Experimental study on water transfer of remolded loess under freezing

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Abstract. The change of the internal moisture field of the loess is an important factor for the study of the cause of the loess engineering disease, and the freezing effect has a certain effect on the change of the internal moisture field of the loess. In order to analyze the law and mechanism of water distribution in the loess under four different factors, the indoor experiments of water transfer were carried out under different temperature gradients and different temperature levels. The results show that: Under the action of freezing, the greater the temperature gradient applied on both ends of the soil sample, the farther away from the top of the steady-state freezing front, the lower the water content increment in the early stage, and the higher the water content increment in the later stage, and the more obvious the change of water content near the steady-state freezing front, the greater the total amount of water migration; For the soil samples with higher dry density, the closer the frozen front is to the top, the increase of water content in the early stage is decreasing, and that in the later stage is increasing; With the increase of the initial moisture content, the water transfer of the soil sample increases, and the position of the steady-state freezing front of the soil sample with different initial moisture content is basically the same; At different temperature levels, the lower the cold plate temperature is, the farther the frozen front is from the top. When the cold plate temperature is in a certain range, the water transfer phenomenon is significant.

1. Introduction

Loess is widely present in seasonal frozen soil areas. The surface soil temperature is low in winter, and the water in the soil migrates upward under the action of freezing. This migration causes changes in the soil’s humidification-dehumidification cycle, resulting in soil-water effects, which in turn affects the structure, strength, and deformation of the soil, so as to cause engineering diseases [1-2]. The physical and mechanical properties of soil are closely related to the changes of its internal water state. Therefore, it is of great significance to carry out the experiment of water transfer of loess under the action of freezing, to explore the law of water transfer of shallow loess field with the change of temperature in the upper part of each construction project, and to make clear the influence of freezing on the change of water content in the loess, so as to reduce the occurrence of Engineering diseases in the loess area.

The problem of loess moisture migration has always been highly concerned by experts and scholars at home and abroad. Foreign scholars such as Harlan R.L [3] and Miller [4] have revealed the general law of water transfer in soil under the action of temperature; Konrad [5] has studied the change rule of the water flux under the influence of temperature; Chinese scholar Zhao Gang [6-7] obtained the water migration rule under the influence of various factors through a large number of experiments; Ye
Wanjun [8] explored the changes in water migration of reshaped loess under different positive temperature changes; Zhang Ting [9] explored the experimental rules of water migration under the influence of different initial moisture content, different dry density and different freezing time; Zhang Hui [10] discussed the influence of soil density, freezing temperature, moisture content and freezing mode on the water transfer law of loess; Wang Tiexing [11-16] carried out a large number of laboratory experiments, studied the loess soil-water characteristic curve under the influence of density and temperature, and studied the law of mixed migration of liquid and state water under freezing and the law of water migration under different conditions of positive temperature.

In summary, the current research results are of great significance for studying the influence of different influencing factors on the water movement of the loess. However, there is little research on the influence of different temperature levels on the water transfer of loess under the action of freezing, and there is no systematic consideration of the influence of temperature gradient, dry density, initial water content and temperature level on the water transfer of loess. Based on this, this paper carries out the water transfer test of the loess under the action of freezing, studies the influence law of different factors on the water transfer of the loess, and discusses the influence mechanism of various factors on the water transfer of the loess under the action of freezing. The research results provide a theoretical basis for the formation mechanism of Engineering diseases of loess under the action of freezing.

2. Test plan

2.1. Sample preparation

The test soil sample is from the disturbed loess of Xi'an Metro Line 3, which belongs to the upper Pleistocene eolian Malan loess (Q32eol). The basic physical property parameters are shown in Table 1.1.

| Natural moisture content(%) | Saturated water content(%) | Density/(g/cm³) | Void ratio/e | Plastic limit(wp,%) | Liquid limit(wl,%) | Soil Gravity |
|----------------------------|-----------------------------|-----------------|--------------|---------------------|-------------------|-------------|
| 17.7                       | 31.09                       | 1.43            | 1.08         | 21.2                | 32.5              | 2.72        |

2.2. Test scheme

The test instrument in this paper consists of two DH-2120 low temperature thermostatic baths, KG-01 data automatic acquisition system, YXDT type frozen soil temperature and moisture change tester, and soil temperature and humidity sensors. The connection of the entire test equipment is shown in Figure 1.1.

![Fig.1.1 Schematic diagram of test instrument connection](image-url)
A total of 9 soil samples were selected for the test, and the water migration test was performed on the loess considering the effects of temperature gradient, dry density, initial moisture content, and temperature level. The specific scheme of test condition design is shown in Table 1.2.

Table 1.2 Test conditions for moisture transfer of loess under freezing

| Test number | Temperature setting | Initial moisture content (%) | Dry density (g/cm³) |
|-------------|---------------------|-----------------------------|--------------------|
|             | Roof temperature/°C | Floor temperature/°C         |                    |
| D1          | -5                  | 15                          | 16.3               | 1.40               |
| D2          | -10                 | 15                          | 16.3               | 1.40               |
| D3          | -15                 | 15                          | 16.3               | 1.40               |
| D4          | -10                 | 15                          | 16.3               | 1.25               |
| D5          | -10                 | 15                          | 16.3               | 1.55               |
| D6          | -10                 | 15                          | 11.8               | 1.40               |
| D7          | -10                 | 15                          | 20.1               | 1.40               |
| D8          | -10                 | 10                          | 16.3               | 1.40               |
| D9          | -15                 | 5                           | 16.3               | 1.40               |

2.3. Test procedure

① First, the soil is sieved through a 2mm sieve, and the required water is added according to the configuration requirements. The soil samples with the target moisture content of 11.8%, 16.3%, and 20.1% are configured, and their dimensions are 61.8mm × 20mm;

② Loading sample: Take the required soil sample and layer it into the water migration soil sample tube according to the requirements, and evenly compact it to the corresponding dry density with a compactor, 5cm per layer;

③ After compacting each layer of soil, shave the surface with a knife. A temperature sensor and a humidity sensor are respectively implanted from the reserved holes on both sides of the instrument, and the next layer of soil is filled until the design position;

④ After filling, place the top of the water bath thermostat on the soil sample, fill the contact gap in the upper part of the instrument with liquid RTV silicone rubber, so that the soil sample is in a closed system;
⑤ Wrap 5cm thick insulation cotton on the outside of the soil sample tube and on the outside of the upper and lower water bath thermostats, in order to minimize the heat exchange between the soil sample and the outside during the experiment;

⑥ Connect the test equipment (figure 1.3), in the low-temperature constant temperature bath that provides a constant temperature for the top plate, add antifreeze in proportion to industrial alcohol and water, and apply liquid-type RTV silicone rubber on the cover of the low-temperature constant temperature bath to seal it to prevent alcohol from volatilizing. The experimenters open the DH-2120 low temperature constant temperature bath and set the temperature required for the test;

![Fig.1.3 Instrument connection complete](image)

⑦ After the temperature of the liquid in the DH-2120 low temperature constant temperature bath reaches the test temperature, turn on the "cycle" switch, carry out tests, set a set of temperature and moisture content data to be collected every 30 minutes in the data acquisition system until the end of the test. Each soil sample is stable for 10 days under the set test conditions;

⑧ According to the above test steps, the other 8 soil samples are tested.

3. Analysis of test results

3.1. Influence of temperature gradient on water content distribution of soil samples

The three curves in Fig. 2.1 are the distribution curve of water content of soil samples D1, D2 and D3 with depth.

![Fig.2.1 The variation curves of soil sample D1, D2 and D3 water content with depth](image)

As we can see from the figure, under the same dry density and initial moisture content of soil sample, after different temperature gradients are applied at the upper and lower ends, the moisture content distribution in the soil sample changes very significantly. There are some differences and
regularities in the three soil sample water content curve changes, which are mainly manifested in the following four aspects:

(1) The positions of steady-state freezing fronts of soil samples with different temperature gradients at both ends are different, the greater the applied temperature gradient, the further the steady-state freezing front is from the top. Analyze the reasons: After the soil sample temperature field is stable under the action of freezing, each point of the axis presents nearly linear distribution. When the bottom plate temperature is the same, the larger the temperature gradient is, the farther the frozen surface is from the top of the soil sample, so the farther the position of the steady-state frozen front is from the top.

(2) The increment of water content at the same depth is different for soil samples with different temperature gradients applied at both ends. The greater the temperature gradient applied, the earlier the moisture content will decrease, and the latter will increase. This shows that different freezing rates have a certain effect on the water content of each point in the soil sample. The temperature potential of soil sample increases with the increase of temperature gradient, and the greater the temperature potential is, the faster the moving speed of the frozen front is in the early stage, but the amount of water migration from the unfrozen area to the frozen front decreases in the same time, resulting in a smaller increase in the water content of the unfrozen area. The temperature field stabilization speed of soil samples is proportional to the temperature gradient applied at both ends. At the later stage, the position of the stable frozen front was basically stable, and the moisture in the unfrozen area decreased to the frozen front in the same time, which resulted in a larger increase in the water content of the unfrozen area.

(3) The maximum water content of soil samples with different temperature gradients applied at both ends is different. The applied temperature gradient is directly proportional to the maximum moisture content at the front of steady-state freezing, and the smaller the minimum moisture content in the unfrozen area near it is. Under the influence of temperature potential, the moving rate of frozen front increases with the increase of temperature gradient applied on both ends of soil sample, this reduces the time needed to form a steady-state frozen front, and increases the time for the water in the unfrozen soil to migrate to a steady-state frozen front formed in advance.

(4) Soil samples with different temperature gradients on both ends have different water migration, which increases with the increase of temperature gradients. When the temperature gradient applied at both ends of the soil sample is larger, the greater the temperature potential is. In order to make the water transfer in a balanced state, more water needs to move to the frozen area.

3.2. Influence of dry density on water content distribution of soil samples
The three curves in Fig. 2.2 are the water content distribution curve of soil samples D2, D4 and D5 with depth.
From the figure, it can be seen that after the same temperature gradient is applied to both ends of the soil sample with the same initial water content and different dry density, the change of water content in the soil sample is very obvious, and the water migration of the three soil samples is basically the same. Through observation, the main performance is as follows:

(1) When other conditions are the same, different dry density soil samples have different positions of frozen front. Specifically, the higher the dry density of the soil sample, the closer the frozen front is to the top of the soil sample. This is because the saturation of soil sample increases with the increase of dry density. Under the action of freezing, the increase of water content and thermal conductivity in frozen soil area decreases, which makes the movement of frozen front more slowly.
(2) When other conditions are the same, the increase of water content at the same depth is different for different dry density soil samples. The specific rules are as follows: The water content increment of soil samples with different dry density is different before and after the test. The water content increment is less in the early stage of the test and more in the later stage. The thermal conductivity of soil sample increases with the increase of dry density. Therefore, in the early stage, the movement rate of frozen front is faster, and the water in the unfrozen area moves faster to the frozen front, which makes the increase of water content in the early stage of soil sample decrease with the increase of dry density. The saturation of soil sample increases linearly with dry density, which makes the increase of water content and thermal conductivity decrease. Thus, the movement speed of frozen front is slowed down, and the water transfer speed from unfrozen area to frozen front is accelerated, resulting in the increase of water content of soil samples with higher dry density in the later stage.

When other conditions are the same, the maximum water content of soil samples with different dry density is different. The maximum moisture content of the frozen front increases with the increase of dry density, and the minimum moisture content of the unfrozen area near the frozen front decreases. The thermal conductivity of soil sample increases with the increase of dry density, and the time needed to reach the stable frozen front is shortened. This makes the water in the unfrozen soil samples have a large amount of time to migrate to the steady-state freezing front, and the greater the water migration in the adjacent unfrozen soil samples.

3.3. Influence of initial water content on water content distribution of soil samples

The three curves in Fig. 2.3 are the water content distribution curve with depth of soil samples D2, D6 and D7.
Fig. 2.3 The variation curves of soil sample D2, D6 and D7 water content with depth

As we can see from the figure. By applying the same temperature gradient to the upper and lower ends of soil samples with the same dry density and different initial moisture content, the distribution of water content in soil samples has changed significantly, and the positions of steady-state freezing front of three soil samples are basically the same. It shows that the initial moisture content has little effect on the position of the steady freezing front. It can also be seen from the figure that there are certain differences in the water content curve of three groups of soil samples with different initial moisture. With the increase of soil moisture content, the water transfer increases, and the change range of water content increases at the end of the test. Analysis cause: When the dry density and temperature gradient are constant, the thermal conductivity of soil increases with the increase of initial moisture content, and the stable frozen front reaches a stable state faster. Therefore, the soil samples with larger initial moisture content in the unfrozen area have more time to migrate and supply to the freezing front. At the end of the test, the larger the soil water content is, the greater the water migration is.

3.4. Influence of different temperature levels on water content distribution of soil samples

The three curves in Fig. 2.4 are the water content distribution curve with depth of soil samples D1, D8 and D9.

Fig. 2.4 The variation curves of soil sample D1, D8 and D9 water content with depth

From the above figure, after applying the same temperature gradient and different temperature levels to the two ends of soil samples with the same initial moisture content and dry density. The
distribution of water content in soil samples has changed significantly, and the distribution curves of water content in different soil samples are different. The specific performance is as follows: The lower the cold plate temperature is, the farther the frozen front is from the top. Under the action of freezing, the temperature of each point on the axis of soil sample is nearly linear. For the soil samples with the same temperature applied at both ends, the lower the bottom temperature is, the farther the freezing temperature is from the top, and the farther the position of the stable freezing front is from the top. It can also be seen from the above figure that the influence of different temperature levels on soil sample water distribution has certain limitations. The results show that when the cold plate temperature is too high or too low, the moisture transfer and the moisture content of the steady-state frozen cover are smaller than that of the soil samples with the cold plate temperature in a certain range. Analyze the reasons, it is generally believed that the lower the cold plate temperature is, the closer the initial freezing temperature is to the bottom of the soil sample. At the same time, the faster the temperature field changes, the higher the water migration of the soil sample and the water content at the steady-state frozen front. However, since we are conducting experiments under self-made closed conditions, there is no source of external water supply. Therefore, for this test, although the steady-state frozen front of soil samples with a temperature level of $5\degree C-(-15)\degree C$ is the fastest. Due to the lack of water provided by the unfrozen area, the water content of the soil sample is small, and the total amount of water migration is also small.

4. Conclusions

(1) Under the action of freezing, the positions of frozen front of soil samples with different temperature gradients on both ends are different. The greater the temperature gradient is, the farther the frozen front is from the top. The larger the peak value of water content in the frozen front is, the smaller the minimum value of water content in the unfrozen area near the frozen front is, the larger the total amount of water migration is, and the increment of water content in the former and later stages is different.

(2) When other conditions are the same, the position of steady freezing front, the increment of water content at the same depth and the maximum value of water content of soil samples with different dry densities are different.

(3) The initial moisture content has little influence on the position of the steady-state freezing front, and the total amount of water transfer increases with the increase of the moisture content of the soil sample, and the change range of the moisture content of the soil sample also increases.

(4) The experimenters set up three groups of soil samples, their initial moisture content is equal, and their dry density is also equal. After applying the same temperature gradient to the two ends of these three groups of soil samples, but the temperature difference of different temperature levels. The lower the temperature of the cold plate is, the farther away from the top of the frozen front is. Under the action of freezing, the temperature of each point on the axis of soil sample is nearly linear distribution, and the influence of different temperature levels on the water distribution of soil sample has certain limitations.

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