Experimental Study on Water-Salt Migration of Fine Saline Soils under Different Water-Isolation Condition

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Abstract. In the alluvial plain area of the Ush Talar River, there is a widespread distribution of fine saline soils. Due to the special properties of fine saline soils, they are highly prone to issues such as salt heaving, thaw settlement, and mud pumping, which often cause harm to engineering structures. Water-salt migration is a key process that leads to changes in the physical and chemical properties of saline soils and is a major cause of the damage that occurs in these soils. To analyze the impact of different control measures on water-salt migration, this study conducted water-salt migration column experiments under different water-isolation conditions. The results show that the rate of increase in water-salt content in the middle of the treated soil columns was significantly lower than that in the control group. During the experimental period, the highest salt content in the middle of the control group soil column was 1169 mg/L, and the water content was 11.3%. The use of aeolian sand replacement and the installation of a "two fabrics and one membrane" isolation layer reduced the salt content by 47.7% and 70.4%, and the water content by 33.6% and 48.7%, respectively. These results indicate that both isolation conditions effectively inhibit water-salt migration in fine saline soils, with the isolation layer proving to be more effective. This study provides reference and theoretical data support for practical engineering and soil salinization prevention projects.

Keywords: Saline soil; Water and salt migration; Aeolian sand replacement; Geotextile partition

1 Introduction

Saline soils are widely distributed in coastal areas and the northwest inland regions of China. In the arid areas of northwest inland China, saline soils account for about 60% of the total saline soil area in the country. The distribution of saline soils in Xinjiang is extensive. Existing research shows that salts can reduce the strength of rocks or soils [1-2]. Moreover, due to the effects of temperature and moisture, salts migrate to the surface with water, forming salt efflorescence, which causes significant damage to surface structures, especially roads. Engineering projects often face challenges such as

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dissolution, salt efflorescence, and corrosion [3]. To mitigate the damage caused by water-salt migration in saline soils, numerous studies have been conducted both domestically and internationally. Richard [4] was the first to analyze water-salt migration in soils from the perspectives of dynamics and mass-energy conservation. Subsequent studies on water-salt migration in saline soils have been largely based on this approach. Wen [5] developed an improved mathematical model of water-heat-gas-salt by considering factors such as salt's effect on soil particle surface tension and the filling effect of salt particles. Shokri-Kuehni [6] conducted evaporation experiments using soil columns to study the impact of external factors, such as temperature, and salt types on the salt precipitation on sandy media surfaces. Li Penglin [7] revealed the water retention and permeability behavior of unsaturated saline soils and made corresponding modifications to water-salt migration models. Xiao Ze'an [8] studied the influence of water-salt phase transitions on the soil matrix suction during cooling and examined the moisture migration driving force during freezing. Wang [9] explored the salt-heaving patterns of sulfate saline soils under different vertical salt distributions. Wang Yaqiang [10] analyzed water-salt migration patterns under different salt replenishment sources using indoor soil column experiments. Zhou Fengxi [11] established a fully coupled multi-field mathematical model of unsaturated saline soils under temperature gradients, considering factors like pore evolution, salt phase changes, and moisture infiltration.

From the above studies, it can be seen that most scholars conduct research by establishing water-salt migration models. However, due to the unique regional geology, hydrogeology, and climate characteristics in southern Xinjiang, there has yet to be systematic research on the improvement of fine-grained saline soils in Xinjiang. Therefore, this paper sets different water isolation conditions to simulate various improvement measures in actual engineering projects, exploring the water-salt migration patterns and filling the research gap in the field of fine-grained saline soil improvement and treatment technologies in Xinjiang.

2 Engineering Overview

Due to the special engineering properties of saline soils, water-salt migration leads to a dissolution-crystallization cycle of salts within the soil. Consequently, roads built in saline soil areas often suffer from issues such as salt heaving, mud pumping, leaching, wet collapse, and corrosion, which severely affect the quality and service life of road infrastructure, thereby restricting regional economic development.

Based on the typical saline soils found in the alluvial plain of the Ushtara River (Figure 1), phenomena such as the visible white salt crust on the surface and the thick loose surface soil in dry areas are observed. These soils are primarily fine-grained and contain a large amount of Na2SO4. The area is located deep within the inland arid zone, characterized by a temperate continental semi-arid to arid climate. The evaporation rate greatly exceeds the precipitation, and the salt in the groundwater continually migrates to the surface due to evaporation, leading to a dissolution-crystallization cycle of salts in the soil. This process causes further thaw settlement and salt heaving, which result in significant damage to roads, such as swelling and cracking of the subgrade and pavement, erosion of shoulder slopes, aggravated frost heaving, and mud pumping. When exposed to water, the strength of the roadbed dramatically decreases, leading to subsidence and deformation. Therefore, this paper primarily investigates the water-salt migration patterns under the influence of groundwater recharge by conducting column soil water-salt migration experiments. The column soil water-salt migration experiment not only allows for intuitive observation of the water-salt migration paths, but also enables monitoring of water-salt content at different positions using sensors, thereby analyzing the dynamic changes in water-salt migration. Additionally, by setting different water isolation conditions in the soil columns, the paper explores the inhibitory effects of various prevention and control measures on water-salt migration, providing references and theoretical data support for practical engineering and soil salinization prevention projects.

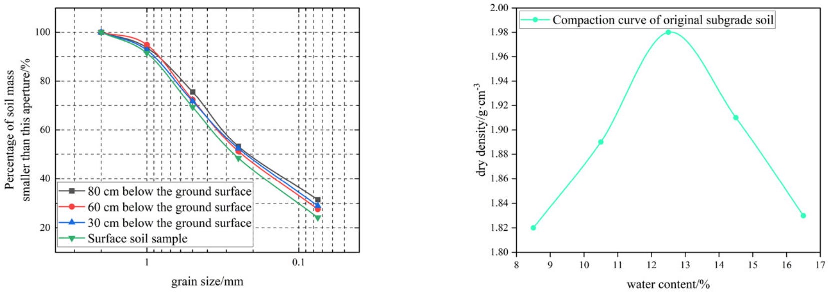
(a) Saline soil samples (b) Ushtara River floodplain

Fig. 1. Saline soils of the Ushtara River floodplain.

3 Water-Salt Migration Experiment

3.1 Experimental Materials

In order to ensure that the experimental conditions align with the actual engineering conditions, the materials for the experiment were directly obtained from the construction site. For the original subgrade soil, samples were taken from a depth of 80 cm below the surface to represent the actual soil conditions of the subgrade. According to the on-site test results, the initial moisture content of the original subgrade soil was 17.44%, and the dry density and particle gradation are shown in the Figure 2.



(a) Original roadbed particle size distribution

(b) Original roadbed compaction curve

Fig. 2. Physical properties of original roadbed soil.

3.2 Experimental Scheme

The experimental plan uses a column soil water-salt migration test. To facilitate the observation of water-salt migration paths, the soil column device is made of an acrylic transparent tube with an inner diameter of 200mm, wall thickness of 5mm, and length of 800mm. The bottom of the cylindrical tube is sealed with an acrylic plate, and a ring of small holes is created around the bottom to simulate the groundwater and salt supply in actual engineering projects. Holes are made every 100 mm along the height of the soil column to place sensors for data collection. Data collection utilizes an eight-in-one soil sensor that can monitor salt content, moisture, and temperature in real-time. The layout is shown in the Figure 3. To investigate the effects of different control measures on water-salt migration, the experiment is divided into three groups, as illustrated. Group 1 consists of 40 cm of original subgrade soil, 10 cm of wind-blown sand, and 30 cm of natural gravel; Group 2, the reference group, consists of 50 cm of original subgrade soil and 30 cm of natural gravel; Group 3 consists of 50 cm of original subgrade soil, 15 cm of natural gravel, a layer of geotextile, and an additional 15 cm of natural gravel on top. To control for variables and ensure the experimental effect, all other experimental conditions were kept consistent.

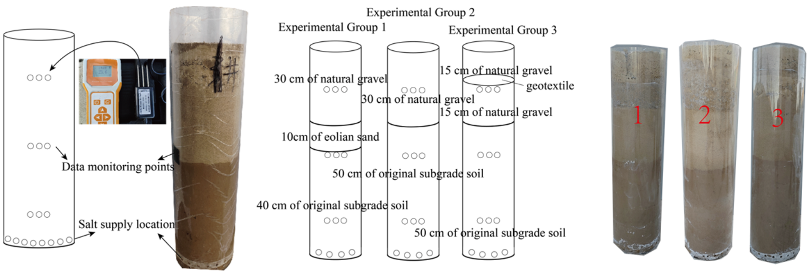


Fig. 3. Wate-salt migration experiment.

3.2.1 Material Preparation and Treatment

The soils needed for the soil column were all excavated from the site to ensure consistency with the actual engineering conditions. The excavated samples were sealed and stored to prevent moisture evaporation and salt loss. A 3% sodium sulfate solution was prepared according to the experimental requirements to simulate the groundwater supply.

3.2.2 Soil Column Filling and Compaction

The soil column was filled using a layered compaction method, with a 5 cm height for each layer. After filling each layer, a compaction tool was used to ensure that the compaction degree reached 95%. To enhance continuity between layers, the surface of each layer was roughened after compaction to eliminate interlayer effects and ensure that water and salt migration in the soil column was not affected by discontinuities between layers.

3.2.3 Data Collection and Recording

During the experiment, temperature, salt content, and moisture data were collected every 24 hours. The collection points were arranged at 100 mm intervals along the height of the soil column. Data were collected using the eight-in-one soil sensor to ensure the accuracy and reliability of the monitoring data. The entire experiment lasted for 28 days to obtain complete dynamic data on water-salt migration.

3.3 Results and Discussion

Due to the unique climate in the Xinjiang region, where the annual evaporation rate is much higher than the annual precipitation, the dry and arid environmental characteristics had a significant impact on the experiment. During the experiment, due to the dry air, a strong evaporation of moisture was observed at the top of the soil column. Additionally, salt migrated along with the water, and thus, as moisture evaporated and migrated, salts redistributed within the soil column. The real-time monitoring with high-precision sensors and visual observations allowed for the clear capture of dynamic processes of moisture and salt migration within the soil column, including moisture evaporation, salt crystallization, and concentration changes.

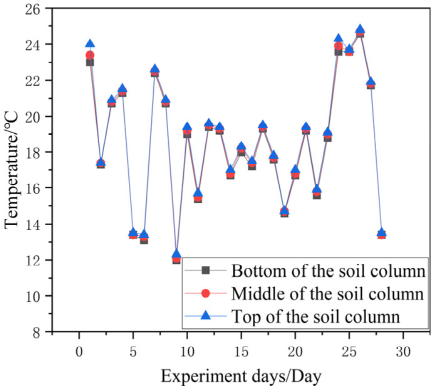
In the early stages of the experiment, due to the small diameter of the soil column, the rate of moisture evaporation from the surface was slow, making it difficult to observe noticeable changes in moisture or salt crystallization by eye. To simulate the effect of groundwater on water-salt migration in soil, a continuous supply of salt and moisture was provided at the bottom of the soil column. The real-time monitoring data from high-precision sensors showed that the moisture and salt content at the bottom gradually increased. Under the influence of capillary action and the water potential gradient, moisture migrated upward from the bottom, and salt accumulated with the movement of the moisture.

Around the 10th day of the experiment, a clear upward migration of moisture was observed along the sides of the soil column due to capillary forces. Moisture gradually moved from the bottom to the top, forming a distinct moisture migration front. Although the moisture migration phenomenon was evident, no noticeable salt crystallization was observed along the column's sides. This may be due to the high solubility of sulfate salts, which had not yet reached the saturation point for precipitation.

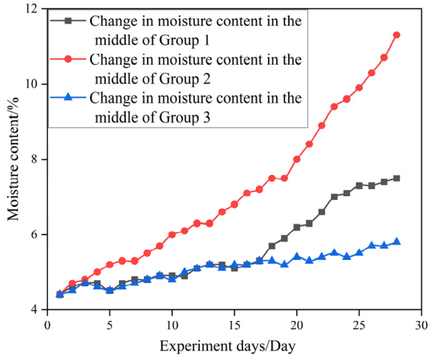
In the later stages of the experiment, due to the water-salt migration control measures in experimental Groups 1 and 3 (wind-blown sand replacement and the addition of a "two cloths, one membrane" barrier layer), moisture migration was significantly restricted. Specifically, a distinct barrier effect was formed under the geotextile layer, preventing further upward migration of moisture and creating a "lid effect," where moisture accumulated below the barrier and could not continue migrating upward. At the same time, white crystalline substances appeared on the surface of the soil columns without the "two cloths, one membrane" barrier layer, indicating that salts had precipitated and crystallized on the surface as a result of moisture evaporation.

Figure 4 shows the temperature, moisture content, and salt content inside the soil columns under replenishment conditions, as monitored by the high-precision sensors. As shown in Figure 4(a), throughout the experiment, the temperature was highest at the top of the soil column, lower in the middle, and lowest at the bottom. The overall temperature fluctuated within a range of 12–24.8°C, with an average temperature of 18.5°C, influenced by weather conditions, but tended to stabilize over time. The moisture content in the middle of the soil columns showed a steady increase, with Group 2's moisture content rising the fastest. Groups 1 and 3 exhibited similar moisture increase rates during the earlier and middle stages, but in the later stages, Group 1 had a faster rate than Group 3, indicating that the wind-blown sand replacement and the addition of geotextile isolation layers effectively inhibited water-salt migration in the soil. Due to the isolation effect of the geotextile, moisture in Group 3 was unable to migrate effectively to the upper parts of the soil column. During the experimental period, the highest moisture content in the control group soil column was 11.3%. The replacement with aeolian sand and the setting of the "two fabrics and one membrane" barrier layer reduced the moisture content by 33.6% and 48.7%, respectively, effectively blocking the transfer of moisture within the soil column.

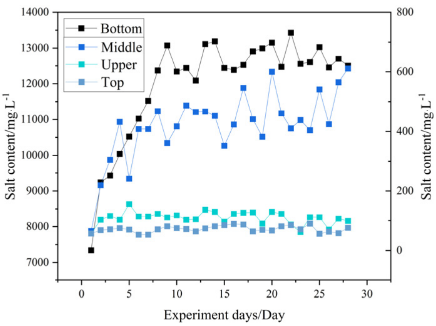
Comparing the salt content across the three experimental groups, the salt content at the top of the soil columns in all groups remained low. Since no control measures were applied in Group 2, the salt content was significantly higher than in the other groups, with the salt content in the middle of Group 2 increasing rapidly throughout the experimental period. In the other experimental groups, the salt content followed a similar trend to the moisture content, rising during the early and middle stages before stabilizing. The salt content at the bottom of the soil column, due to its direct contact with simulated groundwater, was much higher than at other levels. During the experimental period, the highest salt content in the control group soil column was 1169 mg/L. The replacement with aeolian sand and the setting of the "two fabrics and one membrane" barrier layer reduced the salt content by 47.7% and 70.4%, respectively, effectively blocking the transfer of salt within the soil column.



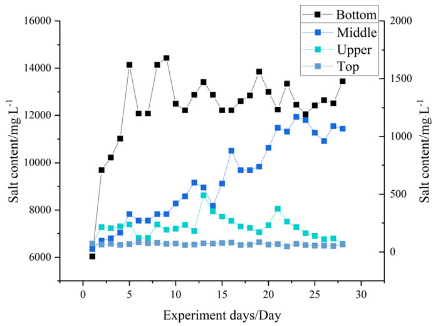
(a) Soil temperature



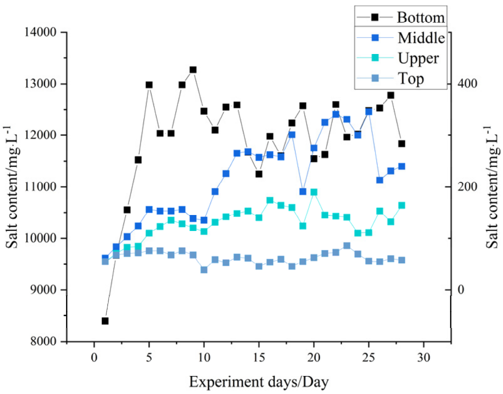
(b) Moisture content in the middle of the soil column



(c) Salt content of group 1



(d) Salt content of group 2



(e) Salt content of group 3

Fig. 4. Changes of water, heat and salt in saline soil under different prevention and control measures.

4 Conclusion

Using the saline soil in the Ushitala River alluvial plain area as an example, soil column experiments on water and salt migration were conducted to analyze the effects of different control measures on the migration path and parameters of water and salt migration under groundwater recharge. The conclusions are as follows:

(1) The soil column experiment on water and salt migration directly shows that the wind-blown sand replacement and the "two fabrics and one membrane" isolation layer both effectively inhibited the water and salt migration in the saline soil.

(2) In the early stage of the experiment, no significant changes in moisture or salt crystallization were observed. Around the 10th day, clear observations of moisture migrating upward due to capillary action were made on the sidewall of the soil column, but no obvious salt crystallization was seen. In the later stage of the experiment, a white frosty substance appeared on the surface of the soil column, indicating the occurrence of crystallization. Monitoring data indicated that, due to the effects of the windblown sand and the "two fabrics and one membrane" barrier layer, moisture migration was significantly suppressed throughout the experiment. During the experimental period, the highest moisture content in the middle of the control group soil column was 11.3%, and the use of windblown sand and the "two fabrics and one membrane" barrier layer reduced the moisture content by 33.6% and 48.7%, respectively. Additionally, the surface of the soil column in Group 3, with the "two fabrics and one membrane" installed, showed almost no detectable salt presence. The highest salt content in the middle of the control group soil column was 1169 mg/L, and the windblown sand and the "two fabrics and one membrane" barrier layer reduced the salt content by 47.7% and 70.4%, effectively blocking the migration of salt.

Through experimental comparison and analysis, it was found that both prevention and control measures can effectively block water-salt migration in saline soils. By utilizing the physical barrier effect generated by aeolian sand and the barrier layer, water-salt migration is effectively suppressed, providing references and theoretical data support for practical engineering and soil salinization prevention projects.

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