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# Numerical study on the effect of frost heave prevention with different canal lining structures in seasonally frozen ground regions

Zhuo Li<sup>a</sup>, Sihong Liu<sup>a,\*</sup>, Youting Feng<sup>b</sup>, Kang Liu<sup>a</sup>, Chenchen Zhang<sup>a</sup>

<sup>a</sup> College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China

<sup>b</sup> Water Authority of Ningxia, Yinchuan 750001, China

# A R T I C L E I N F O

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# ABSTRACT

Frost heave damage problems in canal linings are a common phenomenon in seasonally frozen ground regions. These problems are regarded as interactions between heat transport and moisture flow processes. To research the influence of frost heave prevention in two types of canal structures in the Ningxia irrigation district of China, a two-dimensional coupled heat transport and moisture flow model was used to analyze temperature characteristics in the traditional canal lining structure and a new type of canal lining structure for frost heave prevention. The simulated results from this numerical model are in agreement with in situ temperature measurements for both canal lining structures. The in situ measurement results show that the new canal lining structure exhibits low seepage, low thermal conductivity, quick drainage speed and less uneven deformation. Therefore, this new canal lining structure is a good choice for frost heave prevention in seasonally frozen ground regions.

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# 1. Introduction

Seasonally frozen ground regions comprise approximately 25% of the land surface in the Northern Hemisphere. In China, seasonally frozen ground regions cover approximately 53.5% of the country (Xu et al., 2001), with the areas mainly concentrated in the vast northeast, northwest and northern regions of China between 25° N. Lat. and 50 ° N. Lat. Canal linings are the main components of irrigation canals located in irrigation districts. To date, there are approximately 3 million km of irrigation canals in China, and approximately 80% of these canals have canal linings and are located in seasonally frozen ground regions. Because of the freezingthawing cycle, many constructed canal linings suffer from varying degrees of destruction, which not only affects the normal operation of the project by increasing operational difficulty and maintenance costs but also affects the seepage of the canal linings. It is estimated that in Northern China, some provinces may spend over 1 million US dollars every year in work to repair the damage to canal linings caused by freezing-thawing cycle action. Thus, the water resources departments and water management agencies in Northern China are highly interested in research on the prevention of frost heave in canal linings. During the Ministry of Water Resources of the People's Republic of China XII Five-Year Plan, many canal linings in irrigation districts are scheduled to be constructed in seasonally frozen ground regions. Further research is needed on the prevention of frost heave in canal linings. The particular interest is the variation in the distribution of seasonally frozen ground regions and analysis of the characteristic differences between the new canal lining structure for frost heave prevention and the traditional canal lining structure.

Previous studies have indicated that frost heave damage in canal linings is mainly caused by the interaction of heat transport and moisture flow processes in soil. The possibility of numerically modelling the complex processes that occur during simultaneous heat transport and moisture flow in a freezing soil has received a significant amount of attention since the 1970s. Previous modelling and numerical simulation investigations have been based on coupled heat transport and moisture flow in freezing soils (Harlan, 1973; Guymon Luthin, 1974; Taylor and Luthin, 1978: Sheppard et al., 1978: Jame and Norum, 1980: Guymon et al., 1984; An Weidong, 1985). Hopke (1980) first proposed a model of frost heave that included an applied load. Gilpin (1980) and O' Nell and Miller (1985) predicted ice lensing and considered the effect of external load, respectively. Williams and Wood (1985) experimentally investigated the internal stress during soil freezing with small transducers. Sally and Susan (1997) used a coupled heat transport and moisture flow model to simulate large-scale freeze-thaw experiments to assess the model's ability to predict soil moisture conditions. Li et al. (1998) modeled the heat stability of embankment in the degrading permafrost district of Chang Shitou Mountain in Hua Shixia Valley, China. Lai et al. (2003) calculated the temperature distribution in a Qing-Tibet railway embankment from the governing equations used to study forced convection of incompressible fluids in porous media that were derived through Galerkin's method. Zhang et al. (2005a,b) researched a numerical representation of the unsteady two-dimensional continuity, momentum (non-Darcy) and energy equations for thermal convection in an incompressible fluid in porous media to analyze temperature characteristics of a traditional ballast

<sup>\*</sup> Corresponding author. Tel.: +86 25 83786727. *E-mail address:* sihongliu@hhu.edu.cn (S. Liu).

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embankment, a horizontal ripped-rock embankment and two U-shaped ripped-rock embankments over a 50-year period. Li et al. (2009) proposed a thermal-dynamic coupled model and a specific analytical procedure that was based on the governing differential equations for a transient temperature field with phase change. Based on theories of heat and mass transfer, Zhang et al. (2011) presented a three-dimensional theoretical and numerical model to analyze the temperature characteristics of embankments in permafrost regions. The model and procedure were used to compute and analyse the temperature distribution in a railway embankment or road.

Engineering practices have found that frost heave and thaw settlement in seasonally frozen ground regions can cause instability and destruction of the slope of canal linings. Canal linings in the Yellow River irrigated area of Ningxia suffered from frost heave damage (shown in Fig. 1). A large number of techniques have been developed in the last few decades that can be utilised to protect canal linings from frost heave damage and thaw settlement. In general, these techniques can be divided into two categories: (1) the traditional canal structure, which is an unlined canal, and (2) a new canal lining structure that uses the thermal characteristics of natural or man-made materials to prevent frost heave damage.

In this paper, the governing heat transport and moisture flow equations are combined into a two-dimensional coupled heat transport and moisture flow model, which is then used to study the problem of frost heave prevention in canal linings in the Ningxia region. It is hoped that a new engineering measure can be used to prevent frost heave damage in canal linings in seasonally frozen ground regions.

# 2. Location and method for observation

The experimental site is located at the Yellow River irrigated area of Ningxia (37°53'N and 106°04'E). The Yellow River irrigated area of Ningxia is in a seasonally frozen ground region. The mean annual air temperature is 8.8 °C, with a maximum temperature of 32 °C in mid-July and a minimum temperature of -23.7 °C in late January. The annual freezing period is 140 days, the average annual frost depth is 1 m, and the canal is oriented in an east–west (E-W) direction.

A temperature monitoring system was installed along the slope surface of the canal lining. The canal lining test section designed for frost heave prevention was completed in October 2008, so datasets from October 2008 and May 2011 were available for this study. Ground temperatures were measured by strings of thermistors installed in boreholes, with data collected by a data logger on a daily basis. Temperature detector sensors were placed in the slope surface under the canal lining at depths of 0, 0.3, 0.5, 0.6, 0.9, 1.2, 1.5, 1.8 and 2.1 m (Fig. 2a). The moisture content of soil was measured

# (a) The damages of canal lining



(b) The damages of canal lining



**Fig. 1.** Canal linings were damaged by freezing–thawing action in the Yellow River irrigated area of Ningxia. (a) The experimental region of canal lining. (b) The new-type of canal lining structure.

(a) The experimental region of canal lining



(b) The new-type of canal lining structure



Fig. 2. The new type of canal lining structure in the Yellow River irrigated area of Ningxia.

by neutron probes, which were placed in the slope surface under the canal lining at depths of 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0 m. There were three thermometric holes. The canal lining was partially excavated and then partially refilled.

#### 3. Governing equations and numerical model

Due to freezing-thawing cycle action in seasonally frozen ground regions, canal linings can be seriously damaged, potentially causing a reduction in lining stability. The freezing-thawing cycle process redistributes heat and soil moisture toward with the surface under the influence of a positive temperature gradient. The behaviour of soils in seasonally frozen ground regions is strongly influenced by temperature; therefore, the analysis of ground thermal regimes is important in many problems of scientific interest. The problem of frost heave damage in canal linings in seasonally frozen ground regions is a complex heat transport and moisture flow interaction. In general, a negative temperature, a frost-susceptible soil and the presence of soil moisture can induce frost heave in soil.

The new type of canal lining structure offers the advantages of being economical by maintaining good drainage and good frost heave prevention with low thermal conductivity. Thus, it offers water system security and environmental protection. We have used numerical models to analyse two lining systems.

Based on the theory of heat transport and moisture flow transport, a comprehensive analysis of soil freezing must ultimately consider a two-dimensional coupled system of heat transport and moisture flow model. Such a system is proposed below. The model results will be compared with in situ temperature measurements. The results will demonstrate the excellent resistance of the new canal lining structure.

#### 3.1. Soil-layer zone

The temperature distribution in seasonally frozen ground regions is a key factor in determining canal lining frost heave damage.

The well-known two-dimensional heat transport equation for a freezing or thawing soil may be written as follows (Li et al., 1998; Lai et al., 2009):

$$\frac{\partial}{\partial x}\left(k_{x}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial Y}\left(k_{y}\frac{\partial T}{\partial y}\right) = c\rho\frac{\partial T}{\partial t} - L\rho_{i}\frac{\partial\omega_{i}}{\partial t}$$
(1)

where  $k_x$  is the thermal conductivity of the soil in the *x* direction,  $k_y$  is the thermal conductivity of the soil in the *y* direction, the spatial coordinates (*x*, *y*) represent the horizontal direction perpendicular to the canal lining and the vertical direction, respectively,  $\omega_i$  is the volumetric ice content, *L* is the volumetric latent heat of fusion for liquid water,  $\rho_i$  is the density of ice,  $\rho$  is the density of the soil, *c* is the heat capacity of the soil, and *T* is the temperature.

The two-dimensional moisture flow equation for steady or unsteady flow in a saturated or partially saturated soil during freezing can be written as follows (Li et al., 1998; Lai et al., 2009):

$$\frac{\partial}{\partial x}\left(K_{x}\frac{\partial\varphi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{y}\frac{\partial\varphi}{\partial y}\right) = \frac{\partial\omega_{u}}{\partial t} + \frac{\rho_{i}}{\rho_{w}}\frac{\partial\omega_{i}}{\partial t}$$
(2)

$$\varphi = \phi + G \tag{3}$$

where  $K_x$  is the hydraulic conductivity of the soil in the *x* direction,  $K_y$  is the hydraulic conductivity of the soil in the *y* direction, the spatial coordinates (x, y) represent the horizontal direction perpendicular to the canal linings and the vertical direction, respectively,  $\varphi$  is the total potential of water in soil,  $\rho_i$  is the density of ice,  $\rho_w$  is the density of water,  $\omega_u$  is the volumetric fractions of unfrozen water content,  $\phi$  is the volumetric potential of water in the soil, and *G* is the gravitational

potential. In most cases, the effect of the gravitational component on moisture flow in frozen ground regions is negligible; therefore,  $\varphi = \phi$ . Eq. (2) can be rewritten as follows (Li et al., 1998; Lai et al., 2009):

$$\frac{\partial}{\partial x}\left(K_{x}\frac{\partial\phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{y}\frac{\partial\phi}{\partial y}\right) = \frac{\partial\omega_{u}}{\partial t} + \frac{\rho_{i}}{\rho_{w}}\frac{\partial\omega_{i}}{\partial t}$$
(4)

According to the study by Taylor and Luthin (1978), moisture content and temperature are functionally related at below-freezing temperatures through the following equation:

$$\omega_{\rm u} = f(T) \tag{5}$$

The thermal gradient of moisture content is defined by Sheppard et al. (1978) as

$$\frac{\partial \omega_{\rm u}}{\partial t} = \frac{\partial \omega_{\rm u}}{\partial T} \frac{\partial T}{\partial t} \tag{6}$$

According to the soil-water characteristic curve, moisture content and temperature are functionally related within the freezing region of soil by

$$\frac{\partial \phi}{\partial T} = \frac{\partial \phi}{\partial \omega_{\rm u}} \frac{\partial \omega_{\rm u}}{\partial T} \tag{7}$$

Therefore, Eqs. (1), (4), (5), (6) and (7) can be combined into one governing equation as follows (Li et al., 1998; Lai et al., 2009):

$$\left( c\rho + L\rho_{w} \frac{\partial \omega_{u}}{\partial T} \right) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_{x} + L\rho_{w} D_{x} \frac{\partial \omega_{u}}{\partial T} \right) \frac{\partial T}{\partial x} + \frac{\partial}{\partial y} \left( k_{y} + L\rho_{w} D_{y} \frac{\partial \omega_{u}}{\partial T} \right) \frac{\partial T}{\partial y}$$

$$(8)$$

where  $D_x$  is the soil–moisture diffusivity in the *x* direction,  $D_y$  is the soil–moisture diffusivity in the *y* direction,  $D_x = K_x \frac{\partial \phi}{\partial \omega_u}$ ,  $D_y = K_y \frac{\partial \phi}{\partial \omega_u}$ , and  $\frac{\partial \phi}{\partial \omega_u}$  is the slope of the suction–water content curve, which is related to the temperature–unfrozen moisture content curve for frozen soil.

The heat capacity of the soil is determined by the following relationships (Xu et al., 1985):

$$\begin{cases} c_{\rm u} = (c_{\rm su} + \omega c_{\rm w})\rho_{\rm d} \\ c_{\rm f} = \left[c_{\rm sf} + (\omega - \omega u)c_{\rm i} + \omega_{\rm u}c_{\rm w}\right]\rho_{\rm d} \end{cases}$$
(9)

where the subscripts f and u represent the frozen and unfrozen states, respectively,  $c_{su}$  is the soil's volumetric heat capacity,  $c_{sf}$  is the frozen soil's volumetric heat capacity,  $\omega$  is the volumetric water content,  $\rho_d$  is the dry density of the soil,  $\lambda_i$  is the thermal conductivity of ice, and  $\lambda_w$  is the thermal conductivity of water.

The unfrozen moisture content in frozen soil is dependent on the soil temperature and given by

$$\omega_{\rm u} = aT^{-b} = \omega_0 \theta_{\rm f}^b T^{-b} \tag{10}$$

where  $\omega_0$  is the initial moisture content, *T* is the absolute value of negative temperatures,  $\theta_f$  is the freezing temperature of the soil, and *a* and *b* are constant parameters related to the physical properties of the soil that are determined experimentally and through calculations. From Eqs. (10) and (9),

$$\begin{cases} (c_{su} + \omega_0 c_w)\rho_d & (T \ge -\theta_f) \\ \rho_d c_{sf} + \rho_d c_i \omega_0 + \rho_d (c_w - c_i)\omega_0 \theta_f^b (-T)^{-b} & (T \prec -\theta_f) \end{cases}$$
(11)



Fig. 3. The new-type canal lining model. Part ① is gravel, Part ② is clay, and part ③ is silty loam.

The soil thermal conductivity is determined according to the following relationships (Xu et al., 1985):

$$\begin{split} \lambda &= \lambda_{s}^{\phi_{1}} \lambda_{w}^{\phi_{2}} \lambda_{i}^{\phi_{3}} \\ &= \begin{cases} \lambda_{u} &= \lambda_{w}^{\phi} \lambda_{s}^{1-\phi} = (0.55)^{\phi} \lambda_{m}^{1-\phi} \\ \lambda_{f} &= \lambda_{i}^{\phi-\Delta\phi} \lambda_{w}^{\Delta\phi} \lambda_{s}^{1-\phi} = (2.22)^{\phi-\Delta\phi} (0.55)^{\Delta\phi} \lambda_{m}^{1-\phi} \end{cases} \end{split}$$
(12)

where  $\lambda_{s}$ ,  $\lambda_{w}$  and  $\lambda_{i}$  are the thermal conductivities of soil grains, water, and ice, respectively, with  $\lambda_{w} = 0.55 \text{ W/m}^{\circ}\text{C}$  and  $\lambda_{i} = 2.22 \text{ W/m}^{\circ}\text{C}$ . In this paper, the thermal conductivity of the soil is as follows:

$$K_{x} = K_{y} = \begin{cases} \lambda_{u} & (T \ge -\theta_{f}) \\ \lambda_{f} & (T \prec -\theta_{f}) \end{cases}$$
(13)

#### 4. Numerical results and comparisons

#### 4.1. Computational model

The computational domains of the canal lining structures are shown in Figs. 3 and 4. According to the design specification for canal lining structures in the Yellow River irrigated area of Ningxia, canal lining layers are mainly composed of clay and silty loam. The computational domain is shown in Fig. 5. The effect of a sunnyshady slope is neglected in this paper. Many studies have demonstrated that with the effect of annual temperature changes, the curve of a canal is a sinusoid with a period of approximately 365 days.

Long-term observations of the temperature conditions in the Yellow River irrigated area of Ningxia, which is located in the northwest of China, were performed to obtain the variation equations for the annual temperatures at different surfaces in the Yellow River irrigated area of Ningxia. Using meteorological information of air stations from the Wu Zhong County, and by regression analysis of the sine function, we can reduce the upper boundary temperature of canals surface to the following sine function. According to the principles on the adhere layer (Wu et al., 1988), we obtained the mean annual temperature at the ground surface.

The temperature at the native surface IJ, LA and CD (Fig. 3) is changed according to the following expression (Lai et al., 2009) (IJ and CD are the natural ground surfaces of canals; LA is the bottoms of canals):

$$T_{\rm s} = 8.8 + 19.3 \sin\left(\frac{2\pi}{8760}t_{\rm h} - \frac{5\pi}{9}\right) \tag{14}$$

The temperature at the pavement side slope JK, KL, AB and BC of the canal lining (Fig. 3) is given by the following function:

$$T_{\rm s} = 11.3 + 16.5 \sin\left(\frac{2\pi}{8760}t_{\rm h} - \frac{5\pi}{9}\right) \tag{15}$$

The temperatures at the grave side slopes of canals IK, KL, LA, AB and BD (Fig. 4) are given by the following function (IK and BD are the natural ground surfaces of canals; LA is the bottoms of canals; KL and AB are the grave side slopes of canals):

$$T_{\rm s} = 8.8 + 19.3 \sin\left(\frac{2\pi}{8760}t_{\rm h} - \frac{5\pi}{9}\right) \tag{16}$$

The geothermal heat flux  $q = 0.06 \text{ W/m}^2$  at the boundary GF is based on Lai et al. (2009), and the lateral boundaries IHG and DEF are assumed to be adiabatic.

The media thermal parameters for the calculation domains shown in Figs. 3 and 4 are given in Tables 1 and 2, respectively, where  $C_{sf}$ ,  $C_{su}$ ,  $\lambda_{f}$ , and  $\lambda_{u}$  are the volumetric heat capacities (*C*) and thermal conductivities of the media ( $\lambda$ ) in the frozen and unfrozen areas, respectively,  $C_{w}$  and  $C_{i}$  are the volumetric heat capacities of water and ice, respectively, *L* is the latent heat of fusion per unit volume,  $\omega_{0}$  is the initial moisture content,  $D(\theta)$  is the soil–moisture diffusivity of the media,  $-\theta_{f}$  is the



Fig. 4. The traditional canal lining model. Part (1) is clay, and part (2) is silty loam.



Fig. 5. The element grid.

freezing temperature of the media, and b is a constant parameter related to the physical properties of the soil that is determined experimentally and through calculations (Xu et al., 1985).

The model developed in this study to simulate frost heave prevention in canal linings in seasonally frozen ground regions was based on the following primary assumptions:

The soil medium is nondeformable in terms of moisture flux; i.e., consolidation is negligible. Moisture transport in the frozen and unfrozen zones occurs only in the form of liquid water, so the air phase and vapour transfer have negligible effects on the net water transfer. The effect of salt exclusion is negligible.

The volume of the soil particles remains constant during the freezing process; thus, soil particles with the same initial moisture content and density are isotropic, without changes of in the volumetric heat capacity or thermal conductivity in the frozen or unfrozen areas. The freezing point depression of ice in the soil under loading is negligible.

#### 4.2. The new canal lining structure

Fig. 3 shows the new canal lining structure for frost heave prevention, in which the canal lining is partially excavated and then partially refilled. A compound geomembrane is placed at the bottom of the canal lining at a depth of 0.2 m, and then clay soil is compacted by vibrating rollers in the bottom of canal linings at a depth of 0–0.2 m. Part ① is a combination of concrete slabs, sandy gravel layers, polystyrene insulation board and compound geomembrane. The total thickness of the part ① layer is 0.5 m, with a concrete slab thickness of 0.08 m, a sandy gravel layer thickness of 0.34 m, and a total thickness of the polystyrene insulation board and compound geomembrane of 0.08 m. The material characteristics of part ① are regarded as sandy gravel for the computational model, and part ① is 0.5 m thick. Part ② is clay, and the part ② layer is 4.5 m thick. Part ③ is silty loam, and the part ③ layer is 9.0 m thick.

January is the lowest temperature month of the year in the Yellow River irrigated area of Ningxia. The temperature fields for the structure have been analysed. The temperature distribution is shown in Fig. 6. The lowest temperature under the bottom of the canal lining was -2 °C, i.e., the temperature at y = -0.08 m under the slope surface of the canal was -2 °C. The highest temperature of the embankment was 12 °C. The coordinate of the 0 °C isotherm under the slope surface of the canal lining was from y = -0.18 m to y = -0.21 m,

while it was at y = -0.27 m under the embankment on January 10, 2009. We can see that the canal lining froze under the slope surface of the canal lining at depths between 0 and 0.21 m.

Frost heave prevention measures can be adopted in the light of the three factors that cause heaving: soil, moisture and temperature. Frost heave on a canal is greatly affected by the soil moisture conditions. The new canal lining structure is composed of concrete slabs, a polystyrene insulation board, sandy gravel layers and a compound geomembrane. The concrete slabs exhibit low seepage. The polystyrene insulation board has a low thermal conductivity and low density and is low cost; thus, it can effectively prevent heat exchange between the air and soil. Canal linings often suffer from damage due to frost heave arising from the uneven distribution of canal section deformations. Because sandy gravel is a coarse-grained material, it cannot cause frost heave. Thus, it prevents uneven settlement during a freezing-thawing cycle. Sandy gravel also exhibits low thermal conductivity and rapid drainage, and compound geomembrane is waterproof. Frost heave deformation usually leads to the differential displacements of canal lining, which cause canal lining crack and unevenness deformation. So, some measures to prevent frozen damage are to strengthen drainage and structural layers, to apply insulating and isolating layer. From in situ experimental data, for the new-type canal lining structure, the total frost heave reaches 1.98 cm and the frost depth is about 32 cm, so the frost heave ratio is 6.18%. For the traditional canal lining structure, the total frost heave reaches 6.4 cm and the frost depth is about 53.3 cm, so the frost heave ratio is 12.01% and the total frost heave of the traditional canal lining structure is much larger than the total frost heave of the new-type canal lining structure.

Therefore, the frost heave prevention effect of the new canal lining structure can eliminate the cooling influence of the lowest temperature in winter. This characteristic also means that the new canal lining structure can be an effective measure to ensure the stability of canal linings due to its positive heat-insulation effect.

#### 4.3. The traditional canal lining structure

Fig. 4 shows the traditional canal lining structure, which has two parts. Part ① is a 4.5-m-thick layer of clay, while part ② is a 9.0-m-thick layer of silty loam.

Table 1					
Thermal parameters	of the	media	in	canal	lining.

Physical variables	ω <sub>0</sub> (%)	$\lambda_f (W/m^\circ C)$	$C_{\rm sf} (J/m^{3} °C)$	$\lambda_u \; (W/m^\circ C)$	$C_{su}$ (J/m <sup>3</sup> °C)	$L(J/m^3)$
Sandy gravel Clay Silty loam	8.3 17.5 27.7	2.01 0.79 1.39	$\begin{array}{c} 1.559 \!\times\! 10^6 \\ 1.785 \!\times\! 10^6 \\ 2.224 \!\times\! 10^6 \end{array}$	1.52 0.84 1.01	$\begin{array}{c} 1.879 \times 10^{6} \\ 2.049 \times 10^{6} \\ 2.634 \times 10^{6} \end{array}$	$\begin{array}{c} 20.4\!\times\!10^{6} \\ 60.3\!\times\!10^{6} \\ 31.7\!\times\!10^{6} \end{array}$

<b>Table 2</b> Thermal parameters of the	e media in canal li	ning.	
Physical variables	ω <sub>0</sub> (%)	$ ho_{ m d}~({ m kg}~{ m m}^{-3})$	$D (cm^2 s^{-1})$

Physical variables	ω <sub>0</sub> (%)	$ ho_{ m d}$ (kg m <sup>-3</sup> )	$D (cm^2 s^{-1})$	$-\theta_{\rm f}$ (°C)	В	$C_w (J/m^{3\circ}C)$	$C_i (J/m^{3\circ}C)$
Sandy gravel Clay Silty loam	8.3 17.5 27.7	1800 1300 1420	$5.65 \times 10^{-4}$ 2.81 × 10 <sup>-3</sup> 9.32 × 10 <sup>-3</sup>	-0.20 -0.55 -0.02	0.6100 0.5553 0.4735	$\begin{array}{c} 4.18\!\times\!10^{3} \\ 4.18\!\times\!10^{3} \\ 4.18\!\times\!10^{3} \end{array}$	$\begin{array}{c} 2.09 \times 10^{3} \\ 2.09 \times 10^{3} \\ 2.09 \times 10^{3} \end{array}$

Fig. 7 shows the temperature distribution for a traditional canal lining structure for 1 year following construction. From this figure, the lowest temperature was -7 °C under the embankment on January 10, 2009, compared to -2 °C for the new structure (Fig. 6). The 0 °C isotherm line is from y = -0.47 m to y = -0.50 m under the slope surface of the canal, compared with the isotherm under the new canal lining, which ranges from y = -0.18 m to y = -0.21 m. These results show that the temperature fields of the canal linings are similar but that the new canal lining structure plays a very important role in frost heave prevention. The ground temperature difference under the slope surfaces of the two types of canal clearly ranges from 0 to 0.6 m during the winter, indicating that the 0–0.6 m depth range under the slope surface of the canal lining should be of particular interest in seasonally frozen ground regions.

## 4.4. Effects of the traditional and new canal lining structures

A preliminary analysis was performed on the thermal regimes and slope temperatures for the two types of canal lining structures. The data were measured in situ on January 10, 2009. The effect of the slope on the thermal regime can be seen from the depth of the temperature profiles, as shown in Fig. 8. The figure presents two temperature characteristics. The temperatures under the new canal lining structure were notably higher than those under the traditional canal lining structure at the same depth. For the depth range of 0–0.3 m, the two types of canal lining structures had clear temperature differences. Under the new canal lining structure, the temperatures at the depths of 0, 0.3, 0.5, and 0.6 m were -4.4, 1.2, 2.5 and 3.3 °C, respectively. In contrast, the temperatures under the traditional canal lining structure at the depths of 0, 0.3, 0.5, and 0.6 m were -15.1, -3.2, -0.2 and 1.1 °C, respectively. Comparing the temperature curves of the two types of canal lining structures (Fig. 8), it can be seen that the temperatures changed significantly in the depth of 0-1.0 m under the slope surface of the two types of canal lining structures. For the canal lining structure with a frost depth of approximately 1.0 m in seasonal frozen ground regions, these results prove that the new canal lining structure is an effective structure for frost heave prevention. We can also see in Fig. 8 that the simulated numerical model results are in agreement with the in situ experimental temperature results, and the model appears to accurately describe both the new type of canal lining structure for frost heave prevention and the traditional canal lining structure.

#### 4.5. Moisture content and the traditional and new canal lining structures

Soil moisture content is the most variable parameter and plays the most important role in frost heaving in canal lining structures. The moisture contents at 0 m below the two types of canal lining structures were measured on January 10, 2009, with the results presented in Fig. 9. Fig. 9 shows that the moisture content under the traditional canal lining structure was larger than that under the new canal lining structure. In particular, the moisture content was noticeably different at depths of 0–1.0 m under the slope surfaces of the canals. From Figs. 8 and 9, it can be seen that the new canal lining structure did not cause frost heave below a depth of 0.3 m. while there was little moisture in the soil from depths of 0–0.3 m. The traditional canal lining structure had little impact on frost heave below the depth of 0.6 m, while the moisture content of the soil was higher at depths ranging from 0 to 0.6 m. The moisture contents under the new

canal lining structure at depths of 0, 0.2, 0.4, and 0.6 m were 8.5%, 10.1%, 16.2% and 19.2%, respectively, while the moisture contents under the traditional canal lining at depths of 0, 0.2, 0.4, and 0.6 m were 28.8%, 28.9%, 29.1% and 30.2%, respectively. The moisture content profile only changed slightly under the surface of the traditional canal lining structure. However, the moisture content changed significantly at various depths under the new canal lining structure. This result shows that the new-type canal lining structure can prevent water from seeping downward, has good drainage and a high thermal insulating effect, and cuts off the migration of foundation moisture. Thus, the frost heave for a traditional canal lining structure was greater than that for the new-type canal lining structure at the lowest temperature during the year. It is clear from this figure that the new canal lining structure has low seepage and prevents frost heave.

## 5. Summary and conclusions

A two-dimensional coupled system of heat transport and moisture flow models was described for canal lining structures for frost heave prevention in seasonally frozen ground regions. From the above analyses of frost heave prevention effects with different canal lining structures, a new type of canal lining structure was proposed. Based on the results of the analysis, the following conclusions can be drawn:

- (1) The agreement between the simulations carried out with the coupled model established in this paper, and in situ temperature measurements appears to be good for both the new canal lining structure for frost heave prevention and the traditional canal lining structure. Variations in the temperature field during freezing were also accurately predicted by this model.
- (2) The new canal lining structure has a significantly better frost heave prevention effect than the traditional canal lining structure. Low seepage, good drainage, good insulation, and little uneven deformation are the key factors in preventing frost heave in canal linings. The thickness of the linings under the slope surface of the canal is also a very important factor for frost heave prevention.
- (3) The new canal lining structure can be an effective frost heave prevention structure with a 0.5-m-thick gravel layer, which consists of concrete slabs, a polystyrene insulation board, sandy gravel layers and a compound geomembrane. The concrete



**Fig. 6.** The temperature distributions of the new-type canal lining structure on Jan. 10, 2009 (unit: °C).



**Fig. 7.** The temperature distributions of the traditional canal lining structure on Jan. 10, 2009 (unit: °C).

slabs have low seepage, and the polystyrene insulation board has low thermal conductivity and low density and is low cost. Thus, it can effectively prevent heat exchange between the air and soil. The sandy gravel is a coarse-grained material, so it cannot cause frost heave and prevents uneven settling during freezingthawing cycle action. Furthermore, it exhibits low thermal conductivity and rapid drainage. The compound geomembrane is waterproof. Thus, in addition to preventing seepage, the new canal lining structure can also prevent frost heave damage.

(4) From in situ experimental data, it was observed that the temperature distribution under the traditional canal lining structure



(a) New type canal lining



(b) Traditional canal lining

Fig. 8. The temperature profile of two kinds of canal lining structure on Jan. 10, 2009.



Fig. 9. The moisture content profile of two kinds of canal lining structure on Jan. 10, 2009.

was obviously affected by winter temperatures, especially from 0 to 0.6 m below the slope surface of the canal, which can cause significant frost heave damage in the canal lining structure. Special attention should be paid to the depth range of 0–0.6 m below the slope surface of canal linings in seasonally frozen ground regions.

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