].

Recent investigations have delved deeper into the micro-mechanisms and long-term behaviors using advanced testing methods. For instance, Yu et al. [21] utilized direct shear and nuclear magnetic resonance (NMR) tests to demonstrate that the shear strength of expansive soils decreases slightly with increasing NaCl concentration (below 1.0 mol/L), attributing this to changes in pore-size distribution. Yao et al. [22] conducted free-swelling rate and direct shear experiments, along with scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP), on expansive soils immersed in different concentrations of NaCl and CaCl_2 solutions to study the influence of pore-fluid chemistry on deformation and strength. Yu et al. [23] studied the effect of NaCl solution on water retention and microstructural characteristics of expansive soils using the pressure plate method, MIP, and SEM. Makeen et al. [24] investigated the long-term expansion behavior of expansive soil under different NaCl solution concentrations by monitoring mineralogical and microstructural alterations. Additionally, recent studies have begun to unravel the complex interplay between pore fluid chemistry and environmental dynamics, specifically focusing on freeze–thaw processes and drying–wetting cycles [25,26].

Despite these advances, several knowledge gaps remain. First, most existing studies focus on conventional salt solutions such as NaCl and KCl, while the effects of potassium iodide (KI) solution, a common contrast agent used in X-ray computed tomography (CT), have received significantly less attention. Guber et al. [27] developed and tested a new physically based segmentation approach to account for the partial saturation of image voxels by liquids in soil. Their study, which utilized CT on soils treated with varying KI solution concentrations (0–20 wt%), recommended a 10 wt% KI solution for quantifying the spatial distribution of liquids via dual-energy X-ray microtomography. Notably, the same KI concentration range (0–20 wt%) is adopted in the present study, allowing our NMR results to directly complement their CT-based findings by revealing the corresponding effects of KI on pore-water relaxation behavior. Beyond its utility as an imaging tracer, the large ionic radius of the iodide ion (I^-) (approximately 220 pm) and its weak hydration may distinctly influence the diffuse double-layer thickness and particle flocculation patterns in expansive soils compared with chloride ions (Cl^-). Second, the coupled effects of salt concentration, moisture content, and dry density on transverse relaxation time (T_2)

have not been systematically quantified. Third, quantitative relationships between NMR parameters and these three controlling variables are lacking in the literature.

Nuclear Magnetic Resonance (NMR) technology is a core method for pore structure research due to its non-destructive and rapid quantification capabilities. In porous media, T_2 is proportional to pore size, while the peak area reflects the amount of detectable water. Therefore, NMR provides an effective means to probe pore water distribution and its response to external perturbations.

To address the above gaps, this study aims to systematically investigate the pore-water T_2 relaxation characteristics of expansive soils under the coupled effects of KI solution concentration, moisture content, and dry density using NMR technology. The responses of T_2 at peak (indicative of dominant pore size) and peak area (reflecting detectable water content) to each of the three variables are quantified, and empirical relationships are established. The findings provide a theoretical basis for accurate microstructure characterization in geotechnical engineering and offer insights into the quantitative assessment of salt solution effects on expansive soils.

2. Materials and Methods

2.1. Material Properties

The expansive soil used in this laboratory study was collected at a depth of about 3.0 m under the subsurface from Nanyang Basin, Henan Province, China ($32^{\circ}54'40''$ N, $111^{\circ}46'19''$ E), as shown in Figure 1. The test soils are in a hard state with a reddish-brown color. Table 1 shows the chemical and physical properties of the soil. X-ray diffraction analysis was carried out, and mineral compositions were identified by analyzing characteristic diffraction peaks with Jade 5.0 analysis software. The grain size distribution of the expansive soil is shown in Figure 2, which shows that the clay, silt, and sand contents of the expansive soil correspond to 31.4, 63.1, and 5.5%, respectively. The plasticity index, free swell value, and standard absorption moisture content are 29.2, 62, and 6.7%, respectively, suggesting that the soil shows medium-level expansiveness based on the Chinese standard JTG C20-2011 [28] for expansive soil classification.

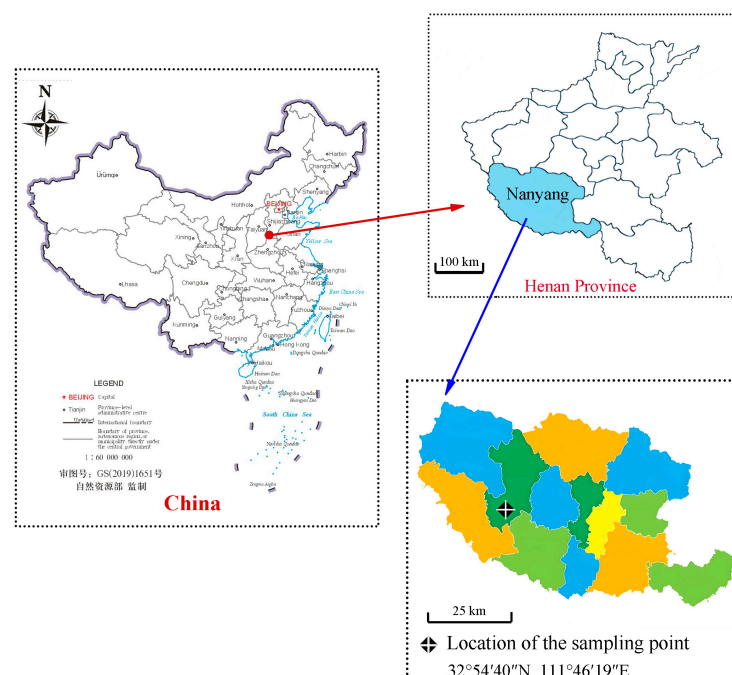


Figure 1. The location of the sampling point: (a) Map of China. The base map is sourced from the Standard Map Service of the Ministry of Natural Resources of China (<http://bzdt.ch.mnr.gov.cn>) and

bears the official review number GS(2019)165 with the supervisory label “自然资源部 监制” (Supervised by the Ministry of Natural Resources of China). These are mandatory administrative identifiers confirming the map’s compliance with national cartographic regulations and do not represent scientific data; (b) Map of Henan Province, with Nanyang City highlighted in color; (c) Enlarged map of Nanyang City, with different colors indicating its administrative districts. The sampling point is shown in panel (c).

Table 1. Chemical and physical properties of the expansive soil.

Mineralogical Components	Concentration (%)	Properties	Unit	Magnitude
Quartz	40	Specific gravity	-	2.71
Feldspar	8	Free swell value	%	62
Montmorillonite	16	Plastic limit	%	26.2
Chlorite	18	Liquid limit	%	55.4
Illite	8	Plasticity index	%	29.2
Kaolinite	10	Maximum dry density	g/cm ³	1.79
		Optimum moisture content	%	16.7
		Standard absorption moisture content	%	6.7

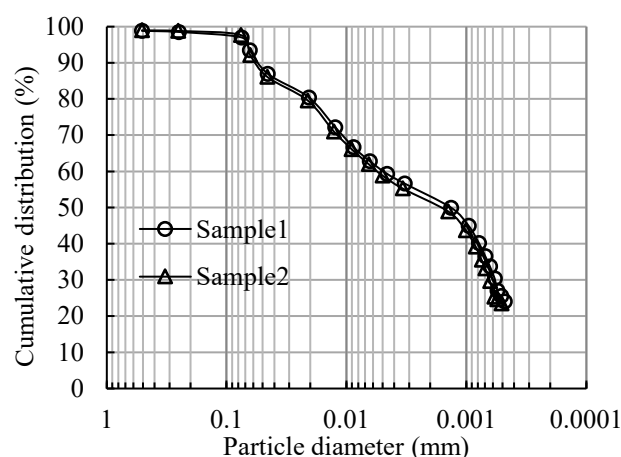


Figure 2. The particle size distribution curve of the expansive soil.

2.2. Sample Preparation and NMR Testing Procedure

The collected soil samples were first air-dried at room temperature, pulverized, and sieved through a 0.5 mm sieve. The initial moisture content of the sieved fraction was determined to be 4% using the oven-drying method (105 °C to constant mass), in accordance with the Chinese standard JTG 3430-2020 [29]. Subsequently, the soil fraction was thoroughly mixed with either distilled water or a potassium iodide (KI) solution to achieve the predetermined target moisture contents. The KI solutions were prepared by dissolving the required mass of KI powder in distilled water to achieve the predetermined weight-to-weight (*w/w*) concentrations. To ensure homogeneous water distribution within the soil matrix, the moist samples were sealed in plastic bags and cured for at least 48 h prior to compaction. Subsequently, the prepared samples were statically compacted into specially designed Teflon plastic rings to meet the targeted dry densities. This specific ring material was selected to replace conventional steel rings in order to eliminate magnetic interference from iron (Fe) during magnetic field application. The prepared specimens were cylindrical, measuring 45 mm in diameter and 20 mm in height. To ensure data reliability and minimize test errors, two groups of parallel samples were fabricated for each specific condition according to the test scheme summarized in Table 2. The test results showed that the T_2 spectra of the two parallel samples were nearly overlapped, with

the same T_2 at peak and maximum relative deviations of less than 3% for peak area, indicating good experimental reproducibility. Therefore, error bars are not shown in the following figures because they are comparable to or smaller than the size of the data point symbols. All reported data are the average values of the two parallel measurements.

Table 2. Experimental scheme.

Moisture Content (%)	Dry Density (g/cm³)	KI Concentration (%)
18.7	1.26	0, 3, 7, 10, 20
	1.35	
	1.44	
	1.52	
	1.61	
	1.70	
	1.79	
8.7	1.59	
12.7		
16.7		
18.7		
20.7		
24.7		
26.0		

Following sample preparation, the T_2 relaxation characteristics of the pore water in the expansive soil specimens were measured using NMR technology. A low-field NMR spectrometer (Model PQ-001 MiniNMR, manufactured by Niumag Corporation, Suzhou, China) was employed to acquire T_2 distributions via the Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence with the following acquisition parameters: echo time (TE) = 0.260 ms and number of echoes (NECH) = 2000. The resulting T_2 distributions were then used to characterize the pore water relaxation behavior of the specimens, with particular attention to the T_2 at peak and the peak area as indicators of the dominant relaxation component and detectable water content, respectively.

3. Results and Discussion

3.1. The Influence of Different KI Concentrations on the Water Distribution of Expansive Soils

Figure 3 depicts the T_2 distribution curves with different KI concentrations. The magnitude of T_2 accounts for the pore radius of soil, while the signal amplitude represents the moisture content in the pores. Due to the similar variation patterns of T_2 curves with KI concentrations across different moisture contents, only the curves corresponding to moisture contents of 8.7%, 16.7%, and 24.7% are presented. Figure 3 shows that each T_2 spectrum curve exhibits a single peak, indicating a dominant pore-size distribution within the soil matrix.

Figure 4 shows the relationship between KI concentration and T_2 at peak under different moisture contents. The “ T_2 at peak” represents the relaxation time corresponding to the maximum NMR signal, which is widely used to characterize the dominant pore size saturated with water at a given moisture content. At a constant moisture content, T_2 at peak decreases by up to 33.3% with increasing KI concentration and eventually approaches a stable value. This reduction can be attributed primarily to the physicochemical effects of the salt on the expansive soil. The increase in ionic strength compresses the diffuse double layer surrounding the clay particles, leading to particle flocculation and a reduction in the dominant pore size. Since the transverse relaxation time is proportional to

pore size, this structural shrinkage results in a lower T_2 at peak. The stabilizing trend at higher KI concentrations suggests that the double layer has been compressed to its near-limiting thickness, beyond which further increasing ionic strength does not significantly alter the pore structure. Additional contributions from increased solution viscosity and potential changes in surface relaxivity may also accelerate transverse relaxation.

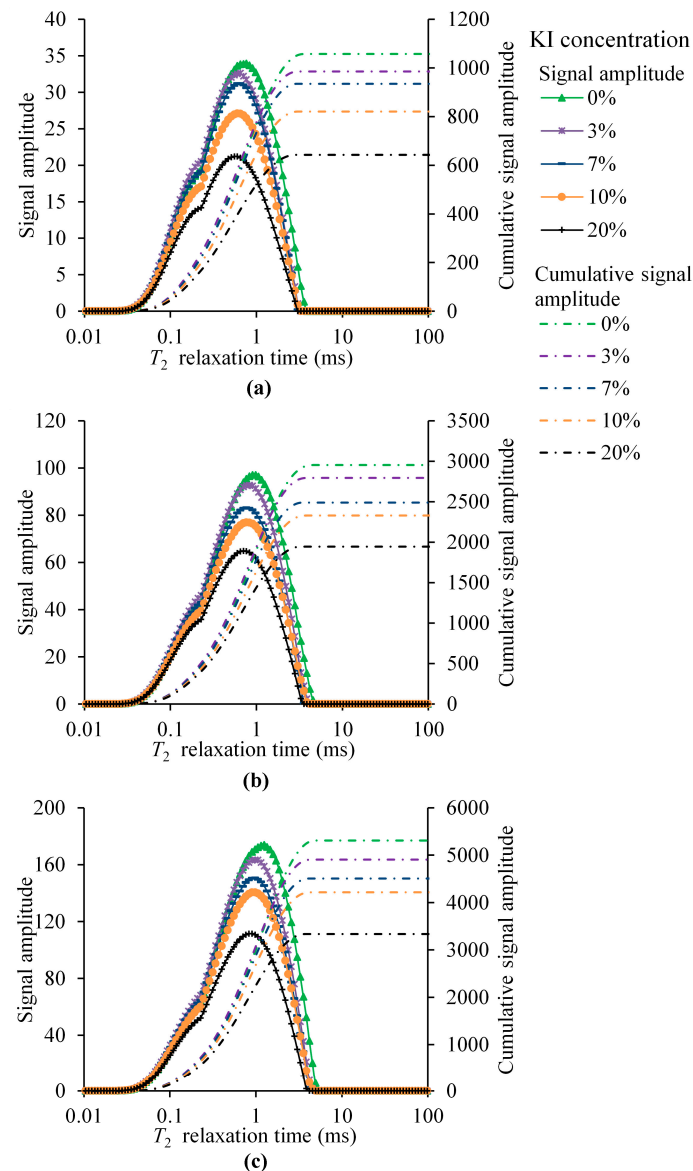


Figure 3. T_2 curves under different KI concentrations: (a) $\omega = 8.7\%$; (b) $\omega = 16.7\%$; (c) $\omega = 24.7\%$.

The area under the T_2 distribution curve is termed the “peak area”, which theoretically corresponds to the population of water molecules, indicating the amount of moisture content in the soil sample. Figure 5 shows a linear decrease in peak area with increasing KI concentration at a fixed moisture content, reaching a maximum reduction of approximately 44.0% within the tested range. This indicates that dissolved KI not only shortens the transverse relaxation time but also causes a reduction in the observable NMR signal intensity. This attenuation is primarily attributed to the compression of the diffuse double layer by the high ionic strength, which forces water into nano-scale pores where transverse relaxation is extremely fast. Additionally, increased solution viscosity may further accelerate relaxation. As a result, the T_2 of a fraction of the water molecules falls below the detection limit of the NMR measurement, leading to a reduction in the integrated peak area. Despite this signal attenuation, the strong linearity suggests that the effect of KI on

the NMR response is systematic and predictable, allowing for potential calibration for quantitative analysis. The fitting equations corresponding to the linear relationships in Figure 5 are provided in the Supplementary Materials.

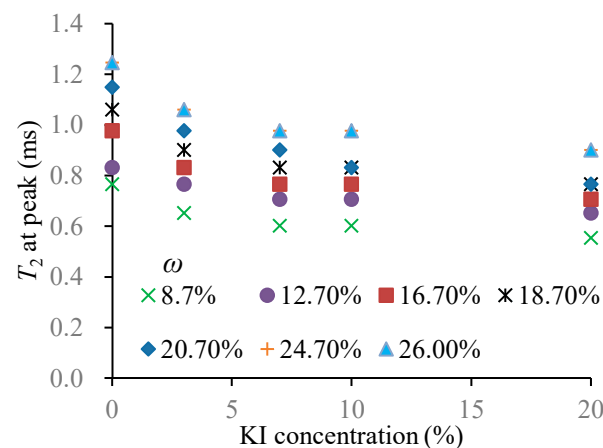


Figure 4. The relationship between KI concentration and T_2 at peak under different moisture contents.

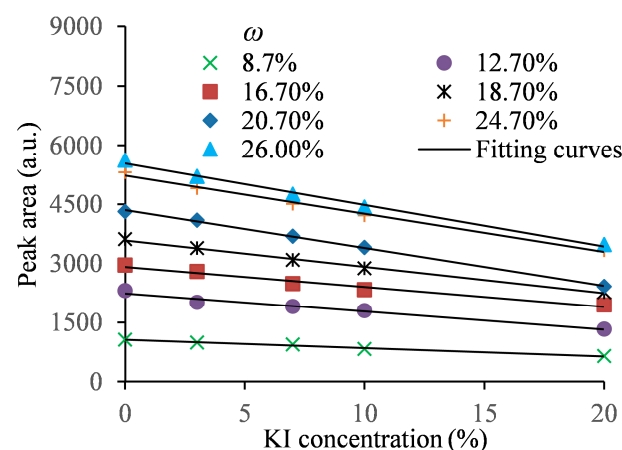


Figure 5. The relationship between KI concentration and peak area under different moisture contents. Symbols denote experimental data; solid lines represent the fitting curves ($R^2 > 0.97$ for all fitting lines).

It should be noted that the above mechanistic interpretation is based on the KI solution system. I^- possesses a relatively large ionic radius (approximately 220 pm) and weak hydration, and its interaction with clay mineral surfaces may differ from that of Cl^- or SO_4^{2-} . Therefore, the conclusions of this study should be understood as system-specific to KI, and direct extrapolation to other salt systems, such as NaCl or Na_2SO_4 , requires caution. In addition, all T_2 spectra in this study exhibited a single peak, without bimodal or trimodal features. This observation is consistent with the findings of Yu et al. [21], who reported that a weakly expansive clay treated with various concentrations of NaCl solution consistently showed a single T_2 peak. However, the T_2 spectral shape is sensitive to specific experimental conditions. For instance, Ma et al. [30] found that expansive clay during the drying-wetting cycle typically exhibited a single T_2 peak when the moisture content was below 27%, but showed a bimodal distribution when the moisture content reached 46% or when soil powder was used. Luo et al. [31] reported a trimodal characteristic for expansive soil unmodified or modified by different superhydrophobic nano- SiO_2 contents, and Li et al. [32] also found a trimodal characteristic for expansive soil under the effect of

freeze–thaw cycles. The single-peak distribution observed in our study may therefore be attributed to the relatively low montmorillonite content of the tested soil, the static compaction procedure, and particle aggregation induced by KI, rather than to insufficient sensitivity of the NMR method. Under the present experimental conditions, the single-peak distribution is sufficient to reflect the dominant pore-water characteristics.

3.2. The Influence of Moisture Content on the Water Distribution of Expansive Soils

Figure 6 depicts the T_2 distribution curves with different moisture contents at KI concentrations of 0%, 7%, and 20%. As the moisture content increases, the signal intensity increases significantly, the T_2 distribution becomes broader, and the peak position shifts toward longer relaxation times. In samples with higher moisture content, water fills a wider range of pore spaces, with a greater proportion existing as bulk-like water in relatively larger pores. This bulk-like water experiences weaker surface interactions, resulting in prolonged T_2 relaxation times. Therefore, the increase in T_2 at peak reflects a higher proportion of bulk-like water with increasing moisture content, confirming that water residing in larger pores is less constrained by surface relaxation effects. Quantitatively, increasing moisture content from 8.7% to 26.0% resulted in increases of approximately 63% in T_2 at peak and 408–439% in peak area.

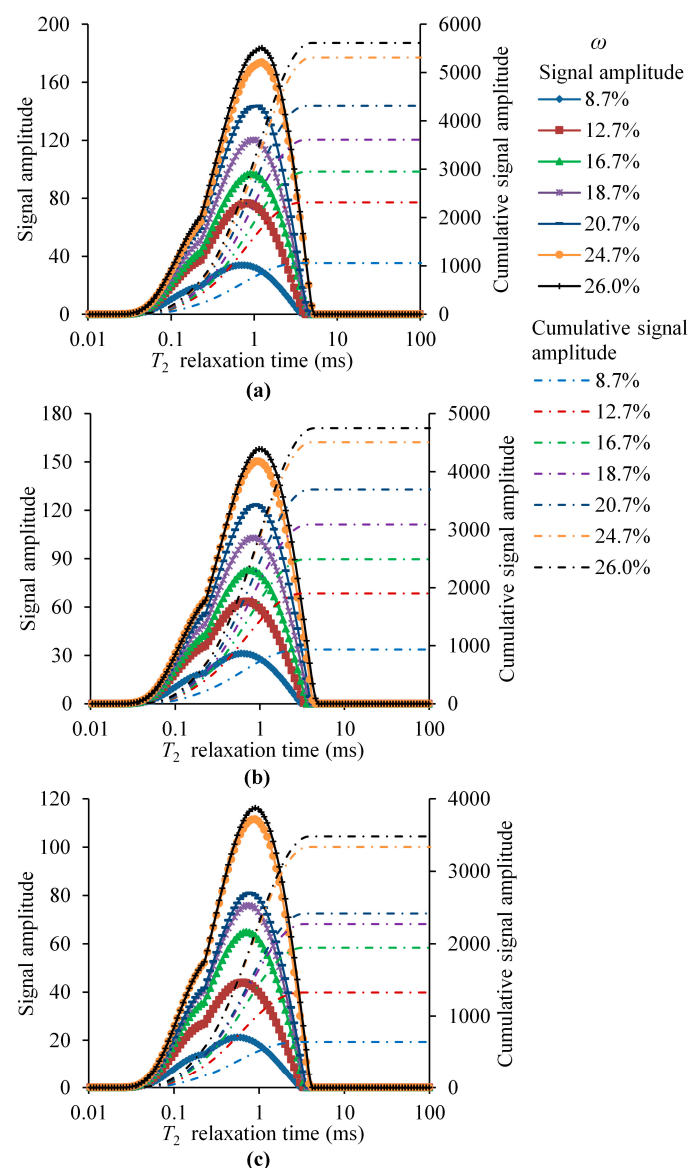


Figure 6. T_2 curves under different moisture contents: (a) KI = 0%; (b) KI = 7%; (c) KI = 20%.

To further quantify the evolution of pore water, the relationships between moisture content and both T_2 at peak and peak area are plotted in Figures 7 and 8, respectively. Under a constant KI concentration, both parameters exhibit a strong linear correlation with moisture content within the tested range. These relationships can be described by the following linear equations:

$$T_{2,\text{peak}} = A\omega + B \quad (1)$$

$$A_{\text{peak}} = M\omega + N \quad (2)$$

where $T_{2,\text{peak}}$ presents T_2 at peak; A_{peak} presents peak area; ω is the moisture content of the soil sample; A , B , M , and N are the fitting parameters.

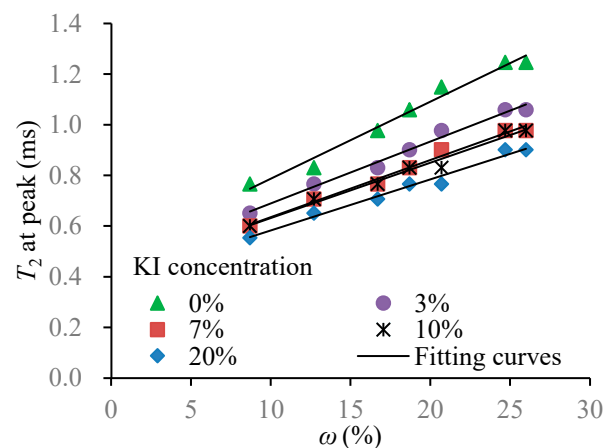


Figure 7. The relationship between the moisture content and T_2 at peak under different KI concentrations. Symbols denote experimental data; solid lines represent the fitting curves ($R^2 \geq 0.98$ for all fitting lines).

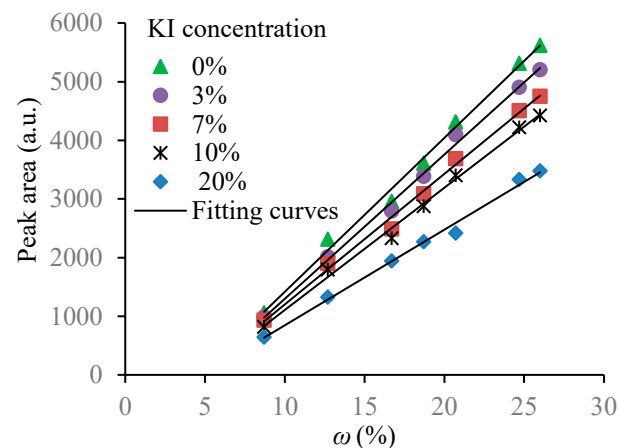


Figure 8. The relationship between the moisture content and peak area under different KI concentrations. Symbols denote experimental data; solid lines represent the fitting curves ($R^2 > 0.99$ for all fitting lines).

The fitting parameters listed in Table 3 reveal distinct trends with varying KI concentrations. Specifically, both A and B decrease as KI concentration increases, indicating that dissolved KI ions enhance the relaxation rate and shift the baseline. Furthermore, the fitting parameter M shows a linear negative correlation with KI concentration, whereas N exhibits a positive linear correlation. This suggests that the presence of KI significantly influences both the sensitivity (slope) and the offset (intercept) of the NMR-based moisture measurement.

Table 3. Fitting parameters between $T_{2,\text{peak}}$, A_{peak} , and ω under different KI concentrations.

KI Concentration (%)	Fitting Parameters Between $T_{2,\text{peak}}$ and ω			Fitting Parameters Between A_{peak} and ω		
	A (ms/%)	B (ms)	R^2	M (a.u./%)	N (a.u.)	R^2
0	0.0304	0.4871	0.980	262.14	−1202.9	0.994
3	0.0244	0.4446	0.987	245.96	−1162.4	0.996
7	0.0225	0.4101	0.987	222.29	−1019.3	0.994
10	0.0218	0.4133	0.980	208.56	−979.94	0.995
20	0.0201	0.3810	0.980	163.08	−783.99	0.994

It should be emphasized that the empirical relationships established in this section are strictly applicable only within the tested ranges (KI concentration 0~20%, moisture content 8.7%~26.0%, dry density 1.26~1.79 g/cm³). Extrapolation beyond these ranges may yield physically unrealistic results and should be avoided.

3.3. The Influence of Dry Density on the Water Distribution of Expansive Soils

Figure 9 depicts the T_2 distribution curves for samples with varying dry densities under KI concentrations of 0%, 3%, 10%, and 20%. As dry density decreases, the T_2 distribution becomes broader, indicating a wider range of pore sizes in less compacted soils. However, the peak position remains essentially unchanged.

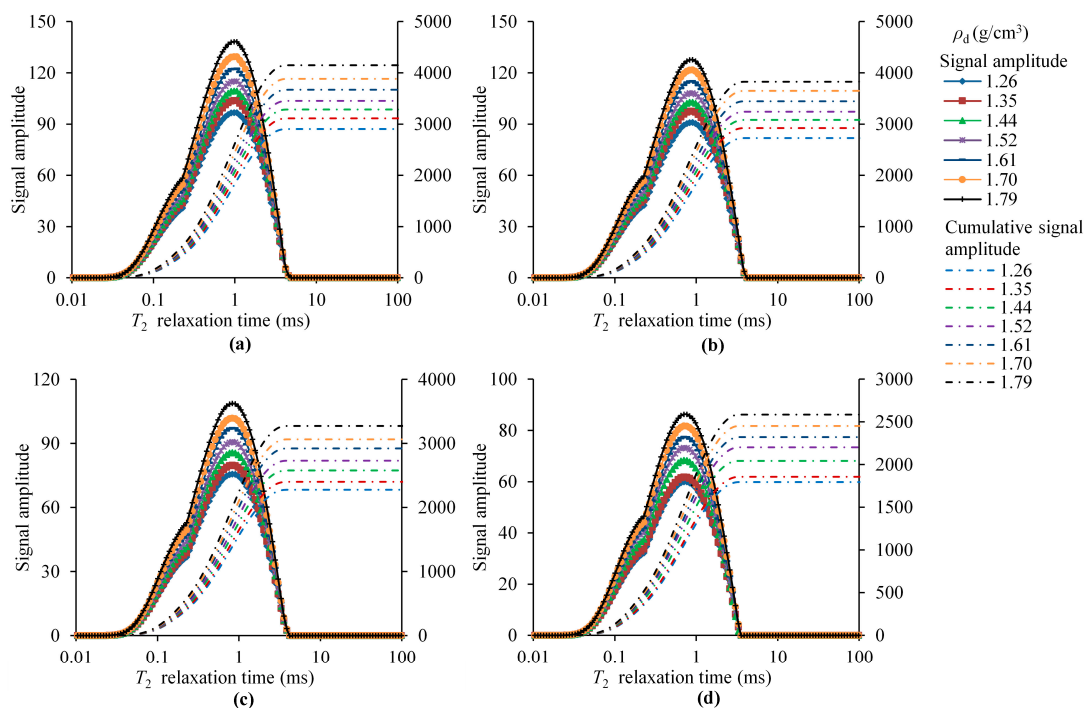
**Figure 9.** T_2 curves under different dry densities: (a) KI = 0%; (b) KI = 3%; (c) KI = 10%; (d) KI = 20%.

Figure 10 shows that T_2 at peak decreases with increasing KI concentration within the tested range under different dry densities. Notably, for samples with the same KI concentration, T_2 at peak remains almost constant regardless of dry density. This is consistent with the findings of [32], where the main peak position remained stable across different compaction conditions, even though the T_2 distribution exhibited multiple peaks. These observations indicate that KI concentration is the primary factor governing the observed relaxation rate, whereas dry density does not produce a detectable shift in the dominant T_2 peak position.

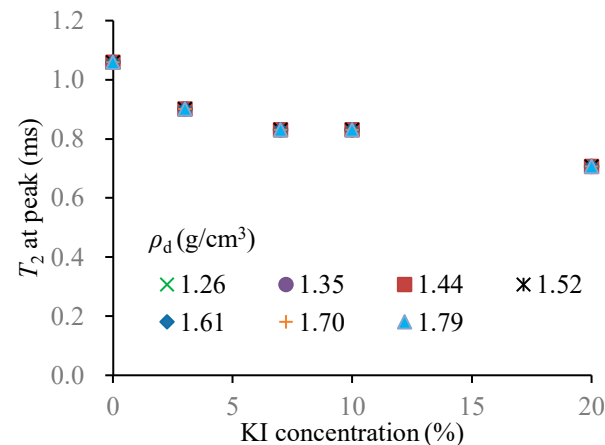


Figure 10. The relationship between KI concentration and T_2 at peak under different dry densities. The T_2 at peak values appear coincident across different dry densities at each KI concentration, reflecting the actual experimental outcome.

Figure 11 illustrates the relationship between KI concentration and peak area at different dry densities. The peak area shows a clear negative linear correlation with KI concentration within the tested range at a constant dry density, indicating that dissolved KI causes a systematic attenuation of the NMR signal. This is attributed to the shortening of T_2 relaxation times, which renders a fraction of pore water undetectable under the fixed NMR acquisition parameters.

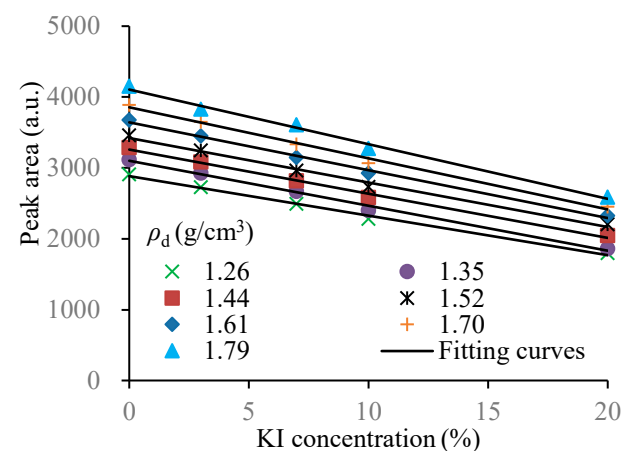


Figure 11. The relationship between KI concentration and peak area under different dry densities. Symbols denote experimental data; solid lines represent the fitting curves ($R^2 > 0.99$ for all fitting lines).

Figure 12 demonstrates a strong linear relationship between peak area and dry density within the tested range under a fixed KI concentration. This linearity confirms that under fixed moisture content, the NMR peak area is linearly proportional to the dry mass of the soil in the sample, consistent with mass balance. The fitting equations corresponding to the linear relationships in Figures 11 and 12 are provided in the Supplementary Materials.

It should be noted that all samples in this study were statically compacted, and the observed independence of T_2 at peak from dry density is interpreted within the context of compacted specimens only. The comparison among different dry densities is internally valid because the compaction method was held constant across all samples. Control tests comparing compacted versus loose samples were not performed, as the present study fo-

cuses on compacted conditions relevant to engineering practice. Future studies may include such controls to further isolate the effect of compaction from the effect of dry density.

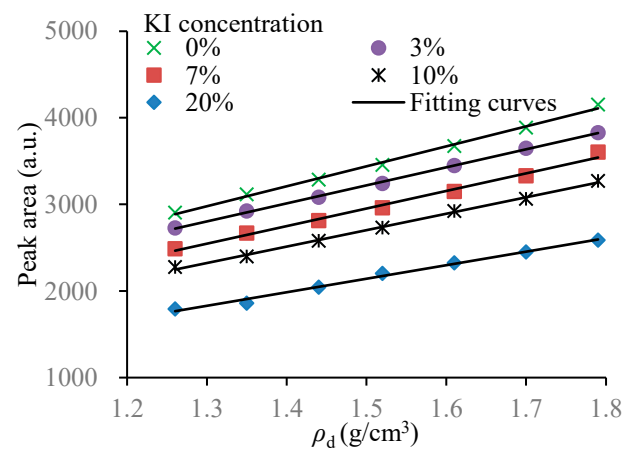


Figure 12. The relationship between dry density and peak area under different KI concentrations. Symbols denote experimental data; solid lines represent the fitting curves ($R^2 > 0.99$ for all fitting lines).

3.4. Integrated Discussion: Mechanisms, Engineering Implications, and Limitations

Among the three factors investigated, moisture content exerts the most significant influence on T_2 relaxation behavior, followed by KI concentration, while dry density shows the least effect within the tested range. This hierarchy is evident from the magnitude of changes in both T_2 at peak and peak area. Specifically, increasing moisture content from 8.7% to 26.0% resulted in substantial increases in T_2 at peak by approximately 63% and in peak area by approximately 408–439% across different KI concentrations. In comparison, increasing KI concentration from 0 to 20% at a fixed moisture content led to a reduction in T_2 at peak by approximately 33.3% and in peak area by approximately 44.0%. Varying dry density over the range of 1.26 to 1.79 g/cm³ produced no detectable change in T_2 at peak and only a moderate linear increase in peak area attributable to mass balance. This suggests that water saturation level is the primary control on the relaxation behavior, with pore fluid chemistry playing a secondary but still significant role, while the physical packing of soil particles plays a minor role.

The observed T_2 relaxation behavior can be interpreted through a unified framework. Moisture content controls the water saturation level and the relative proportions of bound versus free water. At low moisture content, water is predominantly held as bound water within the double layer or in nanopores, yielding shorter T_2 values and narrower distributions. As moisture content increases, more water resides in larger pores as bulk-like free water, which experiences weaker surface interactions and thus exhibits longer T_2 relaxation times and broader distributions. KI concentration determines the thickness of the diffuse double layer surrounding clay particles through ionic strength effects. Higher KI concentrations compress the double layer, promoting particle flocculation and reducing the effective pore space accessible to water, which accelerates transverse relaxation and shifts T_2 at peak to shorter values. Concurrently, the increased ionic strength and viscosity reduce molecular mobility and may cause a fraction of pore water to relax so rapidly that it falls below the NMR detection limit, resulting in a decrease in the observable peak area. In addition, the increased electrical conductivity of the pore fluid at higher KI concentrations may contribute to RF field attenuation and signal loss. At higher concentrations (e.g., >10%), additional effects such as cation exchange or mineral dissolution may also contribute to the observed NMR responses, although DDL compression remains the primary

mechanism for KI-induced changes. Dry density, in contrast, affects the total pore volume and thus the total water mass per unit sample volume, but it does not significantly alter the dominant relaxation component that determines the T_2 at peak position. This is because compaction primarily reduces macropores or inter-aggregate voids, while the dominant pore population associated with the main water-filled pores remains relatively stable. The combined effects of these three factors result in systematic and predictable changes in T_2 at peak and peak area, which can be captured by the linear empirical relationships established in this study.

The salt-induced changes in pore-water distribution revealed by NMR have direct implications for the engineering behavior of expansive soils in coastal, arid, and saline environments. The reduction in bound water content under increasing KI concentration indicates compression of the diffuse double layer, which, based on the DDL theory, would lead to a decrease in swelling pressure, an effect that might initially appear beneficial for mitigating heave-related distress. However, this interpretation must be balanced against accompanying adverse effects. The observed increase in free water proportion suggests reduced inter-particle effective stress, which may result in a decrease in shear strength and an increase in hydraulic conductivity. Furthermore, the particle flocculation induced by high salt concentrations could alter the soil fabric in ways that affect compressibility and volume-change behavior. These competing effects highlight the complexity of salt-expansive soil interactions and underscore the need for site-specific evaluation rather than simplistic assumptions. In this context, NMR-derived parameters, particularly the bound-water fraction and T_2 at peak shifts, offer a rapid and non-destructive means of assessing the status of pore-water distribution, which can serve as a diagnostic indicator for the potential susceptibility of salt-affected expansive soils to volume change and strength loss. However, the correlations established in this study remain qualitative to semi-quantitative at this stage; direct quantitative relationships between NMR parameters and macroscopic engineering properties, including swelling pressure, shear strength, compressibility, and hydraulic conductivity, should be established through parallel NMR-mechanical tests such as direct shear, consolidation, and swelling pressure tests before the method can be applied with confidence in routine engineering practice.

Several limitations of this study should be acknowledged to properly contextualize the findings and to guide future research. First, the experiments were conducted using only a single salt type (potassium iodide, KI) and reconstituted specimens. As discussed in Section 3.1, the specific physicochemical properties of I^- may differ from those of other anions commonly encountered in field conditions, including Cl^- and SO_4^{2-} , and the reconstituted specimens lack the natural fabric, micro-fissures, and cementation present in undisturbed field soils. Generalization of the findings to multi-salt systems and undisturbed conditions requires further experimental validation. Second, the empirical relationships established in Sections 3.2 and 3.3 are strictly applicable only within the tested ranges (KI concentration: 0~20%, moisture content: 8.7%~26.0%, dry density: 1.26~1.79 g/cm³). Extrapolation beyond these ranges may yield physically unrealistic results and should be avoided. Third, this study focused on short-term equilibrium responses under constant temperature (20 ± 1 °C) and idealized boundary conditions, and did not address time-dependent processes such as mineral dissolution, secondary precipitation, ion exchange, or cyclic wetting-drying effects, all of which may significantly alter the soil structure and pore-water distribution over extended periods in the field. In addition, post-leaching re-testing was not performed to evaluate the reversibility of the observed changes at high KI concentrations; this remains an open question for future investigation. Future studies should address these limitations through: (1) multi-salt comparative experiments, such as NaCl, Na₂SO₄, and CaCl₂, to evaluate the generality of the observed trends; (2) temperature calibration experiments covering the range of 5 °C to 40 °C to establish correction

functions for field applications; (3) long-term soaking and leaching experiments, as well as multiple wetting-drying cycle tests to capture the time-dependent evolution of pore-water responses; (4) validation using undisturbed field samples to assess the effect of natural soil fabric; and (5) parallel NMR-mechanical tests to establish direct quantitative relationships between NMR parameters and engineering properties. These steps are essential for bridging the gap between laboratory calibration and practical field implementation of NMR-based characterization methods for salt-affected expansive soils.

4. Conclusions

This study systematically investigated the effects of KI concentration (0–20%), moisture content (8.7–26.0%), and dry density (1.26–1.79 g/cm³) on the NMR transverse relaxation time (T_2) characteristics of pore water in expansive soils. The main findings are summarized as follows.

- (1) KI concentration is the dominant factor controlling the relaxation behavior. Increasing KI concentration decreases both T_2 at peak and peak area within the tested range. This is attributed to diffuse double-layer compression, which induces particle flocculation and pore shrinkage, as well as to signal loss caused by T_2 shortening below the NMR detection limit. The maximum reductions of approximately 33.3% for T_2 at peak and 44.0% for peak area from 0% to 20% KI concentration.
- (2) Moisture content governs pore water distribution. Higher moisture content broadens the T_2 distribution and increases both T_2 at peak and peak area, indicating that water progressively occupies larger pore spaces as moisture content rises. Specifically, increasing moisture content from 8.7% to 26.0% resulted in increases of approximately 63% in T_2 at peak and 408–439% in peak area. Strong linear correlations ($R^2 \geq 0.98$) were established between moisture content and both NMR parameters.
- (3) Dry density linearly regulates the peak area but does not affect T_2 at peak. This linear relationship between peak area and dry density within the tested range is consistent with mass balance, because at a fixed moisture content, higher dry density corresponds to greater dry soil mass and thus a larger total amount of water.
- (4) The underlying microscopic mechanism involves double-layer compression forcing pore water into nano-scale pores, where T_2 becomes extremely short and falls below the detection limit, rendering a fraction of the pore water NMR-invisible.

The systematic linear relationships observed among T_2 at peak, peak area, and the three experimental variables demonstrate that NMR is a promising tool for the quantitative assessment of salt solution effects on pore water in expansive soils. This finding provides a theoretical basis for microstructural characterization in geotechnical engineering practice, particularly in chemically aggressive environments. Future research should focus on multi-salt comparative experiments, long-term evolution monitoring, and temperature calibration to bridge the gap between laboratory calibration and field application.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18131623/s1>, Table S1. Fitting parameters between A_{peak} and c_{KI} under different moisture contents. Table S2. Fitting parameters between A_{peak} and c_{KI} under different dry densities. Table S3. Fitting parameters between A_{peak} and ρ_d under different KI concentrations.

Author Contributions: Conceptualization, J.L., L.J., and X.L.; Data curation, J.L.; Formal analysis, L.J.; Funding acquisition, J.L. and X.L.; Investigation, L.J.; Methodology, J.L. and X.L.; Supervision, X.L.; Validation, J.L. and X.L.; Visualization, J.L.; Writing—original draft, J.L. and L.J.; Writing—review and editing, X.L. All authors have read and agreed to the published version of the manuscript.

Funding: The present work was supported by the National Natural Science Foundation of China (Grant number 12002121), Henan Outstanding Youth Science Foundation (Grant number 242300421153), and Open Research Fund of State Key Laboratory of Geomechanics and Geotechnical Engineering Safety, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences (SKLGME022027).

Data Availability Statement: The original contributions presented in this study are included in the article and Supplementary Materials. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Hou, T.S.; Xu, G.L.; Shen, Y.J.; Wu, Z.Z.; Zhang, N.N.; Wang, R. Formation mechanism and stability analysis of the Houba expansive soil landslide. *Eng. Geol.* **2013**, *161*, 34–43. <https://doi.org/10.1016/j.enggeo.2013.04.010>.
- Jamei, M.; Guiras, H.; Olivella, S. Analysis of slope movement initiation induced by rainfall using the Elastoplastic Barcelona Basic Model. *Eur. J. Environ. Civ. Eng.* **2015**, *19*, 1033–1058. <https://doi.org/10.1080/19648189.2014.996670>.
- Dai, Z.; Chen, S.; Li, J. The failure characteristics and evolution mechanism of the expansive soil trench slope. In *PanAm Unsaturated Soils*; American Society of Civil Engineers: Dallas, TX, USA, 2017; pp. 196–205. <https://doi.org/10.1061/9780784481691.020>.
- Kong, L.W.; Zeng, Z.X.; Bai, W.; Wang, M. Engineering geological properties of weathered swelling mudstones and their effects on the landslides occurrence in the Yanji section of the Jilin-Hunchun high-speed railway. *Bull. Eng. Geol. Environ.* **2018**, *77*, 1491–1503. <https://doi.org/10.1007/s10064-017-1096-2>.
- Li, J.; Kong, L.; Jin, L.; Li, X. Influence of rainfall conditions and loading modes on the stability of expansive soil cut slopes: Insight from in situ borehole shear test. *Water* **2025**, *17*, 694. <https://doi.org/10.3390/w17050694>.
- Dai, Z.; Huang, K.; Chi, Z.; Chen, S. Model test study on the deformation and stability of rainfall-induced expansive soil slope with weak interlayer. *Bull. Eng. Geol. Environ.* **2024**, *83*, 76. <https://doi.org/10.1007/s10064-024-03576-2>.
- Liang, C.; Wu, Z.; Liu, X.; Xiong, Z.; Li, T. Analysis of shallow landslide mechanism of expansive soil slope under rainfall: A case study. *Arab. J. Geosci.* **2021**, *14*, 584. <https://doi.org/10.1007/s12517-021-06829-6>.
- Xu, L.; Dai, F.; Chen, J.; Iqbal, J.; Qu, Y. Analysis of a progressive slope failure in the Xiangjiaba reservoir area, Southwest China. *Landslides* **2014**, *11*, 55–66. <https://doi.org/10.1007/s10346-012-0373-1>.
- Pei, P.; Zhao, Y.L.; Ni, P.P.; Mei, G.X. A protective measure for expansive soil slopes based on moisture content control. *Eng. Geol.* **2020**, *269*, 105527. <https://doi.org/10.1016/j.enggeo.2020.105527>.
- Xu, Y.; Su, C.; Huang, Z.; Yang, C.; Yang, Y. Research on the protection of expansive soil slopes under heavy rainfall by anchor-reinforced vegetation systems. *Geotext. Geomembr.* **2022**, *50*, 1147–1158. <https://doi.org/10.1016/j.geotextmem.2022.07.006>.
- Homand, S.; Shao, J.F. Mechanical behavior of a porous chalk and water/chalk interaction. Part I: Experimental study. *Oil Gas Sci. Technol.-Rev. IFP Energ. Nouv.* **2000**, *55*, 591–598. <https://doi.org/10.2516/ogst:2000044>.
- Xu, Y.F.; Xiang, G.S.; Jiang, H.; Tao, C.; Chu, F.F. Role of osmotic suction in volume change of clays in salt solution. *Appl. Clay Sci.* **2014**, *101*, 354–361. <https://doi.org/10.1016/j.clay.2014.09.006>.
- Bolt, G.H. Analysis of the validity of the Gouy-Chapman theory of the electric double layer. *J. Colloid Sci.* **1955**, *10*, 206–218. [https://doi.org/10.1016/0095-8522\(55\)90027-1](https://doi.org/10.1016/0095-8522(55)90027-1).
- Rao, S.M.; Thyagaraj, T.; Thomas, H.R. Swelling of compacted clay under osmotic gradients. *Géotechnique* **2006**, *55*, 707–713. <https://doi.org/10.1680/geot.2006.56.10.707>.
- Rao, S.M.; Thyagaraj, T. Swell-compression behaviour of compacted clays under chemical gradients. *Can. Geotech. J.* **2007**, *44*, 520–532. <https://doi.org/10.1139/T07-002>.
- Thyagaraj, T.; Thomas, S.R.; Das, A.P. Physico-chemical effects on shrinkage behavior of compacted expansive clay. *Int. J. Geomech.* **2017**, *17*, 06016013. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000698](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000698).
- Sakr, M.A.; Azzam, W.R.; Meguid, M.A.; Hassan, A.F.; Ghoneim, H.A. Enhancing the swelling characteristics and shear strength of expansive soil using ferric chloride solution. *Int. J. Geosynth. Ground Eng.* **2021**, *7*, 76. <https://doi.org/10.1007/s40891-021-00320-8>.
- Zhang, S.; Li, D. The effects of salt-lake salt solution on the strength of expansive soil. *Geofluids* **2022**, *2022*, 2798281. <https://doi.org/10.1155/2022/2798281>.
- Thyagaraj, T.; Rao, S.M.; Suresh, P.S.; Salini, U. Laboratory studies on stabilization of an expansive soil by lime precipitation technique. *J. Mater. Civ. Eng.* **2012**, *24*, 1067–1075. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000483](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000483).

20. Han, S.; Wang, B.; Gutierrez, M.; Shan, Y.; Zhang, Y. Laboratory study on improvement of expansive soil by chemically induced calcium carbonate precipitation. *Materials* **2021**, *14*, 3372–3394. <https://doi.org/10.3390/MA14123372>.
21. Yu, H.; Sun, D.; Tian, H. NMR-based analysis of shear strength of weakly expansive clay in sodium chloride solution. *Magn. Reson. Imaging* **2019**, *58*, 6–13. <https://doi.org/10.1016/j.mri.2019.01.002>.
22. Yao, C.; Liu, J.; An, R. Effects of chemical solution on the deformation and strength characteristics of expansive soil. *Environ. Earth Sci.* **2024**, *83*, 375. <https://doi.org/10.1007/s12665-024-11599-x>.
23. Yu, M.; Zhou, C.; Han, X.; Niu, G. Effect of salt solution on water-retention and microstructure characteristics of Ningming expansive soil. *Water* **2025**, *17*, 700. <https://doi.org/10.3390/w17050700>.
24. Makeen, G.M.H.; Awad, S.A.; Dilawar, H. Amelioration of soil expansion using sodium chloride with long-term monitoring of microstructural and mineralogical alterations. *Arab. J. Sci. Eng.* **2021**, *46*, 4461–4476. <https://doi.org/10.1007/s13369-020-04966-w>.
25. Estabragh, A.R.; Amini, M.; Javadi, A.A.; Salehzadeh, H. Effect of temperature and salt concentration of pore fluid on the behaviour of an expansive soil during drying and wetting cycles. *Geomech. Geoengin.* **2024**, *19*, 1038–1054. <https://doi.org/10.1080/17486025.2024.2342245>.
26. Yu, H.; Hao, F.; Yi, P.; Zhang, Q.; Ma, T. Experimental investigation on the effect of salt solution on the soil freezing characteristic curve for expansive soils. *Sustainability* **2024**, *16*, 363. <https://doi.org/10.3390/su16010363>.
27. Guber, A.; Kutlu, T.; Rivers, M.; Kravchenko, A. Mass-balance approach to quantify water distribution in soils based on x-ray computed tomography images. *Eur. J. Soil. Sci.* **2020**, *72*, 578–592. <https://doi.org/10.1111/ejss.13005>.
28. *JTG C20-2011*; Code for Highway Engineering Geological Investigation. China Communications Press: Beijing, China, 2011. (In Chinese)
29. *JTG 3430-2020*; Test Methods of Soils for Highway Engineering. China Communications Press: Beijing, China, 2020. (In Chinese)
30. Ma, T.; Wei, C.; Yao, C.; Yi, P. Microstructural Evolution of Expansive Clay during Drying–Wetting Cycle. *Acta Geotech.* **2020**, *15*, 2355–2366. <https://doi.org/10.1007/s11440-020-00938-4>.
31. Luo, X.; Kong, L.; Bai, W. Effect of Superhydrophobic Nano-SiO₂ on the Hydraulic Conductivity of Expansive Soil and Analysis of Its Mechanism. *Appl. Sci.* **2023**, *13*, 8198. <https://doi.org/10.3390/app13148198>.
32. Li, T.; Kong, L.; Liu, B. The california bearing ratio and pore structure characteristics of weakly expansive soil in frozen areas. *Appl. Sci.* **2020**, *10*, 7576. <https://doi.org/10.3390/app10217576>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.