Research Article

“Covering Effects” under Diurnal Temperature Variations in Arid and Semiarid Areas

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“Covering effects” dominated by water vapor migration in arid and semiarid areas threaten the stability of engineering entities. To explore the “covering effects” dominated by water vapor migration under the influence of diurnal temperature variations, a series of one-side evaporation experiments were conducted. Characteristics of water vapor migration between the unsaturated loess soil column with and without a lid were compared in detail to illustrate the “covering effects” on water vapor migration, as were the effects of test time. Further, the characteristics of “covering effects” in loess and sand soil columns were compared. The results show that the “covering effects” formed in the loess soil column with a lid by cycling day and night temperature differences led water vapor to accumulate and condense beneath the lid. However, unlike the “covering effects” during freezing conditions that lead to a significant increase in the moisture content in the top layer, in this study, the moisture content in the top layer (0–8 cm) decreased. Although “soil lid” and the “soil covering effects” exist in both loess soil columns with and without lids, the “soil covering effects” for the former are much more obvious, and the moisture content in the upper part of the loess soil column (8–45 cm) shows a significant increase. By cycling day and night temperature differences, the “covering effects” or “soil covering effects” grew as the test time increased. Compared to the loess soil column, the “covering effects” in the sand soil column were extremely weak, and the moisture migration in the sand soil column was dominated by the downward movement liquid water. This paper illustrates the “covering effects” under the influence of diurnal temperature variations and reveals the mechanism of water vapor migration in subgrade soils in arid and semiarid areas.

1. Introduction

In arid and semiarid areas, water vapor migration in unsaturated soils is very common due to the climatic characteristics of low rainfall, deep groundwater level, sufficient sunshine, high evaporation, and great diurnal temperature variations [1–3]. For example, in agricultural applications, water required for the growth of the plant root in arid and semiarid areas is mainly supplemented by upward movement of water vapor. In landfills and nuclear waste storage depot, there are also water vapor migration phenomena [4, 5].

Usually, water vapor exchanges freely between the soil and the atmosphere to maintain the water vapor pressure balance if there is no covering layer on the soil; water vapor in the soil enters the atmosphere by evaporation, or the moisture in the atmosphere enters the soil through rainfall. However, if there is a covering layer on the soil, the water vapor exchange between the soil and the atmosphere will be hindered. Engineering entities such as highways, railways, and airport roads have covering layers on their subgrades. Additionally, when the covering layers are impermeable, the water vapor that migrates to the covering layer will accumulate beneath the covering layer. Then, the accumulated water vapor will condense at low temperature and convert into liquid water, resulting in the excessive moisture content in the upper part of the subgrade (see Figure 1) and eventually may lead to engineering failure. This phenomenon of water vapor migration upward through the soil and accumulating beneath the covering layer was defined as the
“covering effect” [6]. Engineering projects such as highway pavement, high-speed railway pavement, and airport pavement have reported engineering problems due to “covering effects” [7–10].

The “covering effects” have attracted increasing attention in recent years. The “covering effects” were divided into two types by Teng et al. [11]: the first type concerns liquid water migration, which often occurs in areas with a shallow groundwater level, and the second type concerns water vapor migration, which often occurs in soils with a low initial moisture content in arid and semiarid areas where the climate is characterized by high evaporation, low rainfall, and deep groundwater levels. Similarly, it was also highlighted by Bai et al. [12] that under the influence of “covering effects,” moisture migration was dominated by water vapor if there was low initial moisture content; on the contrary, it was mainly liquid water if there was high initial moisture content. Researchers [11, 13–15] conducted theoretical calculations and laboratory experiments on the two types of “covering effects,” and concluded that the increase in the moisture content under the covering layer caused by the second type of “covering effects” was much greater than that caused by the first type of “covering effects.” That is, the engineering failure due to the second type of “covering effects” was more serious than the first type of “covering effects.”

Zhang et al. [16] conducted indoor tests to study the water vapor transfer in relatively dry calcareous sands under freezing conditions, and the results showed that water vapor transfer may lead to full saturation of the soil at the surface. It has been confirmed by many researchers that for railway engineering, water vapor diffusion under the “canopy effects” is a major contributor to the formation of near-surface ice [8, 16, 17]. Hence, in arid and semiarid areas with large evaporation and deep groundwater levels, more attention should be paid to the “covering effects” dominated by water vapor migration. Previous studies regarding the “covering effects” dominated by water vapor migration under freezing conditions reported that the main factors affecting the “covering effect” dominated by the water vapor migration were initial water content, fine particle content, and temperature gradient. For example, Gao et al. [18] investigated the mechanism of frost heaving of coarse-grained soil for high-speed railway considering “covering effect” by conducting one-side freezing tests of coarse-grained soils with different initial moisture contents and concluded that the effect of water vapor migration on the frost heave of coarse-grained soils was more pronounced in the case of a lower initial moisture content. Nevertheless, the phenomenon of water vapor migration became extraordinarily weak when there was quite low initial moisture content [19]. For coarse-grained soil under freezing tests, the water vapor migration was more obvious when the fine particle contents increased [20]. Furthermore, it is believed that the phenomenon of the water vapor migration will be more obvious if there is a larger temperature gradient [10].

As shown from the above research results, researchers have realized the adverse effects of the “covering effects” dominated by water vapor migration on engineering projects. However, it must be noted that most of the existing studies on the “covering effects” were performed under freezing conditions. Furthermore, the above research has been focused on the coarse-grained soil for railways. At present, less attention has been paid to the “covering effects” dominated by water vapor migration under day and night temperature differences. In arid and semiarid regions, there is strong daytime evaporation resulting from sufficient sunshine. Coupled with the great diurnal temperature variations, the phenomenon of “covering effects” is more prominent. In addition, for highway engineering in arid and semiarid areas in China, the majority of subgrade fills are loess and sand, which are quite different from the fills for railways. Based on the reasons mentioned above, the main purpose of this study is to investigate the “covering effects” under the influence of diurnal temperature variations in arid and semiarid areas by conducting a series of one-side evaporation experiments for loess and sand with no groundwater supplied. First, this study has emphasized the distinction of water vapor migration between the unsaturated loess soil column with and without a lid to illustrate the “covering effects” on water vapor migration. Then, it has investigated the influence of test time on the “covering effects.” In addition, this study has compared the “covering effects” in loess and sand soil columns. The preliminary results obtained in this study shed light on the water vapor migration in unsaturated subgrade soils under diurnal temperature variations.

2. Materials and Methods

2.1. Materials. The materials used in this study were loess and sand, typical soil types in arid and semiarid areas in China. The specific gravity, compaction characteristics, and Atterberg limits of the test soils were measured according to ASTM D854 [21], ASTM D1557 [22], and ASTM D4318 [23], respectively. The results are shown in Table 1.

The grain size distributions for the soils are shown in Figure 2. It should be noted that the distribution of particle sizes larger than 0.075 mm was determined using sieve analysis according to ASTM C136/C136M-14 [24], while the distribution of particle sizes smaller than 0.075 mm was...
Table 1: Physical properties of the test soils.

| Soil type | Specific gravity | Optimum moisture content (%) | Maximum dry density (g/cm³) | Liquid limit (%) | Plastic limit (%) | Plasticity index |
|-----------|------------------|------------------------------|-----------------------------|------------------|------------------|------------------|
| Loess     | 2.66             | 14.1                         | 1.8                         | 30.5             | 17.69            | 12.81            |
| Sand      | 2.67             | 9                            | 1.6                         | —                | —                | —                |

Table 2: The coefficients of uniformity ($C_u$) and curvature ($C_c$) for the tested soils.

| Soil type | $d_{50}$ (mm) | $d_{10}$ (mm) | $d_{10}$ (mm) | $C_u$ | $C_c$ |
|-----------|---------------|---------------|---------------|-------|-------|
| Loess     | 0.59          | 0.09          | 0.012         | 49.17 | 1.14  |
| Sands     | 0.17          | 0.12          | 0.082         | 2.07  | 1.03  |

2.2. Test Apparatus. In this test, one-side evaporation test apparatus (as shown in Figure 7) was developed to explore water vapor migration in the unsaturated soil under diurnal temperature variations. The apparatus was mainly composed of a soil column model ($\mathbb{①} + \mathbb{②}$), a moisture monitoring system ($\mathbb{③} + \mathbb{④}$), a temperature monitoring system ($\mathbb{⑤} + \mathbb{⑥}$), a temperature control device ($\mathbb{⑦}$), and an environmental chamber ($\mathbb{⑧}$) to keep the environmental temperature constant.

The soil column was mainly used to simulate the one-dimensional subgrade model. It should be noted that the soil column is a closed system with no groundwater supplied to simulate the condition of deep groundwater level. The soil column mainly consisted of a plexiglass cylinder ($\mathbb{①}$, 20 cm inner diameter and 65 cm height) and a sealed lid ($\mathbb{②}$, 20 cm inner diameter). The sealed lid was used to simulate the rigid or semirigid base layer that laid on the subgrade. On the side of the soil column model, small holes with a diameter of 0.5 cm were placed at 5 cm intervals along the vertical direction to let the moisture sensors and temperature sensors pass through.

The moisture monitoring system ($\mathbb{③} + \mathbb{④}$), consisted of Time Domain Reflected (TDR) moisture sensors ($\mathbb{③}$) and a MiniTrase moisture collector ($\mathbb{④}$), was mainly used to acquire the soil moisture content data in real time, while the temperature monitoring system ($\mathbb{⑤} + \mathbb{⑥}$, consisted of PT100 soil temperature sensors ($\mathbb{⑤}$) and an ECR90 paperless

for testing. To ensure the accuracy of the test, five parallel specimens were made for each type of soil. Finally, the measured data were fitted using the van Genuchten model [27], as shown in equation (1). The SWCCs for the soils are shown in Figure 6.

$$\theta = \theta_s + \frac{\theta_r - \theta_s}{[1 + (\alpha \psi)^n]^m}$$

where $\theta$ is the moisture content (%), $\theta_s$ is the residual moisture content (%), $\theta_r$ is the saturated moisture content (%), $\psi = u_r - u_w$ is the matrix suction (kPa), $\alpha$ is the parameter related to the intake state (kPa$^{-1}$), $n$ is the parameter related to the pore size distribution of the soil, and $m$ is the parameter related to the overall symmetry of the SWCC, $m = 1 - 1/n$.  

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Figure 3: XRD patterns of test soils. (a) Loess. (b) Sand.

Figure 4: Mineral compositions of test soils. (a) Loess. (b) Sand.

Figure 5: Pressure chamber test apparatus.
temperature recorder (⑥), was used for obtaining the soil temperature in real time. The temperature control device (⑦) mainly referred to the Philips infrared lights, and it was adopted to control the temperature of the soil column. The open lights were suspended above the soil column to simulate the condition of sunlight during the daytime, and then the lights were extinguished to simulate the night condition.

2.3. Test Design and Method. Several groups of one-side evaporation tests were conducted to investigate water vapor migration in the unsaturated soil under the influence of diurnal temperature variations, as shown in Table 3. Groups A and B were used for investigating the distinction of water vapor migration between the unsaturated soil column with and without a lid to illustrate the influence of “covering effects” on the characteristic of water vapor migration. In group C, characteristics of water vapor migration at 1, 10, 20, 30, 40, 50, and 60 days were compared to explore the influence of test time on the “covering effects.” Group A and group D were used to study the difference between water vapor migration in the loess and the sand soil column influenced by “covering effects.” To ensure the accuracy of the test, three parallel soil columns were made for each group.

First, the loess and sand soil samples with the optimum moisture content (14.1% and 9%, respectively) were prepared. Then, the prepared soil samples were filled in layers into the soil column model and compacted with the compaction degree of 97%. To ensure the uniformity of the soil compaction, the thickness of each layer was controlled so as to not exceed 5 cm.

During the filling process, moisture and temperature sensors were buried at 5 cm, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, and 60 cm, respectively, from the top of the soil column model to monitor the soil moisture and temperature. After the soil column was filled completely, the sealed lid was placed closely on the soil sample immediately. Excess holes, excess space between the sensors and the holes, and excess space between the sealed lid and the plexiglass cylinder were carefully sealed with glass glue to prevent the outflow of water vapor inside the soil column or water vapor in the external environment from entering the soil column.

Finally, the working times of the infrared lights were controlled to explore the water vapor migration under the effect of diurnal temperature variations. The infrared lights were turned on from 7:00–18:00 to simulate sunshine conditions during the daytime, while they were turned off from 18:00–7:00 the next day to simulate the night conditions. During the test, the height of the infrared lights was adjusted to control the temperature at the top of the soil column. In the extreme temperature conditions, the temperature at the top of the subgrade reaches approximately 50°C [28]. Thus, the maximum temperature at the top of the soil column model in this test was controlled at approximately 50°C to simulate this extreme condition. The whole apparatus was then placed in an environmental chamber with a temperature of approximately 5°C.

3. Results and Discussion

3.1. Temperature Distribution in the Soil Column. Figure 8 shows the temperature distribution in the soil column during a cycle (from 7:00 to 7:00 the next day). The temperature at the top of the soil column (0 cm) was approximately 5°C before the lights were turned on at 7:00, while the temperature was 9°C at the bottom of the soil column (60 cm). After turning on the lights, the temperature at the top of the soil column rose sharply due to the replenishment of the heat source, and it increased as the lights were kept on. The temperature at the top of the soil column reached as high as 56°C at 18:00. Meanwhile, the heat at the top of the soil column transmitted to the lower part of the soil column under the effect of the temperature gradient, resulting in a gradual increase in the temperature of the soil within the depth of 5–55 cm. In addition, the soil closer to the top layer exhibited a greater temperature increase. However, the soil
at the depth of 60 cm was little affected by the top soil temperature, and its temperature was always stable at around 9°C. His phenomenon is in consistent with the conclusion drawn by Zheng et al. [29] that the variation in soil temperature was reduced with depth. Ran and Li [28] also concluded that temperature fluctuations gradually decreased from top to bottom by on-site monitoring of the temperature inside a subgrade in a strong evaporation area. During the daytime, the maximum temperature difference between the soil at 0 cm and 60 cm can reach up to 45°C.

After extinguishing the lights at 18:00, the temperature at the top of the soil column began to decrease first under the influence of the lower room temperature. Subsequently, in the lower part of the soil column, the temperature gradually decreased. At 3:00 to 7:00 the next day, the temperature at the top dropped to approximately 5°C, which was extremely close to the chamber temperature, whereas the temperature at the bottom of the soil column (60 cm) was always maintained at around 9°C, which was higher than that at the top of the soil column during this period.

3.2. Effect of “Covering Effects” on the Water Vapor Migration

3.2.1. Water Vapor Migration in the Loess Soil Column with a Lid. For the soil column model with a lid, the distribution of the moisture content is shown in Figure 9. It can be seen from Figure 9 that after 60 days, for the depth of 8–45 cm and 60 cm, the soil moisture content increased compared to the initial state, and at the depth of 20 cm, the soil moisture content reached the maximum (23.7%); nevertheless, for the depth of 0–8 cm and 45–60 cm, the soil moisture content showed a decreasing trend compared to the initial state. According to the distribution characteristics of the moisture content along the depth direction, it can be divided into two regions, as shown in Figure 9.

For region I (0–8 cm), the temperature at the top of the soil column reached as high as 56°C during the daytime (as shown in Figures 8 and 9). Under this high temperature, liquid-phase soil water transformed into the vapor phase and moved upward due to evaporation. The upward water vapor was prevented by the lid from escaping out, and it accumulated under the lid. Meanwhile, soil in region I shrunk owing to the rapid water loss [30] (as shown in Figure 9), resulting in the decrease in the void ratio [31, 32]. As a result, the soil became low permeable due to the close proximity of soil particles. This was equivalent to forming a covering layer again, and it was named “soil lid” in this paper.

After extinguishing the lights at night, the temperature at the top dropped rapidly, especially from 3 to 7 o’clock the next day; the soil temperature dropped to approximately 5°C (shown in Figures 8 and 9). Under the influence of this low temperature, the vapor collected under the lid condensed into the liquid phase. This phenomenon in which the water vapor migrates upward, condenses, and accumulates under the lid is the “covering effect” proposed by Li et al. [6]. Niu et al. [8] also found this phenomenon that the water vapor will condense under the lid, releasing energy back into liquid water. However, unlike the water vapor migration under the freezing conditions [12, 15, 17, 18], this part of liquid water did not completely return to the soil at the top but mostly adhered to the lid and the wall of the cylinder (as shown in Figure 9) due to the shrinkage of the soil in region I. Furthermore, the moisture sensors could not detect this part of moisture. Hence, the soil moisture content at the top showed a final decreasing trend.

For region II (8–60 cm), the soil temperature at the depth of 8–45 cm was above 30°C at 12:00–20:00, as can be seen from Figure 8. Similarly, the moisture in this part of soil partly changed from the liquid phase to the vapor phase. In addition, this vapor also could not move out due to the presence of the “soil lid”. It should be noted that the soil moisture decreased due to the phase change from liquid to vapor, while the matrix suction increased because of the negative correlation between moisture content and matrix suction (as shown in Figure 6), making the soil moisture in the lower part move upward under the driving force of matrix suction. After extinguishing the lights at night, the soil temperature at the depth of 8–45 cm decreased (as shown in Figures 8 and 9), making the vapor in the soil condense into the liquid phase. Therefore, the

| Group | Soil type | Initial moisture content (%) | Lid | Test time (day) |
|-------|-----------|-----------------------------|-----|-----------------|
| A     | Loess     | 14.1                        | Yes | 60              |
| B     | Loess     | 14.1                        | No  | 60              |
| C     | Loess     | 14.1                        | Yes | 1, 10, 20, 30, 40, 50, 60 |
| D     | Sand      | 9                           | Yes | 60              |

Table 3: Test design of the water vapor migration.
moisture content at night was slightly larger than during the day (Figure 9). Under the alternating temperature differences between day and night, the moisture content at the depth of 8–45 cm finally showed an increasing trend. Our observations show that the phenomenon of “covering effects” occurred again in this study, and it was termed “soil covering effects.” This phenomenon has rarely been mentioned in previous studies. Similarly, Ran and Li [33] and Zhang Yu et al. [34] monitored on-site the moisture content of a subgrade in Xinjiang, China, in a strong evaporation area and found that the moisture content in the depth of 40–80 cm was the largest, while if the depth was less than 40 cm or more than 80 cm, the moisture content decreased. However, the researchers were unaware of the existence of the “soil covering effects.”

It is worth noting that the temperature gradient between the depth of 8 cm and 20 cm was extremely small. The moisture in the liquid phase at the depth of 8 cm moved downward under the driving force of gravity, resulting in the maximum moisture content at the depth of 20 cm. The results of this paper are consistent with the findings of Ran and Li [28], who monitored the moisture content of a highway subgrade in Xinjiang, China, and found that the moisture content of the soil at the depth of 60 cm was the largest, rather than at the top of the subgrade. For soil at the depth of 50–60 cm, part of the water vapor moved upwards under the influence of “soil covering effects,” and part of it moved downward under the action of gravity. Moreover, the influence of gravity on the water vapor migration increased with the increase in depth, which eventually led to a slight increase in the moisture content at the bottom layer.

3.2.2. Water Vapor Migration in the Loess Soil Column without a Lid. The temperature distribution in the soil column model without a lid is similar to that with a lid and will not be described here.

It can be seen from Figure 10 that, for the soil column without a lid, the soil moisture content at the depth of 0–35 cm and 45–60 cm decreased after 60-day’s test, while the soil moisture content at the depth of 35–45 cm showed a slight increase. Similar to the case of the soil column with a lid, the moisture content at night was slightly larger than that during the day.

The moisture content of the soil can be divided into two regions according to its distribution along the depth direction. For region I′ (0–35 cm), the surface of the soil column (0 cm) belonged to the free evaporation surface. The moisture of the soil at the surface changed from the liquid phase to the vapor phase under the high temperature during daytime. Meanwhile, the water vapor on the surface of the soil continuously evaporated into the atmosphere under the drive force of water vapor pressure since the water vapor pressure on the surface of the soil was much greater than that in the atmosphere. Therefore, the soil moisture content at the surface continuously decreased, and the water vapor pressure also decreased when matrix suction increased. The moisture in the lower region (10–35 cm) migrated upward under the drive force of water vapor pressure and matrix suction. As a result, the soil moisture content at the depth of less than 35 cm decreased continuously.

Similar to the formation of the “soil lid” in the soil column with a lid (see Figure 9), there was also a “soil lid” formed at the depth of 35 cm due to the continuous decrease in the moisture content in region I′. It can be seen from Figure 10 that, in region II′ (35–60 cm), “soil covering effects” similar to those in Figure 9 also occurred. Under the influence of the “soil covering effects,” the water vapor migrated from the lower layer to the upper layer, and the maximum soil moisture content (22.34%) occurred at the depth of 40 cm. It is worth noting that, although the soil
moisture at the depth of 50–60 cm was affected by the “soil covering effects” and gravity, the effect of the “soil covering effects” was always greater than the role of gravity, resulting in a reduction in soil moisture content.

After extinguishing the light at night, the evaporation decreased as the temperature decreased. Part of the water vapor in the soil condensed from the vapor phase to the liquid phase. Since the moisture sensors can only detect liquid water, the measured moisture content at night was slightly larger than that during the day (Figure 10).

3.2.3. Moisture Content Comparison. Figure 11 shows that there are significant differences in the moisture distribution between the soil column with and without a lid. For the soil column with a lid, the “covering effects” occurred and the water vapor accumulated under the lid (as shown in Figure 11). However, for the soil column without a lid, the top surface was a free evaporation surface. For both soil columns with and without a lid, the soil moisture content at the top all decreased compared with the initial moisture content. Nevertheless, their reduction extents show significantly different; the moisture content for the soil column with a lid decreased by 10.29%, while the moisture content for the soil column without a lid decreased by 31.24%, which is three times as much as the former. Similarly, in agriculture engineering, researchers also found that film mulching could reduce soil moisture loss, and the surface soil moisture content under film mulching conditions was higher than that under bare land conditions [35–37].

It can be seen from Figure 11 that, for both soil columns with and without a lid, the “soil lid” is formed due to the soil shrinkage. Furthermore, there were “soil covering effects” in both soil columns. The shapes of the moisture content distribution curves in the “soil covering effects” are particularly similar: the “soil covering effects” caused the water vapor to migrate upward and accumulate beneath the “soil lid,” resulting in the continuous increase in moisture content beneath the “soil lid.” However, the positions of the “soil lid” for the two kinds of soil columns were obviously different; for the soil column with a lid, the “soil lid” was located at the depth of 8 cm, which was much closer to the top, while for the soil column without a lid, the “soil lid” was located at the depth of 35 cm.

Moreover, the impacts of the “soil covering effects” on the water vapor migration were also quite different. For the soil column with a lid, the soil moisture content at the depth of 8–45 cm increased, and the largest soil moisture content was at the upper part (20 cm) of the soil column, while for the soil column without a lid, the soil moisture content at the depth of 35–45 cm showed a slight increase. Consequently, the “soil covering effects” in the soil column were much more obvious than those in the soil column without a lid. In other words, with a covering layer, the engineering damage is even greater. For highway subgrade with a sealed covering layer in arid and semiarid areas, the water vapor migration may seriously threaten the engineering stability.

3.3. Influence of Test Time on the “Covering Effects”. Figure 12(a) shows that the moisture content varied with time. The distribution curves of the moisture content at different times were similar: the soil moisture content decreased at the depth of 0–8 cm and 45–60 cm; conversely, the moisture content increased at the depth of 8–45 cm and 60 cm. Figure 12(a) also illustrates that as the test time increased, the moisture content in the upper part (8–40 cm) of the soil column became increasingly large, showing that water vapor has been migrating under the “covering effects” over time.

Here, the difference between the moisture content and the initial moisture content divided by the test time was defined as the change rate of the moisture content (%/day), and its positive and negative values were defined as increase...
rate (%/day) and decrease rate (%/day), respectively. As can be seen from Figure 12(b), the maximum increase rate of the moisture content was at the depth of 20 cm, while the maximum decrease rate of the moisture content was at the depth of 50 cm.

Figure 12(b) also shows that the change rate of the moisture content becomes smaller gradually as the test time went by. For example, at 1 day, the increase rate of the moisture content at the depth of 20 cm is 0.5%/day, and the decrease rate of the moisture content at the depth of 50 cm is –1.26%/day, whereas when the test time is 30 days, the change rate at the depth of 20 cm is only 0.06%/day, and the change rate at the depth of 50 cm is –0.13%/day. Subsequently, the change rate varied little over time; when the test time is 60 days, the change rate at the depth of 20 cm and 50 cm is 0.035%/day and –0.091%/day, respectively. This phenomenon is consistent with the conclusions drawn by Wang et al. [38], who demonstrated that the change rate of moisture content decreased with time. Luo et al. [39] also highlighted that as time increases, the coefficient of moisture migration increased but gradually stabilized.

However, it must be acknowledged that the “covering effects” and “soil covering effects” were more obvious than as time passed, and the soil moisture content at the upper part of the soil column became greater and greater (see Figure 12(a)). Eventually, it may reach saturation after a long time. It is well known that the excessively high moisture content may lead to a decrease in the strength of the soil [40–42], which eventually leads to engineering failure. Yao et al. [9] and Niu et al. [8] also emphasized that the moisture content increase at the surface soil caused by the “covering effects” would seriously threaten the safety of the engineering project.

3.4. Comparison of “Covering Effects” in the Loess and Sand Soil Columns. As shown in Figure 13, the moisture content distribution curves of the loess and sand are strikingly different. For the sand soil column, the moisture content at the depth of 0–38 cm decreased, while the soil moisture content at the depth of 40–60 cm increased. Unlike the loess soil column, the moisture content at the upper part of the sand soil column did not show an increase. There were no obvious “covering effects” or “soil covering effects” in the sand soil column. Furthermore, for the loess soil columns, the moisture content in the upper part of the soil column at night was slightly larger than during the day, while for the sand soil column, the soil moisture content at the depth of 0–38 cm at night was smaller than that during the daytime.

In general, water in the soil is affected by various forces, but not all forces can have an important influence on the moisture migration process in the soil under any circumstances. In this test, the water vapor migration in soil was mainly driven by evaporation and gravitational potential. For the sand, the soil particles were relatively larger (as shown in Figure 2), and the water holding capacity was weaker (as shown in Figure 6). Further, the permeability coefficient of sand was large. The influence of gravitational potential on the moisture migration in the sand was more significant.

During the daytime, liquid water in the pores of the sand partially converted into the vapor phase under the high temperature and migrated upward due to evaporation. Meanwhile, liquid water also moved downward under the influence of gravitational potential. Clearly, the effect of gravitational potential was significantly greater than evaporation. Wang et al. [43] also showed that the water migration in the unsaturated sand soil was dominated by liquid water by investigating the characteristics of water migration.
in unsaturated soils. Therefore, for the sand soil column, moisture migration shows a downward trend under the influence of the gravitational potential, resulting in a decrease in the moisture content in the upper part of the soil column and an increase in the moisture content of the lower part.

After extinguishing the light at night, the vapor in the pores of the sand changed into the liquid phase at the low temperature, and due to the poor water holding capacity of sand particles, liquid water further moved downward under gravitational potential. This explains why the moisture content in the upper part at night was lower than during the daytime. As a result, the moisture content in the upper part of the sand soil column decreased and the moisture content in the lower part increased.

It is interesting to note that, for the sand soil column, the reduction of moisture content does not increase with decreasing depth. At the depth of 0–10 cm, the moisture content decay decreased when the depth of the soil decreased. This may be because the soil temperature was higher near the top of the soil column, and the effect of evaporation was relatively stronger, which greatly reduced the downward migration trend of water vapor driven by the gravitational potential.

It can be found that the water vapor of the soil in the sand soil column mainly migrated downward under the driving force of gravitational potential. The phenomenon of the “covering effects” in the sand soil column was particularly insignificant compared with the loess. However, for the loess soil column, there were obvious phenomena of “covering effects” and “soil covering effects.” This may be due to the fact that the “covering effects” were more obvious when the fine particle contents increased [20], and it can be seen from Figure 5 that the loess soil contained more fine particles than the sand soil. In conclusion, soil type may be one of the important factors affecting the “covering effects.” The “covering effects” in more soil types need to be further investigated.

4. Conclusions

In arid and semiarid areas, water vapor migration is a common phenomenon and is one of the important causes of water damage in engineering. In this study, several one-side evaporation experiments were performed to explore the “covering effects” dominated by water vapor migration in unsaturated soil under the influence of diurnal temperature variations. The influence of the covering layer on the water vapor migration was illustrated by comparing the characteristics of water vapor migration in a loess soil column with and without a lid. Afterwards, the effects of test time on the “covering effects” were analyzed. In addition, the characteristics of the “covering effects” in the loess and sand soil columns were investigated. The following conclusions can be drawn:

1. The “covering effects” existed under the influence of diurnal temperature variations. However, unlike the “covering effects” under freezing conditions, the moisture content at the top of the soil column (0–8 cm) showed a decreasing trend.

2. The characteristics of water vapor migration in loess soil columns with and without a lid were quite different. It was first found that the “soil lid” and “soil covering effects” appeared in both soil columns due to the soil shrinkage. Nevertheless, the “soil covering effects” for the soil column with a lid were much more obvious than those without a lid; for the soil column with a lid, the moisture content in the upper part (8–45 cm) significantly increased, which may lead to a decrease in the mechanical properties of the soil and cause engineering failures, while for the soil column without a lid, the moisture content in the lower part of the soil column (35–45 cm) increased.

3. The “covering effects” or “soil covering effects” dominated by water vapor migration were more obvious as time went by. This led to the moisture content in the upper part of the soil column becoming increasingly large although the increase rate became smaller when the test time exceeded 20 days.

4. The “covering effects” are closely related to the soil type. The moisture migration in the sand soil column was dominated by liquid water migration and mainly moved downward affected by the gravitational potential. In this study, the “covering effects” in the loess soil column were much more obvious than those in the sand soil column.

Data Availability

All the figures and tables data used to support the findings of this study were supplied by corresponding author under
license and so cannot be made freely available. Requests for access to these data should be made to Xuesong Mao, School of Highway, Chang’an University, Middle Section of South Second Ring Road, 710064, Xi’an, Shaanxi, China (tel: 086-02982334869; email: xuesongmao@chd.edu.cn).

Conflicts of Interest

The authors declare no conflicts of interest.

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