Study on water and salt migration of saline soil under the condition of freeze-thaw cycles

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Abstract
In order to study the effect of freeze-thaw cycles on the water-salt migration of saline soil subgrade, the saline soil was subjected to zero, three, five, seven and nine times respectively under the conditions of optimum water content and salt content of 2%. The sub-freeze-thaw cycle test was carried out to monitor the change of water and salt, and the test results were compared and analyzed. The results show that with the increase of freeze-thaw cycle times, the water content at each layer height increases and the water channel gradually penetrates. The water content shows a tendency of upper part and small part. The initial state salt is evenly distributed. With the increase of freeze-thaw cycle times and with the boundary of 40cm, the salt content of the upper part of the soil column shows an increasing trend, and the salt content of the lower part shows a decreasing trend. The salt migration channel begins to form after the three cycles. After the channel is completely formed, the salt in the subgrade gradually migrates from the bottom to the cold end; the freeze-thaw cycle contributes to the formation of water and salt migration channels, and promotes the migration of water and salt.

Key words: freeze-thaw cycles, saline soil, water, salt, migration

1 Introduction
Saline soil is a poorly used soil in road engineering. When it is used as a roadbed filler, the roadbed is prone to diseases such as subsidence, salt swelling and corrosion, which is harmful to road construction in saline soil areas [1, 2]. Under the external environmental factors, due to the temperature difference between day and night and the change of seasons, the subgrade in the soil will undergo freezing and melting processes. As the temperature changes, the water movement in the subgrade will also change. For the subgrade in the saline soil area, during the movement of water, there is also the movement of salt, and the change of the temperature of the outer boundary. The roadbed in the saline soil area is prone to various diseases, and in this process, the water and salt migration is a more complicated process. Therefore, it is important to study the water-salt migration of subgrade in saline soil under the conditions of freezing and thawing.

At present, domestic and foreign scholars have done a lot of research on the water and salt migration of saline soil under the conditions of freezing and thawing. In 1961, Skopp J and Nielsen [3, 4] obtained experimental equations to obtain the equations of motion for the migration of water, heat and salt in soil. Hanlan [5], Taylor [6] and Cary [7] constructed a one-dimensional hydrothermal motion model of unsaturated frozen soil. Gray [8] analyzed the dynamic migration law of water and salt in unsaturated soil in frozen state by numerical simulation method, and studied the variation of water and salt in saline soil under the action of multiple factors of water and heat; PP Overduin [9] analyzed the law of water and salt migration of saline soil through indoor freezing test, and concluded that the migration of water and salt still occurred in the frozen saline soil. Shafique U [10] carried out laboratory experiments to analyze the transport law of salt ions in the salt solution during the freezing...
process. Bao Weixing [11] took natural saline soil as the research object and carried out freeze-thaw cycle test study on it under the condition of open system. The study showed that under the action of freeze-thaw cycle, the soluble salts in the soil moved together with water and had great consistency in distribution, and salt migrated from bottom to top or to the cold end; Xu Shuang [12] took Inner Mongolia saline soil as the research object, carried out indoor freezing and thawing experiments on reshaped soil, and explored the law of water and salt migration and change in the freezing and thawing process of saline soil. Wang Wenhua [13] carried out the moisture transfer test of soil samples by direct method and freeze-thaw method through large-scale indoor simulation test, studied the changes of soil salt content and water content before and after freeze-thaw, and analyzed the water and salt transfer characteristics of soil. Wu Daoyong [14] prepared silty clay with different salt content for salinized permafrost and conducted one-way freezing model test. The results showed that water and salt migrated vertically upward when the temperature decreased, and in the process of temperature rise, they migrated in opposite directions. Hu Jianrong, Zhang Hong et al[15] tested the moisture content and electrical conductivity of model soil column with a self-made test device, and studied the influence of temperature gradient on the water and salt migration rule in subgrade under the condition of optimal moisture content. Based on laboratory tests, this paper simulates the change of water and salinity of saline soil roadbed under climate change conditions, and studies the law of water and salt migration in order to provide basis for roadbed disease prevention and control in saline soil area.

2 Experimental design of water and salt migration of saline soil under freezing and thawing cycles

2.1 Basic parameters of the sample

The test soil was selected from the northern suburbs of Xi'an and belong to fine-grained soil. The soil particle analysis was shown in Table 1. After manually preparing the sulfate saline soil with a salt content of 2%, according to Test Methods of Soils for Highway Engineering (JTG E40-2007) [16], the indoor test analysis can obtain: the optimum water content is 15.95%, and the maximum dry density is 1.733g/cm³, the liquid limit is 28.4%, the plastic limit is 17.7%, and the plasticity index is 10.7.

<table>
<thead>
<tr>
<th>Soil particle diameter (nm)</th>
<th>&lt;0.002</th>
<th>0.002-0.005</th>
<th>0.005-0.01</th>
<th>0.01-0.075</th>
<th>&gt;0.075</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil particle mass percentage (%)</td>
<td>22.3</td>
<td>17.4</td>
<td>15.7</td>
<td>42.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

2.2 Test plan

The freeze-thaw cycle test of soil column in saline soil was carried out by freeze-thaw testing machine. The soil column had a salt content of 2%, an upper water content of 10%, a lower water content of 15%, and a freeze-thaw cycle of zero times, three times, five times, seven times, nine times. The upper temperature limit was set to 5℃ and the lower temperature limit was set to -20℃. Each cycle was 48h (freezing 24h, melting 24h). In order to simulate the actual freezing and thawing condition of saline soil in natural environment, the experiment adopted a mode in which the upper layer temperature was low and the lower layer temperature was high, and the temperature rise was adopted as the natural rewarming mode. In order to prevent the heat exchange between the soil column and the external environment,
the plexiglass tube was wrapped with an insulating sponge and sealed with tape. In order to prevent salt migration from the side wall of the test tube sensor hole overflow, a glass seal was used.

2.3 Test procedure

(1) Filling in the test mode. In the test, the height of the filled soil column was 55cm, and the soil sample was filled in 5 layers. The control compaction degree was 94%. Sensors were installed at the height of 15, 25, 35, 45 and 55cm, respectively, to measure the moisture content and salt content at different heights of the soil column.

(2) After the filling was completed, a cooling head was installed at the bottom and top of the sample. The cooling head was connected to the cold bath and they were connected to the freeze-thaw cycle machine. After the sealing package was completed, opened the freeze-thaw cycle machine and started cooling at the set temperature.

(3) The sensor was connected to the data acquisition instrument and recorded the test data.

3 Analysis of water and salt migration characteristics under freezing and thawing cycles

3.1 Analysis of water and salt migration after three freeze-thaw cycles

![Graph showing volume moisture content after three freeze-thaw cycles](image)

a. volume moisture content
It can be seen from Fig. 1a that after three freeze-thaw cycles, compared with the initial state moisture content, the moisture content at each layer presents an increasing trend, and the water distribution of soil pillar roadbed at different heights generally presents a parabolic shape of opening to the right. Under 35 cm, the closer to the bottom of the specimen, the greater the water content will be. The water content at the bottom of 15 cm is the largest, and the volume water content reaches about 31.45%. The soil volume moisture content at 35 cm is the smallest, which is about 28.6%. This is mainly due to the water migrate from the lower unfrozen soil layer to the upper frozen soil layer, which increases the water content of the upper soil layer. The bottom of the test piece is under the action of hydration, so that the bottom water content increases rapidly. The water content also increases correspondingly at 25~35 cm, but the migration amount is relatively weak, indicating that the water migration channel in the soil column subgrade has not been formed after three freeze-thaw cycles.

It can be seen from Fig. 1b that the change curve of salt migration in roadbed is different from that of water, and the distribution curve of salt presents a "3" shape, indicating that salt migration under the action of freeze-thaw cycle is more than a simple state of salt walking with water. Compared with the initial state of salt content, at the height of 15, 35 and 55 cm, salt content decreases, and the salt content of the middle tier level reduces the most, and at the height of 25, 45 cm, salt content increases, which shows that after three freeze-thaw cycles, salt migration in roadbed happen to both ends up and down by the middle tier level, but at this stage salt mainly migrate to the cold end.

3.2 Analysis of water and salt migration after five freeze-thaw cycles
Fig. 2 Curve of water content and salinity of soil column after five freeze-thaw cycles

As you can see from Fig. 2a, after five freeze-thaw cycles, the moisture content distribution at each layer is still open to the right of the parabolic form. Compared with the curve after three freeze-thaw cycles, the moisture content still increases with the height. The difference is that compared with three freeze-thaw cycles, the water transfer amount of each soil layer in the subgrade increases, and the bottom moisture content increases slightly, but the increase is mainly at the height above 25cm. This indicates that with the increase of freeze-thaw cycles, water transfer channels within soil pillar subgrade are gradually forming, and water transfer starts from the bottom to the top.

As can be seen from Fig. 2b, compared with three freeze-thaw cycles, the distribution of salt in the roadbed changes. In addition to the subgrade height of 25cm and 45cm, the salinity
of other layers is lower than the initial salinity, and the salinity of 55cm changes from the previous decreasing trend to an increasing trend, which is about 1.96%, and the salinity migration of other soil layers increases. After five freeze-thaw cycles, subgrade internal salt migration channel begin to form, making the salt migration rate from the bottom to the cold end is higher than that after three cycles salt. However, due to the short freezing-thawing cycle time, the salt channel has not been completely formed, showing the difference of salt content in different layers.

3.3 Analysis of water and salt migration after seven freeze-thaw cycles

![Graph of water content and salinity](image)

**Fig.3** Curve of water content and salinity of soil column after seven freeze-thaw cycles
It can be seen from Fig.3a that after seven freeze-thaw cycles, the shape of the water distribution curve in the soil column has changed, and the water content increases with height. In the end, the water content at the height of 55cm is the largest, and the water content is about 36%, while the water content at the bottom is still not obvious. This is because after seven freeze-thaw cycles, the water transfer channel in the subgrade has been completely formed, resulting in the continuous upward migration of water at the bottom. However, under the condition of constant groundwater recharge, the change of water content has been in a relatively stable state with only small fluctuations.

It can be seen from Fig.3b that after seven freeze-thaw cycles, the salt in the soil column subgrade migrates from the middle to the both ends, and the salt content at 45cm is higher than the initial salt content. The salt content at 25cm and 55cm is close to the initial state, and the salt content at the bottom end is decreasing from the previous one, indicating that the salt is also moving from the bottom upward, and the salt migration channel inside the subgrade gradually forms.

3.4 Analysis of water and salt migration after nine freeze-thaw cycles
b. salt content

Fig.4   Curve of water content and salinity of soil column after nine freeze-thaw cycles

It can be seen from Fig.4a that the water distribution law is basically the same as seven freeze-thaw cycles, and the water content at each layer height is not changed much. The water content generally tends to be stable and the water distribution law is stronger. The migration of water from the bottom to the top occurs, and the moisture content at each layer basically reaches a stable state, which indicates that the saline soil subgrade has been completely formed and continuous in this stage, that is, the moisture migrates to the cold end.

It can be seen from Fig.4b that the salt distribution of the soil column after nine freeze-thaw cycles is similar to that of the last freeze-thaw cycle, and the salt content below the intermediate layer is decreasing. The amount of salt is increasing, and the salt migration is large at the height of 25~45cm. At the top, the salt content increases but the increment is small, which is mainly related to the physical properties of sodium sulfate, and its solubility is closely related to the temperature. With the decrease of temperature, the salt content in the water crystallizes out. However, the salt content still increases, indicating that under the action of freeze-thaw, the salt migrate to the cold end due to the effect of temperature, and its migration trend is more obvious than last time. It can be seen that salt migration channels have been fully formed under the action of nine freeze-thaw cycles.

3.5 Analysis of migration of water and salt with freeze-thaw cycles

In order to more intuitively compare and analyze the distribution of water content and salt content at different heights in the soil column roadbed under the action of freeze-thaw cycles, there are five states of zero, three, five, seven, and nine freeze-thaw cycles. The values of water content and salt content in the soil column are plotted in a graph for comparison and analysis. The distribution curves of water content and salt content are shown in Fig.5 and Fig.6 respectively.
Fig. 5  Curve of water content change at each height of soil column after freeze-thaw cycle

It can be seen from Fig. 5 that compared with the initial state water content, with the increase of the number of freeze-thaw cycles, the moisture content at each layer of soil column increases. After five freeze-thaw cycles, the moisture content at the bottom does not change significantly. The main reason is that the increment of water content is large and almost reaches the saturation state. Before seven freeze-thaw cycles, water transfer mainly occurs at the height of 35cm or above, which is mainly because the water transfer channel in the soil column subgrade has not been fully formed in the early freeze-thaw cycle. In the freeze-thaw state, the temperature difference at the cold end is large, forming a large temperature gradient, and the soil at the cold end also has a high salinity. But for the sodium sulfate saline soil, the salt concentration is high, which is beneficial to reduce the freezing point of water, so that the moisture in the middle layer rapidly migrates from the high temperature zone to the low temperature zone. And the moisture migrates in the lower part, but it is weak. After seven freeze-thaw cycles, the water transfer channel in the soil pillar subgrade has been completely formed, and the water transfer phenomenon is obvious from the bottom to the top. After nine freeze-thaw cycles, the moisture content at various heights is almost stable and reaches a state of equilibrium. The results show that the freeze-thaw cycle contributes to the formation of water transfer channels in subgrade and promotes water transfer.
According to the comparative analysis of salinity ratios at different heights of soil column subgrade after freeze-thaw cycle in Fig. 6, in the early freeze-thaw period, due to the randomness of particle size, pore size and mineral composition of saline soil filler at different heights of soil column subgrade, the salt migration channel has not been formed. After three and five freeze-thaw cycles, the salt migration is localized, and it is not simple that the salt migrates from the bottom to the top. Above the 35cm height of the soil column, the salt curve has a large fluctuation. The salt content of subgrade soil within this height range migrates to the cold end with the capillary water under the action of temperature potential, and the amount of salt content migrates gradually with the increase of freeze-thaw cycle. In addition, the salt content of soil layer migrates weakly. With the increase of the number of freeze-thaw cycles, the internal water and salt migration channels gradually form and penetrate, and the salt in the subgrade also begin to migrate from the warm end to the cold end on the whole, and the migration is obvious. The salt content increases significantly at the height of 45cm, mainly due to the fact that the soil layer filler above this height is almost in contact with the external environment and is in the maximum negative temperature zone when frozen, resulting in the upward migration of salt in this layer under the action of temperature gradient. But because the solubility of sodium sulfate decreases with temperature, only a small fraction can migrate up, while the rest has crystallized. When it melts, the water will carry salt with it. Under the action of its own gravity potential, the water will migrate along the pores to the embankment at a height of 45cm, so there is a high salinity at a height of 45cm. From the distribution trend of the whole curve, salt migrates from the bottom to the top. After the test, it can be seen that salt accumulates at the top, and the freeze-thaw cycle promotes the formation.
of salt migration channels.

4 Conclusions

1) With the increase of the number of freeze-thaw cycles, the internal moisture content of the test piece shows an increasing trend. When the freeze-thaw cycle is 3 to 5 times, the water migration channel is not penetrated, and the water content of the upper and lower parts of the soil column is larger than that of the soil column. As the number of freeze-thaw cycles increases, the water channel gradually penetrates, and the water content at each layer height increases, and the water content shows a tendency of large upper part and small lower part.

2) The salt content in the initial state is evenly distributed. With the increase of the number of freeze-thaw cycles, the salt content of the upper part of the soil column increases with the 40cm boundary line, and the salt content of the lower part shows a decreasing trend. In the first three cycles, the salt migration channel in the saline soil roadbed was not formed, and the salt mainly migrated from the middle layer to the upper and lower layers. The salt migration channel begins to form after the third cycle. When the salt migration channel is completely formed, the salt in the subgrade gradually migrates from the bottom to the cold end. Compared with the initial state, the salt content of the top is only slightly increased.

3) Under the whole freeze-thaw cycle, a comprehensive analysis of the water-salt migration of the soil is carried out, and it is concluded that the freeze-thaw cycle contributes to the formation of water and salt migration channels and promotes the migration of water and salt.

References
[11] Bao Weixing, Xi Yongli, Yang Xiaohua. Experimental study on water-salt migration and


