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## Abstract

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# Laboratory soil-column investigation of thermo-hydro-saline migration in saline soil with sand replacement layers under evaporation

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**Abstract:** In arid regions, saline subgrades are highly susceptible to deterioration caused by evaporation-driven water-salt migration, which can induce salt accumulation, cracking, and long-term loss of stability. To investigate the role of sand replacement layers in regulating thermo-hydro-saline (THS) migration under evaporation, we conducted indoor soil-column experiments in combination with microstructural observations. The effects of sand type (coarse, medium, and fine sand) and replacement ratio (0.00%, 20.00%, 35.00%, and 50.00%) were systematically examined under simulated high-temperature and strong-evaporation conditions typical of northwestern China, with continuous monitoring of temperature, relative humidity (RH), and electrical conductivity (EC). The results show that sand replacement effectively inhibited capillary rise, reduced surface salt accumulation, and alleviated shrinkage cracking. Among the tested sand types, coarse sand exhibited the strongest inhibitory effect on upward water-salt migration, whereas fine sand showed the weakest effect because its smaller pores and stronger capillary continuity facilitated upward water-salt migration. Under the medium sand condition, increasing the replacement ratio was associated with stronger suppression of surface salt accumulation, with the 50.00% replacement ratio showing the strongest effect. However, the influence of replacement ratio was not monotonic across all response indicators. A replacement ratio of approximately 35.00% maintained relatively continuous pathways for heat and moisture transfer, whereas higher replacement ratios produced a looser soil skeleton and weaker capillary continuity. Microstructural observations further revealed that salt crystals mainly accumulated near the evaporation front and the lower replenishment zone, while coarse sand tended to form larger pores and reduce matric suction, thereby disrupting upward migration pathways. These findings provide a theoretical basis and technical support for optimizing saline subgrade design and mitigating salt-related damage in arid regions.

**Keywords:** saline soil; sand replacement layers; thermo-hydro-saline (THS) migration; evaporation; microstructural analysis

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## 1 Introduction

Soil salinization is a widespread environmental and geotechnical problem, affecting approximately 7.00% of the global land surface (Cho et al., 2010). Saline soils are extensively distributed in arid and semi-arid regions and, in China, are particularly concentrated in the northwest, accounting for 69.03% of the country' s total saline-soil area (Li et al., 2009). Under arid climatic conditions characterized by intense evaporation and limited precipitation, saline subgrades are highly susceptible to deterioration, including softening, salt-induced heave, and loss of bearing capacity, all of which seriously threaten the long-term performance of transportation infrastructure (Li et al., 2023; Chou et al., 2024). In such environments, evaporation-driven upward migration of saline pore water, followed by near-surface salt accumulation, is widely recognized as the principal process responsible for mechanical degradation and surface distress in subgrade soils (Bayomy et al., 1996; Teng et al., 2019; Zhang et al., 2019; Gao et al., 2025).

Extensive studies have investigated water-salt migration in saline soils through both field observations and laboratory experiments, with particular attention to the effects of soil type, solute type, boundary conditions, groundwater supply, and thermal conditions (Wu et al., 2016). Representative laboratory and model-scale studies have reported evaporation-driven salt accumulation at the roadbed surface (Tian et al., 2019), early-stage salt precipitation and pore-structure evolution affecting coupled moisture and heat transport (Shokri-Kuehni et al., 2017), freeze-thaw effects in saline fills (Li et al., 2019; Wan et al., 2019), and soil-column observations of evaporation-induced migration in loess-type saline soils (Zhang et al., 2025a). In addition, the effects of initial moisture content, dry density, and salt concentration on migration behavior under freeze-thaw conditions have been discussed (Xu et al., 2017). Microstructural evidence has also been provided through computed tomography (CT)-based mapping of salt crystals (Nachshon et al., 2018) and microscopic characterization of pore structure and salt crystallization under thermo-hydro-saline (THS) coupling conditions (Zhang et al., 2022).

In parallel with these mechanistic studies, various mitigation strategies have been proposed for saline subgrades, including densification, reinforcement, increased embankment height, isolation layers, and soil replacement techniques (Yang et al., 2011; Wang, 2017; You et al., 2022; Qiu et al., 2025; Zhao et al., 2025). Among these approaches, sand replacement is considered particularly attractive because of its wide material availability, ease of construction, and potential to regulate pore structure and capillary water movement. Several laboratory and model studies have demonstrated its effectiveness under different configurations, including aeolian sand substitution (Mao et al., 2025), model tests conducted in the Hexi Corridor focusing on microscale degradation mechanisms (Li et al., 2024), and loess-sand replacement layers with different mixing ratios (Yang et al., 2023).

However, despite these advances, two important issues regarding sand replacement layers in saline subgrades remain insufficiently addressed. First, most existing studies have focused either on undisturbed saline soils or on case-specific improvement schemes, whereas systematic comparisons that jointly consider sand type and replacement ratio under evaporation-driven THS migration remain limited. Second, the microstructural mechanisms by which sand replacement modifies migration behavior, including changes in pore structure, hydraulic continuity, and salt-crystal distribution, have not yet been fully clarified, particularly across different sand gradations and replacement ratios. To address these gaps, this study conducted laboratory soil-column experiments under top-heating evaporation conditions to investigate the effects of sand type and replacement ratio on THS migration in saline soil subgrades. Surface cracking and salt crystallization were documented, while temperature, relative humidity (RH), and electrical conductivity (EC) were continuously monitored at different depths. Microstructural observations were further carried out to interpret pore-structure evolution and salt-crystal morphology. The results provide experimental evidence and theoretical support for optimizing the design of sand replacement layers and mitigating salt-related damage in saline soil subgrades in arid regions.

## 2 Materials and methods

### 2.1 Experimental materials

The soil materials used in this study included saline soil and natural sand. As shown in Figure 1, the saline soil was collected from a representative saline-alkali area in Qinghai Province, China. The saline soil was obtained using a disturbed bulk sampling method. Before sampling, the loose surface layer, plant residues, and visible impurities were removed. Several sub-samples were collected from the exposed saline soil layer around the selected sampling point using a shovel, mixed thoroughly on site to reduce local heterogeneity, and then sealed in plastic bags for transportation to the laboratory. After sampling, the soil was oven-dried, crushed, and manually cleaned to remove visible impurities. In accordance with the Highway Geotechnical Test Procedures (JTG 3430-2020), a particle-size distribution test was conducted on the saline soil, and the results are presented in Figure 2 (Ministry of Transport of the People' s Republic of China, 2021). The test results indicate that the saline soil had a coefficient of uniformity ($C_u$) of 3.06 and a coefficient of curvature ($C_c$) of 1.36, both of which satisfy the relevant specification requirements. This particle-size distribution suggests that the soil possesses favorable compaction characteristics and relatively stable permeability. The basic physical properties of the saline soil are summarized in Table 1.

The natural sand was obtained from a sand and gravel plant in Qinghai Province. After natural air-drying, impurity removal, and sieving, the sand was classified into three particle-size groups: coarse sand (0.50000–1.00000 mm), medium sand (0.25000–0.50000 mm), and fine sand (0.10000–0.25000 mm). The basic physical properties of each sand sample are summarized in Table 2.

**Fig. 1** Sampling location of the experimental soil

### 2.2 Experimental apparatus

Figure 3 presents the schematic configuration and photographs of the indoor water-salt migration experiment. The experimental system was custom-designed and assembled, comprising an acrylic soil column, a Mariotte bottle water-supply system, a data acquisition system, an infrared lamp heating device, and an intelligent microscope. The acrylic soil column had a height of 35.0 cm, an inner diameter of 20.0 cm, and a wall thickness of 5.00000 mm. Monitoring ports with a diameter of 2.5 cm were installed at heights of 5.0, 10.0, 15.0, 20.0, 23.0, 26.0, and 29.0 cm above the base of the column to measure soil temperature, RH, and EC. Specifically, the ports were spaced at 5.0 cm intervals between 5.0 and 20.0 cm and at 3.0 cm intervals between 20.0 and 29.0 cm, thereby providing higher spatial resolution in the upper part of the soil column. The water-supply system consisted of Mariotte bottles filled with a 3.00% sodium chloride (NaCl) solution (Shokri-Kuehni

et al., 2017), which was used to simulate continuous groundwater recharge and compensate for water loss induced by evaporation.

*Visible labels in Fig. 2:* Particle size distribution; Cumulative volume fraction; Particle size distribution (%); Cumulative volume fraction (%); Particle diameter (mm); $d_{10} = 0.00017$ mm; $d_{30} = 0.00035$ mm; $d_{60} = 0.00052$ mm; $C_u = 3.06$; $C_c = 1.36$.

**Fig. 2** Particle size distribution of the saline soil. $d_{10}$, $d_{30}$, and $d_{60}$ are the particle diameters corresponding to 10.00%, 30.00%, and 60.00% cumulative volume fractions, respectively; $C_u$, coefficient of uniformity; $C_c$, coefficient of curvature.

**Table 1** Index properties of the saline soil

| Sample type | Optimum moisture content (%) | Maximum dry density (g/cm$^3$) | Minimum dry density (g/cm$^3$) | Liquid limit (%) | Plastic limit (%) | Internal friction angle (°) |
|---|---|---|---|---|---|---|
| Saline soil | 16.20 | 1.54 | 1.27 | 24.10 | 13.90 | 26.13 |

**Table 2** Basic physical properties of river sand

| Sand sample | Particle size range (mm) | Coefficient of curvature ($C_c$) | Coefficient of uniformity ($C_u$) | Maximum dry density (g/cm$^3$) | Minimum dry density (g/cm$^3$) |
|---|---|---|---|---|---|
| Coarse sand | 0.50000–1.00000 | 2.23 | 4.48 | 1.92 | 1.50 |
| Medium sand | 0.25000–0.50000 | 1.62 | 3.06 | 1.85 | 1.44 |
| Fine sand | 0.10000–0.25000 | 1.35 | 2.54 | 1.76 | 1.32 |

*Visible labels in Fig. 3:* (a) Mariotte bottle; Infrared lamp; Acrylic soil column; Data logger; Plain soil; Replacement fill; 10.0 cm; 20.0 cm; 3.0 cm; 5.0 cm. (b)

**Fig. 3** Schematic diagram (a) and photograph (b) of the water-salt migration test

The data acquisition system was equipped with a YY-1000 three-in-one sensor (Shandong Jianda Renke Electronic Technology Co., Ltd., Jinan, China) for measuring soil temperature, RH, and EC. The corresponding measurement ranges were −30°C to 80°C for temperature, 0.01% to 99.99% for RH, and 0.01 to 20.00 mS/cm for EC. To establish a quantitative relationship between soil salinity and EC, we calibrated the sensor using a gradient salinity method. The resulting

salinity-EC calibration curve is shown in Figure 4. As illustrated in the figure, the fitted relationship yielded an $R^2$ value of 0.997, indicating a strong positive linear correlation between EC and soil salinity over the salinity range of 0.00%-3.20%.

[Figure content: legend "Measured" and "Fitted" ; vertical axis "EC (µS/cm)" ; horizontal axis "Solution concentration (%)" ; fitted relation $y = 2687.4x + 44.5$ ($R^2 = 0.997$).]

**Fig. 4** Relationship between electrical conductivity (EC) and salt content. In the fitted equation, $x$ denotes the NaCl solution concentration.

The experiment required repeated daily heating and a stable ambient temperature throughout the test period. A 250 W infrared lamp was used as the heat source to simulate the evaporation conditions typical of arid regions, following previously reported experimental approaches (Zhou et al., 2020; Zhang et al., 2022). Before the experiment began, the preset operating parameters were checked to ensure stable light intensity and temperature conditions. After each daily 5 h heating cycle, macroscopic top-view photographs of the entire circular soil-column surface were first taken to document the overall surface morphology and crack development. Representative local microscope images were then collected at a fixed position on the same surface using a DDL-M2 intelligent microscope (BeaverLab, Shenzhen, China). Equipped with an optical magnification of up to 800× and a 1080p high-definition imaging system, the microscope was used to capture and document the formation and morphological evolution of salt crystals on the soil surface.

## 2.3 Experimental process

The collected saline soil samples were naturally air-dried and then gently crushed. Because the samples contained soluble salts that could affect the experimental results, we used distilled water for salt leaching according to a previously reported method (Bing et al., 2011). The leaching procedure was repeated until the EC of the leachate stabilized within the range of 200–300 µS/cm, indicating that the soluble salts had been effectively removed. The treated soil was then dried, crushed, and mixed with sand at different proportions. The initial gravimetric water content of the saline soil was adjusted to 35% before column preparation to provide a sufficiently wet initial condition for evaporation-driven water-salt migration.

According to the Technical Specifications for Highway Subgrade Construction (JTG/T 3610-2019), we prepared the soil column in six layers, each with a thickness of 5.0 cm (Ministry of Transport of the People' s Republic of China, 2019). The surface of each layer was roughened before placement of the subsequent layer to prevent interlayer separation, and the degree of compaction was controlled at 95%. To investigate the effect of sand replacement on water-salt migration, we designed the lower 0.0–20.0 cm portion of the soil column as a sand-mixed replacement layer, whereas we retained the upper 20.0–30.0 cm portion as saline soil. The outer wall of the acrylic column was wrapped with thermal insulation cotton to reduce external temperature fluctuations and maintain a relatively stable thermal field during the test. Temperature, RH, and EC sensors were installed at predetermined positions for real-time monitoring. The experimental setup and test procedure for the water-salt migration experiment are

shown in Figure 5.

**Fig. 5** Process flow diagram of the water-salt migration test

Salt leaching → Oven-drying → Soil specimen preparation → Moisture equilibration → Soil weighing → Compaction in layers → Thermal insulation monitoring → Water replenishment and heating

## 2.4 Experimental design

To investigate the influence of sand replacement layers on water-salt migration in saline soil subgrades, we considered two variables in the experimental design: sand type and sand replacement ratio, as summarized in Table 3. The incorporation of sand particles can modify the pore structure of saline soil and reduce capillary rise. Different sand gradations may influence water-salt migration in different ways. Coarse sand generally forms larger pores and exhibits higher permeability, which is conducive to interrupting capillary continuity. Medium sand can improve particle gradation and may form a relatively stable skeleton-filling structure with saline soil particles. Fine sand, owing to its smaller particle size and larger specific surface area, tends to produce a denser structure when mixed with saline soil. Therefore, three sand types, namely coarse, medium, and fine sand, were selected as one of the main experimental variables. Based on engineering practice in the arid regions of Qinghai Province, sand replacement ratios ranging from 20.00% to 50.00% have shown good applicability in the improvement of saline soil subgrades. Accordingly, three replacement ratios, namely 20.00%, 35.00%, and 50.00%, were adopted in this study.

To simulate the high-temperature and strong-evaporation conditions typical of northwestern China, we selected the experimental heating regime with reference to summer surface temperatures of 50°C–60°C reported for saline soil areas in Gansu Province. The heating temperature was set at 50°C and applied for 5 h/d over 5 consecutive days. For comparative analysis, the tests were divided into two comparison groups and one control group. Group T (sand type) was used to investigate the effect of sand type, with coarse, medium, and fine sand tested at a fixed replacement ratio of 35.00%. Group R (sand replacement ratio) was used to investigate the effect of replacement ratio, with 20.00%, 35.00%, and 50.00% medium sand adopted under the same sand-type condition. Group C (without replacement) contained no sand replacement layer. Specimen R2

(35.00% medium sand) was identical to specimen T2 and was therefore used as the shared reference case in both comparison groups.

**Table 3** Experimental design

| Test ID | T1 | T2 | T3 | R1 | R2 | R3 | C |
|---|---|---|---|---|---|---|---|
| Sand type | Coarse sand | Medium sand | Fine sand | Medium sand | Medium sand | Medium sand | None |
| Sand replacement ratio (%) | 35.00 | 35.00 | 35.00 | 20.00 | 35.00 | 50.00 | 0.00 |

## 2.5 Scanning electron microscopy (SEM) sampling and observation

After the water-salt migration tests, the microstructural evolution of the saline soil under different sand replacement conditions was characterized using a Nova NanoSEM 450 field-emission scanning electron microscope (FEI Company, Hillsboro, OR, USA). To compare the effects of sand type and replacement ratio, we collected soil samples from a height of 20.0 cm in each soil column. In addition, for the column with 35.00% medium sand replacement, samples were taken from heights of 10.0, 15.0, 20.0, and 26.0 cm to examine the vertical variation in soil microstructure.

The sampling locations and SEM preparation procedure are shown in Figure 6. The extracted samples were dried and sputter-coated before SEM observation. SEM images were obtained at magnifications of 500× and 2000×. The observation focused on particle arrangement, pore morphology, interparticle bonding, and salt crystal distribution.

**Fig. 6** Sampling locations for scanning electron microscopy (SEM) observation within the soil column

# 3 Results

## 3.1 Macroscopic response characteristics

### 3.1.1 Characteristics of surface crack development

Macroscopic top-view photographs of the entire circular soil-column surface were taken after each daily 5 h heating cycle, and the corresponding surface morphologies are presented in Figure 7. As shown in the figure, the soil surface underwent radial shrinkage during heating because of the restraint imposed by the column wall, resulting in the formation of annular cracks near the boundaries. In several columns, the crack patterns observed on the fifth day were broadly similar to those on the third day, suggesting that the surface layer had largely dried and that evaporation had slowed markedly.

Figure 7 further shows that, overall, both the number and width of surface cracks were smaller in the sand-replaced columns than in the no-replacement column, indicating that sand replacement generally mitigated surface cracking. This effect can be attributed mainly to the shrinkage-modifying role of the replacement layer. The incorporation of sand reduces the proportion of active fine particles and lowers the shrinkage potential of the soil, thereby decreasing the likelihood of drying-induced tensile stress under radial wall restraint. Among the columns with a replacement ratio of 35.00%, the fine sand specimen exhibited the greatest number of surface cracks, followed by the medium sand specimen, whereas the coarse sand specimen showed the fewest. In addition to this material-related effect, differences in water-salt migration may also have contributed to the observed crack patterns. Reduced upward liquid supply during heating can weaken near-surface drying and thereby suppress crack development, which is consistent with the fewer cracks observed in the coarse sand column. Under the medium sand condition, the 20.00% replacement ratio produced the most severe surface cracking, followed by the 50.00% replacement ratio, whereas the 35.00% replacement ratio resulted in the least cracking. These results suggest that, under the present test conditions, a moderate replacement ratio provided the greatest resistance to surface cracking, whereas an excessively high replacement ratio diminished this beneficial effect.

**Fig. 7 (visible in-image labels).** Column headings: Without replacement; 20.00% medium sand; 50.00% medium sand; 35.00% coarse sand; 35.00% medium sand; 35.00% fine sand. Row labels: 1 d; 3 d; 5 d. Panel labels: (a)–(r). Annotations: Indentation; Annular crack; Crack; Radial shrinkage.

**Fig. 7** Evolution of macroscopic surface crack patterns on the circular soil-column surface under different conditions during evaporation after 1 d (a, d, g, j, m, and p), 3 d (b, e, h, k, n, and q), and 5 d (c, f, i, l, o, and r) heating. The small circular marks visible in some photographs are contact marks caused by microscope positioning and do not affect the identification of macroscopic crack patterns.

### 3.1.2 Mechanism of salt precipitation and accumulation

Figure 8 presents representative local microscope images acquired at the same fixed position on the soil-column surface, illustrating the evolution of surface salt crystallization after 1, 3, and 5 d of heating under different test conditions. On the first day, the relatively high initial water content and heat capacity of the soil slowed the temperature rise and evaporation, resulting in little to no visible salt crystallization on the surface. As heating proceeded, evaporation intensified, thereby promoting water–salt migration and leading to the gradual accumulation of salt at the soil surface.

**Fig. 8 (visible in-image labels).** Column headings: Without replacement; 20.00% medium sand; 50.00% medium sand; 35.00% coarse sand; 35.00% medium sand; 35.00% fine sand. Row labels: 1 d; 3 d; 5 d. Panel labels: (a)–(r). Annotations: Salt lump; Salt crystals; Salt crust; Salt-clay aggregate.

**Fig. 8** Evolution of surface salt crystallization on local areas of soil columns under different sand replacement conditions after 1 d (a, d, g, j, m, and p), 3 d (b, e, h, k, n, and q), and 5 d (c, f, i, l, o, and r) heating. The white particles or patches shown in the images are surface sodium chloride (NaCl) crystals.

In the column without replacement, a considerable amount of salt crystals appeared on the soil surface after 3 d of heating. By the fifth day, the salt deposits had further accumulated and formed a more continuous salt crust on the soil surface, indicating pronounced surface salt accumulation. In contrast, the extent of salt crystallization varied significantly among the sand-replaced columns with different sand types and replacement ratios. At a replacement ratio of 35.00%, the fine sand specimen exhibited noticeable surface salt crystallization after 5 d, although the amount remained lower than that in the column without replacement. The medium and coarse sand specimens exhibited fewer surface salt crystals, with the coarse sand specimen showing the strongest inhibitory effect on salt accumulation, reflecting its greater capacity to regulate water-salt migration.

For the medium sand columns, the extent of surface salt crystallization generally decreased with increasing replacement ratio, with the 20.00% specimen showing the most pronounced crystallization, whereas the 35.00% and 50.00% specimens exhibited markedly weaker salt deposition. This trend indicates that a higher sand replacement ratio more effectively suppressed upward water-salt migration. At higher replacement ratios, the reduced fine-particle content enlarged the pore spaces and weakened capillary action, thereby restricting the upward transport and accumulation of salt.

## 3.2 Coupled heat-water-salt transport process

### 3.2.1 Temperature distribution and conduction characteristics

(1) Different replacement ratios

Figure 9 shows the short-term evolution of temperature profiles along the soil-column height from the initial state through the first 5 h of heating on Day 1 for the specimen without replacement and the specimens with 20.00%, 35.00%, and 50.00% medium sand replacement. All tests started from similar initial temperatures close to ambient temperature, indicating consistent initial thermal conditions. As top heating proceeded, the temperature fields gradually differentiated among the treatments, as reflected by differences in the height-dependent thermal response and the degree of vertical thermal stratification. As heating proceeded, the vertical temperature gradient became more evident, and the treatment-dependent differences were mainly reflected in the replacement zone and the lower part of the column. Figure 10 further shows the temperature response at a height of 29.0 cm during the same period, where the temperature increased rapidly in the early stage and then continued to rise at a slower rate. At this height, however, the differences among the treatments remained relatively small throughout the heating period, indicating that the thermal response near the top of the column was governed mainly by the imposed top-heating boundary and was less sensitive to changes in the replacement ratio below.

Compared with the column without replacement, the effect of sand replacement on short-term downward heat transfer became more evident below the 20.0 cm height, which corresponds to the upper boundary of the replacement layer (Fig. 9). Within the replacement zone, the specimen with 20.00% medium sand exhibited the weakest warming response, whereas the specimen without replacement showed a slightly stronger temperature increase than the 20.00% replacement case. As the replacement ratio increased further, the warming response within the replacement zone became more pronounced in the 35.00% and 50.00% medium sand specimens, with the 50.00% specimen exhibiting the most homogeneous temperature distribution among the tested replacement ratios. These results indicate that sand replacement modified the short-term heat-transfer pattern within the replacement zone. From the perspective of heat transfer, this behavior is consistent with an increase in the effective thermal conductivity of the soil matrix after sand replacement, which may be related to improved particle contact and moisture redistribution during heating (Zhou et al., 2024a). Overall, the results suggest that the influence of sand replacement ratio on short-term downward heat transfer was non-monotonic, and that a relatively high replacement ratio was more favorable for enhancing the thermal response within the replacement zone.

Figure 11 compares the temperature responses measured at four heights (10.0, 15.0, 20.0, and

**Fig. 9** Temperature profiles along the soil-column height from the initial state through the first 5 h of heating on Day 1 under different medium sand replacement ratios. (a), initial; (b), 1 h; (c), 2 h; (d), 3 h; (e), 4 h; (f), 5 h.

**Fig. 10** Variation in soil temperature at a height of 29.0 cm during the first 5 h heating period on Day 1 under different medium sand replacement ratios

**Fig. 11** Temperature responses at heights of 10.0 (a), 15.0 (b), 20.0 (c), and 26.0 cm (d) measured at the end of each daily 5 h heating cycle over the 5 d test period under different medium sand replacement ratios. In this figure, 0 denotes the initial state before heating, whereas 1–5 denote the measurements recorded at the end of each daily 5 h heating cycle on Days 1–5, respectively.

26.0 cm) at the end of each daily 5 h heating cycle over the 5 d test period for the without replacement column and the columns with 20.00%, 35.00%, and 50.00% medium sand replacement. Across all treatments and monitoring heights, the temperature increased sharply after the first day and then rose more gradually over the subsequent days, indicating a rapid initial thermal adjustment followed by a slower approach to a quasi-steady state. The temperature generally increased with height, and the 26.0 cm position exhibited the highest temperature because it was closest to the heating boundary.

The influence of sand replacement was strongly height-dependent. Within the replacement zone (10.0–20.0 cm), the 50.00% medium sand specimen showed a distinct temperature response, whereas the without replacement, 20.00%, and 35.00% cases exhibited relatively similar temperature curves, indicating that the thermal effect of sand replacement became more evident only at a relatively high replacement ratio. At 26.0 cm, the temperature curves also showed a clear hierarchy rather than complete convergence, with the sand replacement specimens generally exhibiting higher temperatures than the without replacement specimen. This suggests that the modified lower structure still affected heat transfer in the upper plain-soil zone. However, because this position was close to the imposed heating boundary, the influence of the replacement ratio was weakened but not eliminated. Overall, the 50.00% medium sand specimen exhibited the strongest thermal response within the replacement zone, which may be associated with changes in conductive-path continuity and coupled moisture redistribution after sand replacement.

**(2) Different sand types** Figure 12 presents the temperature profiles along the soil-column height from the initial state through the first 5 h of heating on Day 1 for the columns with 35.00% coarse, medium, and fine sand replacement. All specimens started from a similar initial thermal state, and the lower part of the columns showed only a limited response during the early heating stage because evaporation in the upper zone limited the downward transfer of heat, while the heating boundary was relatively far from the bottom. As heating proceeded, heat gradually propagated downward, whereas the degree of vertical temperature stratification differed markedly among the three sand types.

As shown in Figure 12, the fine sand column exhibited the strongest vertical thermal stratification, with a more pronounced curvature of the temperature profile. This result indicates a steeper vertical temperature gradient and weaker heat penetration into the replacement zone. Such behavior is consistent with the smaller pore size and greater tortuosity associated with fine sand, which tends to enhance water retention and concentrate evaporation, together with the associated latent heat consumption, in the upper zone. As a consequence, downward heat transfer into the replacement zone was delayed, and a sharper temperature gradient was maintained. In contrast, the coarse and medium sand columns showed smoother and more uniform temperature profiles, implying more effective downward heat transfer under the same replacement ratio.

Figure 13 further presents the variation in temperature at a height of 29.0 cm during the first 5 h of heating on Day 1 for the three sand types, providing a direct comparison of the thermal response at this monitoring height. The temperature increased rapidly in the early stage, after which the rate of temperature increase gradually approached a relatively stable level. The differences among the three sand types remained relatively small throughout the heating period, indicating that the thermal response at 29.0 cm was governed mainly by the imposed top-heating boundary. Specifically, the coarse sand column exhibited the lowest temperature throughout the heating period, whereas the fine sand column showed slightly higher temperatures during the intermediate stage, and the medium sand column reached the highest value at the end of heating. These results suggest that, at a fixed replacement ratio, sand type influences the development of the temperature field mainly by regulating coupled heat-moisture processes and heat-transfer pathways within the replacement zone (Zhang et al., 2025).

Figure 14 compares the temperature responses at four heights (10.0, 15.0, 20.0, and 26.0 cm), measured at the end of each daily 5 h heating cycle over the 5-day test period, for columns with 35.00% coarse, medium, and fine sand replacement. At all monitoring heights, the temperature increased progressively with test day, although the magnitude of the increase varied with position in the column. The curves at 26.0 cm remained relatively close to one another, indicating that the

**Fig. 12** Temperature profiles along the soil-column height from the initial state through the first 5 h of heating on Day 1 for different sand types. (a), initial; (b), 1 h; (c), 2 h; (d), 3 h; (e), 4 h; (f), 5 h.

*Visible plot text:* Coarse sand; Medium sand; Fine sand. Height (cm); Temperature (°C). Plain-soil zone; Replacement zone.

**Fig. 13** Variation in soil temperature at a height of 29.0 cm during the first 5 h of heating on Day 1 for different sand types

*Visible plot text:* Coarse sand; Medium sand; Fine sand. Temperature (°C); Heating duration on Day 1 (h).

**Fig. 14** Temperature responses at heights of 10.0 (a), 15.0 (b), 20.0 (c), and 26.0 cm (d) measured at the end of each daily 5 h heating cycle over the 5 d test period under 35.00% coarse, medium, and fine sand replacement. In this figure, 0 denotes the initial state before heating, whereas 1–5 denote the measurements recorded at the end of each daily 5 h heating cycle on Days 1–5, respectively.

*Visible plot text:* 35.00% fine sand; 35.00% medium sand; 35.00% coarse sand. Temperature (°C); Test day (d). (a) 10.0 cm; (b) 15.0 cm; (c) 20.0 cm; (d) 26.0 cm.

thermal response in the upper plain-soil zone was governed mainly by the imposed heating boundary. In contrast, clearer differences among the three replacement conditions developed within the 10.0–20.0 cm range, suggesting that the thermal response in the replacement zone was more strongly affected by the type of sand used in the replacement layer.

A consistent trend was observed within the replacement zone: the temperature response was greatest in the coarse sand replacement column, followed by the medium sand replacement column and then the fine sand replacement column. This difference was most pronounced at 10.0 and 20.0 cm, where the thermal response was more sensitive to structural differences within the replacement layer than to the surface heating boundary alone. In addition, the temperature curve at 20.0 cm under coarse sand replacement evolved more smoothly than those under medium and fine sand replacement, indicating a more gradual thermal transition near the replacement layer boundary. These results suggest that coarse sand replacement favored more effective downward heat propagation across the replacement layer, whereas fine sand replacement tended to maintain stronger temperature stratification. Overall, the results indicate that the sand type used in the replacement layer influenced not only the magnitude of the temperature response within the replacement zone, but also the overall uniformity of heat transfer through the soil column under top-heating conditions.

### 3.2.2 Humidity variation and moisture transport

(1) Different replacement ratios

Figure 15 shows the RH profiles from the initial state to the end of each daily 5 h heating cycle over the 5 d test period under different medium sand replacement ratios. At the beginning of the test, the RH in all columns remained close to saturation, with the initial RH profile being approximately 100.00% throughout the column. Under the imposed high-temperature and strong-evaporation boundary, the RH variations were concentrated mainly in the upper part of the column, whereas the lower part remained at a relatively high RH level, where moisture transport was still dominated by liquid flow and hydraulic continuity could be maintained (Li et al., 2020). A pronounced transition zone developed in the middle-to-upper part of the column, particularly within the upper transition region near 29.0 cm, where RH decreased more markedly and vapor transport became increasingly important. This zone can be regarded as the evaporation-front region separating the lower liquid-dominated zone from the upper evaporation-controlled zone.

Figure 16 further presents the variation in RH at a height of 29.0 cm over Days 1–5, providing a direct comparison of drying behavior near the evaporation-front region. The RH at this height decreased sharply after the first day and then continued to decline more gradually over the subsequent days, indicating an initially intense drying stage followed by a progressively moderated process. Compared with the without replacement column, the presence of a sand replacement layer generally resulted in a greater reduction in RH near the evaporation front, and this effect became more evident as the replacement ratio increased. These results suggest that sand replacement partially restricted the upward replenishment of liquid water from deeper layers. With increasing replacement ratio, the reduction in fine-particle content and the weakening of pore-water continuity reduced capillary-driven liquid supply to the evaporation front, thereby promoting a shift toward vapor-dominated transport in the upper part of the column.

The experiment simulated daytime high-temperature conditions by applying 5 h of heating each day. During the interval between two consecutive heating cycles, the RH within the soil generally increased to different extents as a result of moisture redistribution (Liu et al., 2019). This interval, extending from the end of one day' s heating to the beginning of the next day' s heating, was defined as the non-heating period. Over the 5 d test period, a total of four non-heating periods were recorded. RH values were measured at the end of each daily heating cycle and again at the beginning of the subsequent heating cycle. The increase in RH during each non-heating period was defined as the difference between the RH measured before the start of heating on a given day and that measured immediately after the end of heating on the previous day:

$$\Delta \mathrm{RH} = \mathrm{RH}_b - \mathrm{RH}_a, \tag{1}$$

where $\Delta$RH represents the increase in relative humidity, expressed as a percentage (%); $\mathrm{RH}_b$

**Fig. 15** Variation in relative humidity (RH) along the soil-column height from the initial state to the end of each daily 5 h heating cycle over the 5 d test period under different medium sand replacement ratios. (a), initial; (b), 1 d; (c), 2 d; (d), 3 d; (e), 4 d; (f), 5 d.

Visible plot annotations: legend—Without replacement; 20.00% medium sand; 35.00% medium sand; 50.00% medium sand. Panel labels—(a) Initial; (b) 1 d; (c) 2 d; (d) 3 d; (e) 4 d; (f) 5 d. Axes—Height (cm); RH (%). Zone labels—Plain-soil zone; Replacement zone.

**Fig. 16** Variation in RH at a height of 29.0 cm over Days 1–5 under different medium sand replacement ratios. At the beginning of the test, the RH profile remained close to saturation, with the initial RH being approximately 100.00% throughout the column.

Visible plot annotations: y-axis—RH (%); x-axis—Test day (d). Groups—Without replacement: 79.36, 67.65, 62.50, 59.64, 58.15; 20.00% medium sand: 74.46, 65.04, 60.30, 55.72, 53.45; 35.00% medium sand: 72.30, 62.10, 56.20, 52.10, 48.50; 50.00% medium sand: 67.16, 57.58, 51.69, 43.01, 41.29.

denotes the relative humidity before heating on the current day (%); and $\mathrm{RH}_a$ indicates the relative humidity after heating on the previous day (%).

Figure 17 shows the increase in RH at a height of 29.0 cm during the four non-heating periods for soil columns with different medium sand replacement ratios. As shown in the figure, the largest increase in RH for all columns occurred during the second non-heating period. During the first and second non-heating period, the 20.00% replacement column exhibited the greatest increase in RH, whereas the 50.00% medium sand replacement column showed the smallest increase. During the third and fourth non-heating periods, the differences among the treatments became more stable, with the without replacement column showing the largest RH increase and the 50.00% medium sand replacement column remaining the lowest.

Overall, the increase in RH during the non-heating periods did not vary monotonically with replacement ratio. Instead, the 50.00% replacement column consistently exhibited the smallest RH increase, indicating the strongest restriction on upward moisture replenishment near the evaporation-front region. The pronounced RH increase during the second non-heating period in all columns suggests that moisture redistribution was most active at this stage. In contrast, the weaker RH increase during the later non-heating periods indicates that the capacity for upward moisture replenishment gradually decreased, thereby limiting liquid-water redistribution from deeper layers.

**Fig. 17** Increase in RH at a height of 29.0 cm during the four non-heating periods under different medium sand replacement ratios

### (2) Different sand types

Figure 18 shows the RH profiles from the initial state to the end of each daily 5 h heating cycle over the 5-day test period for columns with 35.00% coarse, medium, and fine sand replacement. At the beginning of the test, all columns remained close to saturation. As heating proceeded, a pronounced RH gradient gradually developed in the upper part of the column, whereas the middle and lower parts remained at relatively high RH levels. This behavior reflects the strongly non-uniform boundary condition imposed from the top surface. The large temperature gradient near the surface intensified evaporation and vapor transport, resulting in a more evident reduction in RH in the upper zone (Shen et al., 2025).

The differences among the three replacement conditions were most evident near the evaporation-front region. Overall, the fine sand replacement column maintained the highest RH, followed by the medium sand replacement column, whereas the coarse sand replacement column exhibited the lowest RH, indicating the strongest suppression of upward moisture replenishment. Figure 19 further presents the variation in RH at a height of 29.0 cm over Days 1–5 for the three sand types and confirms the same overall trend. This result provides a direct reflection of drying intensity near the evaporation front. From a mechanistic perspective, this dependence on sand type is consistent with differences in pore structure and capillary behavior. Coarser grains tend to form larger pores and reduce matric suction as well as liquid-phase continuity, thereby weakening capillary-driven upward liquid supply and promoting drier conditions near the evaporation front. In contrast, fine sand retains moisture more effectively because of its smaller pores and stronger capillary effect.

Figure 20 illustrates the increase in RH at a height of 29.0 cm during the four non-heating periods for columns with 35.00% coarse, medium, and fine sand replacement. As shown in the figure, the fine sand column exhibited the greatest

Fig. 18. Variation in RH along the soil-column height from the initial state to the end of each daily 5 h heating cycle over the 5-day test period for columns with 35.00% coarse, medium, and fine sand replacement.

Figure 1: Fig. 18. Variation in RH along the soil-column height from the initial state to the end of each daily 5 h heating cycle over the 5-day test period for columns with 35.00% coarse, medium, and fine sand replacement.

Fig. 19. Variation in RH at a height of 29.0 cm measured at the end of each daily 5 h heating cycle over Days 1–5 for columns with 35.00% coarse, medium, and fine sand replacement

Figure 2: Fig. 19. Variation in RH at a height of 29.0 cm measured at the end of each daily 5 h heating cycle over Days 1–5 for columns with 35.00% coarse, medium, and fine sand replacement

RH increase throughout all four non-heating periods, followed by the medium sand column and then the coarse sand column. For all three sand types, the RH increase reached its maximum in the second non-heating period, with values of

**Fig. 18** Variation in RH along the soil-column height from the initial state to the end of each daily 5 h heating cycle over the 5-day test period for columns with 35.00% coarse, medium, and fine sand replacement. (a), initial; (b), 1 d; (c), 2 d; (d), 3 d; (e), 4 d; (f), 5 d.

**Fig. 19** Variation in RH at a height of 29.0 cm measured at the end of each daily 5 h heating cycle over Days 1–5 for columns with 35.00% coarse, medium, and fine sand replacement

13.30%, 14.40%, and 17.40% for the coarse, medium, and fine sand columns, respectively, whereas the increases in the third and fourth periods fell below the first-period level.

During the first two non-heating periods, continued evaporation progressively reduced the moisture content in the upper part of the column. Under the combined effects of temperature and moisture gradients, moisture redistribution became more pronounced, leading to the marked RH increase observed during the second non-heating period. In the later non-heating periods, the reduction in RH increase was mainly associated with progressive surface drying and crack development, which weakened hydraulic continuity and restricted upward water-salt migration. In addition, salt crystallization within surface pores further impeded moisture transport. The relatively small RH increase observed in the coarse sand column indicates that coarse sand replacement was most effective in restricting capillary-driven upward replenishment near the evaporation-front region. This behavior can be attributed to the larger pores and weaker

liquid-phase continuity associated with coarse sand, which reduced the efficiency of upward moisture migration.

**Fig. 20** Increase in RH at a height of 29.0 cm during the four non-heating periods for columns with 35.00% coarse, medium, and fine sand replacement

#### 3.2.3 EC distribution and salt transport

(1) Different replacement ratios

Figure 21 presents the EC profiles along the soil-column height from the initial state to the end of each daily 5 h heating cycle over the 5 d test period under different medium sand replacement ratios. After the first day of heating, EC increased throughout the profile, and the distribution gradually became more non-uniform with test day. The increase in EC was more pronounced within the sand replacement layer, whereas the upper plain-soil zone showed relatively smaller changes. This pattern indicates that the evolution of the EC field was more sensitive to salt accumulation and liquid-phase transport within the lower part of the column than in the upper zone. Compared with the without replacement column, the sand replaced columns generally exhibited lower EC values throughout the profile and a weaker vertical EC gradient, indicating that sand replacement alleviated salt enrichment within the column. Differences among the replacement ratios further suggest that increasing the replacement ratio strengthened this moderating effect by weakening capillary continuity and reducing the efficiency of upward liquid supply.

Figure 22 further compares the variation in EC at a height of 29.0 cm over Days 1–5 under different medium sand replacement ratios, providing a direct indication of salt accumulation near the evaporation-front region. At this monitoring height, EC increased continuously over the 5 d test period, with a relatively rapid increase during the early stage followed by a more gradual increase thereafter. This trend indicates that salt accumulation near the evaporation front was most active during the initial stage of evaporation and became progressively moderated with continued heating. At all monitoring times, the without replacement column exhibited the highest EC, followed by the 20.00%, 35.00%, and 50.00% medium sand replacement columns. These results suggest that sand replacement reduced salt accumulation near the evaporation-front region, and that this effect became more pronounced as the replacement ratio increased. The slower EC increase observed in the later stage may be related to progressive surface drying and the associated reduction in upward water-salt migration.

(2) Different sand types

Figure 23 presents the EC profiles along the soil-column height from the initial state to the end of each daily 5 h heating cycle over the 5 d test period for columns with 35.00% coarse, medium, and fine sand replacement. With continued heating, EC generally increased in all columns, but the magnitude of increase varied with height. More pronounced EC increases were observed within the sand replacement layer, whereas the upper plain-soil zone showed comparatively smaller

Fig. 21. Variation in soil EC along the soil-column height. Legend: Without replacement; 20.00% medium sand; 35.00% medium sand; 50.00% medium sand. Panels: (a) Initial; (b) 1d; (c) 2d; (d) 3d; (e) 4d; (f) 5d. Axes: Height (cm); EC ($×10^{3}$ $\mu$S/cm). Zones marked: Plain-soil zone and Replacement zone.

Figure 3: Fig. 21. Variation in soil EC along the soil-column height. Legend: Without replacement; 20.00% medium sand; 35.00% medium sand; 50.00% medium sand. Panels: (a) Initial; (b) 1d; (c) 2d; (d) 3d; (e) 4d; (f) 5d. Axes: Height (cm); EC ($×10^{3}$ $\mu$S/cm). Zones marked: Plain-soil zone and Replacement zone.

Fig. 22. Variation in EC at a height of 29.0 cm. Groups: Without replacement, 20.00% medium sand, 35.00% medium sand, and 50.00% medium sand. Axis labels: EC ($\mu$S/cm) and Test day (d). Visible values by group over Days 1–5: Without replacement, 586, 927, 1486, 1630, 1744; 20.00% medium sand, 543, 824, 1113, 1297, 1394; 35.00% medium sand, 440, 683, 947, 1075, 1157; 50.00% medium sand, 427, 586, 753, 838, 912.

Figure 4: Fig. 22. Variation in EC at a height of 29.0 cm. Groups: Without replacement, 20.00% medium sand, 35.00% medium sand, and 50.00% medium sand. Axis labels: EC ($\mu$S/cm) and Test day (d). Visible values by group over Days 1–5: Without replacement, 586, 927, 1486, 1630, 1744; 20.00% medium sand, 543, 824, 1113, 1297, 1394; 35.00% medium sand, 440, 683, 947, 1075, 1157; 50.00% medium sand, 427, 586, 753, 838, 912.

changes. This pattern indicates that dissolved salt redistribution and accumulation were mainly concentrated in the replacement layer, where liquid-phase transport was more active than in the upper part of the profile.

**Fig. 21** Variation in soil EC along the soil-column height from the initial state to the end of each daily 5 h heating cycle over the 5 d test period under different medium sand replacement ratios. (a), initial; (b), 1 d; (c), 2 d; (d), 3 d; (e), 4 d; (f), 5 d.

**Fig. 22** Variation in EC at a height of 29.0 cm measured at the end of each daily 5 h heating cycle over Days 1–5 under different medium-sand replacement ratios

Figure 24 further compares the EC variation at a height of 29.0 cm over Days 1–5 for the three sand types. At this monitoring height, EC increased continuously over the 5 d test period, with a rapid increase during the early stage followed by a more gradual rise thereafter. Throughout the test period, a clear and stable trend was observed: the coarse sand replacement column exhibited the lowest EC, the medium sand replacement column showed intermediate values, and the fine sand replacement column exhibited the highest EC. This result indicates that, at the same replacement ratio, coarse sand replacement most effectively suppressed upward water-salt transport and reduced salt accumulation near the evaporation-front region. Mechanistically, this dependence on sand type is consistent with differences in pore structure and capillary behavior. Coarser grains tend to form larger pores and weaken matric suction as well as liquid-phase

continuity, thereby reducing capillary-driven upward liquid supply and limiting salt accumulation in the upper part of the column. In contrast, finer sand maintains stronger capillary continuity and facilitates more sustained upward transport toward the evaporation-affected region (Wang and Shao, 2018).

**Fig. 23** Variation in soil EC along the soil-column height from the initial state to the end of each daily 5 h heating cycle over the 5 d test period for columns with 35.00% coarse, medium, and fine sand replacement. (a), initial; (b), 1 d; (c), 2 d; (d), 3 d; (e), 4 d; (f), 5 d.

**Fig. 24** Variation in EC at a height of 29.0 cm measured at the end of each daily 5 h heating cycle over Days 1–5 for columns with 35.00% coarse, medium, and fine sand replacement

## 3.3 Evolution of soil microstructure

During saline soil evaporation, liquid-vapor phase change and coupled THS migration can alter the soil microstructure through capillary water-salt transport, salt crystallization, and drying-induced pore deformation. Dissolved salts migrate with capillary water toward the evaporation front and precipitate as water evaporates. Meanwhile, drying shrinkage and salt precipitation may modify particle contacts, pore morphology, and pore connectivity, thereby influencing the subsequent migration of water and salts.

Based on the SEM observation procedure described in Section 2.5, the microstructural characteristics of the soil samples were analyzed in terms of particle arrangement, pore morphology, interparticle bonding, and salt crystal distribution. These observations provide microstructural evidence for the macroscopic changes in evaporation behavior, salt accumulation, and surface distress, and help explain the attenuation of upward water-salt migration and the downward recession of the evaporation front during the later evaporation stage.

### 3.3.1 Different heights

Figure 25 presents SEM images of the soil column with 35.00% medium sand replacement at different heights. The images indicate that the soil structure gradually changed from relatively dense to relatively loose between 10.0 and 26.0 cm. At 10.0 and 15.0 cm, stronger cementation made individual particles difficult to distinguish at a magnification of 500×, and the flocculent aggregates remained comparatively intact. In contrast, at 20.0 and 26.0 cm, particle boundaries became clearer, indicating weaker interparticle bonding and a looser soil fabric.

**Visible annotations in Fig. 25:** scale bars of 20 $\mu$m for the left column and 5 $\mu$m for the right column.

- **(a) 10.0 cm:** Dense structure; Salt crust; Cementation.
- **(b) 15.0 cm:** Compact structure; Cementation; Salt crystals.
- **(c) 20.0 cm:** Open structure; Particle separation; Salt crystals.
- **(d) 26.0 cm:** Loose structure; Macropores; Salt crust.

**Fig. 25** SEM images of the soil column with 35.00% medium sand replacement at 10.0 cm (a), 15.0 cm (b), 20.0 cm (c), and 26.0 cm (d). The left and right columns correspond to 500× and 2000× magnifications, respectively.

At a higher magnification of 2000×, local cementation, salt-crystal accumulation, particle separation, and pore development could be identified more clearly. Consistent with the EC measurements, salt accumulation was more evident at the upper and lower parts of the sampled profile but less pronounced in the middle. At 10.0 and 26.0 cm, salt deposits were evident on the particle surfaces, whereas more discrete salt crystals were observed at 15.0 and 20.0 cm. This observation further confirms the spatial distribution of salt accumulation.

### 3.3.2 Different working conditions

Figure 26 presents SEM images of the soil columns at a consistent height of 20.0 cm, with the left column captured at 500× magnification and the right column at 2000× magnification. The images indicate that, after water-salt migration, the microstructure was characterized by soil particles, pores, and salt crystals, with clear differences among the replacement conditions. The salt crystals, primarily composed of NaCl, appeared as flaky or blocky structures that filled pores, adhered to particle surfaces, and aggregated with saline soil particles. In the without replacement column, particle surfaces were heavily covered with abundant salt crystals. This phenomenon may be attributed to the large specific surface area of the clay fraction, the dense pore structure, the strong capillary effect, and the relatively high salt transport capacity during moisture migration.

Among the columns with a 35.00% replacement ratio, the fine sand column exhibited the most compact structure, whereas the coarse sand column showed a more porous fabric with more evident sand-clay separation and relatively large intergranular pores. The medium sand column displayed an intermediate microstructure. In the fine sand column, finer particles filled the voids more effectively and formed a compact structure with fewer visible pores. However, the smaller pores and stronger capillary continuity could still facilitate capillary-driven upward water-salt migration, resulting in more salt crystallization on particle surfaces. As the sand particle size increased from fine to coarse, the amount of surface salt crystallization decreased. This indicates that coarse sand replacement was more effective in restricting upward water-salt migration. Larger sand particles disrupted the continuity of migration pathways and increased pore size, thereby reducing matric suction and weakening capillary-driven liquid transport.

For the medium sand columns, different replacement ratios resulted in markedly different microstructures. At a replacement ratio of 20.00%, the 2000× image showed numerous pores and abundant salt crystals adhering to particle surfaces. As the replacement ratio increased, the amount of visible salt crystals generally decreased. At a replacement ratio of 50.00%, the soil structure became distinctly looser, characterized by larger pores and fewer adhered salt crystals. This behavior is mainly related to the reduction in clay content, weaker interparticle bonding, and diminished capillary effects associated with the looser arrangement of sand particles.

## 4 Discussion

### 4.1 Conceptual model of evaporation-driven THS coupling and distress evolution

Evaporation is widely recognized as the dominant driving force for upward water–salt migration and near-surface salt accumulation in arid and semi-arid environments. Under sustained evaporation, capillary rise transports dissolved salts toward the evaporation front and the soil surface, where concentration, precipitation, and crystallization lead to the formation of salt crusts and efflorescence (Dai et al., 2016; Licsandru et al., 2019; Li and Guo, 2022; Lü et al., 2025). Consistent with these established findings, the without replacement columns in this study exhibited typical evaporation-driven behavior, as reflected by a continuous decrease in near-surface RH, a pronounced increase in EC, and progressive salt enrichment toward the upper part of the column. These observations are in good agreement with previous field and laboratory studies (Maxwell and Condon, 2016; Lai et al., 2021).

Figure 27 further summarizes how evaporation-driven THS coupling develops into cracking-salinization distress. Evaporation establishes a moisture gradient that sustains upward capillary flow and salt transport toward the near-surface zone. With continued evaporation, salt crystallization and moisture loss induce microstructural changes and shrinkage deformation,

Scale bars: left column, 20 $\mu$m; right column, 5 $\mu$m.

Panel annotations:

- **(a) Without replacement**: Abundant salt crystals.
- **(b) 35.00% coarse sand**: Porous structure; sand-clay separation; relatively large pores; minor salt crystals.
- **(c) 35.00% medium sand**: Salt crystals.
- **(d) 35.00% fine sand**: Compact structure; pores; salt crystals.
- **(e) 20.00% medium sand**: Pores; salt crystals.
- **(f) 50.00% medium sand**: Porous structure; relatively large pores.

**Fig. 26** SEM images at a height of 20.0 cm for soil columns under different replacement conditions. (a), without replacement; (b), 35.00% coarse sand; (c), 35.00% medium sand; (d), 35.00% fine sand; (e), 20.00% medium sand; (f), 50.00% medium sand. The left and right columns correspond to 500× and 2000× magnifications, respectively.

leading to heterogeneous tensile stresses and the initiation of primary cracks. These cracks then enlarge the effective evaporation area and create preferential pathways for moisture loss, thereby accelerating further drying and promoting secondary crack development. This positive feedback among transport, crystallization, and cracking provides a mechanistic explanation for the progressive intensification of surface distress under evaporation-dominated boundary conditions.

Visible labels in the figure: Soil particle; Water; Water loss; Primary crack; Salt crystal; Secondary crack.
(a) Ground cracking (b) Continuous evaporation in saline soil (c) Soil salinization

**Fig. 27** Mechanism of crack formation and salt crystallization in saline soil under evaporation, and typical cracking and salinization distress observed in subgrades of saline soil regions. (a), ground cracking; (b), continuous evaporation in saline soil; (c), soil salinization.

Importantly, Figure 28 complements Figure 27 by explaining why coupled transport became increasingly limited during the later heating stage. Progressive surface drying and salt crystallization can lead to the formation of a hardened crust, which restricts further surface evaporation and promotes the downward migration of the evaporation front into deeper zones. This phenomenon has been widely reported in evaporating saline soils (Fujimaki et al., 2006; Dong et al., 2021). Meanwhile, salt tends to accumulate preferentially at pore throats and particle contacts near the evaporation front, leading to pore narrowing and even localized blockage of migration pathways. This interpretation is consistent with microstructure-based explanations for the attenuation of upward water migration and the reduced EC growth rate during the later stage of evaporation (Lü et al., 2018; Zhang et al., 2022). Therefore, the observed evolution can be interpreted as a transition from an early evaporation-driven regime to a transport-limited regime controlled by crust formation, downward migration of the evaporation front, and pore constriction and clogging.

## 4.2 Pathway control by sand-replacement design: continuity threshold and skeleton/liquid-bridge mechanisms

Compared with the columns without sand replacement, the introduction of a sand replacement layer can substantially modify the internal pore structure and thereby alter water-salt migration pathways and the spatial distribution of salt accumulation (Zhang et al., 2025b). This interpretation is consistent with the general understanding that an increase in coarse-particle content enlarges pore size and reduces matric suction, thereby weakening sustained capillary rise and suppressing upward salt transport under evaporation-dominated conditions (Yang et al., 2022;

Zou et al., 2022; Xu et al., 2025). Accordingly, coarse-grained modification has been regarded as an effective strategy for mitigating evaporation-induced near-surface salinization (Zhang et al., 2023; Zhou et al., 2024b).

*Text shown in the figure:* Radiation; Increased precipitation of salt crystal; Evaporation front recede downward; Water-salt pathway; Water vapour; Liquid-vapour interface; Salt crystal; Soil particle; Saline solution.

**Fig. 28** Evaporation front downward shift under continuous evaporation in saline soil subgrade

A notable finding of the present study is that the effect of replacement ratio on coupled THS behavior was not strictly monotonic. At an intermediate replacement ratio of approximately 35.00%, sand grains and fine particles tended to form a relatively stable skeleton-filling structure, in which pore pathways remained relatively connected, so the restriction on coupled water-salt migration was weaker than that under the 50.00% replacement ratio. In contrast, when the replacement ratio increased to 50.00%, the reduction in fine-particle content weakened capillary driving forces and disrupted the continuity of upward migration pathways, resulting in a more pronounced suppression of upward salt transport. Similar nonlinear tendencies have been mentioned qualitatively in related studies, but they have rarely been discussed from the perspective of pathway continuity (Ma et al., 2024). These results suggest that pathway continuity, rather than porosity alone, plays a controlling role, and that a threshold-like response may emerge when pore connectivity and matrix suction regulation change simultaneously.

Figure 29 provides further support for this interpretation from the perspective of heat transfer. When soil water content remains within an appropriate range, thin water films can form around particles and generate liquid bridges, which enhance solid-liquid heat-transfer pathways (Gong et al., 2025). This mechanism helps explain the relatively stronger thermal transfer observed when connected moisture pathways were still preserved. By contrast, under a high replacement ratio, the soil structure became more skeleton-dominated, which tended to produce a more uniform temperature field while simultaneously altering the capillary regime governing upward water-salt migration. Overall, these results indicate that sand replacement acts as a regulator of structural pathways by reorganizing capillary continuity and modifying the position of the evaporation front, thereby redistributing salt accumulation away from the surface and producing a distinctly non-monotonic response to replacement ratio under evaporation-dominated THS coupling.

## 4.3 Possible salinity-related effects on effective thermal conductivity

In addition to particle-size composition and moisture redistribution, salinity may also contribute to the observed thermal response by modifying interparticle interactions and the physical state of pore water. As illustrated in Figure 30, salt enrichment may compress the electrical double layer and reduce the repulsive spacing between adjacent particles, thereby favoring closer particle contacts. This change could, to some extent, facilitate heat transfer through the solid skeleton

(Zhang et al., 2025a). At the same time, increased salinity may alter the distribution of free water and bound water within the pore system, which can influence heat transfer across particle surfaces and thin water films. Therefore, the relatively enhanced downward heat transfer observed in salt-enriched zones may not be controlled solely by moisture pathways, but may also be related to salinity-induced changes in particle-contact conditions and pore-water state (Wu et al., 2016).

*Figure labels:* Water film; Soil particle; Liquid bridge.

**Fig. 29** Schematic diagram of the "liquid bridge" phenomenon. The thin arrows indicate local heat transfer between soil particles and the surrounding water films, while the thick arrow represents the enhanced heat-transfer pathway formed by the liquid bridge.

*Figure labels:* Soil particle; Stern layer; Diffuse layer; Electrolyte solution.

**Fig. 30** Schematic diagram of electrical double layer compression

It should be noted, however, that the present study did not directly measure thermal conductivity or electrical double-layer thickness. Therefore, the above interpretation should be regarded as a plausible mechanistic explanation on the basis of the coupled evolution of temperature, RH, and EC observed in the soil columns, rather than as direct evidence of microscopic heat-transfer processes. Nevertheless, the results support the view that THS coupling in saline subgrades is bidirectional: salt redistribution is affected by evaporation and heat transfer, while the resulting salt enrichment may in turn modify local heat-transfer conditions (Yang et al., 2023). This interpretation is also consistent with indicator-based assessments of saline soils, in which EC variation and salinization patterns are commonly used to reflect the coupled evolution of salt and moisture.

# 5 Conclusions

This study experimentally investigated the effects of sand replacement layers with different

particle sizes and replacement ratios on THS migration in soil columns under evaporation conditions. The main conclusions are as follows:

(1) Evaporation drove upward water-salt migration, leading to surface salt accumulation and shrinkage cracking. In the without replacement column, the most severe salt enrichment and the most pronounced annular cracking were observed, indicating strong capillary continuity.

(2) The introduction of sand replacement layers effectively suppressed upward water-salt migration and reduced near-surface salinization. Among the tested sand types, coarse sand exhibited the strongest inhibitory effect on salt accumulation by weakening capillary continuity and upward moisture replenishment. Under the medium-sand condition, increasing the replacement ratio generally reduced salt accumulation near the evaporation-front region, with the 50.00% replacement ratio showing the strongest suppression.

(3) Sand replacement altered the coupled thermal-moisture response of the soil column. Coarse sand and relatively high replacement ratios tended to promote downward heat transfer and weaken capillary continuity, thereby reducing the upward migration of water and salt toward the soil surface. However, the influence of replacement ratio was not entirely monotonic across all response indicators.

(4) Microstructural observations showed that sand replacement modified the pore structure and particle-contact conditions of saline soil. Among the tested sand types, coarse sand produced a looser and more porous fabric with larger intergranular pores and weaker capillary continuity, whereas fine sand tended to maintain a more compact structure. For the medium-sand series, increasing the replacement ratio reduced clay content, weakened interparticle bonding, and decreased visible salt crystallization. These microstructural differences help explain the observed variations in heat-water-salt migration and salt crystallization behavior.

## Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Author contributions

Conceptualization: LI Zihao; Methodology: GAO Junli, LI Zihao; Formal analysis: DAI Zili; Writing - original draft preparation: LI Zihao; Writing - review and editing: LIU Feiyu; Funding acquisition: GAO Junli, LIU Feiyu, ZHANG Zhen; Resources: DAI Zili; Supervision: GAO Junli; Project administration: GAO Junli, LIU Feiyu; Visualization: LI Zihao, ZHANG Zhen; Validation: DAI Zili; Investigation: GAO Jinbo; Data curation: GAO Jinbo. All authors approved the manuscript.

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*Note: Figure translations are in progress. See original paper for figures.*