Research on frost heave of channels in cold areas based on electroosmotic drainage

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Abstract:In order to study the influence of electroosmosis treatment channel foundation soil on frost heave failure of concrete lining channel in cold areas under different voltages, the surface temperature of concrete lining was calculated according to the principles of atmospheric physics and thermal radiation. The finite element software was used to simulate the use of 20V, 40V and 60V voltage electroosmosis to treat the channel foundation soil, reduce the moisture content of the canal foundation soil, and numerically simulate the frost heave of the lining channel. The results show that after 20V, 40V and 60V voltage electroosmosis treatment, the moisture content of the base soil tends to be stable after 59h, 71h and 90h, respectively, and the moisture content can be reduced by 46.9%, 51.7% and 58.4% respectively compared with the non-electroosmosis treatment. The normal frost heave can be reduced by 37.4%, 42.3% and 49.0% respectively at 20V, 40V and 60V voltages. The normal frost heave force can be reduced by 14.3%, 22.4% and 30.6% respectively at 20V, 40V and 60V voltages. The tangential freezing force can be reduced by 14.3%, 25.1% and 33.9% respectively at 20V, 40V and 60V voltages. The results of this study can provide a reference for channel reduction of frost heave.

1.Introduction

China is the world's third-largest permafrost country, and cold regions account for about 75% of the country's land area. Water transmission channels in cold areas often appear in the form of bulging, bulging, warping, overhead, instability and collapse, and the water loss in irrigation areas accounts for nearly 50% of the total agricultural water use, and the leakage and frost damage of the channels seriously restrict the healthy development of irrigation areas and the safe and efficient operation of water diversion projects[1].Many scholars have carried out research on anti-frost heave measures from different perspectives, such as channel insulation, replacement of canal foundation soil, structural optimization and canal foundation drainage. Zhang Dong et al.[2]and Lu Xiangyu et al.[3]proposed to lay insulation boards of different thicknesses under the concrete lining of the channel, which provided technical support for the thickness design of the insulation board in the subsequent construction of the channel lining. Sun Jie et al.[4]proposed the anti-frost heave technology of mold bag concrete channel, and used different schemes to combine mold bag concrete with polystyrene board, and the results showed that this measure could reduce the frost heave amount of the channel. Liu et al.[5]used the anti-frost heave and thaw settlement scheme of block stone replacement for the channel foundation, and the results showed that the block stone replacement channel had excellent frost heave and thaw settlement effect. Li Zhuo et al.[6]treated the channel with geobags, and the results showed that this measure had a certain anti-frost heave effect on the frozen soil canal slope. Wang Yi et al.[7]used the hierarchical sequence method to construct a dual-objective optimization method for hydraulic and frost heave resistance of the channel section, and the results showed that the optimized channel improved the adaptability to frost heave deformation. Wang Zhengzhong[8]studied the mechanism and quantitative influence of different longitudinal joints in rigid lining channels to reduce frost heave, and the results showed that reasonable longitudinal joints can make the frost heave distribution more uniform and reduce the frost heave failure of rigid lining channels. Wang Xucun et al. [9] used a combination of capillary permeable drainage belt and drainage pipe to remove groundwater from the base soil and reduce the water content in the embankment soil, but the drainage rate was low. Meyer, CR[10] combined a mechanical model with an enthalpy method to explain ice lens formation, predicting the thickness of the frozen edge and the spacing of ice lenses in subglacial and subglacial sediments. Potter J C[11] injects an intumescent structural polymer underneath the road for insulation, effectively reducing frost heave under the road Sarsembayeva A[12] provided a more realistic laboratory approach to assessing potential freeze-thaw impacts, and the effects of de-icing agents on soils beneath roads, and in different settings..For the existing anti-frost heave measures, the main ideas are to take insulation board insulation, use joints to alleviate the frost heave stress of the channel,

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etc., and the electroosmosis drainage method is mostly used to deal with silt soil and soft soil foundation reinforcement, etc, but has not been applied in the field of channel frost heave. In order to reduce the damage of the moisture in the channel foundation soil to the frost heave of the channel, the electroosmosis treatment of the channel base soil is used in this paper, which can quickly discharge the moisture in the soil from the frozen soil layer in a short time before the channel soil temperature reaches the freezing temperature, so as to avoid the frost heave damage of the channel. In this paper, the frost heave of the channel after different voltages are treated, and the frost heave amount and frost heave force of the channel are reduced to a certain extent. By applying the electroosmotic drainage method simulation, in order to provide a new anti-frost heave method for the channel.

2. Methodology

Permafrost is a heterogeneous, anisotropic four-phase complex composed of four basic components: solid particles, ice, liquid water, and gas[13]. The mechanical properties of frozen soil are affected by the composition and proportion of each phase, and its failure characteristics are extremely complex and unstable. To facilitate analysis, the model is simplified appropriately.

2.1 Basic Assumptions

For the mathematical model of channel frost heave, the following assumptions are made:

(1) The soil of the canal foundation is regarded as a uniform, continuous and isotropic material;

(2) The frost heave problem of the channel was treated as a plane strain problem;

(3) The migration change of water during the freezing process is only considered by the migration of liquid water;

(4) The charge transfer in the soil satisfies Ohm's law;

2.2 Governing equations of temperature field

According to Fourier's law, the differential equation for heat conduction of the model is:

$$\rho C(\theta)\frac{\partial T}{\partial t} = \lambda(\theta)\nabla^2 T + L\cdot\rho_I\frac{\partial\theta_I}{\partial t} \tag{1}$$

where: ρ is the density of the soil,kg/m3; $C(\theta)$ is the volumetric heat capacity,J/kg·°C; T s the temperature, °C; t is the time, s; λ is the thermal conductivity; θ is the volumetric moisture content; L is the latent heat of phase change, which is generally 334.56kJ/kg; ρ_I is the ice density, kg/m3; θ_I is the volume content of void ice.

2.3 Governing equations of the moisture field

The law of water transport in soil conforms to Richards' equation:

$$\frac{\partial\theta_u}{\partial t}+\frac{\rho_I}{\rho_w}\frac{\partial\theta_I}{\partial t}=\nabla\left[D(\theta_u)\nabla\theta_u+k(\theta_u)\right] \tag{2}$$

where: θ_u is the volume of unfrozen water; ρ_w is the density of water, kg/m3; k is the permeability coefficient of the soil.

The introduction of the solid-liquid ratio[14], which represents the ratio of the volume of pore ice in the permafrost to the volume of unfrozen water, is denoted as B_I representation.

$$B_I=\frac{\theta_I}{\theta_u}=\begin{cases}1.1\left(\dfrac{T}{T_f}\right)^B-1 & (T<T_f)\\ 0 & (T\ge T_f)\end{cases} \tag{3}$$

where B is a constant, which is related to soil type and salt content, and the empirical value is 0.56, and T_f is the freezing temperature of the soil, °C.

2.4 Governing equations of stress field

Equilibrium Equation:

$$L\sigma = 0 \tag{4}$$

Geometric equations:

$$\varepsilon = Lu \tag{5}$$

Thereinto:

$$L=\begin{bmatrix}\frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z}\\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0\\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x}\end{bmatrix} \tag{6}$$

The temperature-dependent stress-strain constitutive equation is:

$$\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{Bmatrix}=\begin{bmatrix}\frac{1}{E} & -\frac{\mu}{E} & -\frac{\mu}{E} & 0 & 0 & 0\\ -\frac{\mu}{E} & \frac{1}{E} & -\frac{\mu}{E} & 0 & 0 & 0\\ -\frac{\mu}{E} & -\frac{\mu}{E} & \frac{1}{E} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{2(1+\mu)}{E} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{2(1+\mu)}{E} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{2(1+\mu)}{E}\end{bmatrix}\times\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{zx}\end{Bmatrix}+\begin{Bmatrix}\alpha\\ \alpha\\ \alpha\\ 0\\ 0\\ 0\end{Bmatrix}\times\Delta T \tag{7}$$

where σ_x , σ_y and σ_z are positive strains in the x, y, and z directions, respectively; γ_{xy} , γ_{yz} , and γ_{zx} are shear strains in the x, y, and z directions, respectively; σ_x , σ_y and σ_z are normal stresses in the x, y, and z directions, respectively. τ_{xy} , τ_{yz} and τ_{zx} are the shear stresses in the x, y, and z directions, respectively. E

is the elastic modulus of the canal foundation soil, Mpa; α is the expansion coefficient of the soil line of the canal foundation; ΔT temperature gradient of the base soil of the T canal; Poisson's ratio of the μ canal base soil.

2.5 Principle of electroosmosis

When an electrode is inserted in a soil-water system and an electric current is applied, the water molecules in the soil will gradually migrate from the anode to the cathode under the action of the electric field, and the anode water molecules will gradually decrease, and the moisture content of the nearby soil will gradually decrease.

The electrolytic reaction of water occurs when the electricity is applied:

Near the anode:

$$2H_20+4\mathrm{e}^{-1}\rightarrow O_2\uparrow+4H^+ \tag{8}$$

Near the cathode:

$$4H_20-4\mathrm{e}^{-1}\rightarrow 2H_2\uparrow+4OH^- \tag{9}$$

3. Results and discussions

3.1 Finite element model and parameter selection

Taking the water conveyance channel in an irrigation area of Xinjiang as an example, the channel is a trapezoidal channel lined with concrete slab, and the channel section is shown in Figure 1. The irrigation area belongs to the seasonal permafrost area, with an average temperature of 6.3 °C for many years, an extreme minimum temperature of -36.8 °C for all years, and an average groundwater depth of more than 30m. The channel base soil is silty loam, which belongs to frost heave soil, with a maximum permafrost depth of 1.43m and an initial volume moisture content of 43.7%. The strength grade of the concrete lining is C20, the thickness of the yin and yang slope and the bottom plate lining is 12cm, the elastic modulus is 2.55×104Mpa, the elastic modulus of unfrozen soil is 15MPa. The values of the main material calculation parameters are shown in Table 1.

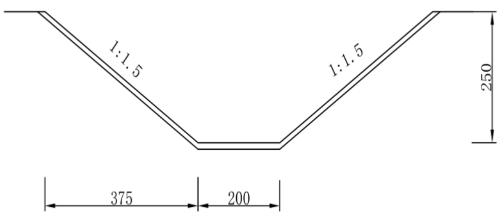

Figure.1. Trapezoidal channel size

Table 1 Material calculation parameters

parameter	Concrete	Frozen soil	Unfrozen soil
$\lambda/\left(W\cdot\mathrm{m}^{-1}K^{-1}\right)$	1.51	2.04	1.46
$C_\mathrm{p}/\left(J\cdot kg^{-1}\cdot K^{-1}\right)$	970	1320	2050
$C_v/\left(J\cdot m^{-3}\cdot K^{-1}\right)$	0.39	0.83	1.28
$\rho/\left(kg\cdot m^{-3}\right)$	2500	1600	1600
μ	0.167	0.330	0.375

Note: λ :Thermal conductivity, C_p :Specific heat capacity, C_v :Volumetric heat capacity, ρ :density, μ : Poisson's ratio.

According to the size and basic situation of the prototype channel, the upper part is the channel concrete lining, the lower part is the channel foundation soil, and the finite element model is shown in Figure 2, and the model simulates the lining plate and the channel foundation soil as a whole.

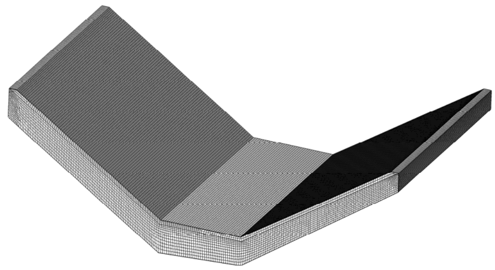

Figure 2: Finite element diagram of a trapezoidal channel

3.2 Boundary conditions

The upper boundary temperature of the model is the surface temperature of the lining, the temperature of each part of the surface of the prototype channel lining plate is calculated, the temperature at the lower boundary of the soil is 0°C, and the left and right boundaries are the thermal insulation boundaries.

Displacement constraints: The upper boundary of the model is free, and the left and right boundaries and the lower boundary are fixed end constraints.

Under different working conditions, the upper surface of the soil is the anode, and its potential values are 0V, 20V, 40V and 60V, respectively, and the lower surface is the cathode, and its potential values are 0. The left and right boundaries of the soil are insulated, and the overall electric potential value is 0. The upper boundary and the left and right boundaries of the soil are in an influid state, and the lower boundary is in a state of free water seepage.

The initial values under different working conditions are shown in Table 2.

Table 2 Simulated working conditions

Operating conditions	Initial volumetric moisture content/%	Voltage/V
I	42.7	0
II	42.7	20
III	42.7	40
IV	42.7	60

3.3 Temperature field analysis

The numerical simulation results of the temperature field are shown in Figure 3, with the shady slope on the left side of the channel, the sunny slope on the right side, and the bottom of the channel in the middle. Because the channel is east-west, the solar radiation energy received by the yin-yang slope and the bottom of the channel is different, resulting in different temperature and moisture distribution of the yin-yang slope and the bottom of the channel, as well as differences in frost heave and freezing depth. From the numerical simulation results, it can be seen that the temperature field is asymmetrically distributed, and the temperature gradient between the shady slope and the bottom of the canal is obviously greater than that of the sunny slope, and the calculated results of the temperature field are in line with the actual frost heave law.

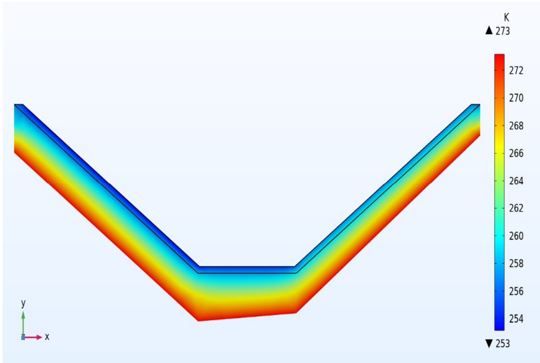

Figure 3: Temperature field contour

3.4Moisture content analysis

The change curve of the volumetric moisture content of the channel base soil under different working conditions is shown in Figure 4. In the process of electroosmosis, the moisture content of the soil continues to decrease. With the increase of the energizing voltage, the volume moisture content of the base soil decreases greater. When the electrification voltage is 20V, the moisture content of the soil does not change significantly after 59 hours of continuous energization, and finally decreases to 23.6%. When the energizing voltage is 40V, the moisture content changes slowly and decreases to 21.3% after continuous energizing for 71 hours. When the energizing voltage is 60V, the final moisture content is reduced to 18.5% after continuous energizing for 90 hours. Compared with the non-electroosmotic treatment of the canal foundation, the moisture content of the canal foundation was reduced by 46.9%, 51.7% and 58.4% after 20V, 40V and 60V treatment, respectively. According to the change of moisture content, the soil moisture content is low when the voltage is 60V, which can be used in the actual drainage project of the canal foundation, so as to reduce the frost heave damage of the channel.

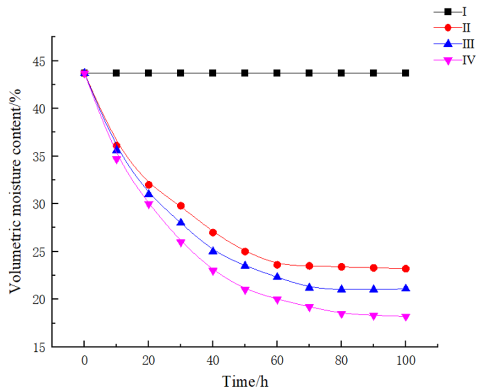

Figure. 4 Curve of volume moisture content

3.5 Analysis of frost heave amount

The variation curve of frost heave along the unfolding length of the channel section is shown in Figure 5. The frost heave amount of shady slope is the largest, followed by the sunny slope, and the bottom of the canal is the smallest, because the frost depth of the yin and yang slopes is larger, and the frost heave soil is more. The simulation results show that the frost heave amount increases gradually from the foot of the slope to the top of the slope, and reaches the maximum value in the middle of the bottom of the canal and about 1/3 of the length of the slope near the foot of the slope. The maximum frost heave at the bottom of the canal is 72.5mm, the maximum frost heave is 94.1mm on the shady slope, and 83.9mm on the sunny slope. When the energizing voltage is 20V, the frost heave amount is significantly reduced, and the frost heave amount can be reduced by up to 35.2mm, which is 37.4%, compared with the non-electroosmotic treatment canal foundation. When the energizing voltage is 40V and 60V, the frost heave amount is reduced by 42.3% and 49.0% respectively compared with the non-electroosmotic treatment foundation. According to the change of frost heave amount, the frost heave amount decreases differently when different voltages are used to treat the canal foundation. The larger the voltage, the more drainage of the base soil, the smaller the moisture content, and the smaller the frost heave. On the contrary, the smaller the voltage, the less the drainage of the base soil, the greater the moisture content, and the greater the frost heave.

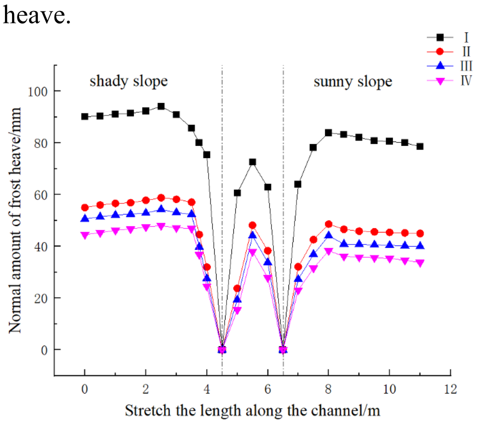

Figure. 5 Frost heave change curve

3.6 Normal frost heave force analysis

As can be seen from Figure 6, the overall distribution of normal frost heave force is that the yin-yang slope of the channel is larger than the bottom of the channel, smaller at the upper part and larger at the bottom of the slope, and is approximately evenly distributed at the bottom of the channel, which is basically consistent with the conclusions of other scholars [15-16]. Because the channel base soil of frost heave is limited by the lining plate, the frost heave amount near the foot of the slope is very small, and the stress can not be released, resulting in a great frost heave force, when the frost heave force exceeds the strength limit of concrete, the channel lining will be damaged, thereby causing the channel to leak, and aggravating the frost heave damage. The maximum normal frost heave force is 4.9Mpa for shady slope and 4.4Mpa for sunny slope without electroosmosis treatment. When the energizing voltage is 20V, the normal frost heave force in the shady slope is reduced by 0.7Mpa, which is reduced by 14.3%, and the maximum frost heave force on the sunny slope is reduced by 0.6Mpa. When the energizing voltage is 40V and 60V, the normal frost heave force is reduced by 22.4% and 30.6% respectively compared with the non-electroosmotic treatment foundation.

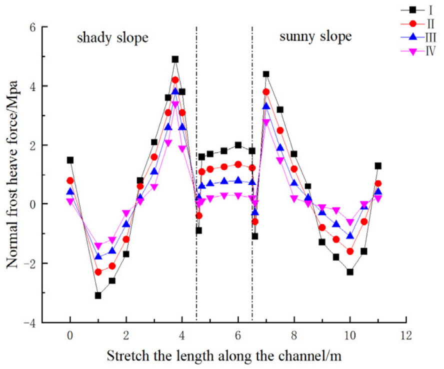

Figure. 6 Normal frost heave force curve

3.7 Tangential freezing force analysis

The tangential freezing force distribution is shown in Figure 7. The tangential freezing force is small at the top of the yin and yang slopes, and close to zero at the bottom of the channel. The tangential freezing force of the yin and yang slopes gradually increased from the top of the slope to the foot of the slope, and reached the maximum value near the foot of the slope, and the tangential freezing force of the yin slope was slightly greater than that of the sunny slope, with a maximum of 5.6 MPa on the shady slope and 5.2 MPa on the sunny slope. The tangential freezing force is about 1/3 of the length of the slope at the foot of the slope along the yin and yang slopes, and is subjected to the tangential freezing force in different directions, resulting in the easy destruction of the canal slope at this part. When the energizing voltage is 20V, 40V and 60V, the maximum tangential frost heave force of shady slope is reduced by 14.3%, 25.1% and 33.9%, respectively, and that of sunny slope by 13.5%, 24.2% and 32.7%, respectively.

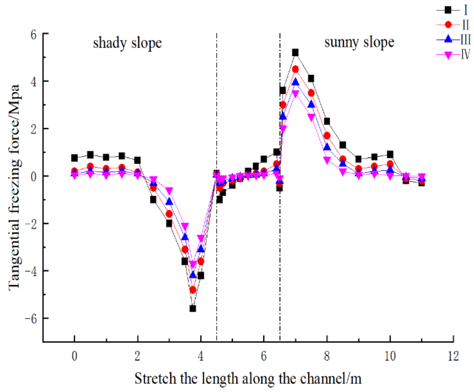

Figure 7: Tangential freezing force curve

4 Conclusions

(1) Different voltages are used to treat the base soil, and the moisture content of the base soil changes differently. The smaller the voltage, the higher the moisture content of the base soil, and the larger the voltage, the lower the moisture content of the base soil. After 20V, 40V and 60V treatment, the moisture content can be reduced by 46.9%, 51.7% and 58.4% respectively compared with the untreated foundation.

(2) After the channel foundation was treated by electroosmosis at different voltages, the maximum normal frost heave of the channel was reduced by 35.2~46.1mm. The normal frost heave force is reduced by 0.7~1.5Mpa; The tangential freezing force is reduced by 0.8~1.9Mpa. The results show that the higher the voltage, the smaller the frost heave amount and frost heave force, and the frost heave damage can be effectively reduced by electroosmotic treatment of the channel foundation. In order to reduce the frost heave of the channel, it is recommended to use a voltage of more than 60V to treat the channel base soil.

(3) The use of electroosmosis to treat the channel base soil can significantly reduce the moisture content, frost heave and frost heave force of the channel, and then reduce the frost heave damage of the channel, which can provide a new idea for the research on anti-frost heave measures of water conveyance channels in cold areas.

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