Study on the Effect of Subsoil Replacement on the Frozen Deformation of Channel Bank Slopes

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Abstract. The water content of base soil is one of the main factors affecting the subsidence of channel bank slopes, the fluffier the soil quality of bank slopes, the greater the water content, the greater the deformation of channel bank slopes, the use of non-frost-sensitive materials to replace the bank slopes of the wet subsidence of the soil is an effective way to solve the frequent freezing and expansion of the channel bank slopes. To solve the problem of frost-distension damage caused by the change of groundwater level and repeated freezing and thawing of seasonally frozen soil foundation in the cold and dry irrigation area of Northwest China, according to the idea of improving the material properties of the frost-distension-sensitive area by replacing the subsoil, we analyze the influence of different replacing materials and depth of replacing on frost-distension of channels through the subsoil replacing test on the site. The results show that: after the soil foundation in the frost-sensitive area of the channel is replaced by 30 mm, 50 mm, and 70 mm thick gravel and fine sand respectively, the frost deformation of the channel bank slope and the base is reduced, and the effect of gravel on the deformation of frost deformation is better than that of fine sand; with the increase of the thickness of the replacement, the reduction of frost deformation is also on a decreasing trend. The research results can provide a theoretical basis and technical support for the anti-freezing and expansion structural modification of channels in permafrost areas.

Keywords: channel frost heave; frozen soil; replacement soil

1 Introduction

In the seasonal permafrost region of northern China, the repeated freezing and thawing cycle process leads to serious damage to the channel's impermeable lining structure by freezing and expansion, which seriously affects the safe operation of the irrigation district and water resource allocation. Ningxia Gu Hai Yangshui Irrigation District in China is one of the typical high lift large-scale irrigation districts in the

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northwest of China. The project was completed in 1986, and during the service period of the project, it was subjected to the constraints of technological level, untimely maintenance, and operation and management, which led to serious aging of the project buildings in the irrigation district, especially the repeated freezing and thawing of the foundations along the channels, resulting in the aggravation of frost and expansion damages to the canal buildings, which seriously affects the safe operation of the project. Figure 1 shows the current situation of freezing and expansion damage of lining structures of water transfer channels in Ningxia Guhai Yangshui Irrigation District.

To investigate the anti-freezing and expansion damage mechanism of irrigation channels, scholars at home and abroad have done a lot of research on the freezing and expansion of channel subsoil in seasonal permafrost areas. Li Bin [1] showed through numerical simulation results that backfilling with gravel material can effectively inhibit the freezing displacement and reduce the freezing force. Sun Hongbao [2] used finite element software to carry out numerical simulations of the temperature field of the canal base soil. When the outside air temperature drops, it will lead to the freezing of the surface soil of the canal base, and with the increase of the depth of the curvilinear base soil, the magnitude of the temperature change will become smaller. An Peng [3] used the finite element analysis method to analyze the hydraulic and temperature fields after laying the pipe, and the results showed that the hydraulic and temperature fields after laying the pipe were significantly reduced, and the freezing strength and freezing force were significantly reduced. Wu Wenjie [4], through the indoor freezing and expansion experiments on the soil at the base of the canal in Shenyang Bayi Irrigation District, found that with the increase of water content, the change of the temperature field of the experimental soil column had a large hysteresis, and the change was slower in the case of water replenishment than in the case of no water replenishment. Rong Guangqiu [5] carried out freezing and expansion experiments on soils with different water contents, and the results showed that with the increase of water content, powdery clay soil had the greatest effect on soil freezing and expansion, followed by clay soil, while dispersed soil had the least effect on soil freezing and expansion. Xu Feng [6] conducted finite element simulation on the soil of the canal base after filling, and the results showed that before and after filling, the lateral displacement of the channel changed less and more uniformly than the lateral displacement when it was not filled. Chunyang Zhang [7] used the results of finite element analysis to show that under the same conditions of particle gradation, the improvement effect of the crushed stone trench on the freezing depth of the channel increases with the increase of temperature gradient and the reduction effect of the freezing depth increases with the increase of particle gradation. Zhelnin M [8] carried out a numerical simulation based on the thermal-hydraulic-mechanical modeling of the freezing process of water-saturated soils, and the results showed that the freezing-induced temperature changes and freezing deformation cause the soil body to be displaced in both vertical and horizontal directions. Roman, L [9] pointed out that the freezing deformation of soil decreases as the dispersion of soil increases as the water content of the soil body increases to a value close to the saturated water content. Guo Fuqiang [10] studied the effect of the change in groundwater level on the freezing deformation of the foundation soil and the freezing force of the channel by using the method of mechanical analysis. The results of the study show that for every 1 cm decrease in groundwater level, the amount of frozen expansion of the foundation decreases by 0.15 cm, and the maximum frozen expansion force of the channel varies with the change in groundwater level. From the above study, it can be found that the performance of the foundation soil material in the frost-sensitive area of the channel bank slope is a very important factor affecting the frost damage of the channel, however, most of the scholars mainly use the method of finite element software analysis to analyze and theoretically calculate the impact of the channel freezing and expansion displacement and the distribution of temperature field, and few of them have carried out the study by the experimental method, to find out the impact of the channel impermeable structure under the action of freezing and thawing on the frost deformation response of the bank slope. To investigate the response law of the channel seepage control structure to the freezing and thawing deformation of the slope subsoil, and to reveal the coupling relationship between the material properties of the channel subsoil and the freezing and thawing damage of the channel, this paper adopts the method of combining on-site monitoring and indoor replacement test to further study the anti-freezing and thawing effect of the material replacement in the freezing and thawing-sensitive area of the channel.

This paper takes the typical trapezoidal cross-section channel in Ningxia Guhai Irrigation District of China as the research object, and carries out an indoor freezing test on the frozen deformation of the channel bank slope by using two kinds of replacement materials of sand and gravel and fine sand, with the depths of replacement of 30, 50 and 70 cm, respectively, and conducts freezing test of indoor replacement of the channel base soil to carry out freezing characterization of the channel base soil for the different cases of replacement, and analyzes the degree of influence of the different kinds of replacement on the damage of the channel freezing to provide a reference for the freezing-resistant design of the channel project.

(a)Concrete slab bulge damage

(b) Concrete slab bulge cracks

(c) Concrete slab slide

(d) Concrete slab overhead damage

Fig. 1. Typical frost damage form of channel

2 Indoor replacement test

2.1 Experimental design

Two different filling methods were used in the experiment: sand and gravel and pulverized fine sand; three different filling depths of 30, 50, and 70 mm were used for indoor filling one-way freezing experiments with a total of seven groups (including one control group), and the experiments were designed as shown in Table 1.

Table 1. Specimen design

Number of test groups	Experiment number	Replacement material	Replacement depth (mm)
1	A	No cross-fill	0
2	A1	Gravel material	30
3	A2	Gravel material	50
4	A3	Gravel material	70
5	B1	Powdered fine sand	30
6	B2	Powdered fine sand	50
7	B3	Powdered fine sand	70

2.2 Test procedure

1) Soil samples taken from outdoors were sequentially removed from impurities, dried for moisture, ground, and sieved, and the replacement gravel material to be used was selected to remove the larger particles from the gravel material;

2) To make an accurate simulation of the frost swelling condition of the actual outdoor channel, the remodeled soil sample was made based on the density of 1.84 g/cm3 and 30% water content of the outdoor measured canal base soil, and after it was made, it was placed in cling film for 8 hours, so that the internal water content of the soil sample could be more evenly distributed;

3) Filling the prepared channel remodeled soil sample with 60 mm high soil column and gravel material blocks with 40 mm high soil column into the test tank in sequential layers and compacting them;

4) A small hole is made every 2 cm in the side of the test tank and a temperature sensor is placed for real-time monitoring of soil temperature changes;

5) The sample is placed in a freeze-thaw cycle unit, adjusted to 15°C, and then stored at a constant temperature. When the temperature of each temperature sensor in the sample is approximately 15°C, the test can be started. The test will start at 0 °C and drop the temperature inside the freeze-thaw cycle unit to -20 °C at a cooling rate of -1.2 °C/h for a total of 16 hours;

6) During the test, the test sample will be monitored in real-time with a temperature sensor, and the displacement sensor during the test will be recorded after the test

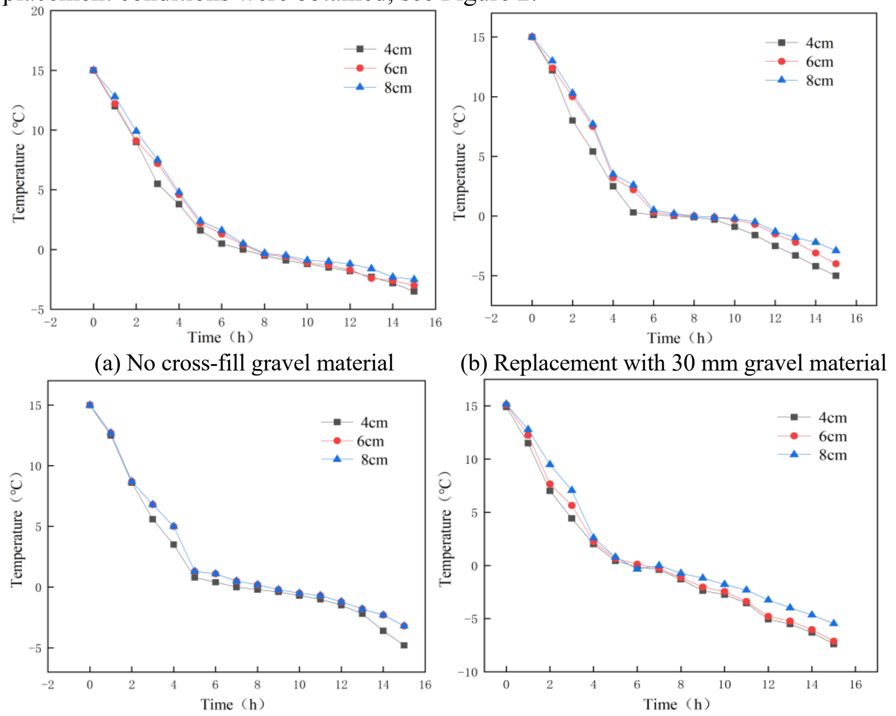
is completed. The other groups of tests only differed in the depth of the filler. The other test methods were the same.

3 Analysis of results

3.1 Temperature analysis of soil samples for different replacement conditions

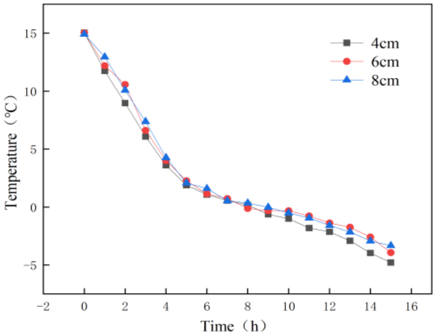
The analysis of the time domain diagram of the internal temperature of the soil can better reflect the temperature distribution and change pattern of the soil at different stages; the simulation results show that the temperature field of the soil changes significantly under different replacement media and different replacement depths.

Under the conditions of the same freezing duration and the same height of soil samples, the temperature of each group of experiments was monitored in real-time, and the temperature-time curves at different heights within the soil under different replacement conditions were obtained, see Figure 2.

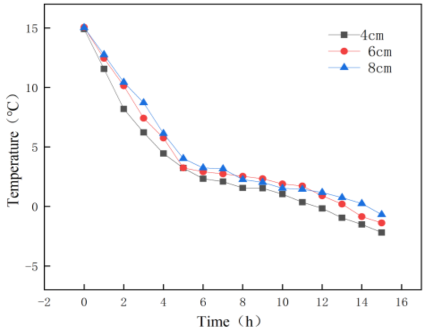


(a) No cross-fill gravel material (b) Replacement with 30 mm gravel material

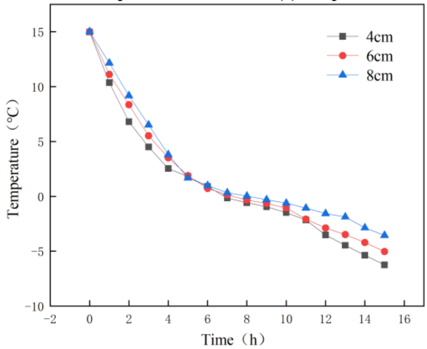
(c) Replacement with 50 mm (d) Replacement with 70 mm gravel material



(e) Replacement of 30 mm fine powder sand



(f) Replacement with 50 mm fine sand



(g) Replacement with 70 mm fine powder sand

Fig. 2. Curve of internal temperature of soil samples with time for different replacement cases

As shown in Figure 2, by comparing the temperature field distributions of the permuted and no permuted groups, we can find that both permuted materials present the effect of accelerating the thermal conduction of the internal temperature of the soil samples. For the part of the soil without replacement treatment in the replacement group and the corresponding part of the test in the no-replacement group, the rate of temperature reduction inside the soil is faster in the former than in the latter for the same freezing duration.

Comparing the effects of the two kinds of replacement materials on the temperature field, it can be found that although both kinds of replacement materials exhibit accelerated temperature reduction of the soil samples, the effect of accelerating the rate of migration of the freezing fronts is more pronounced in the sandy gravel, because the inhomogeneity coefficient of the porosity of the sandy gravel is larger than that of the powdered fine sand [11]. Since the physical characteristics of the powdered sand are closer to the original soil sample than those of the gravel particles, the powdered sand particles take longer to reach the freezing front than the gravel particles do.

The starting freezing time of each layer of the test soil column was fitted based on the measured temperature field data of the soil layers as shown in Table 2.

Table 2. Starting freezing time of each soil layer of the test soil column

Replacement materials	No refill	Gravel materials			Powder fine sand		
Height(cm)	A	A1	A2	A3	B1	B2	B3
4	9.26	7.61	7.19	6.54	8.40	8.12	7.61
6	10.50	9.10	8.07	7.21	9.72	9.28	8.46
8	11.85	9.90	8.83	8.14	10.86	10.19	9.76
Freezing time(h)	8.05	5.30	4.92	4.38	6.88	6.26	6.20

As can be seen from Table 2, under the condition of the same initial conditions and external cooling rate, the onset of freezing time of the soil samples after replacement is faster than the onset of freezing time of the soil without replacement, and the sand and gravel material and powder and fine sand are earlier by 1.6 h and 0.8 h, respectively. Under the same length of freezing time, replacement can shorten the time of freezing time of the in-situ soil, and reduce the frozen thickness of the frost-sensitive soil, which will reduce the amount of frost swelling, and that's an important reason that replacement can reduce the amount of frost an important reason for the damage, thus indicating that temperature and soil moisture content are important factors affecting frost heave [12]. Taking A3 and B3 as examples, the freezing time of the test soil columns was reduced by 45.5% and 22.9%, respectively, and the reduction of freezing time by gravel material was more significant and the freezing speed was faster compared with powdered fine sand. This is because the pore ratio, thermal conductivity, and coefficient of inhomogeneity of the gravel material are larger than those of the fine powdered sand and powdery clay.

3.2 Change in the amount of freezing and swelling of the replacement

Freeze-up damage is an important factor in channel damage [13], and the coefficient of frost heave is a physical parameter that characterizes the frost-heave nature of the soil. As the rate of frost heave increases, the frost heave characteristics of the soil also increase. Through the statistics of the freezing expansion data of the experimental soil columns under different replacement conditions, the freezing expansion rate and the freezing expansion reduction rate of each group were obtained, which are shown in Table 3.

Table 3. Frost swelling characteristics of soil under different working conditions

Replacement material	No cross-fill	Gravel material			Powdered fine sand		
Experimental group	A	A1	A2	A3	B1	B2	B3
Amount of freeze swell (mm)	3.53	2.32	1.83	1.58	2.47	1.89	1.66
Freeze swell rate (%)	5.89	3.87	3.05	2.63	4.12	3.15	2.77
Frost heave reduction rate (%)	0.00	34.28	48.16	55.24	30.03	46.46	52.97

Combining the frost swelling with the frost swelling reduction rate can better reflect the frost swelling reduction rate under different replacement conditions and facilitate the determination of the best replacement plan. Based on the experimentally measured frost swelling, the relationship curves of frost swelling and frost swelling reduction rate with the depth of the caulking were plotted for the two types of caulking materials, as shown in Figure 3 and Figure 4.

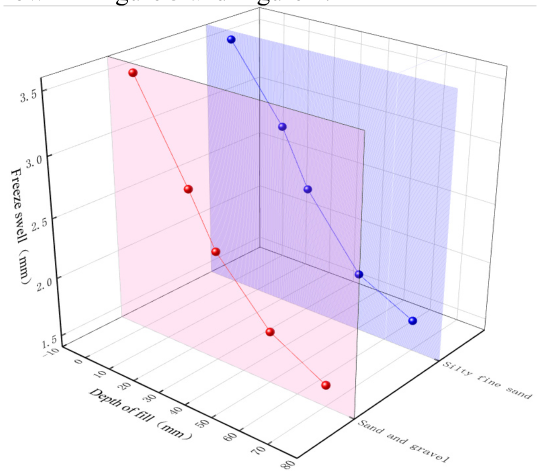


Fig. 3. The relationship between frost heave and depth of replacement

From Figure 3, and Figure 4, it can be found that after replacing the frost-sensitive soil in the channel with weakly frost-swollen soil, the frost swelling of the soil sample showed a significant decrease compared with that without the replacement. From Figure 3, it can be seen that the frost swelling deformation of the soil is inversely proportional to the filling depth, and its frost swelling deformation decreases as the filling depth increases; from Figure 4, it can be seen that there is a certain positive correlation between the reduction rate of frost swelling and the filling depth.

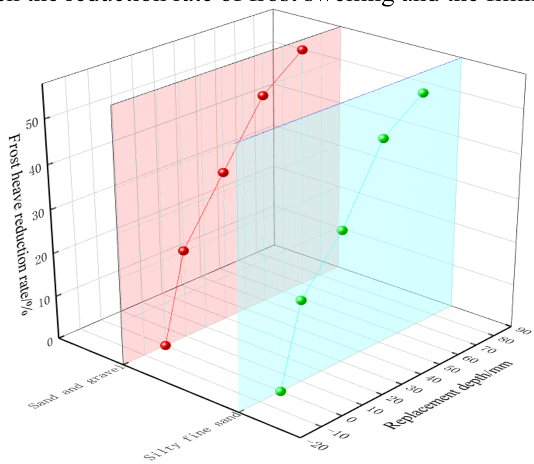


Fig. 4. Frost heave reduction rate versus replacement depth

At the fill thickness of 30 mm, the frost swelling of the replacement sand and gravel material and powder-fine sand soil samples was reduced by 34.28% and 30.03%, respectively. By comparing the two types of replacement fill, it can be seen that the reduction of frost swelling is slightly better for gravel particles compared with chalk particles, mainly because gravel particles have larger pores than chalk particles, and chalk particles are closer to the physical properties of the drainage base soil.

The results of fitting the relationship curves between the frost heave and the depth of replacement were obtained by fitting the frost heave and the depth of replacement for the two replacement materials, as shown in Table 4. (y is the amount of frost heave, mm; x is the depth of replacement, mm).

Table 4. Frozen swelling volume and replacement depth fitting curve equation

Replacement material	Relationship formula	R^2	Standard refill depth(mm)
Gravel material	$y = 0.0002x^2 - 0.0496x + 3.5302$	0.9986	71.79
Powder fine sand	$y = 0.00019x^2 - 0.0444x + 3.5391$	0.998	99.85

From Table 3 and Table 4, it can be seen that the two fitted regression equations R2 are 0.9986 and 0.998, respectively, which prove that the curves fitted for the freezing tests of the two replacement materials in this paper are good and can be used as the prediction equations for the freezing and swelling of the soil for the two materials. The required replacement depths to meet the frost swelling criteria of the drainage base soil were calculated to be 71.79 mm and 99.85 mm, respectively, based on the two regression equations.

4 Conclusions

1) Through the analysis of the internal temperature data of soil samples in different cases, it can be seen that the internal temperature of soil samples shows a rapid decrease first, then the temperature changes gradually flatten out, and the temperature decreases again with an increasing trend, and finally converges to the cooling rate of the freeze-thaw cycle machine.

2) Both gravel and fine sand can improve the frost damage of the channel, in the same depth of filling, the degree of reduction of frost expansion of the former is greater than the latter; with the increase of the depth of filling, the rate of reduction of frost expansion of the two gradually tends to slow down, through the two kinds of filling material frost expansion and the depth of filling curve fitting, it is concluded that the two kinds of materials to meet the design specifications corresponding to the depth of filling are 71.79 mm and 99.85 mm respectively.

3) Single from the replacement of the two replacement materials on the thickness of frost swelling soil body, the replacement of fine sand after the thickness of frost swelling soil body is less than gravel material, reducing the effect of frost swelling better than gravel material. The reason is that the physical properties of powdered sand are more similar to those of canal base soil, and the porosity of gravel material is

larger, so the reduction effect of frost swelling on canal base soil is better than that of powdered sand, and the powdered sand in the saturated state will also produce a certain amount of frost swelling, so the reduction effect of gravel material on the amount of frost swelling is more obvious.

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