An analysis of the influences of groundwater level changes on the frost heave and mechanical properties of trapezoidal channels

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Abstract

In this research study, platforms with different heights were established for the purpose of simulating the different groundwater level conditions. Combined with the prototype channel, the influences of the groundwater level changes on the frost heave deformations in the foundation soil and on the frost heave force of the channel, as well as on the bending moment of the channel section and water content migration of the foundation soil, were studied by the method of mechanical analysis. The research results show that, after a comparative analysis of the ground temperatures in the same layer had been completed, the difference value was found to have been less than 5%. The frost heave of the foundation soil had decreased by 0.15 cm for every 1 cm reduction in the groundwater level. In addition, the maximum frost heave force of the channel was shown to have varied with the change of groundwater level. This study's theoretical calculations determined that the most unsafe groundwater level of a typical channel was 2.61 m. It was concluded that the increase of groundwater level can reduce the amount of soil moisture transfer, while the influence of groundwater level on frost heave of foundation soil can be effectively reduced by laying polystyrene boards.

Keywords: Groundwater level; Normal frost heave force; Sectional bending moment; Water migration

Highlights

- The different groundwater level test platform was established first in China.
- The paper put forward the effect of changes of groundwater level on freezing heave of channel base is presented in this paper.
- The maximum stress position of channel base under different groundwater level conditions is proposed in the paper.
- In this study, the relationship between the maximum frost heaving force and the buried depths of groundwater of a typical channel slope plate were fitted, and the most unsafe burial depth of the groundwater of a typical channel was proposed.

1. Introduction

Frost heave exists in cold regions of the world. However, solving the problem of frost heave is an issue of concern throughout the world. The Hetao Irrigation District of Inner Mongolia, China is a temperate continental arid and semi-arid climatic zone which is characterized by long cold winters, making it a seasonal freezing soil area. The foundation soil is usually frozen by mid-October, and unthawed by the last third of April of the following year. However, the soil in this area may also be unthawed by the first third of May in individual years, which basically forms the area's freezing and melting cycle. Influenced by the irrigation water, the groundwater levels in the Hetao Irrigation District are high. Also, due to the influences of temperature changes, soil quality, groundwater levels, and so on, the Hetao Irrigation District has become a strong frost heave area. The concrete slab lining channels are subjected to frost heave damage to varying degrees after several alternately freezing and melting cycles due to the negative effects of changing temperatures if protection measures are not taken against frost heave. Over time, the frost heave damage to the channels has become increasingly serious. The concrete slabs of lining channels in the Hetao Irrigation District have undergone a great degree of damage, such as overhead, uplift, partial collapses, and so on (Guo, 2019).

In terms of research regarding the influence of soil moisture on frost heave of trapezoidal channels, Everett (1961) first proposed a frost heave theory based on a capillary theory. However, this theory failed to explain how the discontinuous ice lens was formed, and also underestimated the frost heaving pressures in fine granular soil. Miller (1972) proposed a second frost heave theory based on Everett's first frost heave theory, which was able to overcome the drawbacks of the original capillary theory. Also, this improved frost heave theory considered that there were icing edges with low water content and without frost heave on the freezing fronts and bottoms of the majority of warm ice lenses, thereby providing a basis for the establishment of a numerical model. Harlan (1973) proposed a hydro-thermal coupled hydrodynamic model, and then adopted a finite difference method which effectively simulated the water flow and temperature of soil. Bie et al. (2007) believed that the essence of frost heave was the macroscopic expressions caused by water movements within frozen soil. Zhang & Jiang (2016) examined the soil temperatures and water migration processes at 5 cm below the channel bases during a freezing period using the prototype observation results of trapezoid concrete-lined channels undergoing seasonal freezing and melting conditions. They also studied the changes in the soil temperatures and water movement processes of seasonal freeze–melting channel foundations and the resulting induced frost heave deformations.

Regarding the effect of groundwater on frost heave of trapezoidal channels, Xiao et al. (2017) deduced the calculation formula for the frost heaving strength, frost line, and bending moment distribution of channel foundation soil under the influence of groundwater levels, and quantitatively analyzed the inhomogeneity of the frost heaving force distributions in the linings of the trapezoid channels from the aspects of whole and local distribution patterns. In another related study, Li (2005) carried out channel seepage-proof tests of polystyrene boards in Xinjiang and held that when polystyrene boards were used for heat preservation in channels with high groundwater levels, the uplift pressure was larger and the lining layers easily became damaged. In the study conducted by Liu et al. (2016), the expression of the moisture migration at the frozen fronts of saturated frozen soil was established based on a Clapeyron equation and Darcy's law. Zou (2012) studied the application of dry-laid pebbles in the channel in an area with a high groundwater level. It is considered that when the channel is below the groundwater level, then the groundwater level outside the channel will form a hydraulic gradient to

the channel side, and the groundwater will leak out to the channel side, thus resulting in channel fine particles, which cause the channel to produce the destruction. The relationship between channel permeability and groundwater level was studied by Lin & Zeng (2012). The results show that the groundwater level decreases with the increase of the canal-system water use efficiency, and that there is a negative correlation between it and the groundwater level. Zhang & Lu (2012) held that the frost heave of canal foundation soil is closely related to the soil quality, water content, groundwater level, and air temperature. Due to the high groundwater level in irrigation areas, soil moisture is transferred to the frozen surface of surface soil under the action of soil capillary suction, after which, the frost heaving damage of trapezoidal canal is aggravated.

In the field of canal frost heaving mechanics, many previous research studies have been completed, both in China and on a global scale, regarding the heat preservation and anti-frost heaving of channels. For example, Wang (2004) proposed a mechanical model for the frost heaving damage of concrete linings in trapezoidal channels in which the channel slope plates were regarded as simply supported beams, and also solved a calculation formula for the internal forces and maximum tension stresses of channel slope plates. Zhang (2010) conducted a simulation study on the temperature fields, displacement fields, and stress fields of trapezoidal concrete lining channels using a large finite element analysis method, considering that it is reliable to analyze the temperature stress and strain of trapezoidal channels by a finite element method. Liu & Liu (2012) analyzed the frost heaving damage mechanism of a trapezoidal channel, then calculated the suitable paving thicknesses for the polystyrene boards of trapezoidal channels using a theoretical formula. Wang (2010) carried out prototype observation tests on the frost heave processes of trapezoidal cast-in-place concrete channels with arc slope toes, and also explored the occurrence mechanism of frost heave failures and deformations in channel lining layers. In addition, Guo (2013) utilized ANSYS software to analyze the variation laws of the temperature fields, stress fields, and displacement fields of a trapezoidal channel which had been paved with polystyrene boards of different thicknesses in the Hetao Irrigation Area of Inner Mongolia. Compared with the finite element method, the ANSYS method proved to be more convenient and practical. Li et al. (2016) carried out mechanical tests on the existing mold bag concrete trapezoidal channel in large irrigation areas, then analyzed the variation characteristics of the stress and strain in those channels. Shen et al. (2012) believed that the shear of the lining plates, along with the uneven frost heave produced by the foundation soil, were the main factors for the frost heave damage in trapezoidal channel with precast concrete slab linings. Also, using linear elastic fracture mechanics as a basis, Sun et al. (2013) applied existing structural mechanics models for frost heave in channel linings, and proposed a mechanics failure criterion for frost heave fractures which was suitable for the concrete lining boards of channels. Furthermore, they established mechanics models for the frost heaving fractures of concrete lining plates at three different locations (shady slope, sunny slope, and bottom of a channel), as well as a thickness design method for concrete lining plates. Zhang & Wang (2007) summarized the recent frontier research achievements of China's frost heave prevention and control technology in terms of four aspects as follows: the frost heave failure mechanisms of channels; frost heave prediction mode of channels; research on the mechanics model of frost heave in channels; and frost heave prevention and control measures in channels. By analyzing the frost heaving failure mechanisms of composite channel linings, Zheng et al. (2015) pointed out that the slope plates of arc-bottom trapezoid composite lined channels could be simplified as cantilever beams under the joint actions of frost heaving forces, freezing forces, and friction forces. Therefore, the entirety of lining masonry bodies could be classified as bent composite deformation structures. Cheng (2018) proposed a mechanics model for seepage control and anti-frost heave in new

composite material channels with different structural types, including the trapezoidal channel. Gao *et al.* (2015) held that with increases in inclination or thickness of trapezoidal channel, the frost heaving inhomogeneity of linings became decreased, and the frost heave displacements and peak stresses were also correspondingly decreased. The calculation results obtained by Yang (2015) showed that the frost heave forces obtained by a nonlinear model were smaller than those obtained using a linear model, and more accurately reflected the real values of the concrete stress states. Yang (2017) referred to the existing theories, such as the mechanics of frozen soil, three field coupling, material mechanics, elastic mechanics, seepage, and so on, and then analyzed the frost heave of channel foundation soil and lining structures in order to establish a mechanics model for the frost heave failures of channel concrete linings. According to the principle of superposition, Tang & Wang (2016) regarded frost heave as the joint actions of gravity, tangential freezing forces, normal freezing forces, and normal frost heaving forces. The results of their study provided a calculation formula which was convenient for design applications using the equilibrium relationship between the whole and local parts of structures in accordance with the structure type, failure characteristics, as well as the prototype observation results of the channels. In combination with the frost heave problems in the channels of a river irrigation area in northern Xinjiang, Zhong (2015) analyzed the mechanisms of the frost heave damage in channels in order to determine the causes. Moreover, in said study, polystyrene foam plates were experimentally used, and corresponding anti-frost heaving assurance measures were proposed.

Although a large number of experimental research results have been achieved with regard to anti-frost heave conditions in channels in China as well as abroad, there has not yet been any research conducted which has examined the influences of different groundwater levels on the frost heave of foundation soil. The problem of frost heave requires a solution in cold regions of the world. Therefore, the influences of the changes in groundwater levels on the frost heave deformations of foundation soil require further study worldwide. The change laws of the maximum stress locations of channel foundation undergoing different groundwater level conditions have not yet been determined. In order to address these issues, this study selected the backbone channel in the Hetao Irrigation District of Inner Mongolia as the research object. A frost heaving test platform with different elevations was established in the study area in order to simulate the different groundwater level conditions. Then, the influence mechanisms of the different groundwater levels on the frost heave were analyzed. The frost heave and stress variation laws of trapezoid channels undergoing different groundwater levels were expounded from the aspects of soil moisture changes and mechanics, and the most unsafe groundwater levels of a typical channel were proposed.

2. Materials and methods

2.1. Overview of the experimental frost heave test field

2.1.1. Basic conditions of the experimental frost heave test field. This study's frost heave test field is located in the Hetao Irrigation District (Figure 1). The latitude and longitude of the study area are 107.38492716763304 and 40.61910929408867, respectively. The average annual temperature in the study area is 6.9 °C, and the average relative humidity between 40 and 50%. The average annual rainfall is approximately 144.2 mm. The area is characterized by large temperature differences and sufficient light conditions, with an annual sunshine duration of between 3,100 and 3,300 hours. The experimental
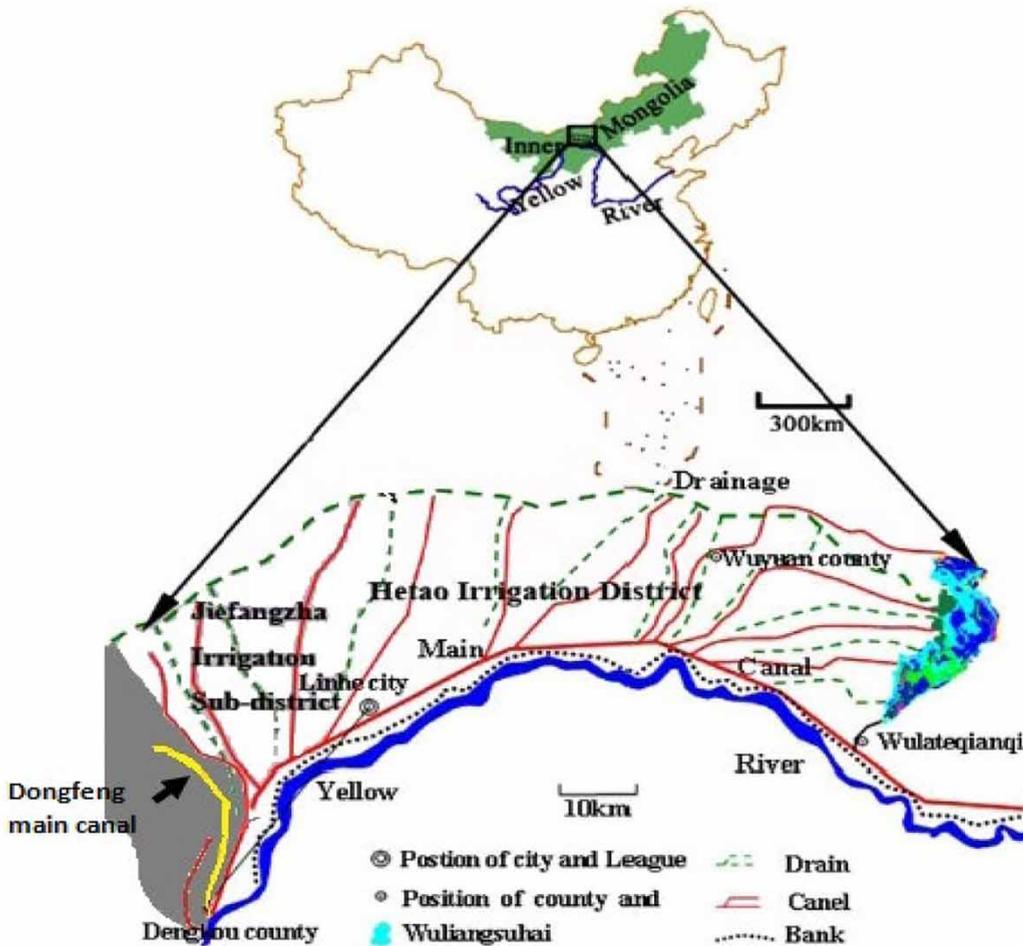
Fig. 1. Location map of the Hetao Irrigation District of Inner Mongolia.

test field is mainly covered by heavy silty loam, which is considered to be strong frost heave soil. The freezing duration of the soil ranged from 180 to 240 days, with a freezing index of 536 to 3,450 °C·d, and freezing depths from 70 to 120 cm.

2.1.2. Test design.   Three different groundwater level test platforms were set up in this study's test field, and each platform had an area of 40 m × 6 m. Platform 1 was flush with the ground; Platform 2 had a relative elevation of 0.5 m; and Platform 3 had a relative elevation of 1.0 m. The three platforms had the same soil properties and unit weights. The platforms were provided with six pieces of 3 m × 3 m test blocks on which precast concrete slabs were placed. One test block was used for comparison purposes without the placement of a heat preservation plate. The other five test blocks were covered by the 2 cm, 4 cm, 6 cm, 8 cm, and 10 cm polystyrene heat preservation plates. The floor plan and vertical layout are respectively detailed in Figures 2 and 3, and the test processing design table is shown in Table 1.
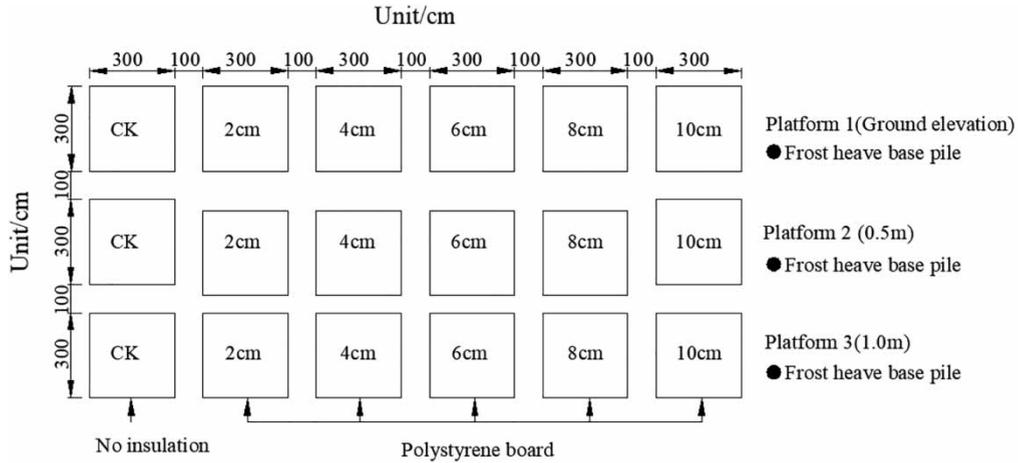
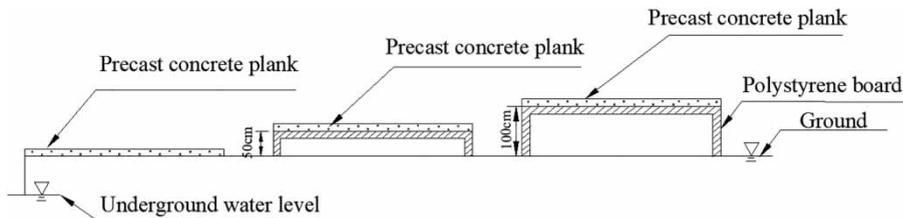Fig. 2. Floor plan of the different groundwater platforms.

Fig. 3. Profile plan of the different groundwater platforms.

Table 1. Design table for the experimental treatment of the different groundwater level platforms.

Elevation settings	Groundwater depth (initial freeze)	Structural type	Thicknesses of the polystyrene boards
Ground elevation	1.28	Precast slab + polystyrene board	0, 2 cm, 4 cm, 6 cm, 8 cm, 10 cm
0.5 m platform	1.78		
1.0 m platform	2.28		

During the experimental testing process, 6 cm thick polystyrene heat preservation plates were laid vertically around each test block, which reduced the peripheral heat exchange and guaranteed one-dimensional thermal motion. This effectively mitigated the influences of the frost heave deformations which occurred along the horizontal direction from affecting the vertical deformations of the test blocks. In addition, replacement fillings were made at 0 to 30 cm between the test blocks using sandy soil, which mitigated the influences of the external frost heave from affecting the foundation soil of test blocks. In addition, three sets of probes were diagonally buried in the same layer of each test block to measure the ground temperatures, with a burial spacing of 1.0 m. The burial depths of these three sets of probes were 10 cm below the heat preservation plates and concrete slab, 30 cm below the concrete slabs, and 50 cm below the concrete slabs.

The data of the test observations mainly included the frost heaving capacities and soil moisture content. The measurement locations for the frost heaving capacities and soil moisture content were in the middle sections of the test blocks. There were three sampling points for the frost heaving capacity and soil moisture content in each test block, with a spacing of 10 cm. The data which were used in this study were the average results of three repeated tests. A benchmark pile was embedded near the test platform, and the frost heaving capacity of each test block was observed by the level. The soil moisture content at different depths was measured using artificial drilling and sample drying methods prior to freezing, at the time of maximum freezing depth, and after the freezing and melting cycle. The depth of soil moisture content measurement was 0–50 cm, with sampling performed every 10 cm. Three samples were taken parallel to each layer, and their averages were calculated.

2.2. Overview of the typical channels

The south sub-main channel of the Hetao Irrigation District was a C20 precast concrete slab-lined trapezoid channel, and was also the area's excavation channel which was situated in an east–west direction. The test section was paved with 4 to 8 cm polystyrene plates with different thicknesses. The maximum frost line was 0.76 m during the observational period, and the freezing index was $I =$ 1,450 °C·d. The duration of the observational period was two years. The channel foundation soil was composed of loam soil, which was characterized by high water content in foundation soil, low bearing capacity, and poor geological conditions. The main hydraulic factors were as follows: channel depth $H = 3.0$ m; bottom width $b = 5.2$ m; slope ratio $m = 1:1.5$; design flow $Q = 12.0$ m^3/s; design water depth $Hm = 1.98$ m; and design longitudinal slope $i = 1/7050$. A diagram of the study area's selected typical channel section is shown in Figure 4.

3. Results and discussion

3.1. Influences of the groundwater level changes on the frost heaving deformations of the foundation soil

Figure 5 details this study's observations of a complete freezing and melting period (from November 2015 to April 2016), in which the process lines of the frost heave changes without heat preservation treatments under three groundwater level conditions are highlighted. The buried depth of the
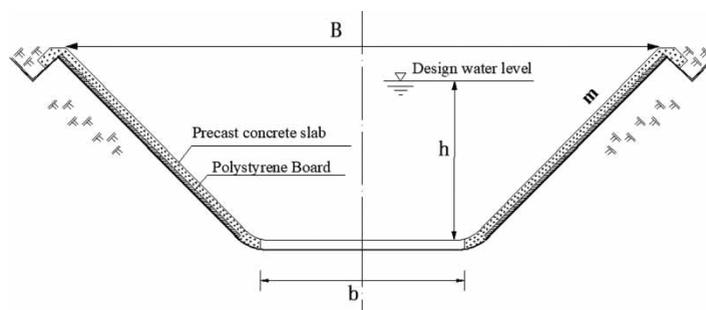

Fig. 4. Typical channel profile (B, top width; b, floor width; h, design water level buried depth; m, slope ratio).
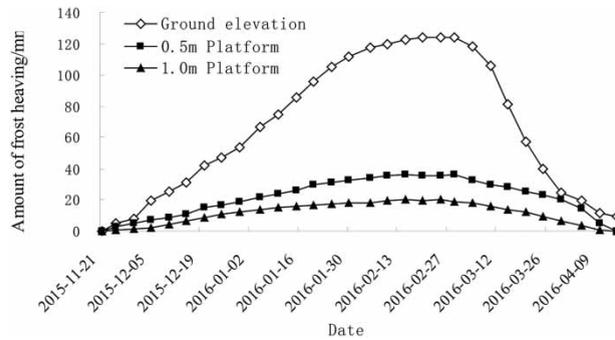
Fig. 5. Change process line of the soil frost heave with no heat preservation treatment under different groundwater levels.

groundwater under the conditions of the actual measured ground elevations during the initial freezing period in December 2015 was 1.28 m. The buried depth of the groundwater on the 0.5 m platform was 1.78 m, and the buried depth of the groundwater on the 1.0 m platform was 2.28 m.

As can be seen in Figure 5, the frost heaving deformations of the foundation soil began to occur in November, and the frost heaving volume gradually increased with time. In the middle and last third of February, a maximum frost heaving period occurred, and as the external temperatures increased, the frost heaving volume of the foundation soil gradually decreased. It was observed that in the middle third of April, the frost heave of the foundation soil processed on the 0.5 m and 1 m platforms was basically eliminated without residual deformations. However, there were residual deformations observed on the 1.0 cm platform under the ground elevation conditions. During the entire freezing–melting period, the frost heaving volumes under the groundwater level conditions of the 0.5 m and 1.0 m platforms were found to be significantly lower than those under the ground elevation conditions.

The bar chart for the calculated maximum frost heave which was treated by laying 2 to 10 cm heat preservation plates under three groundwater level conditions during the freezing and melting period is shown in Figure 6.
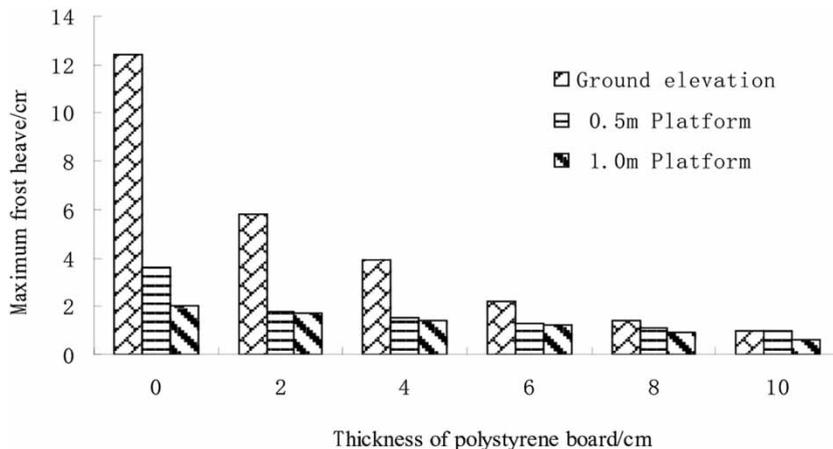

Fig. 6. Maximum frost heave of the EPS plates with different thicknesses.

As detailed in Figure 6, with the increases in the thicknesses of the heat preservation boards, the maximum frost heaving volume had gradually decreased. Moreover, the thicker the heat preservation boards were, the smaller the influences of the groundwater levels on the frost heave of the foundation soil would be.

The obtained maximum frost heaving volume, along with the frost heave reduction volumes under different groundwater level conditions, are shown in Table 2. It can be seen in the table that, when the groundwater level was relatively reduced by 0.5 m, the frost heaving volume was 8.8 cm, and the frost heave reduction rate was 71%. When the groundwater level was relatively reduced by 1.0 m, the frost heave reduction volume was 10.4 cm, and the frost heave reduction rate was 83.8%. Therefore, it was determined that reductions of the groundwater levels could significantly reduce the frost heave volumes of the foundation soil. In addition, the frost heave volumes of the foundation soil could potentially be reduced by 0.15 cm for every 1 cm decrease in the groundwater levels, which indicated that reductions in the frost heave of foundation soil could be effectively achieved in practical engineering applications by lowering the groundwater levels.

3.2. Influences of the groundwater level changes on the normal frost heave forces of the channels

Previously, a large number of related documents and experimental study results (Wang, 2004; Zhang, 2010) have shown that there is a negative exponential relationship between the frost heaving strength of soil and the groundwater level. In a lined channel, the formula for frost heave rate distribution under the specific meteorological, water, and the soil conditions in a specific area can be written as follows:

$$\eta(x) = a \cdot e^{-b \cdot z(x)} \tag{1}$$

In Equation (1) (Shen *et al.*, 2012; Yang, 2017), x is the distance between the calculation point along the slope to the top of the slope, cm; $\eta(x)$ is the frost heave rate, %; $z(x)$ denotes the distance between the calculated point and the groundwater level, cm; a and b represent the empirical coefficients related to the specific weather, water, and soil conditions in a particular area, which are often fitted by a least squares method according to the experimental data. Parameters a and b differ for the various soil properties, and are often determined according to relevant experimental research results and the experience of the researchers. According to the current relevant data, for loam soil, a will be 60 and b will be 0.0145.

The frost heaving displacements of a lined channel will release the force of the frost heaving on the plates to some extent, and its reduction degree will be related to the size of the frost heaving

Table 2. Maximum frost heave and frost heave reduction under the different groundwater level conditions.

Processing	Groundwater buried depth/m	Maximum amount of frost heaving/ cm	Lowest amount of frost heaving/cm	Reduction of frost heave/ %	Reduction of frost heave for every 1 cm reduction in the water level/cm	Average value of freezing expansion decreases with each 1 cm decrease in the water level/cm
Ground elevation	1.28	12.4	\	\	\	\
0.5 m platform	1.78	3.6	8.8	71.0	0.18	0.15
1.0 m platform	2.28	2.0	10.4	83.8	0.11	

displacements. In this study, in order to simplify the calculation, it was assumed that the free frost heaving volume $\Delta h(x)$ was completely constrained, and the reduction of the force of the frost heaving was not considered to be temporary. Then, the free frost heaving volume $\Delta h(x)$ (cm) was calculated using Equation (2):

$$\Delta h(x) = \eta(x) \cdot H(x) \tag{2}$$

$$H(x) = H_{0.} \varphi_{1.} \varphi_{2.} \varphi_3 \tag{3}$$

In Equation (3), $H(x)$ (cm) is the frozen depth value of any point along the slope to the top of the channel; H_0 (cm) is the standard freezing depth value; φ_1 is the soil quality influence coefficient; φ_2 is the influence coefficient of considering regional difference; and φ_3 is the influence coefficient related to the groundwater level at the calculation point.

In accordance with the linear function relationship between the frost heaving force and the frost heave rate proposed by Xiao *et al.* (2017), in combination with Equation (2), the distribution law of normal frost heaving force along a section of lining was obtained as follows:

$$q(x) = E_f \cdot \eta(x) = a \cdot E_f \cdot e^{-b \cdot z(x)} \tag{4}$$

$$z(x) = z_0 - x \sin \theta \tag{5}$$

where $q(x)$ denotes the distribution of the normal frost heaving force of the lining, MPa; E_f is the elasticity of the modulus of the frozen soil, MPa; a and b represent the parameters; x is the distance from the slope top to the slope toe, m; Z_0 is the buried depth of the groundwater; and θ is the dip angle of the channel slope plate. Since Equation (4) is a universal equation, for the channels with different types of sections, the distance function $z(x)$ (m) from each point on the cross section to the groundwater level could be substituted into the coordinate system which had been suitably established. Therefore, by only considering the trapezoidal channel, and regarding the slope plate as a simply supported beam, as described in Figure 7, the slope top was found to suffer the restraint of the normal freezing of the channel foundation soil, and the slope toe was observed to be mutually restrained with the bottom plate.

In Figure 7, x is the distance from the slope top to the slope toe; Z_0 (m) is the buried depth of the groundwater; h (m) denotes the channel depth; and θ represents the dip angle of the channel slope plate.
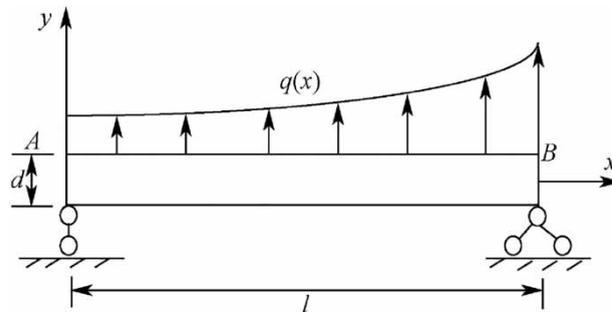

Fig. 7. Distribution of the normal frost heaving force on the lining plate.

When $Z_0 > h$ (for example, when the buried depth of groundwater was larger than the channel depth), the normal frost heaving force was as follows:

$$q(x) = a \cdot E_f \cdot e^{-b \cdot (z_0 - x \sin \theta)} \tag{6}$$

However, when $Z_0 < h$ and $x \cdot \sin \theta < Z_0$ (for example, when the buried depth of groundwater was smaller than the channel depth), the calculation formula for the normal frost heaving force at each point of the channel slope plate above the groundwater level was the same as Equation (6).

Also, when $Z_0 < h$ and $x \cdot \sin \theta > Z_0$ (for example, when the buried depth of the groundwater level was smaller than the channel depth), the normal frost heaving force at each point of the channel slope plate under the groundwater level was as follows:

$$q(x) = a \cdot E_f \cdot e^{-b \cdot (x \sin \theta - z_0)} \tag{7}$$

In accordance with the solutions obtained using Equations (6) and (7), the distribution law of the normal frost heaving force of the south sub-main channel slope along the slope surface was as shown in Figure 8, and the calculated maximum frost heaving forces at different locations were as shown in Table 3.

As detailed in Figure 8 and Table 3, the maximum normal frost heave force of the channel slope varied with the buried depths of the groundwater. When the groundwater level was lower than the channel bottom ($Z_0 = 3.28$ m), then the maximum frost heaving force of the channel slope was located at the top of the channel slope, and the maximum frost heaving force was only 106.64 MPa. When the groundwater was high ($Z_0 = 1.28$ m), the maximum frost heave was located in the lower two-fifths location along the channel slope, and the maximum frost heave force was 194.98 MPa. Furthermore, when the buried depth of the groundwater was greater than one half of the channel depth ($Z_0 = 1.78$ m, 2.28 m, 2.78 m), then the maximum force was located between the midpoint location of channel and slope toe, and the maximum frost heave force location moved upward with the rises in the groundwater levels. The maximum frost heave force was observed to be between 200 and 250 MPa.
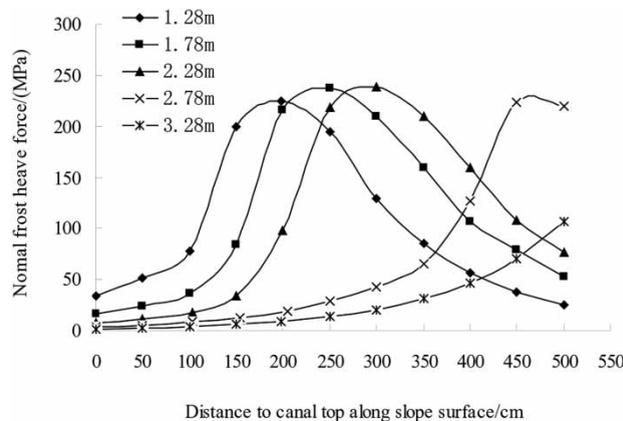

Fig. 8. Distribution of the normal frost heave force of the canal slope with the different groundwater levels.

Table 3. Maximum frost heaving force and maximum stress area under the different groundwater level conditions.

Treatment	Buried depth of groundwater level (m)	Maximum frost heaving force (MPa)	Maximum stress location
Treatment 1	1.28	194.98c	2/5
Treatment 2	1.78	237.12a	1/2
Treatment 3	2.28	238.51a	5/9
Treatment 4	2.78	228.26b	5/6
Treatment 5	3.28	106.64d	Slope toe

Note: a, b, c, d were significant differences at 5% level.

According to the significance analysis of Table 3, there was no significant difference observed between Treatment 2 and Treatment 3, but there were significant differences among the other treatments, such as between Treatment 1 and Treatments 4 and 5.

The relational expression between the maximum frost heaving force of the typical channel slope plate and the buried depth of the groundwater was fitted as follows:

$$Y = -24.226x^2 + 126.8x + 87.184, \ R^2 = 0.9406. \tag{8}$$

According to Equation (8), the maximum frost heaving force of the channel slope plate had first increased and then decreased with the decreases in the groundwater level.

Through the derivative calculation: $\dfrac{dy}{dx} = -48.452x + 126.8 = 0$, $x = 2.61$

Therefore, it was concluded that the underground water level of the typical channel (south sub-main channel) slope plate examined in this study was 2.61 m under the maximum frost heaving force. That is to say, when the underground water level is 2.61 m, then the typical channel slope was most likely to be destroyed by frost heave. In practice, the underground water level can be controlled by pumping and draining the underground water to reduce the frost heave damage to the canal.

3.3. Influences of the changes in the groundwater levels on the sectional bending moment of the channel

When calculating the sectional bending moment of the examined channel slope plate, the channel slope plate was regarded as a simply supported beam for the purpose of the calculation. Then, in accordance with the calculation method of material mechanics, the bending moment of each section of the channel slope plate was calculated, and the distribution law of the cross section was simplified as follows:

$$M(x) = k_1 \cdot x \cdot a \cdot e^{-b \cdot z} \cdot [f(bh) - f(xb \sin \theta)] \tag{9}$$

where $f(bh) = (e^{bh} - 1)/(bh)$, $f(xb \sin \theta) = (e^{xb \sin \theta} - 1)/(xb \sin \theta)$, $k_1 = (l \cdot E_f)/(bh)$, with h denoting the channel depth, cm; $M(x)$ is the sectional bending moment, kN·m; E_f represents the modulus of elasticity, and in accordance with the related research results, the modulus of elasticity will be 3.8 MPa when the frozen soil reaches the lowest winter temperature; and a and b are the experimental parameters related to the specific weather, water, and soil conditions in a specific area. Since the soil in the test

section of the south sub-main channel of the Hetao Irrigation District of Inner Mongolia mainly consisted of loam, then a would be 60 and b would be 0.0145 according to the above data (as previously described).

When $Z_0 > h$ (for example, when the buried depth of the groundwater is larger than the channel depth), $q(x) = a \cdot E_f \cdot e^{-b \cdot (z_0 - x \sin \theta)}$, the normal frost heaving force on the slope top is $q(0) = a \cdot E_f \cdot e^{-b \cdot z_0}$, and the sectional bending moment will be as follows:

$$M(x) = \frac{x \cdot l}{b \cdot h} \cdot q(0) \cdot [f(bh) - f(xb \sin \theta)] = \frac{l \cdot E_f}{b \cdot h} \cdot x \cdot a \cdot e^{-b \cdot z_0} [f(bh) - f(xb \sin \theta)] \tag{10}$$

In Equation (8), $M(x)$ is the sectional bending moment; x (m) is the distance between the calculation point along the slope to the top of the slope; h (m) denotes the channel depth; a and b are specific parameters (as previously described); l (m) is the length of the channel slope plate; E_f represents the modulus of elasticity; and θ represents the dip angle of the channel slope plate.

When $Z_0 < h$ and $x \cdot \sin \theta < Z_0$ (for example, when the buried depth of the groundwater is smaller than the channel depth), each point on the channel slope plate above the groundwater level will be: $q(x) = a \cdot E_f \cdot e^{-b \cdot (z_0 - x \sin \theta)}$.

At that time, the normal frost heaving force of the channel slope top will be: $q(0) = a \cdot E_f \cdot e^{-b \cdot z_0}$.

Also, the sectional bending moment will be:

$$M(x) = \frac{l \cdot E_f}{b \cdot h} \cdot x \cdot a \cdot e^{-b \cdot z_0} [f(bh) - f(xb \sin \theta)]. \tag{11}$$

When $Z_0 < h$ and $x \cdot \sin \theta > Z_0$ (e.g., when the buried depth of the groundwater is smaller than the channel depth), each point on the channel slope plate below the groundwater level will be:

$$q(x) = a \cdot E_f \cdot e^{-b \cdot (x \sin \theta - z_0)} \tag{12}$$

At that time, the normal frost heaving force of the channel slope top will be:

$$q(0) = a \cdot E_f \cdot e^{b \cdot z_0} \tag{13}$$

Also, the sectional bending moment will be:

$$M(x) = \frac{l \cdot E_f}{b \cdot h} \cdot x \cdot a \cdot e^{b \cdot z_0} [f(bh) - f(xb \sin \theta)] \tag{14}$$

In this study's calculations, when the buried depth of the groundwater was higher than the channel bottom, the sectional bending moments at each point on the channel slope plate were calculated by sections.

Then, using Equations (11)–(14), the bending moment distributions of the channel slope plates along the slope surface of the south sub-main channel at different groundwater burial depths could be successfully calculated, as shown in Figure 9.
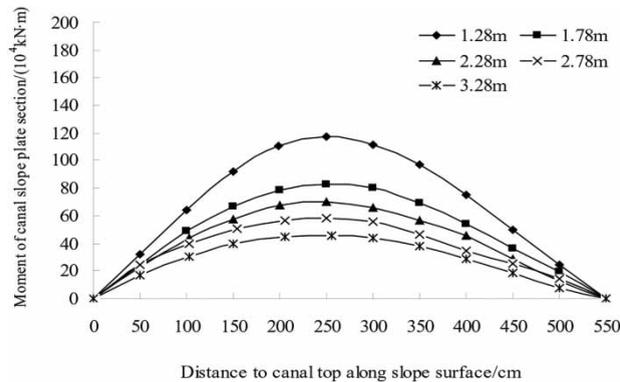
Fig. 9. Section bending moment diagram of the canal slope plate under the different groundwater depths.

As detailed in Figure 9, the sectional bending moment displayed a parabolic variation trend of first increasing and then decreasing from the channel bottom along the channel slope surface. The maximum bending moment of the channel slope plate occurred at a location in the lower one-third to one-half of the channel slope plate. The bending moment was large when the buried depth of the underground water was 1.28 m. However, the maximum bending moment was observed to gradually decrease with the increases in the buried depths of the underground water. Also, when the underground water level had decreased from 1.28 m to 1.78 m, the maximum bending moment displayed the largest amplitude of decrease. Similarly, when the underground water level had decreased from 1.78 m to 3.28 m, the maximum bending moment displayed the smallest amplitude of decrease. The experimental results indicated that when the groundwater level was higher than the bottom of the channel, the depths of the groundwater had major influences on the bending moment of the channel slope plate. It was determined that the shallower the depth of the underground water was, the greater the maximum bending moment would be. Also, the frost heave damage in the channel slope plate were observed to be more severe. Furthermore, the influences on the bending moments of the channel slope plate, as well as the failure occurrences in the channel, were found to be minimal when the groundwater levels were lower than the bottom of the channel. Anti-frost heave technology and measures must be strengthened at the lower one-third to one-half part of the channel slope, e.g., by using thicker polystyrene boards.

3.4. Influences of the groundwater level changes on the soil moisture migration

In this study, the soil moisture content of the 0 to 50 cm soil layers processed at three different elevations before freezing were calculated. Also, the water migration values in the 0 to 50 cm soil layers during the maximum freezing period and after melting were calculated, as shown in Table 4.

As can be seen in Table 4, under the three groundwater level conditions, the soil moisture content in the 0 to 50 cm layers exhibited the same change rule during the periods of 'before freezing, maximum freezing, and melting'. During the 'before freezing to maximum freezing period', the soil moisture content in the 0 to 30 cm soil layers had increased, while the water content in the 30 to 50 cm layers decreased, which indicated that the soil moisture had migrated from the lower layers to the upper layers during the freezing process. During the 'maximum freezing to melting period', the soil moisture content in the 0 to 30 cm soil layers had decreased, while the water content in the 30 to 50 cm layers had

Table 4. Soil water migration and changes in the three different elevation treatments.

Processing	Soil depth/cm	Moisture content before freezing/%	Maximum freeze migration rate/%	Migration rate during ablation/%
Ground elevation	0 to 30	20.17	+51.50	−32.80
	30 to 50	23.45	−42.50	+39.60
0.5 m platform	0 to 30	15.27	+12.60	−22.90
	30 to 50	18.56	−14.90	+13.20
1.0 m platform	0 to 30	9.24	+4.30	−6.50
	30 to 50	11.52	−7.10	+3.67

Note: Mobility = water content during freezing period (melting period) − initial water content; '+' represents an upward migration of the water; '−' indicates a downward movement of the water.

increased, which indicated that the soil moisture had migrated from the upper layers to the lower layers during the melting process. Moreover, with the increases in the depths of the groundwater, the soil water mobility had decreased, which confirmed that the reductions in the groundwater levels could effectively prevent the migration of the frozen front water, as well as reduce the formation of ice layers in the soil, thereby reducing the frost heave deformations in the soil.

In this study's testing process, a foundation soil uplift method was used to simulate the declines in the groundwater levels. In order to illustrate the consistency between the foundation soil uplift and the decline of groundwater levels in regard to their influences on the water content and frost heave of the foundation soil, this study's experimental testing focused on the soil water content migration in the 0 to 50 cm layers under the conditions of the decline of the actual groundwater levels and the foundation soil uplift.

Table 5 shows the moisture content and mobility in the 0 to 50 cm layers of the foundation soil under two groundwater level conditions: the initial freezing stage and the actual decline of the groundwater levels by 46 cm.

According to the significance analysis of Table 5, there was no significant difference between the 0 to 10 cm layer and 10 to 20 cm layer of the migration amount, but there was a significant difference between it and other treatments. At the same time, there was no significant difference between each soil layer of mobility.

Table 6 details the distribution of the soil water content in the 0 to 50 cm layer under the condition of ground elevation during the initial freezing period, and the distribution of the soil water content in the 0 to 50 cm layers of foundation soil on the 0.5 m platform. It also calculates the water mobility in the 0 to 50 cm layers after the ground was raised by 50 cm.

Table 5. Water migration totals of the 0 to 50 cm layers under actual groundwater level decreases.

Groundwater depth conditions	1.28 m	1.74 m		
Soil layer depth/cm	Water content/%		Migration amount/%	Mobility/%
0 to10	23.64d	21.80bc	−1.84a	−7.77a
10 to 20	23.86d	21.00c	−2.86a	−11.99b
20 to 30	25.75c	22.13b	−3.62b	−14.07c
30 to 40	30.60b	25.30ab	−5.30c	−17.32d
40 to 50	33.90a	27.40a	−6.50d	−19.17e

Note: a, b, c, d, and e were significant differences at 5% level.

Table 6. Water transfer totals in the 0 to 50 cm layers with a ground elevation of 50 cm.

Groundwater depth conditions Soil layer depth/cm	1.28 m	1.78 m	Migration amount/%	Mobility/%
	Water content/%			
0 to 10	23.64d	21.30c	−2.34a	−9.88a
10 to 20	23.86d	21.61c	−2.26a	−9.45a
20 to 30	25.75c	22.93b	−2.82b	−10.97b
30 to 40	30.60b	24.77ab	−5.83c	−19.07c
40 to 50	33.90a	25.89a	−8.01d	−23.64d

Note: a, b, c, and d were significant differences at 5% level.

According to the significance analysis of Table 6, there was no significant difference between the 0 to 10 cm layer and 10 to 20 cm layer of the migration amount, but there were significant differences among the other treatments. In addition, there was no significant difference between the 0 to 10 cm layer and 10 to 20 cm layer of mobility, but there were among the other treatments.

As detailed in Tables 5 and 6, the soil moisture content in the 0 to 50 cm layer had decreased under the conditions of the actual declines of the groundwater level and uplift of the ground elevation, and the migration volumes had increased with the increased depths. The differences in the mobility ranged between 1.75% and 4.46%. On one hand, it was indicated that the soil water migration had a consistent change rule regardless of the ground uplift or actual decline in the groundwater level. On the other hand, the frost heave was mainly caused by the water migration. Therefore, the effects of the water migration on the frost heave of the foundation soil were consistent under the conditions of the actual decline of the groundwater levels and uplift of the foundation soil.

4. Conclusions

In this research study, a plane test field and a trapezoid precast concrete channel were used as the research objects for the purpose of simulating the different groundwater levels, and platforms with different heights were set up. The influences of the changes in the groundwater levels on the frost heave deformations of the foundation soil, along with the normal frost heaving forces of the channel slope plate, sectional bending moments, and moisture content of the foundation soil, were analyzed. Then, through the monitoring of the frost heave volumes of the various test platforms with different water levels, in combination with a prototype channel theory, the following conclusions were drawn:

1. After a comparative analysis of ground temperatures in the same layer had been completed, the difference value was found to be less than 5%. This result indicates that the environment had only a minor influence on the frost heave along the horizontal direction of the test blocks, and could thus be ignored.
2. Through the analysis of the frost heave volumes of the different test platforms, it was found that the frost heave reduction rate was 71%–83.8% when the groundwater level was relatively reduced by 0.5 m to 1.0 m, and the decrease in the groundwater level had significantly reduced the frost heave volume of the foundation soil. It was calculated that the frost heave volume of the foundation soil could be reduced by 0.15 cm for every 1.0 cm decrease in the groundwater level.

3. When the groundwater level was lower than the channel bottom ($Z_0 = 3.28$ m), the maximum frost heaving force of channel slope was found to be located at the channel slope toe position, and the maximum frost heaving force was only 106.64 MPa. However, when the groundwater level was higher ($Z_0 = 1.28$ m), the maximum frost heaving position was located at a downward two-fifth location along the channel slope, and the maximum frost heaving force was determined to be 194.98 MPa. It was also observed that when the burial depth of groundwater was larger than one half of the channel depth ($Z_0 = 1.78$ m, 2.28 m, 2.78 m), the maximum stress location was between the middle of the channel and the slope toe, and the maximum frost heaving force location had gradually migrated upwards with the increases in the groundwater levels.

4. In this study, the relationship between the maximum frost heaving force and the buried depths of groundwater of a typical channel slope plate were fitted, and the most unsafe burial depth of the groundwater of a typical channel was proposed to be 2.61 m. Therefore, during the actual operation process of the channel, it was proposed that the maximum frost heave damage of the channel could be avoided by controlling the water levels.

5. The maximum bending moment of the channel slope plate was observed to appear at the lower one-third to one-half location of the channel slope plate. When the groundwater level was higher than the channel bottom, the groundwater level had a major influence on the bending moment of the slope plate. The shallower the buried depth of the groundwater, the greater the maximum bending moment would be, and the more serious the frost heave damage to the channel slope plate would be.

6. During the 'before freezing to maximum freezing period', the soil moisture moved from the lower soil layers to the upper soil layers, and the soil moisture migrated from the upper soil layers to the lower soil layers during the maximum freezing period. With the increases in the burial depths of the groundwater, the soil water mobility was found to gradually decrease.

The main reason for the frost heave was determined to be the soil moisture migration. The declines in the groundwater levels were determined to effectively prevent or delay the increase of capillary water in the soil, and also inhibited the formation of ice interlayers in the soil, which effectively reduced the frost heaving deformations of the soil. In the actual channel construction project, the groundwater levels could be reduced by extracting groundwater or raising the height of channel foundation. These preventive measures would reduce the frost heave of the channel. In addition, polystyrene boards are known to have better heat preservation effects, and the greater the thicknesses of the polystyrene boards, the smaller the influences of groundwater level changes on the frost heave of the foundation soil would be. Therefore, the placement of polystyrene boards under channel slope plates can also reduce frost heaving damage in channels.

Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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