

Article

Stabilization Effects of Inclined Soil–Cement Continuous Mixing Walls for Existing Warm Frozen Soil Embankments

Gaochen Sun ^{1,*} , Long Li ¹, Yufan Huo ¹, Zonghui Fang ², Gao Lv ¹, Tao Chen ¹, Zhengzhong Wang ³ , Meimei Song ¹, Guanqi Lan ¹ and Ziqiang Tang ⁴

¹ School of Civil Engineering, Xi'an Shiyou University, Xi'an 710065, China; 17730623101@163.com (L.L.); 13379589757@163.com (Y.H.); lvgaol16@163.com (G.L.); chentao@163.com (T.C.); songmeimei2016@163.com (M.S.); langq@xsyu.edu.cn (G.L.)

² Gansu Institute of Architecture Design and Research Co., Ltd., Lanzhou 730030, China; 18298385727@163.com

³ College of Water Resources and Architectural Engineering, Northwest A&F University, Yanglin 712100, China; wangzz0910@163.com

⁴ China State Construction Engineering Corporation Aecom Consultant Co., Ltd., Lanzhou 730030, China; show-19870629@163.com

* Correspondence: maomaosg@163.com

Abstract: Affected by climate warming and anthropogenic disturbances, the thermo-mechanical stability of warm and ice-rich frozen ground along the Qinghai–Tibet Railway (QTR) is continuously decreasing, and melting subsidence damage to existing warm frozen soil (WFS) embankments is constantly occurring, thus seriously affecting the stability and safety of the existing WFS embankments. In this study, in order to solve the problems associated with the melting settlement of existing WFS embankments, a novel reinforcement technology for ground improvement, called an inclined soil–cement continuous mixing wall (ISCW), is proposed to reinforce embankments in warm and ice-rich permafrost regions. A numerical simulation of a finite element model was conducted to study the freeze–thaw process and evaluate the stabilization effects of the ISCW on an existing WFS embankment of the QTR. The numerical investigations revealed that the ISCW can efficiently reduce the melt settlement in the existing WFS embankment, as well as increase the bearing capacity of the existing WFS embankment, making it favorable for improving the bearing ability of composite foundations. The present investigation breaks through the traditional ideas of “active cooling” and “passive protection” and provides valuable guidelines for the choice of engineering supporting techniques to stabilize existing WFS embankments along the QTR.

Keywords: existing warm frozen soil (WFS) embankment; melt subsidence disaster; inclined soil–cement mixing continuous wall (ISCW); numerical simulation; melt settlement



Citation: Sun, G.; Li, L.; Huo, Y.; Fang, Z.; Lv, G.; Chen, T.; Wang, Z.; Song, M.; Lan, G.; Tang, Z. Stabilization Effects of Inclined Soil–Cement Continuous Mixing Walls for Existing Warm Frozen Soil Embankments. *Buildings* **2024**, *14*, 1892. <https://doi.org/10.3390/buildings14071892>

Academic Editors: Huayang Yu and Fabrizio Gara

Received: 18 April 2024

Revised: 5 June 2024

Accepted: 12 June 2024

Published: 21 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

China is the third largest country with frozen soil in the world, with the frozen soil area accounting for 68.6% of its total land area [1,2]. With the warming of the global climate, permafrost is gradually transforming into warm frozen soil, and the warm frozen soil (WFS) embankment phenomenon continues to emerge. WFS, also known as plastic frozen soil, is a special frozen soil body undergoing a drastic phase change with a temperature of about $-1\text{ }^{\circ}\text{C}$. It is characterized by high water content, high compressibility, low strength, and poor engineering properties [3,4]. Studies have shown that, in sections with large amounts of WFS, the proportion of embankment diseases is increased. According to experience from the Qinghai–Tibet Railway (QTR), melt subsidence of an embankment is the main disease in permafrost areas [5,6]. In particular, when an embankment begins to melt as the temperature rises in the spring, the soil layer under the pavement melts faster than the soil layer under the road shoulder, forming a concave impervious frozen soil core in the middle of the embankment, which cannot discharge the water of the melted upper soil

mass, causing the embankment to be damaged by churning [7]. It has been found that longitudinal cracks on high embankments in WFS areas are caused by different melting and settling of shaded and sunny slopes. In addition, embankments in WFS areas are prone to settlement, mainly because of the compression deformation and melting consolidation in the WFS layer [8,9]. The continuous generation of WFS has aggravated the occurrence of melt subsidence disasters on the Qinghai–Tibet Railway embankments in frozen soil areas, threatening their safe operation.

In order to reduce the occurrence of melt subsidence disasters, traditional permafrost subgrade insulation measures follow the principles of “active cooling” and “passive protection” [10,11]; however, these measures can only be applied in an environment where future temperature increases remain within 1 °C. With global warming, the protective effect on an existing embankment will be weakened, the effect on the WFS area will not be obvious, and the WFS area will continue to increase. Therefore, these methods also have certain limitations, and there is an urgent need to develop new methods for WFS embankment reinforcement.

Soil–cement mixing walls are often used to strengthen soft soil foundations. The key principle is to use cement as a curing agent and mix the cement with soft soil deep in an embankment using mixing machinery to form a soil–cement mixing wall [12]. The cement hydration reaction with free water in the soft soil changes the physical and mechanical properties of the soft soil and increases its bearing capacity [13,14]. A soil–cement mixing wall used as a composite foundation bears most of the load, which can improve the working performance of the soft soil foundation more than other stabilized methods [15,16]. Through a literature review, we found that the physical and mechanical properties of WFS are similar to soft soil, in terms of their characteristics of high moisture content, low shear resistance, and high compressibility [17]. Some previous studies have shown that adding cement to WFS can alter its characteristics, thus reinforcing the strength of the WFS [18–20]. In permafrost regions that face existing embankment thaw subsidence problems, it is difficult to take advantage of the other techniques for existing embankment stabilization. Hence, through combining the soil–cement mixing wall method with the inclined piles concept, we derive a novel WFS embankment improvement technique, called inclined soil–cement continuous mixing wall (ISCW) installation, for engineering construction in warm and ice-rich permafrost regions.

In this study, the inclined soil–cement continuous mixing wall (ISCW) method was considered for WFS embankments of the QTR presenting the thaw subsidence process, and the associated stabilized effects were numerically simulated. The effects of the ISCW, in terms of stabilizing the WFS embankment, were analyzed by combining thermal and deformation processes. The specific objective of this study is to provide a novel method to reduce the threat of melt subsidence disasters in existing WFS embankments, thus supporting the infrastructural integrity of major projects along the Qinghai–Tibet engineering corridor (QTEC) in the future.

2. Numerical Model of the ISCW for Existing WFS Subgrade

2.1. Assumption

Considering the complexity of the foundation environment of warm frozen soil, a simplified consolidation model is adopted based on the following assumptions:

- (1) The soil in each layer is continuous, homogeneous, and isotropic, and the soil is an ideal elastic–plastic material.
- (2) In the calculation, only the deformation of the embankment caused by the applied load is considered, and the action of gravity is not considered.
- (3) The stress and displacement of soil in the process of pile formation are not considered.
- (4) The deformation and contact between the soil layers are coordinated

2.2. Heat Equations for Frozen Soil

The calculation model of heat conduction in frozen soil can be divided into freezing and melting states (FMSs). Hence, the freezing and melting states equation for the heat conduction of frozen soil can be expressed as Equations (1) and (2) [21]:

(1) Freeze state ($T_s = T_f$):

$$C_f \frac{\partial T_f}{\partial t} = \frac{\partial}{\partial x} (\lambda_f \frac{\partial T_f}{\partial x}) + \frac{\partial}{\partial y} (\lambda_f \frac{\partial T_f}{\partial y}) + \frac{\partial}{\partial z} (\lambda_f \frac{\partial T_f}{\partial z}) \quad (1)$$

(2) Melt state ($T_s = T_u$):

$$C_u \frac{\partial T_u}{\partial t} = \frac{\partial}{\partial x} (\lambda_u \frac{\partial T_u}{\partial x}) + \frac{\partial}{\partial y} (\lambda_u \frac{\partial T_u}{\partial y}) + \frac{\partial}{\partial z} (\lambda_u \frac{\partial T_u}{\partial z}) \quad (2)$$

where T_s represents the FMS temperature; T_f represents the freezing temperature; T_u represents the melting temperature; C_f represents the volumetric heat capacity in the freezing state; λ_f represents the thermal conductivity in the freezing state; C_u represents the volumetric heat capacity in the melting state; and λ_u represents the volumetric heat in the melting state.

The phase change is assumed to occur in a temperature range of $T_m \pm \Delta T$. Therefore, the heat capacity C_s and the thermal conductivity λ_s of the frozen soil are given by Equations (3) and (4), respectively:

$$C = \begin{cases} C_f & T < T_m - \Delta T \\ C_f + \frac{C_t - C_f}{T_a - T_b} (T - \Delta T) + \frac{L}{1+W} \frac{\partial W_i}{\partial T} & T_m - \Delta T \leq T \leq T_m + \Delta T \\ C_t & T > T_m + \Delta T \end{cases} \quad (3)$$

$$\lambda = \begin{cases} \lambda_f & T < T_m - \Delta T \\ \lambda_f + \frac{\lambda_t - \lambda_f}{T_a - T_b} (T - T_m + \Delta T) & T_m - \Delta T \leq T \leq T_m + \Delta T \\ \lambda_u & T > T_m + \Delta T \end{cases} \quad (4)$$

where T_m is the freezing temperature and ΔT is the temperature increment.

Therefore, Equations (3) and (4) can be simplified to (Equation (5)):

$$C_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x} (\lambda_s \frac{\partial T_s}{\partial x}) + \frac{\partial}{\partial y} (\lambda_s \frac{\partial T_s}{\partial y}) + \frac{\partial}{\partial z} (\lambda_s \frac{\partial T_s}{\partial z}) \quad (5)$$

2.3. Thermodynamic Coupling Governing Equation

The stress field under thermodynamic coupling is a plane strain problem, and its governing equations [22] are shown in Equations (6) and (8) as follows:

$$\varepsilon_x = \frac{1 - \mu^2}{E(T)} (\sigma_x - \frac{\mu}{1 - \mu} \sigma_y) + \alpha \Delta T \quad (6)$$

$$\varepsilon_y = \frac{1 - \mu^2}{E(T)} (\sigma_y - \frac{\mu}{1 - \mu} \sigma_x) + \alpha \Delta T \quad (7)$$

$$\varepsilon_{xy} = \frac{2(1 - \mu)}{E(T)} \tau_{xy} \quad (8)$$

where σ_x and σ_y are the x - and y -direction normal stresses; ΔT is the temperature gradient; ε_x and ε_y are the x - and y -direction plane shear strains; ε_{xy} is the plane shear strain in the xy -plane; μ is Poisson's ratio; α is the coefficient of thermal expansion; and $E(T)$ is the elastic modulus of a material.

2.4. Constitutive Model

In this study, both the ISCW and the WFS included in the embankment and foundation were considered as elastoplastic materials. The stress–strain relationship is given by the following increment formulation (Equation (9)) [23]:

$$\{d\sigma\} = \{D_T\} [\{d\varepsilon\} - \{d\varepsilon_p\}] \quad (9)$$

where $\{d\sigma\}$ is the incremental stress matrix; $\{D_T\}$ is the elastic matrix depending on temperature, which can be expressed by E_T (elastic modulus) and ν_T (Poisson's ratio); $\{d\varepsilon\}$ is the total incremental strain matrix; and $\{d\varepsilon_p\}$ is the plastic incremental strain matrix.

According to the plastic potential theory, the plastic strain increment of materials can be formed. For elastoplastic materials, this is related to the stress state and plastic strain of the plastic potential function H . Therefore, the plastic strain increment is given as follows (Equation (10)) [24]:

$$\{d\varepsilon_p\} = d\lambda \frac{\partial H}{\partial \{\sigma\}} \quad (10)$$

Equation (10) determines the relationship between the plastic strain increment and stress increment within the plastic range of geotechnical materials, where $d\lambda$ represents the plastic multiplier.

The elastoplastic model with the Drucker–Prager yield criterion in coordination with the Mohr–Coulomb yield criterion was used in this study. Applying the relevant flow rules (the plastic potential function H is the same as the subsequent yield surface function F), Equation (10) can be rewritten as Equations (11)–(13):

$$\{d\varepsilon_p\} = d\lambda \frac{\partial F}{\partial \{\sigma\}} \quad (11)$$

$$\frac{\partial F}{\partial \{\sigma\}} = \left[\frac{\partial F}{\partial \sigma_r} \quad \frac{\partial F}{\partial \sigma_z} \quad \frac{\partial F}{\partial \sigma_{rz}} \quad \frac{\partial F}{\partial \sigma_\theta} \right]^T \quad (12)$$

$$F = \sqrt{J_2} + \alpha I_1 - k \quad (13)$$

where J_2 is the second-order deviatoric stress invariant, I_1 is the first stress tensor invariant, and k are material parameters related to the cohesion c and the internal friction angle φ variables, defined according to Equations (14) and (15), respectively:

$$\alpha = \frac{2 \sin \varphi}{\sqrt{3}(3 - \sin \varphi)} \quad (14)$$

$$k = \frac{2\sqrt{3}c \cos \varphi}{3 - \sin \varphi} \quad (15)$$

3. Numerical Simulations

3.1. Model Prototype

According to Reference [25] and ISCW design specifications, an unstable embankment in the QTR was selected to establish the calculation model. The embankment top has a width of 8.0 m and a height of 5.0 m. The calculated boundary width of the embankment foundation is 23 m, and the calculated boundary distance between the toes of the embankment is 18.5 m. The foundation depth is 20 m. A cross-section of the model prototype is shown in Figure 1.

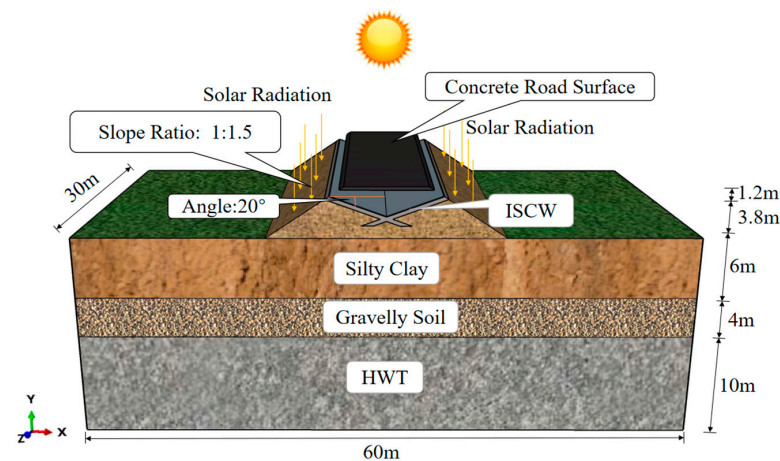


Figure 1. ISCW composite embankment of the WFS embankment model prototype.

A thermo-mechanical coupling finite element analysis model was established, and the size effect was considered. The length, width, and height of the model were 60 m, 30 m, and 20 m, respectively. The embankment height was 5.0 m, the road width was 8 m, and the slope was 1:1.5. The length of the ISCW was $l = 7$ m, the thickness was 0.4 m, and the angle between the diaphragm wall and the horizontal plane was 20° . The top of the diaphragm wall was 1.2 m from the road. C3D8R hexahedral elements were used in the grid, and the total number of elements was 43,320, which was calculated using reduced integrals, as shown in Figure 1. The embankment was divided into concrete pavement (0.3 m), embankment fill (4.7 m), silty clay (6.0 m), gravel soil (4.0 m), and strongly weathered tuff (10.0 m) from top to bottom. The model cross-section is shown in Figure 1, and the thermodynamic parameters of the model are provided in Table 1.

Table 1. Physical parameters of the constructed model.

Material	ρ (kg/m ³)	λ_u /(w/m·°C)	C_u /(J/kg·°C)	E /pa	μ	φ (°)	C /(pa)	H /m
Concrete road surface	2400	1.6	976	30×10^9	0.2	/	/	0.3
Embankment	1900	1.82	1463	20×10^6	0.3	16	12,000	4.7
Silty clay	1800	1.24	2090	65×10^6	0.3	11	55,000	6
Gravelly soil	1900	1.63	1560	85×10^6	0.3	25	50,000	4
HWT	2000	1.6	877	110×10^6	0.25	20	55,000	10
ISCW	2200	1.2	1580	5×10^9	0.25	/	/	7

ρ , dry density; λ_u , heat conductivity; C_u , heat coefficient; E , elastic modulus; μ , Poisson's ratio; C , friction angle; φ , cohesion; H , soil thickness; HWT, highly weathered tuff; ISCW, inclined soil-cement continuous wall.

The calculation of the thermodynamic parameters for each material was based on previous research [26] and the literature such as the Frost Action of Soil and Foundation Engineering [27], Frozen Soil Physics [28], Code for Design of ISCW (Standards Press of China 2010) [29], and Code for Thermal Design of ISCW (China Academy of Building Research 1993) [30]. The values for the materials' mechanical parameters were adopted from the literature [31].

3.2. Finite Element Model

ABAQUS (2022) is a software program used for geotechnical material and other material performance analysis [32]. Because of its command-driven mode, specificity, and openness, ABAQUS has been widely used in the study of soil failure, collapse, and soil consolidation [33]. In this study, the ABAQUS finite difference method was used to

construct the ISCW on the existing WFS subgrade and observe the stabilization effect of the ISCW on the subgrade.

The existing embankment, ISCW, and all soil layers were fine-meshed using hexahedral elements, and nodal points were connected among adjacent solid elements automatically. Figure 2 illustrates the work tree of mesh generation for the embankment, ISCW, and foundation in this study.

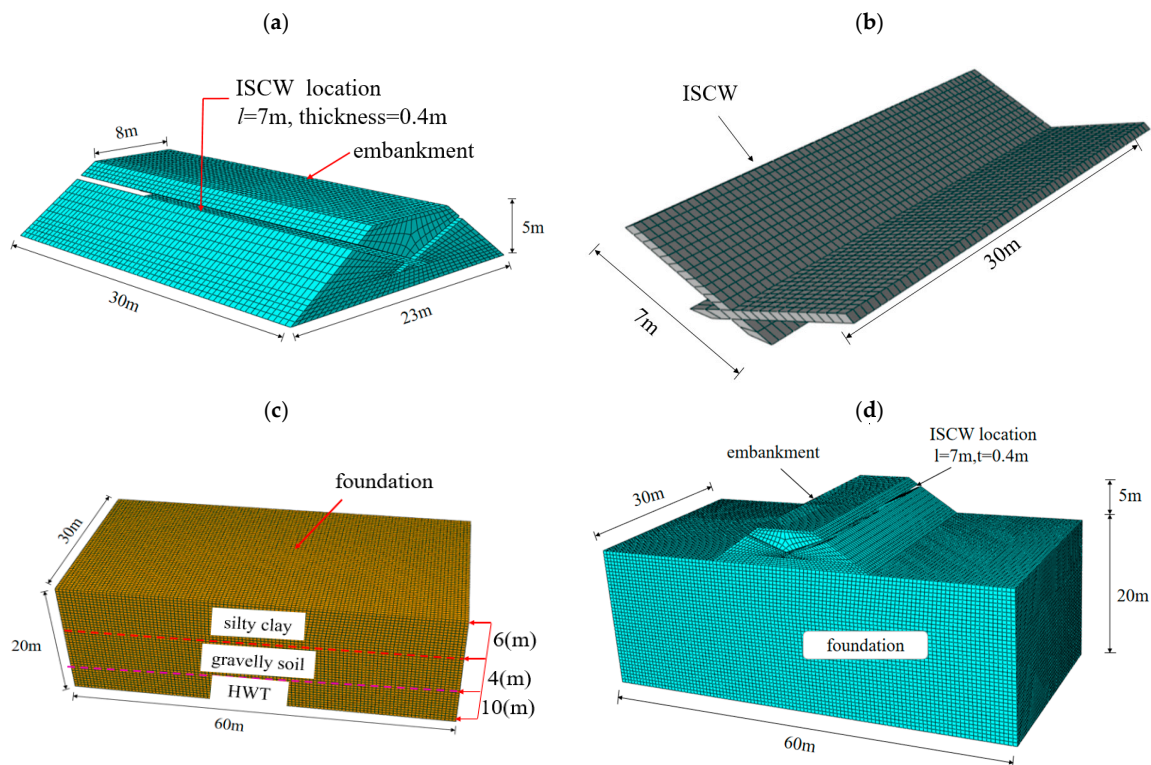


Figure 2. ISCW composite embankment of the WFS embankment finite element model. (a) Embankment; (b) ISCW; (c) foundation; and (d) finite element model.

3.3. Boundary and Initial Conditions

3.3.1. Temperature Field Analysis Steps and Boundary Conditions

In the heat transfer analysis step, the upper surface boundary condition was set as the local surface temperature in December, the shade slope surface was set at $-15.7\text{ }^{\circ}\text{C}$, the central surface of the line was set at $-12.0\text{ }^{\circ}\text{C}$, the sunny slope surface was set at $-11.0\text{ }^{\circ}\text{C}$, and the natural surface temperature was set at $-14.1\text{ }^{\circ}\text{C}$. The lower surface boundary condition was set as a constant temperature condition of $-2\text{ }^{\circ}\text{C}$ [34]. According to the measured data and considering the influence of geothermal energy, the initial temperature was set as the heat insulation condition around the surface, which was used as the initial condition for the subsequent temperature field calculation.

The initial conditions of the stress field were determined in the heat transfer analysis step, and the time length was 120. The K3016 section near Wudaoliang in the QTR was selected as the research object, and the surface temperature during the four months from December to March, for a total of 120 days, was taken as the boundary condition of the temperature field. The parameters of the temperature field for the boundary conditions are detailed in Table 2 [35]:

Considering solar radiation, previous studies [36] used a periodic function to fit the land surface temperature and adopted the simplified boundary temperature condition of the cross-section shown in Figure 1. The fitting formula is shown in Equation (16):

$$T_s = T_0 + A_0 \sin(\omega t + \varphi) \quad (16)$$

Table 2. Parameter assignment for the surface sine temperature function.

$T_0/(^{\circ}\text{C})$	$A_0/(^{\circ}\text{C})$	$\varphi/(\text{rad})$	Surface
−1.4	12.8	$11\pi/18$	Original surface
−0.3	11.3	$5\pi/9$	South slope
−3.0	13.1	$21\pi/36$	North slope
2.6	14.8	$11\pi/18$	Ground

T_0 , annual mean temperature; A_0 , amplitude; φ , phase angle.

3.3.2. Stress Field Analysis Steps and Boundary Conditions

The static general analysis step was adopted, and the time length was 120. The upper boundary of the model was not constrained; the left and right boundary constraint method was phase shift; and the lower boundary constraints were horizontal displacement and vertical displacement.

3.3.3. Contact Element Setting

The surface of the pile sides and bottom was set as the secondary surface, and the soil surface was set as the primary surface. The contact property between the pile and soil was set as follows: the friction formula of tangential behavior was set as the penalty function, where the friction coefficient was 0.5; normal behavior was set to “hard” contact.

4. Results and Analysis

4.1. Temperature Analysis for the Reinforced and Unreinforced Embankments

As the temperature increased, the temperature of the road surface and slope also increased. Because of the effects of shade and sun on the slope, the right-side slope reached the sunny temperature first, and the temperature continued to transfer to the un-melted soil in the lower part of the embankment. As can be seen in Figure 3, melting mainly occurred in the shallow soil of the embankment, and the temperature of the deep soil remained basically stable at about -2°C . Four months after melting, the lowest temperature of the unreinforced embankment was -11.1°C , and the lowest temperature of the composite embankment was -13.5°C ; therefore, the lowest temperature of the composite embankment was 2.4°C lower than that of the unreinforced embankment. The temperature calculation results for the bottom surface of the embankment four months after melting are shown in Figure 4a. The lowest temperature of the composite embankment was 2.1°C lower than that of the unreinforced embankment. As can be seen in Figure 4b, in the range of 0 m to -5 m, the temperature of the composite embankment was lower than that of the unreinforced embankment, and the peak value of the negative temperature occurred. In the range of -5 m to -20 m, the temperature of the composite embankment was higher than that of the unreinforced embankment. This is because the continuous wall under the cement can absorb the negative temperature of the outside world in the cold season and transfer its negative temperature to the embankment, causing the temperature of the embankment to decrease. With an increase in external temperature, the embankment gradually melts, and the continuous wall under the cement land can isolate the temperature of the upper embankment, transferring the negative temperature of the deep soil under the embankment to the upper embankment, thereby reducing the temperature of the embankment. As the temperature of the cement–soil continuous wall was lower than that in other parts, a peak was observed on the temperature curve. The ISCW has the function of reducing the temperature and slowing down the melting settlement of the embankment.

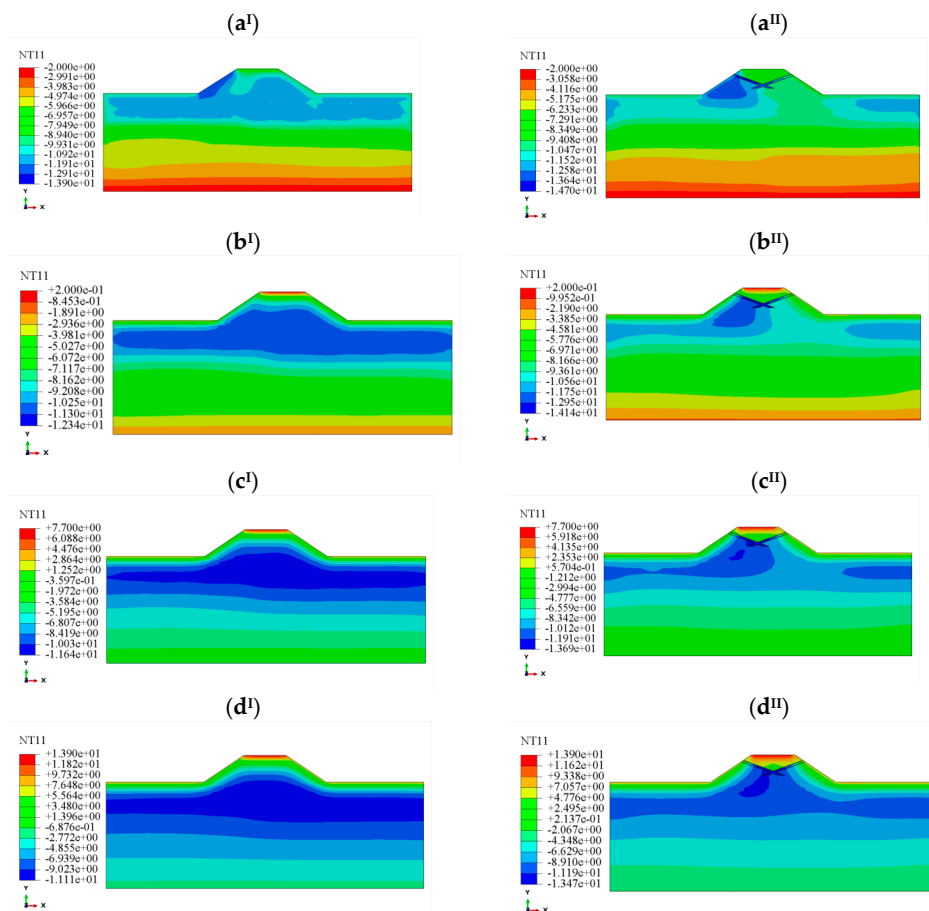


Figure 3. Temperature field cloud image before and after reinforcement (unit: °C). Unreinforced embankment. (a^I) First month; (b^I) second month; (c^I) third month; and (d^I) fourth month. Reinforced embankment. (a^{II}) First month; (b^{II}) second month; (c^{II}) third month; and (d^{II}) fourth month.

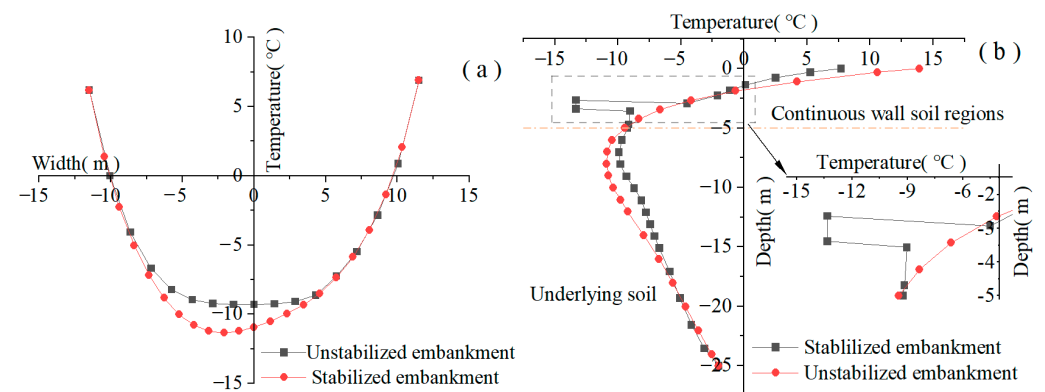


Figure 4. Results of the thermal calculation for the reinforced and unreinforced embankments. (a) Bottom of the embankment and (b) the center line temperature of the embankment along the y-direction after melt.

4.2. Vertical Displacement (Y-Displacement) Analysis of the Reinforced and Unreinforced Embankments

The vertical displacement in the reinforced and unreinforced embankments is shown in Figure 5, from which it can be clearly seen that the settlement range of the composite embankment was larger than that of the unreinforced embankment in the fourth month. This is because the composite embankment is formed from the underground continuous wall and the soil mass, and the load on the road is transferred to the underground continu-

ous wall to jointly bear the load, thus reducing the displacement in the vertical direction. Figure 6 shows the calculation results of the displacement in the vertical direction for the embankment top surface during the four-month period over which the embankment melted. The maximum displacement in the vertical direction for the unreinforced embankment increased from 0.34 cm to 2.37 cm, and the displacement increased by 1.96 cm. The maximum displacement in the y -direction for the composite embankment increased from 0.33 cm to 1.71 cm, and the displacement increased by 1.38 cm. The maximum displacement of the composite embankment was 28% lower than that of the unreinforced embankment. Therefore, the use of a continuous wall under inclined cement soil can effectively reduce the melt displacement of the embankment.

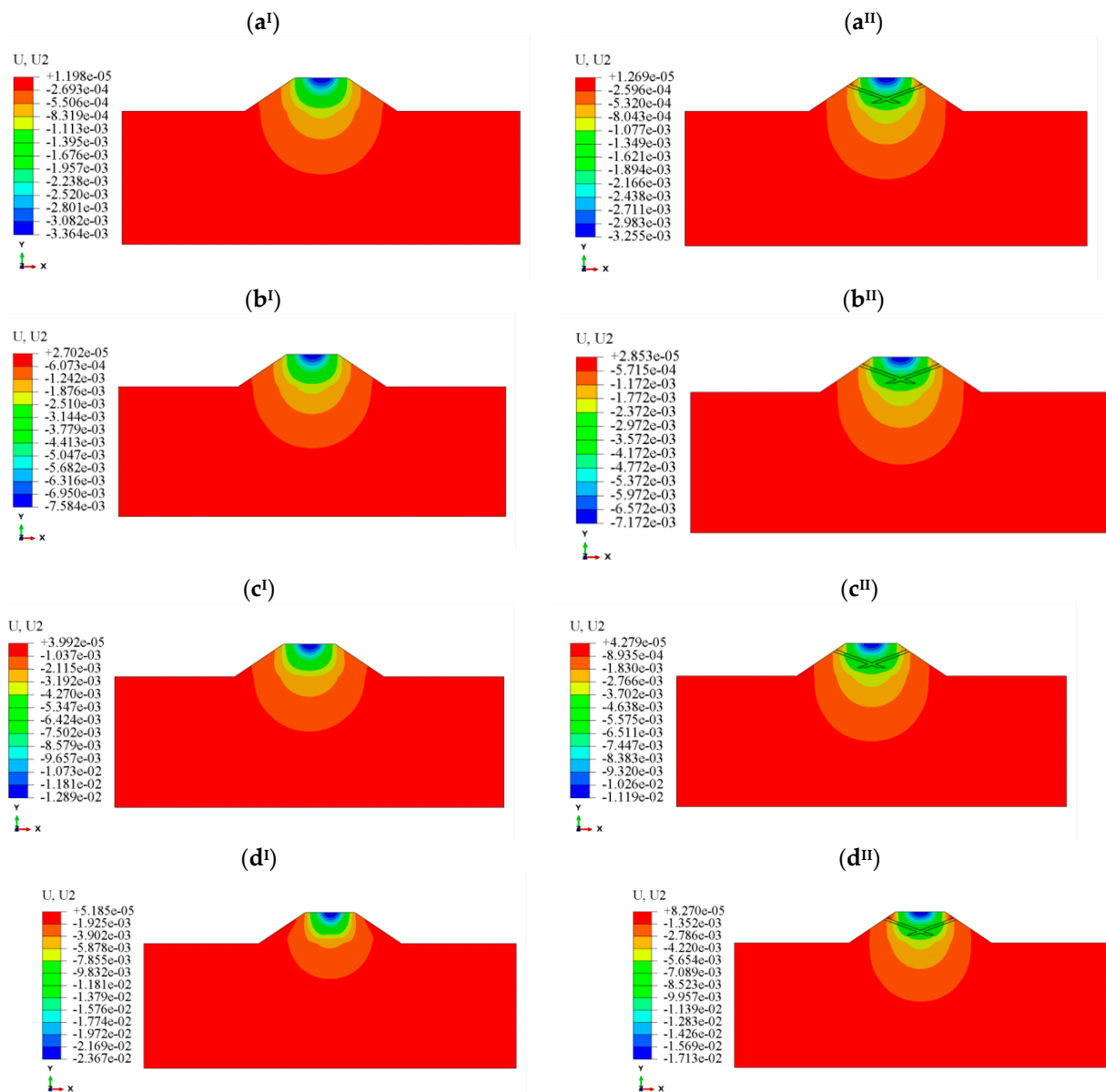


Figure 5. Cloud image of reinforcement before and after vertical displacement (Unit: m). Unreinforced embankment. (a^I) First month; (b^I) second month; (c^I) third month; and (d^I) fourth month. Reinforced embankment. (a^{II}) First month; (b^{II}) second month; (c^{II}) third month; and (d^{II}) fourth month.

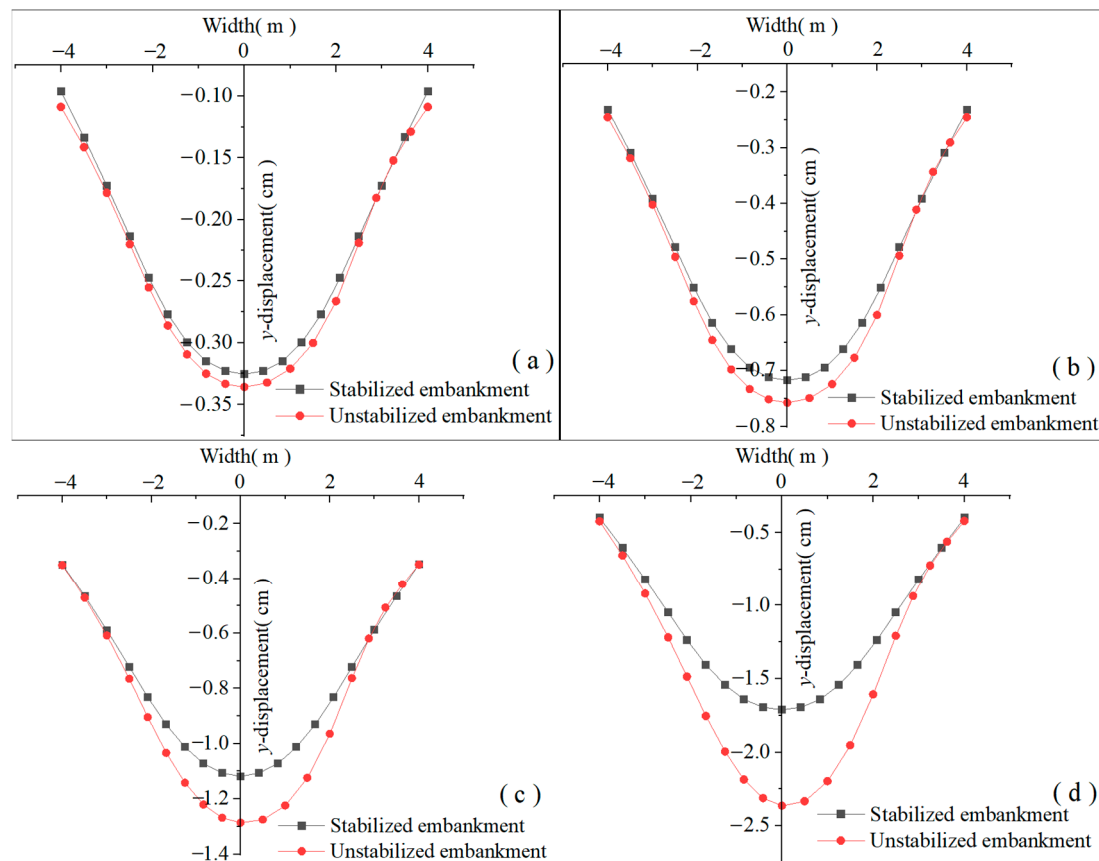


Figure 6. Monthly vertical displacement (Y-displacement) comparison in embankment surfaces before and after consolidation. (a) First month; (b) second month; (c) third month; and (d) fourth month.

4.3. Horizontal Displacement (X-Displacement) Analysis of the Reinforced and Unreinforced Embankments

In Figure 7, it can be seen that the maximum displacement in the horizontal direction for the unreinforced embankment ranged from 0.43 mm to 5.1 mm, and the displacement increased by 4.67 mm. The maximum displacement in the horizontal direction of the composite embankment increased from 0.59 mm to 3.57 mm, and the displacement increased by 2.98 mm. Therefore, the maximum displacement of the composite embankment was 30% less than that of the unreinforced embankment. Figure 8 shows the calculation results for the displacement of the embankment in the horizontal direction at a distance of 3.8 m from the top of the embankment during the four-month period over which the embankment melted. During the four-month period, the displacement of the unreinforced embankment in the x -direction increased from 0.33 mm to 3.44 mm, and the displacement increased by 3.11 mm. The displacement in the x -direction of the composite embankment increased from 0.25 mm to 1.0 mm, and the displacement increased by 0.75 mm. Therefore, the displacement of the composite embankment was 67.8% lower than that of the unreinforced embankment. The deformation of the embankment is mainly due to the load on the road surface. The ISCW can interact with the soil to form a composite embankment, which increases the integrity of the embankment. Moreover, the ISSCW has a “clamping” effect on the soil, and the maximum horizontal displacement occurs in the continuous wall, which greatly reduces the horizontal displacement of the embankment below the continuous wall, thus reducing the deformation of the embankment.

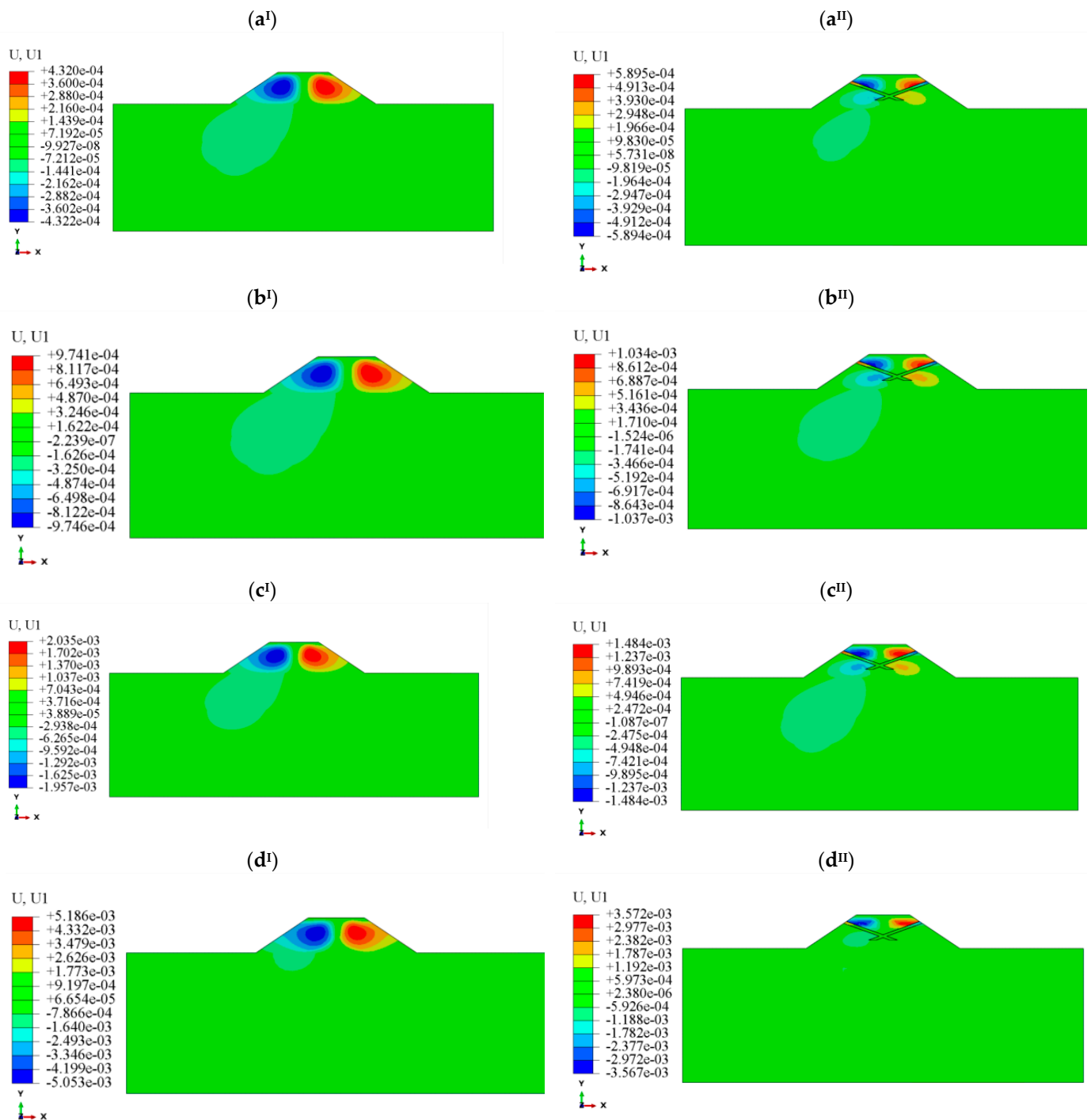


Figure 7. Cloud image of reinforcement before and after horizontal displacement (Unit: m). Unreinforced embankment. (a^I) First month; (b^I) second month; (c^I) third month; and (d^I) fourth month. Reinforced embankment. (a^{II}) First month; (b^{II}) second month; (c^{II}) third month; and (d^{II}) fourth month.

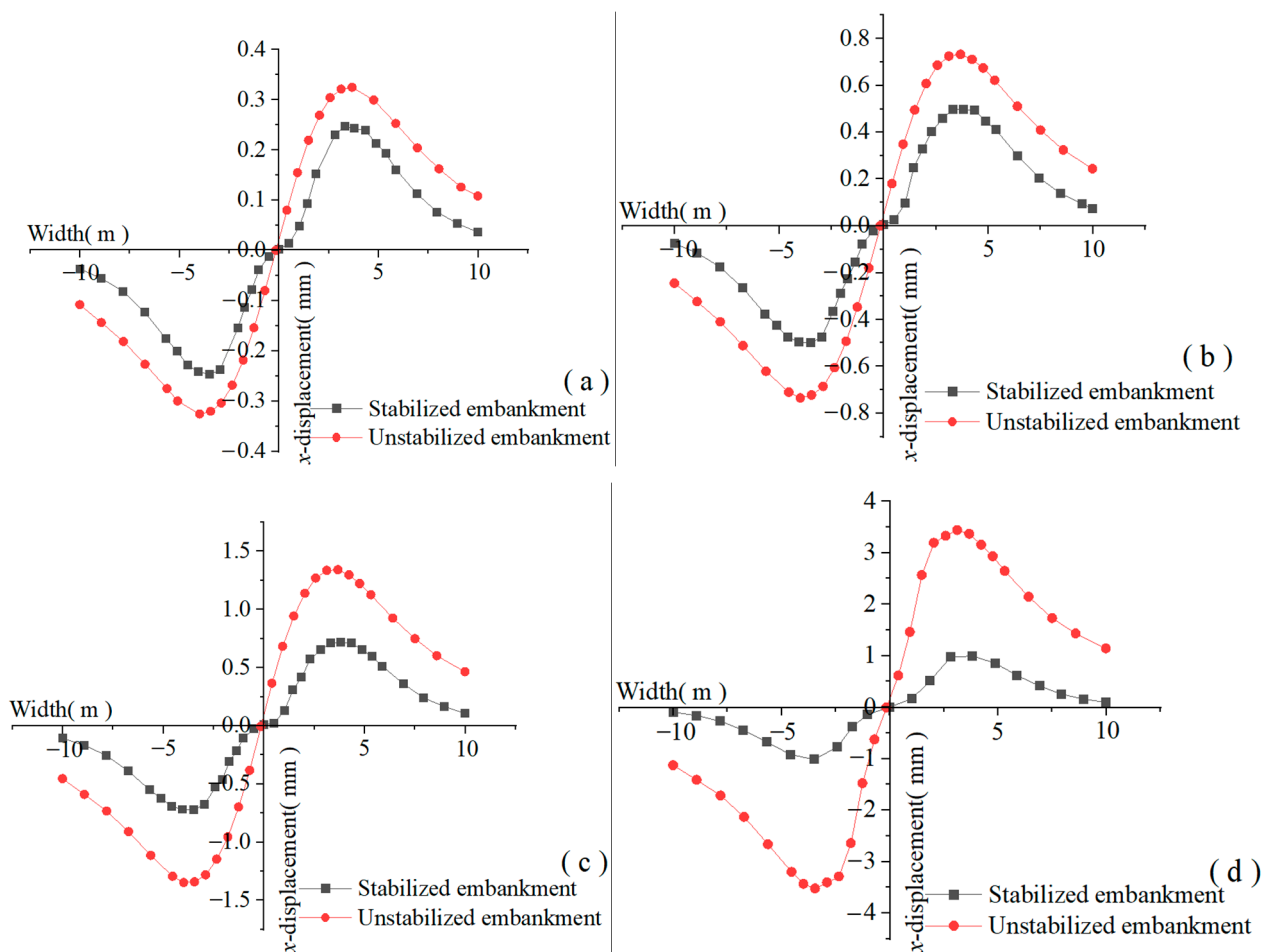


Figure 8. Monthly horizontal displacement (X-displacement) comparison of the embankment bottom before and after consolidation. (a) First month; (b) second month; (c) third month; and (d) fourth month.

5. Discussion

In this study, our results indicated that the ISCW changed the characteristics of the existing WFS embankment. Because of the ISCW support effects on the embankment, the embankment displacement decreased considerably; however, the stress variation law of the ISCW should be studied. The left and right ISCWs were arranged symmetrically. Therefore, the distribution of the displacement of the ISCW was also symmetric. Figure 9 shows the variation in pile stress along the ISCW under different pavement loads. It can be seen that the pile stress increases with the pavement load, and the stress of the piles exhibits maximum stress in the right and left ISCW intersection points.

The deformation of the ISCW is caused by the load on the embankment. The ISCW reduced the z-displacement and x-displacement from the embankment. According to the experiment results of Ye et al. [36], if the thaw collapse displacement is no more than 2 cm, the frozen soil subgrade can be considered stable. The maximum displacement with the ISCW was 1.73 cm, which occurred during the fourth month. According to these findings, the proposed technique effectively stabilized the existing WFS embankment.

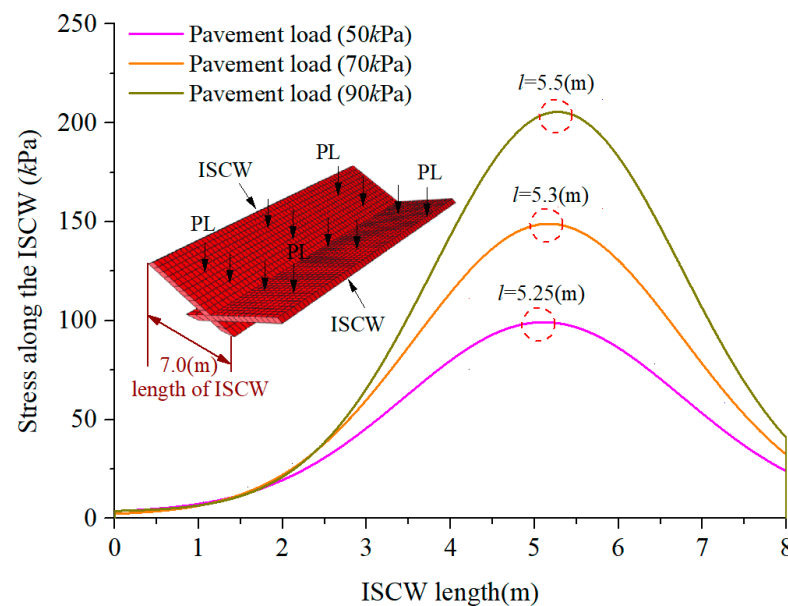


Figure 9. Effect of different pavement loads along the ISCW length.

6. Conclusions and Recommendations

According to the obtained numerical simulation results, an effective novel method was proposed for the reinforcement of WFS embankments. The main conclusions can be summarized as follows:

- (1) In the cold season, the ISCW can absorb the negative temperature of the outside world and transfer it to the deeper soil layer of the embankment, decreasing the temperature of the deep, frozen soil. With an increase in the outside air temperature, the continuous wall under the ISCW can transfer the negative temperature of the deeper frozen soil to the embankment, thus reducing the temperature of the embankment. The minimum temperature of the composite embankment during the considered four-month period was 2.4 °C lower than that of the unreinforced embankment. The continuous wall under inclined cement soil can effectively reduce the embankment temperature and slow down embankment melt settlement.
- (2) A composite embankment is formed between the ISCW and the soil mass, which improves the integrity of the embankment. The maximum melt settlement of the composite embankment was 28% less than that of the unreinforced embankment. The ISCW can effectively reduce the melt settlement of a frozen soil embankment at higher temperatures, thus improving the bearing capacity and stability of the embankment.
- (3) The maximum horizontal displacement of the composite embankment was reduced by 30% compared with the unreinforced embankment, and the horizontal displacement at the bottom of the embankment was reduced by 67.8%. The deformation of the embankment mainly derives from the load on the road surface. As the inclined continuous wall has a “clamping” effect on the soil mass, the maximum horizontal displacement occurs in the underground continuous wall, which has a significant effect on reducing the horizontal displacement of the embankment.

Based on the melting process over four months, after comparative analysis and evaluation of the reinforcement effect of the composite embankment against that of the unreinforced embankment, it is considered that the ISCW provides a feasible approach for the reinforcement of WFS embankments. The proposed technology provides a scientific and theoretical basis for the prevention and control of existing embankment melt subsidence disasters in WFS areas. Thus, the novel method to reduce melt subsidence disasters in existing WFS embankments can be recommended to support the infrastructural integrity of major projects along the Qinghai–Tibet engineering corridor (QTEC) in the future.

Author Contributions: Conceptualization, G.S.; Methodology, L.L. and Y.H.; Software, L.L. and Y.H.; Validation, Z.T.; Investigation, Z.F., G.L. (Gao Lv) and T.C.; Resources, G.L. (Gao Lv) and T.C.; Data curation, Z.F., M.S. and G.L. (Guanqi Lan); Writing—original draft, G.S.; Writing—review & editing, G.S.; Visualization, Z.W. and Z.T.; Supervision, Z.W.; Project administration, M.S. and G.L. (Guanqi Lan). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [National Natural Science Foundation of China] grant number [42301156 and 52308204], [Natural Science Foundation of Shanxi Province] grant number [2023-JC-QN-0626 and 2024JC-YBMS-436], [Shaanxi Provincial Key Laboratory of Geotechnical and Underground Space Engineering open fund] grant number [YT202302] and [Xi'an Shiyou University graduate student innovation and practical ability training program] grant number [YCS23214312].

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Author Zonghui Fang was employed by the company Gansu Institute of Architecture Design and Research Co., Ltd. Author Ziqiang Tang was employed by the company China State Construction Engineering Corporation Aecom Consultant Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Notation

Abbreviation	Explanation
T_s	freezing or thawing state temperature
T_f	freezing state temperature
T_u	thawing state temperature
C_f	volumetric heat capacity in the freezing state
λ_f	thermal conductivity in the freezing state
C_u	volumetric heat capacity in the thawing state
λ_u	thermal conductivity in the thawing state
T_m	freezing temperature
ΔT	temperature increment
C_s	heat capacity of frozen soil
λ_s	heat conductivity coefficient of frozen soil
σ_x, σ_y	x - and y -direction normal stresses
$\varepsilon_x, \varepsilon_y$	x - and y -direction plane shear strains
ε_{xy}	plane shear strain in the xy -plane
$E(T)$	elastic modulus of a material
μ	Poisson's ratio
α	coefficient of thermal expansion
$\{d\sigma\}$	stress increment matrix
$\{D_T\}$	elastic matrix related to temperature
$\{d\varepsilon\}$	total strain increment matrix
$\{d\varepsilon_p\}$	plastic strain increment matrix
$d\lambda$	plastic multiplier
J_2	second deviatoric stress invariant
I_1	first stress invariant
c, φ	cohesion and internal friction angle for frozen soil

References

1. Jin, H.; Jin, X.; He, R.; Luo, D.; Chang, X.; Wang, S.; Marchenko, S.S.; Yang, S.; Yi, C.; Li, S.; et al. Evolution of permafrost in China during the last 20 ka. *Sci. China Earth Sci.* **2019**, *62*, 1207–1223. [\[CrossRef\]](#)
2. Zou, D.; Zhao, L.; Sheng, Y.; Chen, J.; Hu, G.; Wu, T.; Wu, J.; Xie, C.; Wu, X.; Pang, Q.; et al. A new map of permafrost distribution on the Tibetan Plateau. *Cryosphere* **2017**, *11*, 2527–2542. [\[CrossRef\]](#)
3. Zhang, Z.; Zhang, H.; Zhang, J.; Chai, M. Effectiveness of Ionic Polymer Soil Stabilizers on Warm Frozen Soil. *KSCE J. Civ. Eng.* **2019**, *23*, 2867–2876. [\[CrossRef\]](#)
4. Peng, Y.; He, J.; Jiang, H. Experimental Study on Creep Mechanical Properties of Warm Frozen Soils. *Indian Geotech. J.* **2023**, *53*, 1347–1354. [\[CrossRef\]](#)

5. Zhang, Z.Q.; Wu, Q.B. Thermal hazards zonation and permafrost change over the Qinghai–Tibet Plateau. *Nat. Hazards* **2012**, *61*, 403–423. [\[CrossRef\]](#)
6. Cui, K.; Qin, X.T. Landslide risk assessment of frozen soil slope in Qinghai Tibet Plateau during spring thawing period under the coupling effect of moisture and heat. *Nat. Hazards* **2023**, *115*, 2399–2416. [\[CrossRef\]](#)
7. Zhao, R.; Wang, S.; Huang, X.; Ma, T.; Chen, J.; Luo, H. Research on the deformation and damage process of crushed-rock highway embankment in permafrost areas. *Comput. Part. Mech.* **2024**. [\[CrossRef\]](#)
8. Wu, G.; Xie, Y.; Wei, J.; Yue, X. Experimental study and prediction model on frost heave and thawing settlement deformation of subgrade soil in alpine meadow area of Qinghai-Tibet Plateau. *Arab. J. Geosci.* **2022**, *15*, 534. [\[CrossRef\]](#)
9. Zhang, F.; Shi, S.; Feng, D.-C.; Cai, L.-Z. Investigation on creep behavior of warm frozen silty sand under thermo–mechanical coupling loads. *J. Mt. Sci.* **2021**, *18*, 1951–1965. [\[CrossRef\]](#)
10. Sun, X.; Song, J.; Guo, Y.; Zhang, Y.; He, S. Analysis of thermal impact of highway construction in plateau region on frozen soil corridor. *Arab. J. Geosci.* **2021**, *14*, 1271. [\[CrossRef\]](#)
11. He, P.; Niu, F.; Huang, Y.; Zhang, S.; Jiao, C. Distress Characteristics in Embankment-Bridge Transition Section of the Qinghai-Tibet Railway in Permafrost Regions. *Int. J. Disaster Risk Sci.* **2023**, *14*, 680–696. [\[CrossRef\]](#)
12. Pan, H.; Tong, L.; Wang, Z.; Yang, T. Effects of Soil–Cement Mixing Wall Construction on Adjacent Shield Tunnel Linings in Soft Soil. *Arab. J. Sci. Eng.* **2022**, *47*, 13095–13109. [\[CrossRef\]](#)
13. Prakash, K.G.; Krishnamoorthy, A. Stability of Embankment Constructed on Soft Soil Treated with Soil–Cement Columns. *Transp. Infrastruct. Geotechnol.* **2022**, *10*, 595–615. [\[CrossRef\]](#)
14. Alzabeebee, S.; Abdulqader Alkhalidi, S.H.; Keawsawasvong, S. Numerical analysis of the dynamic response of a ballastless railway track rested on non-stabilized and cement-stabilized soft soil considering undrained conditions. *Innov. Infrastruct. Solut.* **2023**, *8*, 334. [\[CrossRef\]](#)
15. Maleki, M.; Khezri, A.; Nosrati, M.; Hosseini, S.M.M.M. Seismic amplification factor and dynamic response of soil-nailed walls. *Model. Earth Syst. Environ.* **2023**, *9*, 1181–1198. [\[CrossRef\]](#)
16. Maleki, M.; Mohammad Hosseini, S.M.M. Assessment of the Pseudo-static seismic behavior in the soil nail walls using numerical analysis. *Innov. Infrastruct. Solut.* **2022**, *7*, 262. [\[CrossRef\]](#)
17. Sun, G.-C.; Yao, G.; Zhang, J.-M.; Li, B.; Li, J.-Q.; Lian, W.-P.; Wei, Y. Stabilized effects of L-S cement-mixed batter pile composite foundation for existed warm frozen soil subgrade. *J. Mt. Sci.* **2023**, *20*, 542–556. [\[CrossRef\]](#)
18. Sun, G.-C.; Zhang, J.-M.; Dang, Y.-S.; Ding, C. Microstructure and strength features of warm and ice-rich frozen soil treated with high-performance cements. *J. Mt. Sci.* **2019**, *16*, 1470–1482. [\[CrossRef\]](#)
19. Shabeer, S.; Asad, S.; Jamal, A.; Ali, A. Train-induced vibration and subsidence prediction of the permafrost subgrade along the Qinghai-Tibet Railway. *Soil Dyn. Earthq. Eng.* **2022**, *14*, 307. [\[CrossRef\]](#)
20. Chai, M.; Zhang, J.; Ma, W.; Yin, Z.; Mu, Y.; Zhang, H. Thermal influences of stabilization on warm and ice-rich permafrost with cement: Field observation and numerical simulation. *Appl. Therm. Eng.* **2019**, *148*, 536–543. [\[CrossRef\]](#)
21. Tang, L.; Yang, L.; Wang, X.; Yang, G.; Ren, X.; Li, Z.; Li, G. Numerical analysis of frost heave and thawing settlement of the pile–soil system in degraded permafrost region. *Environ. Earth Sci.* **2023**, *80*, 693. [\[CrossRef\]](#)
22. Zhang, G.; Liu, E.; Zhang, G.; Chen, Y. Study thermo-hydro-mechanical coupling behaviors of saturated frozen soil based on granular solid hydrodynamics theory. *Arch. Appl. Mech.* **2023**, *91*, 3921–3936. [\[CrossRef\]](#)
23. Mu, S.; Ladanyi, B. Modelling of coupled heat, moisture and stress field in freezing soil. *Cold Reg. Sci. Technol.* **1987**, *14*, 237–246. [\[CrossRef\]](#)
24. Chen, W.F.; Mizuno, E. *Nonlinear Analysis in Soil Mechanics: Theory and Implementation*; Elsevier: Amsterdam, The Netherlands, 1990.
25. Sun, Z.-Z.; Ma, W.; Zhang, S.-J.; Mu, Y.-H.; Yun, H.-B.; Wang, H.-L. Characteristics of thawed interlayer and its effect on embankment settlement along the Qinghai-Tibet Railway in permafrost regions. *J. Mt. Sci.* **2018**, *15*, 1090–1100. [\[CrossRef\]](#)
26. Wang, T.; Liu, J.; Tai, B.; Zang, C.; Zhang, Z. Frost jacking characteristics of screw piles in seasonally frozen regions based on thermo-mechanical simulations. *Comput. Geotech* **2017**, *91*, 27–38. [\[CrossRef\]](#)
27. Liu, M.-H.; Li, G.-Y.; Niu, F.-J.; Lin, Z.-J.; Shang, Y.-H. Porosity of crushed rock layer and its impact on thermal regime of Qinghai–Tibet Railway embankment. *J. Cent. South Univ.* **2017**, *24*, 977–987. [\[CrossRef\]](#)
28. Li, K.-Q.; Yin, Z.-Y.; Qi, J.-L.; Liu, Y. State-of-the-Art Constitutive Modelling of Frozen Soils. *Arch. Comput. Methods Eng.* **2024**. [\[CrossRef\]](#)
29. GB50010-2010; Standards Press of China Code for Design of Concrete Structures. China Architecture and Building Press: Beijing, China, 2010.
30. GB50176-93; China Academy of Building Research Code for Thermal Design of Civil Buildings. China Planning Press: Beijing, China, 1993.
31. Chen, J.; Yuan, Y.; Yang, X.; Wang, Z.; Kang, S.; Wen, J. The Characteristics and Controlling Factors of Water and Heat Exchanges over the Alpine Wetland in the East of the Qinghai–Tibet Plateau. *Adv. Atmos. Sci.* **2016**, *40*, 201–210. [\[CrossRef\]](#)
32. Tang, X.J.; Wang, J. A general shakedown approach for geo-structures under cyclic loading using ABAQUS/Python. *Acta Geotech.* **2022**, *17*, 5773–5788. [\[CrossRef\]](#)
33. Beiranvand, B.; Rozbahani, M.Z.; Mazaheri, A.R.; Komasi, M. Quasi-static and dynamic analysis of pore water pressure in Azadi earth dams using Abaqus software. *Arab. J. Geosci.* **2021**, *14*, 1280. [\[CrossRef\]](#)

34. Wang, T.Y.; Yan, L.E. A heat-flux upper boundary for modeling temperature of soils under an embankment in permafrost region. *Sci. Rep.* **2022**, *12*, 13295. [[CrossRef](#)]
35. Yin, G.-A.; Niu, F.-J.; Lin, Z.-J.; Luo, J.; Liu, M.-H. Performance comparison of permafrost models in Wudaoliang Basin, Qinghai-Tibet Plateau, China. *J. Mt. Sci.* **2016**, *13*, 1162–1173. [[CrossRef](#)]
36. Yu, F.; Qi, J.; Yao, X.; Liu, Y. Degradation process of permafrost underneath embankments along Qinghai-Tibet Highway: An engineering view. *Cold Reg. Sci. Technol.* **2013**, *85*, 150–156. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.