Postprint: Study on Relationships Between Apparent Electrical Conductivity and Water Content, Salt Content, and Particle Size in Sulfate Saline Soils

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Abstract

Taking the Xiaoxigou watershed in the Beishan area of Xining Basin as the study area and the sulfate saline soil within the region as the research object, six groups of soil samples with different particle sizes (<0.075 mm, 0.075~0.1 mm, 0.1~0.25 mm, 0.25~0.5 mm, 0.5~1 mm, 1~2 mm) were obtained through sieving tests. The apparent electrical conductivity (ECa) of soil samples with different water content, salt content (Na2SO4), and particle size was measured, the relationships between ECa and water content, salt content, and particle size were analyzed, and the grey relational degree between ECa and water content as well as salt content was obtained using the grey relational analysis method. The results show that: (1) ECa exhibits an increasing trend with the increase of water content, salt content, and particle size. When the particle size is 0.075~0.1 mm and the salt content is 0.64%, as the water content increases from 5% to 25%, ECa increases by 0.99 mS · cm-1, representing an increase of 2475%; when the particle size is 0.075~0.1 mm and the water content is 10%, as the salt content increases from 0.18% to 12.18%, ECa increases by 1.47 mS · cm-1, representing an increase of 864.71%; when the salt content is 6.18% and the water content is 10%, as the particle size increases from <0.075 mm to 1~2 mm, ECa increases by 0.36 mS · cm-1, representing an increase of 38.71%. (2) By establishing a relational model among ECa, water content, and salt content, it was found that under higher water content conditions (>15%), the correlation between ECa and salt content (P<0.05) is more significant than under lower water content conditions ($ $15%) (P>0.05). Specifically, when the water content is 10% and 20% respectively, and the salt content increases from 3.18% to 12.18%, the ECa increases by 56.41% and 128.91% respectively, indicating that the sensitivity of salt to ECa under high water content conditions is significantly greater than under low water content conditions. (3) Through the application of grey relational analysis, the average grey relational degree between ECa and water content was found to be 0.80, while that between ECa and salt content was 0.68, indicating that when water content ranges from 5% to 25% and salt content ranges from 0.18% to 12.18%, the consistency of development trend between ECa and water content is higher than that with salt content. These research findings provide valuable reference for evaluating the electrical conductivity characteristics and salinization degree of sulfate saline soils.

Full Text

Study on the Relationship Between Apparent Electrical Conductivity of Sulfate Saline Soil and Moisture, Salt Content, and Particle Size

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Abstract

This study investigated sulfate saline soil in the Xiaoxigou watershed of the Beishan area in the Xining Basin. Five groups of soil samples with different particle sizes (<0.075 mm, 0.075-0.1 mm, 0.1-0.25 mm, 0.25-0.5 mm, 0.5-1 mm, and 1-2 mm) were obtained through screening tests. The apparent electrical conductivity (EC) of these samples was measured under varying moisture contents, salt contents (Na_2SO_4), and particle sizes. The relationships between EC and moisture content, salt content, and particle size were analyzed, and the grey correlation degree was calculated using grey correlation analysis. The results demonstrated that EC increased consistently with rising moisture content, salt content, and particle size. For instance, when the particle size was 0.075-0.1 mm, the salt content was 0.64%, and moisture content increased from 5% to 25%, EC increased by 0.99 $mS \cdot cm^{-1}$, representing a 2475% 增幅. When establishing the relationship model between EC , moisture content, and salt content, it was found that under higher moisture content conditions (>15%), the correlation between EC and salt content ($P<0.05$) was significantly stronger than under low moisture content conditions (<15%) ($P>0.05$). Specifically, when moisture content was 10% and 20%, and salt content increased from 3.18% to 12.18%, EC increased by 56.41% and 128.91%, respectively. This indicates that salt sensitivity to EC under high moisture content conditions was significantly greater than under low moisture content conditions. Grey correlation analysis revealed that the average grey correlation degree between EC and moisture content was 0.80, while that between EC and salt content was 0.68. This demonstrates that

the consistency of development trends between EC and moisture content was higher than that between EC and salt content when moisture content ranged from 5% to 25% and salt content ranged from 0.18% to 12.18%. These findings provide valuable reference for evaluating the electrical conductivity characteristics and salinization degree of sulfate saline soils.

Keywords: sulfate saline soil; apparent electrical conductivity; water content; salt content; particle size; grey correlation

1. Introduction

Saline soil is a globally distributed soil type comprising salt-affected soils, alkaline soils, and various salinized and alkalized soils. Soil salinization represents a major environmental risk arising from natural factors (climate, geology, geomorphology, hydrology) and anthropogenic factors (unreasonable human activities in transforming and adapting to nature). Considered one of the world' s most pressing ecological and environmental issues, soil salinization is a primary environmental constraint on global agricultural productivity. Rapid, stable, and accurate determination of soil salt content, analysis of salt distribution and salinization degree, and subsequent evaluation of soil physicochemical properties and engineering geological characteristics have become critical challenges in geological survey work.

Soil electrical conductivity directly reflects the content of mixed salts and serves as an important indicator for measuring soil salinization degree, evaluating soil engineering geological characteristics, and assessing crop yield. The electrical conductivity method, as a rapid and stable approach for determining the spatiotemporal distribution characteristics of soil salinity, has been widely applied in engineering investigation and saline soil research.

Numerous studies on soil electrical conductivity have been conducted worldwide. Kurtuluş et al. investigated the variation characteristics of electrical conductivity of soils along the Izmit road in Istanbul, Turkey, under different moisture conditions and established a soil moisture content calculation model based on electrical conductivity, demonstrating a linear positive correlation between electrical conductivity and moisture content. Luo et al. studied the relationship between electrical conductivity and moisture content of Hangzhou silty soil, noting that total soil electrical conductivity varied approximately linearly with real-time moisture content. Chen et al. examined the relationship between electrical conductivity of saturated sandy soil and pore water, indicating that with constant pore water electrical conductivity, increasing soil porosity led to increased electrical conductivity. Brevik et al. conducted in-situ tests on soil electrical conductivity at different points on the Iowa State University Agricultural Farm, revealing a linear functional increase in electrical conductivity with moisture content, with a goodness-of-fit R^2 reaching 0.84. Other studies have shown that soil electrical conductivity increases continuously with salt content, with higher moisture content amplifying the impact of pore water salt content changes on electrical conductivity. Zhang et al. investigated the relationship between electrical conductivity and salt content in the Weigan River-Kuqa River delta oasis on the southern foothills of the Tianshan Mountains in Xinjiang, reporting a high correlation coefficient of 0.96, reaching an extremely significant level. Serrano et al. tested apparent soil electrical conductivity (EC) on a farm in southern Portugal, demonstrating significant positive correlations with clay, silt content, and moisture content. Usha et al. examined soil electrical conductivity variation characteristics in fields along the Noyyal River in India, noting that soil electrical conductivity decreased continuously with increasing pH. Zheng et al. tested soil electrical conductivity at different depths in the experimental field of the Xinjiang Production and Construction Corps First Division Alar National Agricultural Science and Technology Park, finding that electrical conductivity gradually decreased with increasing soil depth. Guo et al. tested electrical conductivity of typical earthen site soils in northwest China, indicating that water solution electrical conductivity had a greater overall influence than soil particles.

Comprehensive analysis of existing research reveals that soil electrical conductivity exhibits significant correlations with moisture content, salt content, porosity, pH value, and sampling depth. However, no studies have examined the relationship between soil electrical conductivity and soil particle gradation, despite different particle size groups exhibiting varying permeability and porosity, which leads to significant differences in water infiltration velocity, diffusion degree, and filling degree within the soil. Moreover, existing research has primarily revealed the mutual variation relationships between soil electrical conductivity and influencing factors, without statistically analyzing the degree of influence of these factors on soil electrical conductivity. To address these research gaps, this study tested EC of soil samples with different moisture contents, salt contents, and particle sizes, analyzed the correlations between EC and moisture, salt, and particle size, and employed grey correlation analysis to evaluate the grey correlation degree between EC and moisture content and salt content. The objective was to evaluate soil salinization degree, physicochemical properties, and engineering geological characteristics through soil testing.

1.1 Study Area Overview

The study area is located in the central part of the Huangshui Valley in the northeastern Qinghai-Tibet Plateau, within the Xining Basin. Influenced by the Qinghai-Tibet Plateau, the region features a unique geographical environment. The climate is a cold semi-arid plateau continental climate, with an average annual temperature of 5.6°C, average annual precipitation of 376.3 mm, and evaporation of 1762.8 mm. Precipitation is concentrated between June and September, accounting for 70–80% of annual rainfall, primarily in the form of heavy rain and showers characterized by short duration, high intensity, and concentrated rainfall. The terrain is complex, forming high mountains, middle mountains, low mountains, hills, terraces, and valleys from ridge to valley. Soil texture varies from coarse to fine, with chestnut soil as the zonal soil and loess as the primary parent material. Severe water and soil erosion and numerous gravitational landslides occur in the area. Saline soil is widely distributed, mainly consisting of sulfate and subsulfate saline soils, which exhibit not only loess collapsibility but also salt expansion and corrosiveness. Due to the coupling effects of topography, climate, and the specific geotechnical properties of saline soil, this region has become a disaster-prone area. Testing of soluble salt content in Xining Basin saline soils and review of relevant literature indicate that salt content generally ranges from 0.3% to 5.0%, with soluble salts primarily being sulfates and subsulfates, covering a total area of approximately 5.223$\times10^{6}$ m^2.

1.2 Test Soil

Test soil was collected from a slope in the Xiaoxigou watershed of the Beishan area in the Xining Basin. A 10 m$\times$10*mrectangularareawasselectedontheslope*, *withfivesamplingpointsestab*
kg^{-1}$ and a sulfate ion (SO_4^{2-}) content of 3.18 $g \cdot kg^{-1}$. According to the *Engineering Geology Handbook*, the study area soil is classified as moderately sulfate saline soil. The soil originates from strongly weathered mudstone of the Tertiary parent rock, which after dissolution by groundwater and surface water, is transported downslope by water flow and concentrated through evaporation.

1.3 Electrical Conductivity Testing Instruments

The CD-12 portable salt-electrical conductivity-temperature meter is a conventional analytical instrument for measuring soil electrical conductivity and temperature, with a measurement range of 0–20 $mS \cdot cm^{-1}$. The FJA-10 soil salinity sensor features simple structure, stable performance, fast response time, and convenient operation. Combined use of the CD-12 meter and FJA-10 sensor offers stable electrode performance and high sensitivity, making it an ideal instrument for observing and studying saline soil and water-salt dynamics, as well as for research on saline soil evolution and improvement. When buried in soil, this salinity sensor can directly measure soil electrical conductivity.

1.4 Soil Conduction Mechanism

In soils containing certain moisture, EC is primarily determined by soil solution and salt substances in macropores, and is closely related to soil salinization degree. Three conductive pathways exist within soil: solid-liquid phase series coupling conductive pathway, large-pore water continuous liquid phase conductive pathway, and solid-phase surface conductive pathway. As soil moisture content changes, the dominant conductive pathway also varies. Under low moisture content conditions, water preferentially fills small pores while large pores remain unfilled, making the solid-liquid phase series coupling pathway dominant. As moisture content increases, all three pathways become conductive, with conductive ability decreasing in the order: large-pore water continuous liquid phase pathway > solid-phase surface pathway > solid-liquid phase series coupling pathway. As moisture content further increases toward saturation, buoyancy reduces direct contact between soil particles, making the solid-phase surface pathway negligible, and the large-pore water continuous liquid phase pathway dominates.

1.5 Moisture and Salt Content Gradient Setting Method

The prepared soil samples were divided into equal masses of 300 g to create 150 groups of remolded soil samples with different moisture contents, salt contents, and particle sizes for orthogonal testing. Particle size gradients were determined by sieved particle groups: <0.075 mm, 0.075-0.1 mm, 0.1-0.25 mm, 0.25-0.5 mm, 0.5-1 mm, and 1-2 mm. To ensure accuracy and rationality of salt content gradients, salt washing tests were conducted on original soil samples, yielding soil samples with consistent salt content of 0.18% as the initial gradient. Considering the salinization trend in the area, salt content gradient intervals were set at 0.18%, 3.18%, 6.18%, 9.18%, and 12.18%. The average moisture content of prepared soil samples was 0.64%. Given that precipitation in Xining Basin is concentrated in summer and autumn mainly as heavy rain and showers, resulting in relatively high moisture content in soils within 1.0 m depth, the maximum moisture content was set at 25%, with moisture content gradients of 5%, 10%, 15%, 20%, and 25%. To ensure uniform mixing of soil, water, and salt, prepared samples were sealed and left to stand for 24 hours before electrical conductivity testing. During testing, it is crucial to apply moderate and uniform pressure when inserting the sensor into the soil. The average of three conductivity measurements was taken as the EC value under specific moisture, salt, and particle size conditions. The orthogonal testing process is shown in [Figure 4: see original paper], conducted indoors at a constant temperature of 20°C.

1.6 Grey Correlation Analysis Method

Grey correlation analysis evaluates the degree of association between factors based on the similarity or dissimilarity of their development trends, using "grey correlation degree" as the metric. This multi-factor statistical analysis method uses sample data to describe the strength, magnitude, and order of relationships between factors. If sample data show consistent variation trends (direction, magnitude, and speed) between two factors, their correlation degree is large; otherwise, it is small. This method offers clear logic, significantly reduces losses from information asymmetry, and has low data requirements with minimal workload. To further analyze the influence degree of moisture and salt content on apparent electrical conductivity, grey correlation analysis was employed with moisture and salt content as impact factors to calculate the correlation degree between EC and each factor, thereby determining their influence degree on soil apparent electrical conductivity.

The calculation method is as follows:

1) **Reference and comparison sequences**:
Let reference sequence $X_0 = \{X_0(1), X_0(2), \cdots, X_0(n)\}$ represent soil apparent electrical conductivity data; let comparison sequences X = {X (1), X (2), ···, X (n)} (i = 1, 2, ···, m) represent soil salt content and moisture content data sequences, where n is the number of data points in each sequence.

2) **Dimensionless data processing**:
Since reference and comparison sequences have different dimensions and magnitudes, mean standardization was applied for dimensionless processing:

$$X'_{ik} = \frac{X_{ik}}{\bar{X}_i}$$

where X' is the dimensionless value of the k-th data point in the i-th sequence; X is the original value; and $\bar{X}_i$ is the mean of the i-th sequence.

3) **Correlation coefficient calculation**:
The correlation coefficient reflects the association degree between each value of reference and comparison sequences:

$$\zeta_{oi}(k) = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_{oi}(k) + \rho\Delta_{\max}}$$

where Δ (k) is the absolute difference between reference and comparison sequences; Δ and Δ are the minimum and maximum absolute differences; and is the resolution coefficient (typically 0.5).

4) **Correlation degree calculation**:
The correlation degree is the average of all correlation coefficients:

$$\gamma_{oi} = \frac{1}{n}\sum_{k=1}^{n}\zeta_{oi}(k)$$

where γ is the correlation degree between comparison sequence X and reference sequence X_0.

2. Results

2.1 EC Test Results Under Different Moisture Content and Particle Size Conditions

The three-dimensional relationship curve between EC , moisture content, and particle size (at 0.64% salt content) shows that under the same particle size, EC continuously increased with moisture content. When particle size increased from <0.075 mm to 1-2 mm and moisture content rose from 5% to 25%, EC increased from 0.03 mS·cm^{-1} to 0.97 mS·cm^{-1}, a 733.33% 增幅. Comparing EC

增幅 under different particle sizes and moisture contents revealed that moisture content had a more significant effect on EC than particle size. presents EC values under different moisture content and particle size conditions.

The fitting equations between EC and moisture content under different particle sizes () show a power function positive correlation with goodness-of-fit $R^2 = 0.9559–0.9900$ and significance coefficient $P < 0.05$, indicating extremely significant correlation and strong interaction. This result aligns with Xu et al.' s study on loess electrical conductivity in the Changlinggou area of Xining Basin, which also found a power function positive correlation. While Luo et al. found a linear positive correlation for Hangzhou silty soil and Brevik et al. reported linear relationships for Iowa State University farm soils, these differences suggest that functional relationships between soil electrical conductivity and moisture content vary by region and soil type.

Under the same moisture content, EC also increased with particle size. When moisture content was 0.64% and particle size increased from <0.075 mm to 1-2 mm, EC rose from 0.03 mS $\cdot$ cm^{-1} to 0.97 mS $\cdot$ cm^{-1}, a 27.63% 增幅. This occurs because larger particles have greater porosity and permeability, allowing more uniform water diffusion and faster infiltration, resulting in higher EC under identical moisture and infiltration conditions.

2.2 EC Test Results Under Different Salt Content and Particle Size Conditions

The three-dimensional relationship curve between EC , salt content, and particle size (at 0.64% moisture content) demonstrates that under the same particle size, EC continuously increased with salt content. When particle size was <0.075 mm and salt content increased from 0.18% to 12.18%, EC rose from 0.16 mS $\cdot$ cm^{-1} to 1.57 mS $\cdot$ cm^{-1}, an 881.25% 增幅. Under the same salt content, EC also increased with particle size. For example, at 0.18% salt content, EC increased from 0.16 mS $\cdot$ cm^{-1} to 0.24 mS $\cdot$ cm^{-1} as particle size increased.

Notably, when particle size was constant, the EC 增幅 was relatively small when salt content increased from 0.18% to 3.18% but decreased during subsequent salt content increases. For example, at <0.075 mm particle size, the 增幅 was 443.8% when salt content increased from 0.18% to 3.18%, but only 6.90% from 3.18% to 6.18%. This occurs because at low salt content, less salt dissolves, producing fewer conductive ions. When salt content suddenly increases, more salt dissolves, sharply increasing conductive ions. However, as salt content continues increasing toward solubility limits, some salt remains solid and does not significantly enhance EC .

Fitting equations between EC and salt content under different particle sizes () show a quadratic function positive correlation. Comparison of fitting equations across six particle sizes reveals that as particle size increased, goodness-of-fit improved from 0.8232 to 0.9133 and significance coefficients decreased from 0.0046 to 0.0235, indicating stronger correlation between electrical conductivity and salt content in larger particle soils. This suggests that larger pores and higher connectivity in coarse soils enable more uniform water-salt mixing, dissolving more salt and producing more conductive ions.

2.3 EC Test Results Under Different Moisture and Salt Content Conditions

The three-dimensional relationship curve between EC , moisture content, and salt content shows that EC continuously increased with both moisture and salt content. When salt content and moisture content were 0.18% and 5%, respectively, EC was 0.06 $mS \cdot cm^{-1}$; when they were 12.18% and 25%, EC reached 17.05 $mS \cdot cm^{-1}$, a 16.99 $mS \cdot cm^{-1}$ 增幅. Higher moisture content amplified the effect of salt content changes on soil electrical conductivity. Corwin et al. found that larger pores between clay particles are connected by continuous gravitational water, which further dissolves soil salts, rapidly increasing soil electrical conductivity. According to Friedman, soil electrical conductivity is proportional to ion concentration and mobility. Therefore, as moisture content increases, salt ion movement and migration produce more continuous conductive films in pore fluids, enhancing EC .

Fitting equations between EC and moisture content under different salt contents () show a power function relationship with goodness-of-fit of 0.9710–0.9945 and significance levels <0.05, demonstrating excellent correlation. Fitting equations between EC and salt content under different moisture contents () show a quadratic function relationship with significant differences in significance levels: when moisture content was 5%, 10%, and 15%, significance levels were 0.05, 0.01, and 0.001, respectively; when moisture content was 20% and 25%, significance levels were both 0.0001. This indicates that under high moisture content conditions, the correlation between EC and salt content was significantly higher than under low moisture content conditions, demonstrating that high moisture content also increases EC sensitivity to salt content.

2.4 Grey Correlation Degree Between EC and Salt Content/Moisture Content

The grey correlation degree between EC and moisture content under different salt content conditions was 0.771–0.833 (). The highest correlation (0.833) occurred at 9.18% salt content, indicating the strongest consistency in development trends between soil electrical conductivity and moisture content under this condition. At 3.18% salt content, the correlation degree was relatively lower but still reached 0.771, maintaining high correlation.

The grey correlation degree between EC and salt content under different moisture content conditions was 0.565–0.745 (), showing a trend of initial increase followed by decrease. The minimum value (0.565) occurred at 0.64% moisture content, indicating relatively low correlation between EC and salt content under low moisture content conditions.

Comprehensive comparison shows that the average grey correlation degree between EC and moisture content (0.80) was higher than that between EC and salt content (0.68). This indicates that EC correlates more significantly with moisture content than with salt content, and the development trend consistency between EC and moisture is more pronounced than that with salt (Na_2SO_4).

3. Conclusions

1) When moisture content increased from 5% to 25%, EC of six groups of soil samples with different particle sizes showed a power function positive correlation with moisture content, with equation goodness-of-fit $R^2 = 0.9559$–0.9900 and significance coefficient $P < 0.05$, indicating extremely strong interaction and correlation between soil apparent electrical conductivity and moisture content.

2) When salt content increased from 0.18% to 12.18%, EC of six groups of soil samples with different particle sizes showed a quadratic function positive correlation with salt content, with equation goodness-of-fit $R^2 = 0.8232$–0.9133 and significance coefficient $P < 0.05$, indicating strong interaction and correlation between soil apparent electrical conductivity and salt content under these moisture conditions.

3) As particle size increased from <0.075 mm to 1-2 mm, soil apparent electrical conductivity also increased continuously, but particle size-induced changes were less significant than those caused by moisture and salt content, indicating that particle size has a weaker influence on soil apparent electrical conductivity than moisture and salt content.

4) Analysis of soil apparent electrical conductivity variation characteristics under different moisture and salt content conditions revealed that higher moisture content amplified the impact of salt content changes on soil electrical conductivity. For example, when moisture content was 0.18% and 25% and salt content increased from 5% to 25%, electrical conductivity increased by 0.58 $mS \cdot cm^{-1}$ and 15.94 $mS \cdot cm^{-1}$, respectively. Grey correlation analysis showed that the average correlation degree between soil apparent electrical conductivity and moisture content was 0.80, while that with salt content was 0.68, demonstrating that the development trend consistency between soil apparent electrical conductivity and moisture content is significantly stronger than that with salt content.

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