Effect of Subsoil Replacement in Frost-Sensitive Areas on the Frost Deformation of Channel

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Abstract. The water content of the subsoil is one of the main factors affecting the subsidence of the channel bank slopes, the looser the soil quality of the bank slopes, the greater the water content, the greater the deformation of the channel bank slopes, the use of non-freezing and expansion sensitive materials to replacethe bank slopes with wet subsiding soil is an effective way to solve the problem of frequent freezing and expansion of the channel bank slopes. In order to solve the problem of frozen expansion damage caused by groundwater level change and repeated freezing and thawing of seasonal frozen soil foundation in the cold and dry irrigation area in northwest China, ABAQUS software was applied to simulate the influence of the replacement of channel subsoil materials on the temperature and strain fields of the foundation by establishing a finite element model. The results show that: after the soil foundation in the frost-sensitive areaof the channel is refilled with 30cm, 50cm and 70cm thick gravel and fine sand respectively, the frost deformation of thechannel bank slope and foundation is obviously reduced, an the reduction effect of gravel on the frost deformation is better than that of fine sand; with the increase of the thicknessof the refill, the reduction of frost deformation is also on adecreasing trend, and the influence of the channel subsoil refill on the temperature field of the foundation is smaller, but the subsoil will make the temperature field and strain field of the bank slope after the refill. After refilling, the frozen expansion displacement of the bank slope can be dissipated,which can significantly improve the deformation and stress concentration phenomenon on the channel seepage control lining structure. The research results can provide theoretical basis and technical support for the anti-freezing and expansionstructural modification of channels in permafrost areas.

Keywords: channel frost heave; frozen soil; replacement soil; numerical simulation.

1 Introduction

In the seasonal permafrost region in the north of China, due to repeated freeze-thaw cycle process, resulting in channel seepage control lining structure expansion damage isserious, seriously affecting the safe operation of the irrigation district and water

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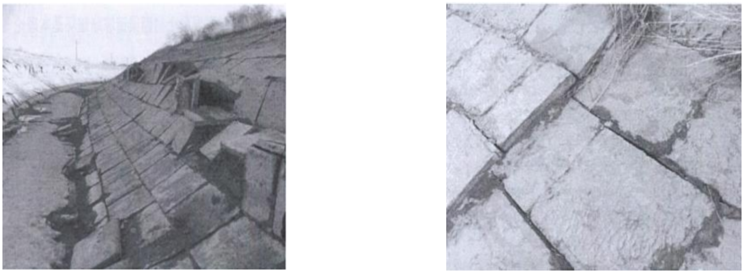
resource allocation. Ningxia Gu Hai Yangshui irrigation district is one of the typical high-lift large-scale irrigation districts in the northwest of China, and the project was completed in 1986. In the project service period, by the technical level, operation and management and other factors, resulting in irrigation district project building aging serious, seriously affecting 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 GuhaiYangshui Irrigation District.

In order 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 aspects of channel base soil in seasonal permafrost areas. Wu Wenjie [1] found that with the increase of water content, the temperature field of the experimental soil column changed with a large hysteresis through the indoor freezing and expansion experiments on the soil at the base of the channel in Shenyang Bayi Irrigation District. Rong Guangqiu [2] carried out freezing and experiments on soils with different water contents, and theresults showed that with the increase of water content, powdery clay soil had the greatest freezing and expansion effect on the soil, followed by clay soil. Xu Feng [3] carried out finite element simulation on the soil of the canal base by filling, and the results showed that before and after filling, the lateral displacement of the trench was smaller than the change of lateral displacement when it was not filled. Li Haiyin [4] analyzed that before the soil moisture content reaches the saturated water content, the freezing rate of soil increases by 0.28% for every 1% increase in water content, and the freezing rate of soil increases by 0.17% for every 1°C decrease in temperature. Li Bin [5] showed through numerical simulation results that backfilling with sand and gravel materials can effectively inhibit the freezing antermate and reduce the freezing force. Roman, L [6] pointed out that with the increase of water content of the soil body close to the saturated watercontent value, the freezing and expansion deformation of the soil will be reduced with the increase of the dispersed nature of the soil. Grahamj [7] for the problem of freezing and expansion damage to the channel carried out a channel base soil test, pointing out that after a freeze-thaw cycle cycle of the channel base soil, the original structure of the soil body has a large degree of damage. Fromthe above study, it can be found that the performance ofthe subsoil material in the frost-sensitive zone of the channel bank slope is a very important factor affecting the frost damage of the channel, however, most of the scholarsmainly use the method of indoor replacement test to analyze and theoretically calculate the impact of the channel freezing and expansion displacement and the distribution of temperature field, and seldom use finite element simulation to carry out the study in accordance with the actualconditions of the site, in order to investigate the impact of the channel impermeable structure on the bank slope under the action of freezing and thawing, and the effect of the frozen and thawing on the soil structure. In order to find out the response law of the channel seepage control structure to the frozen deformation of the bank slope subsoil, and to reveal the coupling relationship between the material properties of the channel subsoil and the frozen damage of the channel, this paper adopts the method of combining on-site monitoring and finite element simulation to further study the anti-freezing effect of the material altermate in the sensitive area of the channel freezing and thawing. This paper takes the typical trapezoidal cross-section channel in Ningxia Guhai Irrigation District of China as the research object, applies ABAQUS software to establisha finite element model, numerically simulates the deformation of the channel bank slope by using two kinds of replacement materials of sand and gravel and fine sand, with the depth of replacement of 30cm, 50cm, and 70cm, respectively, and mainly carries out the coupling analysis of temperature and stress to investigate the influence of the change of channel subsoil materials on the channel's temperature field and stress field, in order to provide a reference for the anti-freezing and expansion 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 Numerical Simulation Trapezoidal Drainage Soil Replacement

2.1 Channel profile and grid division

The lining structure of a typical trapezoidal channel in the Guhai Irrigation District of Ningxia, China, is shown in Figure 2. The impermeable panel is a 6 cm-thick precast concrete panel lining structure, and the side slope coefficient of the channel is m = 1.5. The concrete panel bedding is under the wetted bedrock soil, which is also the sensitive area of the channel for freezing and expansion. On-site monitoring found that the perennial groundwater level at the bottom of the channel is located at about 20 cm below the channel floor.

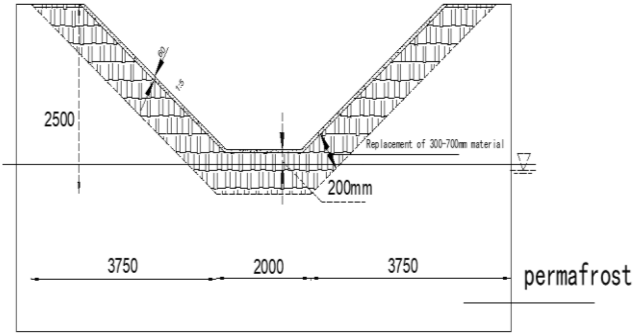


Fig. 2. Schematic diagram of channel replacement structure

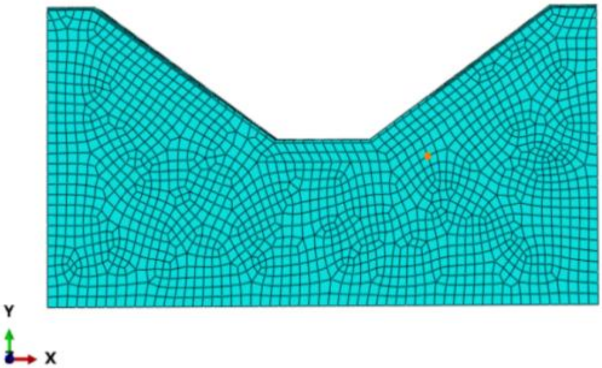


Fig. 3. Grid division diagram

Figure 3 shows the gridding diagram of the finite element model constructed according to the structural type of lining, in order to more accurately analyze the deformation of the channel after freezing and expansion, this paper's grid is divided into cell sizes as small as possible. The meshing diagram in Figure 3 has a total of 11,410 cells and 13,497 nodes, and the simulation analysis is carried out by ABAQUS software.

2.2 Soil frost and swelling model theory

1)Permafrost heat conduction equation.

Channel frost heave is a long-term accumulation process influenced by temperature, moisture content and external loads. During daily operation, the moisture in the subsoil of channel bank slopes will be transported and changed in phase with the change of temperature. In the radialdirection, the channel can be regarded as a long and narrow channel, and the subsoil of the channel can be regarded as a two- dimensional riverbed in the numerical simulation[8,9]. The thermal conductivity equation of the subsoil during the freezing period of the channel is shown inequation (1):

$$\frac{\partial T}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial T}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial T}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)=0 \tag{1}$$

where: λ_x, λ_y, λ_z is the heat transfer coefficient along the x,y,z direction of the permafrost,T is the frost and swelling problem boundary.

2)Permafrost principal structure equation.

Moisture in the soil will form ice crystals in the poredue to the negative temperature, leading to an increase isoil volume [10,11]. At the same time, the moisture in thesubsurface soil will move towards the freezing cover, which leads to the freezing volume and freezing stress and the stress-strain relationship equation is shown in (2):

$$\{\sigma\}=[G]\{\varepsilon\}-\{\beta\}T \tag{2}$$

where: $[G]$is the stiffness matrix, $\{\varepsilon\}$ is the strain matrix,
$\{\sigma\}$ is the stress matrix, and T is the temperature.

2.3 Model parameter selection

In the numerical simulation calculation, the selection of relevant parameters has a great influence on the accuracy of the calculation results, for the base soil material in Ningxia Guhai irrigation area, the main parameters selection is shown in Table 1.Guhai irrigation area, the main parameters selection is shown in Table 1.

Table 1. Selection of matericl parameters

Materials	Density(kg/m^3)	Elastic modulus(Mpa)	Poisson ratio	Heat conductivity(W/m·°C)	Specific heat capacitykJ/(kg·k)	Linear expansion coefficient(1/°C)
Concrete lining	2400	3×10^4	0.18	0.72	780	1.4×10^{-5}
Subsoil	1830	46	0.22	2.12	1222	-0.02
Gravel material	2060	380.8	0.21	1.4	706.6	5.6×10^{-6}
Powder fine sand	1400	100	0.11	0.75	757.6	10.58×10^{-6}

3 Analysis of Results

3.1 Temperature field analysis

For the simulation and analysis of the temperature fieldof the channel subsoil, the CAE module can be selected inAbaqus for the temperature field calculation and analysis, the upper boundary temperature of the channel is selected as the average minimum temperature of the Ningxia Gu HaiIrrigation District in recent years, which is both -8 °C, andas the outside temperature is applied to the concrete liningpanels; the temperature of the channel subsoil is selected as the temperature of the subbase of the trapezoidal channelat -1 °C, which is applied to the bottom of the channel soil; in the absence of the subsoil refilling treatment, the channel is subjected to the simulation and analysis of the temperature field calculation and the results of the temperature-field distribution of the channel are shown in Figure 4.

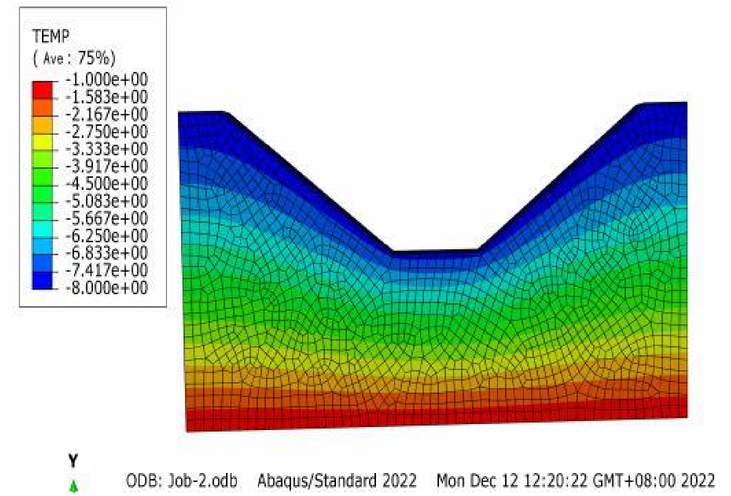
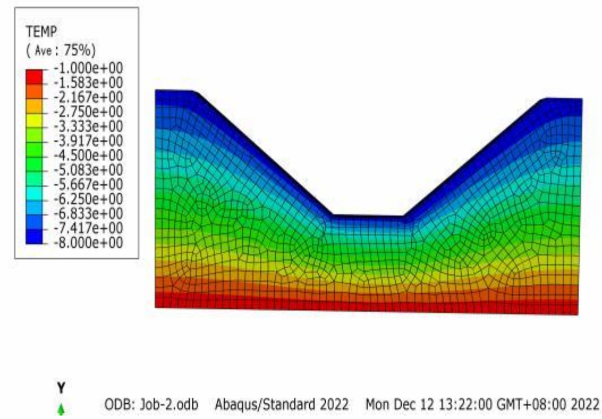


Fig. 4. Cloud diagram of temperature field distribution in the prototype channel

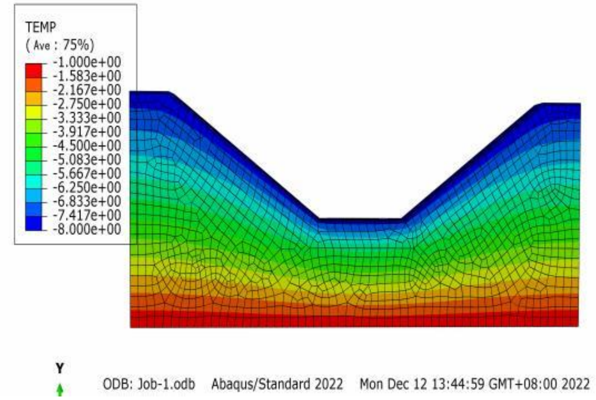
From the results of the simulation in Figure 4, during the winter freeze-thaw period, when the outside world is in continuous negative temperature conditions, the entire channel impermeable lining structure and the bank slope soil layer of thetemperature field changes, the main realization from the surface layer to the subsoil inside the temperature gradient change is relatively consistent, the temperature decreases sequentially from top to bottom, and the amplitude of the temperature reduction contour in the form of a continuous curve.

1)Results of temperature field analysis of sand and gravel replacement material.

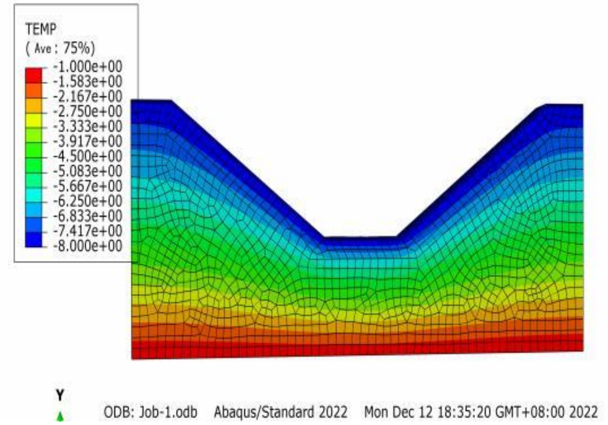
In order to investigate the temperature field changes after replacing the original soil with frost-sensitive sandy material in frost-sensitive area, Abaqus software was applied to construct a model of replacing the originalsoil with sandy material at the depths of 30cm, 50cm and 70cm, and the results are shown in Figure 5 after the simulation analysis and calculation. The temperature field comparison between no refilling treatment and refilling gravel material and different depths shows that in the steady state condition, the temperature field distribution of the channel without refilling treatment and after refilling treatment does not have much change, and the refilling depth has less influence on the temperature field in the steady state condition, but the freezing depth increases slightly with the increase of the refilling depth.



(a)Replacement of 30cm gravel material



(b)Replacement of 50cm gravel material



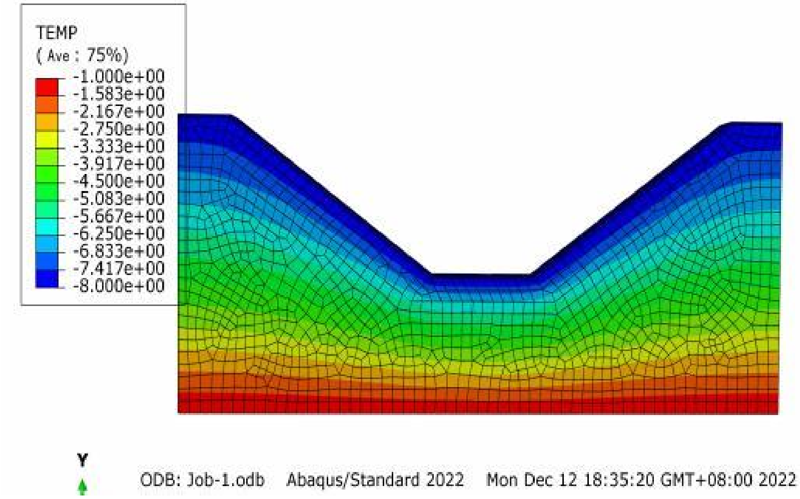
(c)Replacement of 70cm gravel material

Fig. 5. Temperature clouds of different gravel replacement depths

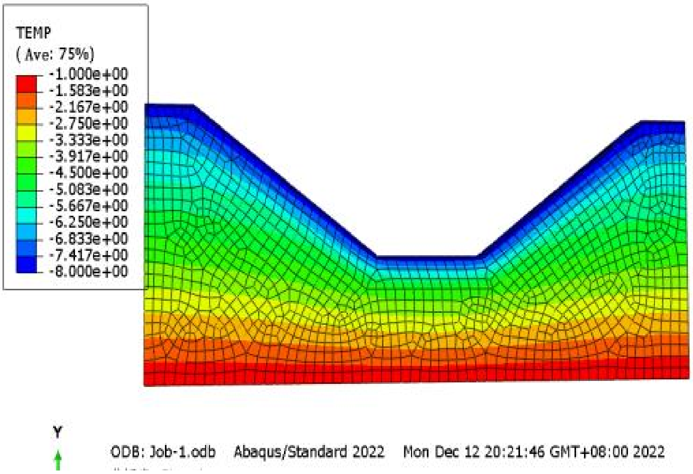
2)Results of temperature field analysis of replacement powder and fine sand.

Figure 6 shows the simulation results of replacing the original map with powdered fine sand cloud diagram, as can be seen from the Figure, the effect of replacing powdered fine sand on the temperature field of the channel lining plate is very small, with the increase of the depth of the replacement, the channel simulation temperature has a slightly smaller upward shift but the effect is not obvious.

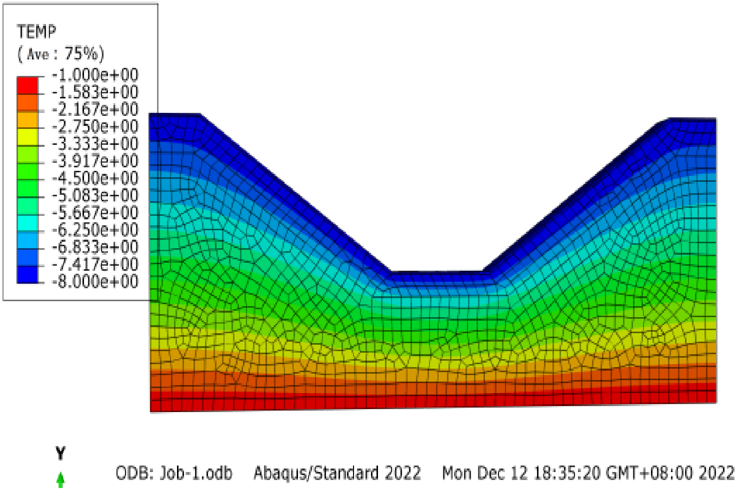
From the comparison of Figure 5 and Figure 6 with Figure 4, it can be seen that the effect of refilling gravel, powder and fine sand and different depth of refilling on the temperature field of the channel lining plate is not very obvious, and the distribution of the temperature field of the channel before and after the refilling does not have too much change, and the effect of the refilling material and the depth of the refilling on the temperature field in the steady state is relatively small.



(a)Replacement of 30cm Powder fine sand



(b)Replacement of 50cm Powder fine sand



(c)Replacement of 50cm Powder fine sand

Fig. 6. Temperature clouds of different replacement powder and fine sand depths

3.2 Strain field analysis

In Abaqus, the CAE model is selected for strain field analysis, and the displacement changes in the x, y, and z directions are constrained for the two sides and the bottom of the channel model. For the upper part of the channel model, the displacement change in the z direction is limited, and no constraints are imposed in the x, y direction; on this basis, the displacement field is solved for the model using the existing temperature field solution results, which areshown in Figure 7

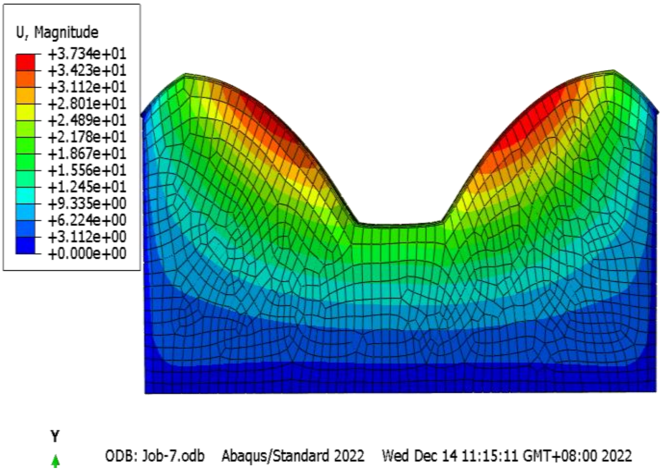
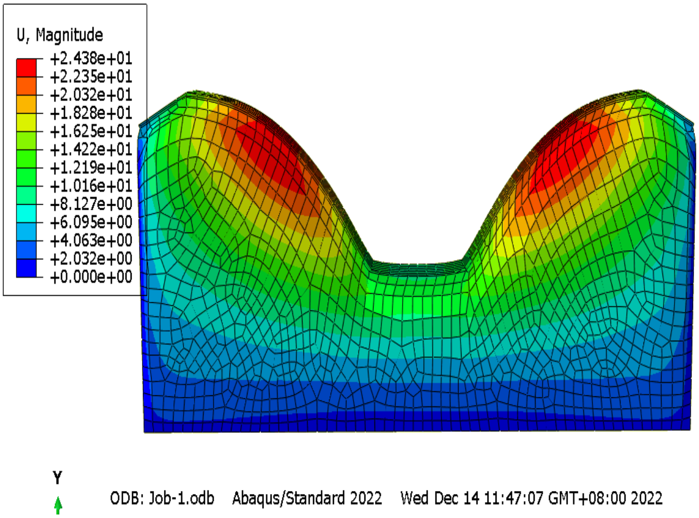


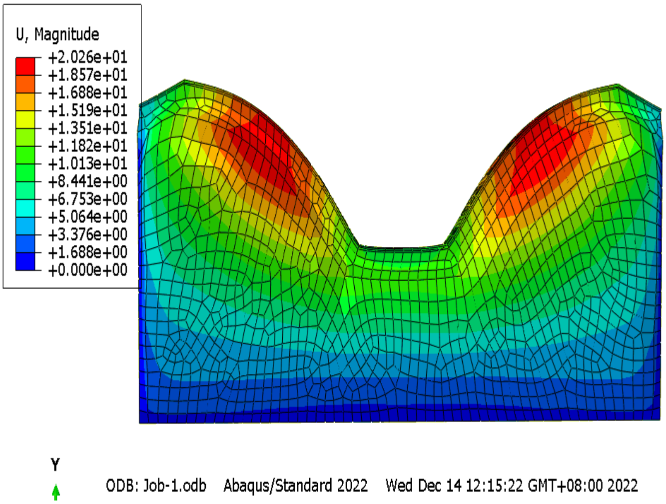
Fig. 7. Cloud map of channel displacement field distribution

1)Analysis results of strain field of replacement powder and fine sand.

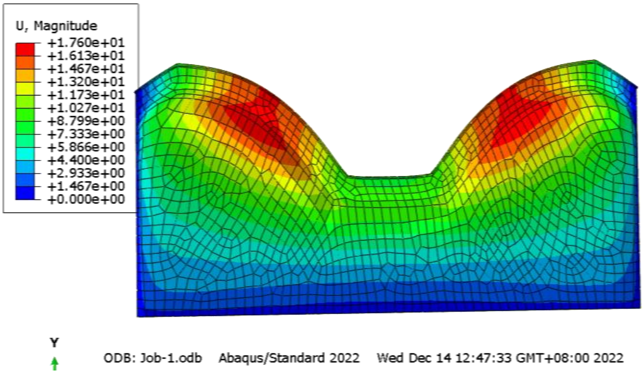
Figure 8 is a cloud diagram of the simulation results of replacing the original diagram with powdered sand, from which it can be seen that, with the increase of the depth ofthe replacement, the frozen expansion of the channel subsoiland concrete lining plate has a significant reduction inthe amount of frost, and the maximum amount of frost appeared to be the location of the obvious downward trend; before the replacement of the maximum simulation of frost expansion for 25.79cm, replaced by 70cm of powdered sand after the maximum amount of frost for the replacement of 17.7cm, the frost abatement rate is 52.60%, indicating that the appropriate increase in the depth of refilling is conducive to reducing the frozen expansion of the channel foundation soil and concrete lining plate.



(a)Replacement of 30cm Powder fine sand



(b)Replacement of 50cm Powder fine sand



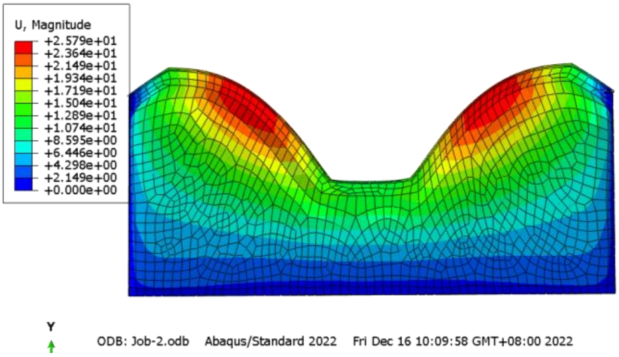
(c)Replacement of 50cm Powder fine sand

Fig. 8. Temperature clouds of different replacement powder and fine sand depths

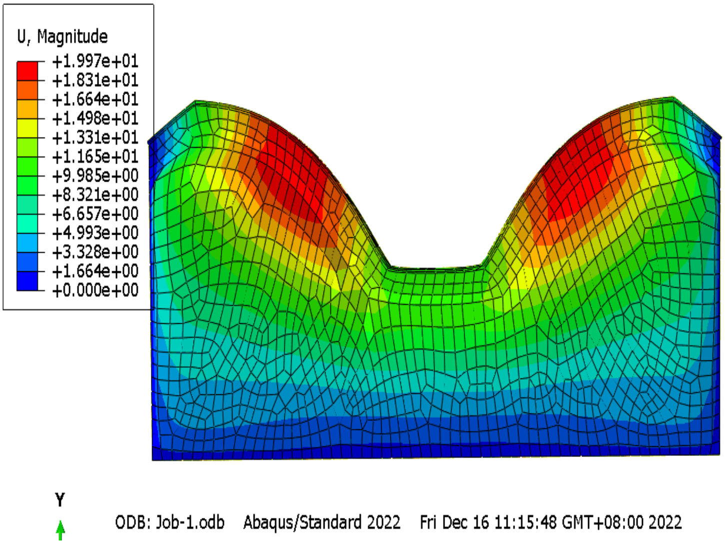
2)Results of strain field analysis of replacement gravels.

From Figure 9 can be seen that the gravel material can make the channel lining plate on the amount of frost expansion dispersed, with the increase in the depth of the refilling, refilling gravel material lining plate on the displacement distribution curve gradually flattened, meaning that the lining plate on the distribution of each part of the displacement is more evenly distributed, therefilling can be effective in improving the amount of frost expansion on the lining of the channel and frost expansionof the stress concentration of the phenomenon, which in turn reduces the damage of the channel freezing and expansion.

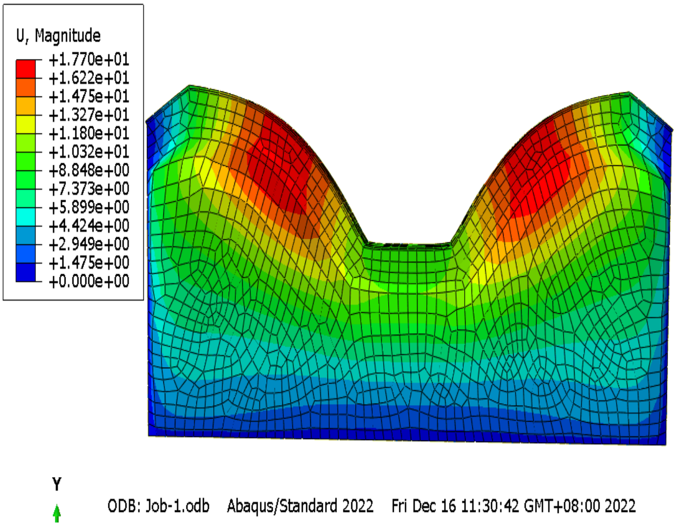
From the comparison of Figures 7 and 8 with Figure 9, it can be seen that the displacement distribution curve onthechannel liner without replacement treatment fluctuates greatly. And the distribution of the frozen expansion amount also varies greatly, there is an obvious frozen expansion amount concentration phenomenon; replacement of gravel and powdered sand after treatment of the channel than no replacement of the channel lining plate freezing expansion is reduced a lot of gravel abatement effect is better than thepowdered sand, and with the replacement of the depth of the increase in the channel lining plate freezing expansion and consequently reduce.



(a)Replacement of 30cm gravel material



(b)Replacement of 50cm gravel material



(c)Replacement of 70cm gravel material

Fig. 9. Temperature clouds of different gravel replacement depths

Single from the replacement material, the replacement of gravel material to reduce the frozen expansion of the channel is better than gravel material, in which the maximum reduction rate of 52.87%; from the thickness of the replacement, in a certain range, with the increaseof the thickness of the replacement, the simulation of the frozen expansion of the smaller. The simulated freezing expansion and abatement effect of channel subsoil under different filling materials and filling depths are shown in Table 2.

Table 2. Comparison of the effect of freezing and swelling volume reduction

Replacement material	Replacement depth(cm)	Simulated freeze swell volume(mm)	Frost heave reduction rate(%)
No cross-fill	0	37.34	0.00
	30	24.38	34.71
Gravel material	50	19.97	46.52
	70	17.6	52.87
	30	25.79	30.93
Powder fine sand	50	20.26	45.74
	70	17.7	52.60

For the frost-sensitive wet loess, both gravel and fine sand can be used to reduce the amount of frost displacement and improve the stress concentration on the liner. In areas where gravel is more abundant, the effect of selecting gravel to reduce the amount of frost heave will be slightly better. Each project can carry out channel refilling treatmen according to the actual situation. Through the field investigation and finite element simulation, thechanges in the amount of frost expansion of channel liningplate after different refilling materials and different depths of refilling can provide technical measures for the management of the phenomenon of serious damage of frost expansion of the channel subsoil, and also provide a reference for the finite element simulation in similar areas.

4 Conclusions

1)The maximum amount of frozen expansion occurred in the channel roughly from the bottom of the channel 1/2~ 1/3 of the slope plate, filling gravel and fine sand can make the channel lining plate on the amount of frozen expansion dispersed to reduce the amount of frozen expansio of the channel foundation soil, effectively improve the amount of frozen expansion on the lining of the channel and frozen expansion of the concentration of the phenomenon ofstress and thus reduce the channel freezing and expansion damage.

2) With the increase of filling depth, the reduction effect of freezing expansion gradually decreases, and the thickness of freezing is also gradually reduced; with the filling depth of 70cm, for example, the two kinds of filling materials are 52.87% and 52.6% of the reduction rate of the freezing expansion of the soil base of the canal, the reductioneffect of the sand and gravel is better than that of the powdered and fine sand, and with the increase of the dept of the filling, the degree of the change of the reduction effec is gradually reduced.

3) Gravel material replacement 50cm, powder fine sand replacement 70cm after the channel lining plate at each point on the frozen expansion displacement will reach the design specification requirements.The actual project can be selected according to the actual situation of the region of the filling material and filling depth, inorder to achieve from the economy, safety and construction are optimal.

Acknowledgment

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