Based on the similarity theory, a laboratory experiment considering the influence of rainfall was performed to study the water-heat behavior and freeze-thaw deformation between the normal embankment and the composite embankment, consisting of permeable geotextile, crushed-rock interlayer, and waterproof geomembrane. The results showed that due to the existence of crushed-rock interlayer, the effective frozen depth of the composite embankment was smaller than that of the normal embankment. In the rainfall period, because of the drainage function of permeable geotextile and a crushed-rock layer, the water content of soil upon the crushed-rock of the composite embankment was lower than that of the normal embankment. Meanwhile, the waterproof geotextile blocks the upward migration of water in the deep soil, which only changes under the freeze-thaw cycles. Therefore, compared with the normal embankment, the composite embankment can reduce the frost heave and uneven deformation of the embankment under the condition of rainfall infiltration, effectively avoiding the formation of longitudinal cracks of the embankment.

1. Introduction

In China, 53.5% of the country’s land area is seasonally frozen ground [1]. The heat exchange between the atmosphere and the ground surface determines the frozen depth in seasonally frozen regions. The frozen depth usually enlarges from the southern part of China to the north and from the lower altitude area to the higher altitude [2]. Embankments constructed in these regions are often damaged by frost heave during the freezing process. More importantly, it will affect the safety of railway operations if the diseases are not controlled effectively. The passenger dedicated line from Harbin to Dalian constructed in the middle-deep seasonally frozen regions is the first high-speed railway in our country. The embankment was constructed with nonfrost heaving A/B group fillings, and a series of measures (such as, insulation layers, coarse-grained soil, addition cement to the graded gravel layer, the base waterproof layer, and drainage measures) had been taken into consideration to solve the frost-heave damage. But according to the observational data [3], the actual amounts of frost heave in typical monitoring sites were still larger than the deformation limit value [4]. Therefore, the frost heaving of the railway embankment in frozen soil regions will still be a complex engineering problem, which incorporated the multi-physical fields coupling process of thermo-hydro-mechanical for frozen soil [5].

For the frost heaving problems encountered in practical engineering, many research has been carried out. Wang [6] indicated that the frost heave characteristic of coarse-grained soil mainly relied on granular composition, moisture, and groundwater [6]. For the frost heave of roadbed fills, the resilient modulus of soil can reduce in larger degrees after several freeze-thaw cycles [7]. Ye et al. [8] presented the frost heave classification of railway embankment fillings and suggested that the antifreezing layer should be placed in the
embankment [8]. Lan and Zhang [9] confirmed the depth and thickness of the replacement layer in seasonally frozen regions by experimental research [9]. Zhang et al. [10], Nie et al. [11], and Wang and Dong [12] showed that the water content is the dominant factor in influencing the frost heave of roadbed fills and graded gravel through laboratory experiments [10–12]. Gao et al. [13] studied the frost heave characteristic of coarse-grained soil by conducting a series of one-side freezing experiments, the results showed that fines content influenced the frost susceptibility of the coarse-grained soil significantly [13]. Yu et al. [14] carried out the triaxial compression tests on silty sand and found that the physical structure of the soil was affected by freeze-thaw cycles [14]. For the antifrost measures, Xu et al. [15–18], Liu et al. [19, 20], and Tian et al. [21] studied the antifrost effect by applying frost-resistant berm, replacing-soil method, and insulation board through the numerical analysis method. The result showed that the insulation had an obvious effect on reducing the seasonally frozen depth, and the effect would be better combined with other antifrost measures [15–21]. Peng had studied the antifrost measures in the passenger dedicated line systematically in seasonally frozen regions [22]. With the method of soft penetrated pipes in drain holes, the initial water content could be reduced and the freeze-thaw disease of embankments could be treated effectively [23]. A new embankment structure, which was consisted of geotextile, crushed-rock layer, and geomembrane, was designed and investigated both in laboratory and in site in cold regions [24]. Fang et al. [25] indicated that macadam bed course and waterproof geomembrane could better decrease the freezing depth and prevent frost heaving deformation of the embankment by the in-situ experiment [25]. Zhao et al. [26] showed that the addition of cement can significantly reduce the rate of frost heave of graded crushed stones [26]. Dong et al. [27] and Lü [28] indicated that the insulation measure could not only decrease the frost heave deformation of the embankment but also reduce the residual deformation [27, 28]. Based on the concept of active heating, Gao et al. [29, 30] established a 3D coupled heat transfer model between the heating two-phase closed thermosyphon (HTPCT) and subgrade fillings and presented a novel embankment structure including HTPCT, frost-resistant berms, and insulation board. The results showed that the HTPCTs are effective to adjust and increase the geotemperature of the embankment, and the novel embankment is an effective measure to weaken the frost heaving of embankment [29, 30].

According to the research results mentioned above, it can be found that the water is the main cause to the frost heaving of the embankment, and the frost heaving mainly happened in the surface of the embankment. The gravel layer with large permeability, good drainage effect, and the insensitive frost heave characteristics, has been widely applied in roadbed engineering. In addition, a crushed-rock layer has the property of well drainage and insulation when the natural convection does not happen, and the geomembrane could prevent water from migrating to the upper soil layer [24, 31]. Therefore, a composite embankment composed of permeable geotextile, crushed-rock interlayer, and geomembrane, and a normal embankment, as contrast one, were established under freeze-thaw cycle conditions to investigate the antifrost effect of the composite embankment considering the rainfall. It is hoped that this study would provide a reference for the design and construction of the railway embankment in seasonally frozen soil regions.

2. Experimental Design

2.1. Experimental Equipment. The experimental equipment used in this test is shown schematically in Figure 1. It is composed of four parts, which are insulation modeling box, ambient temperature controlling system, ventilation system, and data acquisition system, respectively.

The inner dimension of modeling box is 8.0 m × 1.84 m × 2.7 m, which is insulated by the insulation material with 10 cm thick, and it is isolated from the outer ambient temperature. The temperature controller kept the inner ambient temperature close to the desired temperature automatically, which could be set from −60°C to +50°C. The data acquisition system is consisted of temperature sensor, displacement sensor, and moisture sensor. The data was collected with a data logger of CR 3000 at an interval of 20 minutes automatically. The precision of corresponding temperature, displacement, and moisture sensors is ±0.05°C, ±0.01 mm, and ±3%, respectively.

2.2. Experimental Design. To study the antifrost heave effect of the composite embankment, a normal embankment was constructed for comparison at the same time. They were separated by an insulation board with the thickness of 10 cm placed vertically. The geometric sizes of two embankments were same, which were determined according to similarity method [32], as shown in Figure 2. The similarities of geometric sizes and time were 1/4.93 and 1/24.33, respectively. The top and bottom width of the embankment were 1.10 m and 4.70 m, respectively, the height was 1.20 m, and the slope gradient of embankment was 1:1.5. The filling materials of the embankment was nonfrost heaving A/B group fillings, and the water content and dry density of the filling materials was 12.40% and 1.93 g/cm³, respectively. The water content mentioned in this paper was all expressed by volumetric water content. The relationship between dry density and moisture content of the nonfrost-heaving A/B group fills is shown in Figure 3. The accumulative curve of grain size distribution of A/B group fills is shown in Figure 4, the non-uniformity index of the filling materials was 11.3, and the plasticity index was 18.80%, and the quality fines content of the particle size less than 0.075 mm accounted for 1.18%. At the bottom of the subgrade, there was a foundation soil layer with a thickness of 0.20 m and width of 4.90 m, which was 0.10 m wider than the bottom of the embankment. The foundation soils of the two embankments were both clay. The water content and dry density of clay was 20.30% and 1.74 g/cm³, respectively. In the composite embankment, a crushed-rock (the average size of crushed-rock was 10 cm, shown in Figure 5(b)), was embedded with thickness of 0.60 m. The distance from the top and bottom
boundaries of the embankment to the upper and lower boundaries of the crushed-rock layer was 0.30 m. A permeable geotextile and waterproof geomembrane were laid at the upper and lower boundaries of crushed-rock interlayer, respectively.

Figure 5(d) shows the installation of the test embankments. To study the distribution of temperature, moisture, and deformation in the embankment among the freeze-thaw cycles, the mid-sections were selected as the monitoring sections of the two embankments, and the distributions of sensors (30 temperature sensors, 8 Hydra Probe soil sensors, and 2 displacement sensors) were the same, as shown in Figure 6.

In order to investigate the influence of rainfall on frost heave of the embankment, the artificial rainfall was conducted from the fourth to sixth cycles by the shower nozzles (Figure 1). In the western part of China, rainfall is mainly concentrated in July and August, and the annual rainfall is small. So the precipitations were carried out at the beginning
stages of the last three cycles, which were the highest temperature. One millimeter of precipitation is one millimeter of water per unit area. In the laboratory experiment, two kinds of rainfall amounts were identified [35]. The cumulative rainfalls of the three cycles were about 16.88 mm, 18.3 mm, and 18.3 mm, respectively.

3. Experimental Results and Analyses

3.1. Analysis of the Temperature Field.

To compare the variation characteristics of temperature and moisture between the two embankments conveniently, the interfaces between the roadbed fills and the crushed-rock layer were called the upper and lower boundaries of data analysis of the composite embankment, and the corresponding positions of the normal embankment were called the upper and lower boundaries of data analysis of the normal embankment.

Four Hydra Probe soil sensors of S3, S4, S11, and S12 were installed at the upper boundaries of data analysis of the composite embankment and the normal embankment (Figure 6). Two midpoints of S3, S11 were selected to analyze the upper boundary temperatures of two embankments. Figure 8 shows the temperature variations of the two midpoints among the freeze-thaw cycles. It can be seen that the temperatures of S3 and S11 vary periodically with the air temperature, and the temperature of S3 is more susceptible to the circumstance air temperature than that of S11. At the negative air temperature period, the difference is only 0.76°C between S3 and S11. While at the positive period of air temperature, the difference is obvious, and the maximum temperature difference is 6.18°C. It means that the composite embankment could absorb more hot energy from external atmospheric than the normal embankment during the positive temperature period.

Figure 6: Distributions of sensors in the mid-cross sections (unit: cm). (a) Composite embankment. (b) Normal embankment.

Figure 7: The variation curves of air temperature, top surface, and slope temperature of the embankment measured in the first three cycles.
The temperatures at the midpoints S5 and S13 (Figure 6) were selected to analyze the lower boundary temperatures of two embankments. Figure 9 shows the temperature variations of the two midpoints in the freeze-thaw cycles. It can be seen that the temperatures of S5 and S13 are all above 0°C, and the amplitudes are similar to each other. That is to say, the soil under the bottom of the lower boundary of the two embankment is always in a melting state, and the two kinds of embankments both had a good thermal stability.

The two temperature profiles at the highest and lowest air temperatures were plotted to analyze the influence of crushed-rock interlayer on the temperature field of the composite embankment in the fourth cycle (Figures 10 and 11), respectively. It is found from Figure 10 that the closer to the surface of the embankment, the temperature isotherm is more parallel to the outer boundary of the embankment and the isotherm of the composite embankment is symmetrical distribution, more curved than that of normal embankment. Due to the existing of crushed-rock layer, the temperature of the composite embankment is higher than that of the normal embankment at the same position. It is also found from Figure 11 that due to the heat transfer mechanism of the crushed-rock layer by point-to-point, the cold energy cannot influence the deep region of the composite embankment, then the temperature field of the composite embankment is in the symmetrical convex upward state. Meanwhile, because of the freezing fronts penetrating into the crushed-rock interlayer of the composite embankment, the freezing depth and width of the normal embankment are all larger than that of composite embankment. Furthermore, the minimum temperature at the top surface of the normal embankment is ~4.5°C, which is 0.5°C lower than that of the composite embankment. The area with temperature below 0°C in slope and toe of the normal embankment is larger than that of the composite embankment, and the area of crushed-rock interlayer should be subtracted from the area of the negative temperature zone, which induced the frost heave of the embankment. Therefore, the insulation effect of the composite embankment is better than that of the normal embankment. If the two kinds of embankments had the same moisture content, the frost heave of the normal embankment is obviously greater than that of the composite embankment. Different from the cooling effect of the crushed-rock layer in permafrost region, the crushed-rock interlayer established in this paper is in a closed state on both sides of the embankment slope, and its internal velocity field is not affected by external wind speed. The temperature field of the crushed-rock layer is only formed by point to point heat transfer of the rock, and this heat conduction effect is very limited. Therefore, the crushed-rock interlayer proposed in this paper actually plays an insulation effect.

According to the long-term observed results of the in-situ temperature conditions [33], the ambient temperature in the modeling box was set as follows:

\[ T_a = 4.8 + 14 \sin \left( \frac{2\pi \cdot t}{360} + \frac{\pi}{2} \right). \]  \hspace{1cm} (1)

Here, \( t \) is time with a unit of hours, the mean annual air temperature was +4.8°C, the temperature amplitude was 14°C, and one freeze-thaw cycle is 15d or 360 h. The solar radiation was simulated with four heating bulbs (Figure 5(d)), and the height was adjusted manually so as to the mean periodic temperature on the top surface and slopes of embankments would increase about 3°C and 2.7°C than atmospheric temperature, respectively [34].

During the process of the experiment, the atmospheric temperature in the modeling box was set constant for 72 h to make the temperature of the embankments become steady. Then, it was set according to (1) manually for 6 cycles continuously. The variation curves of atmospheric temperature, top surface, and
3.2. Analysis of Moisture. Frost heaving is mainly related to soil properties, temperature, and water content [1]. The soil properties should include size composition, mineral composition, and salt (using salt-free soil in this paper). The water inside the embankment mainly comes from three parts, the construction of the embankment, rainfall, and the surface water. During the construction of the embankment, the water content of subgrade can be controlled effectively by the optimal water content and the maximum compactness of the fillings, and the surface water can be blocked and diverted through the channels along the direction of the embankment. Therefore, the rainfall is the main water source of the embankment in operation. It is well known that the freezing of migrated water is the main cause for the frost heaving of the embankment, which mainly occurred in the surface of the embankment. To study the influence of rainfall on the frost heaving of the embankment, the artificial rainfall was imposed on embankments at the highest air temperature in the latter three cycles, which was represented by A, B, and C in Figure 12, respectively.
It can be seen from Figure 12 that the liquid water content at different depths along the center of two embankments varied with the atmospheric temperature periodically under the freeze-thaw cycles. Generally speaking, the shorter the distance from the surface of the embankment, the faster the temperature decreases. Therefore, it could be concluded that the liquid water content of the embankment surface decreased along with the ambient temperature decreases firstly, and with the increasing of frozen depth, unfrozen water content in the deeper soil also starts to decrease, but a lag exists among them. With the circumstance temperature increasing, the embankment surface starts to thaw, and the liquid water content increases. By the heat energy accumulating, the liquid water content in the deeper soil rises again, but the lag still presents.

In order to analyze the variations of the liquid water content at different depths along the center line of embankments, the variations in liquid water content at the center of the embankment surface, upper, and lower boundaries of two embankments are shown in Figures 13–15, respectively. It can be found that the liquid water contents of the embankment changed periodically. The variation of liquid water content at the center of the embankment can be divided into the non-rainfall period and the rainfall period, as shown in the period I and period II in Figures 13–15, respectively. Figure 13 shows the variation of liquid water content at the embankment surface. For the non-rainfall period, the variations of liquid water contents in every cycle can be further divided into three stages, which are the initial cooling stage, freezing stage, thawing stage (represented by A, B, and C in Figure 13, respectively). At the initial cooling stage, the temperatures at the midpoints (marked as S1 and S9 in Figure 6) of the embankment surface have not yet reached the freezing point. Because of the radiation effect of the heating bulbs installed (Figure 5) above the embankment, the water evaporates and the liquid water content gradually decreases. At the freezing stage, the temperatures of S1, S9 decrease from the freezing point to the lowest point. The liquid water in the pores phases into ice and the unfrozen water content decreases rapidly. The decreasing rates of liquid water content become larger than those at the initial cooling stage obviously, and the inflection points are marked by m and n in Figure 13(a), respectively. The decreasing rates of liquid water content are approximately the same as those of cooling rates. At the thawing stage, the temperatures of S1, S9 rise gradually from the lowest negative temperature to the positive zone. The ice crystals nearing the embankment surface gradually melt, resulting in the increase of liquid water content.

For the rainfall period, the variations of liquid water content in every cycle could be divided into four stages: rainfall stage, initial cooling stage, freezing stage, and thawing stage (represented by a’, b’, c’, and d’ in Figure 13, respectively). At the rainfall stage, the artificial precipitations were carried out at the highest temperature period. The liquid water content of S1, S9 increase rapidly and the volumetric water content of S1, S9 increase from 18.4% to 20.8% to 31.8% and to 31.7%, respectively. At the initial cooling stage, due to the artificial precipitation in the former stage, the soil near the embankment surface is saturated. While infiltrating downward under gravitational potential, the moisture was evaporated by radiation heating, resulting in the liquid water content of S1 and S9 decrease. At the freezing stage, because of the pore water phasing into ice, the unfrozen water content decrease rapidly by the same decreasing rate with the cooling rate. It also exists two inflection points between the initial cooling stage and the freezing stage (marked by m’ and n’, respectively), as shown in Figure 13. At the thawing stage, with the temperature rising again, it can be seen that the liquid water content increase and are greater than those during the former cycle at the same stage. This may be caused by the artificial precipitation, leading to the liquid water content higher than those at the same stages in the non-rainfall period.
From Figure 14, it can be seen that the liquid water content at the center position of upper boundaries of two embankments vary periodically affected by temperature and rainfall. During the non-rainfall period, the embankment fillings are frozen and thawed periodically during the freeze-thaw cycles. And because the moisture migrates upward continuously, the liquid water content of S3 and S11 at the highest air temperature during the freeze-thaw cycles decrease. During the rainfall period, artificial precipitations were carried out in the last three cycles, but the variations of liquid water content of S3 and S11 are opposite. This may be the reason that the moisture holding capacity of embankment fillings is weak and the rainwater could infiltrate downwards continuously. Permeable geotextile was set on the top of the crushed-rock layer, so that the rainwater could flow through into crushed-rock, discharged out of embankment timely, avoiding the accumulation of rainwater. So the liquid water content of S3 decreases continuously. In contrast, in the normal embankment without any protected measures, the moisture accumulates with the rainwater infiltrating and the liquid water content increases.

Figure 15 shows the variations of liquid water content at the center of lower boundaries of two embankments. It can be found that the liquid water content of S5 decreases slowly, and then tends to steady in the freeze-thaw cycle. However, the unfrozen water content of S13 decreases continuously and the decreasing rate in the first cycle is the largest. This may be the fact that the waterproof geomembrane was set under the crushed-rock interlayer, which could cut off the moisture migration upward from the underlying soil, resulting in the accumulation of rainwater. In contrast, the moisture migrated upwards continuously with the freeze-thaw cycle, resulting in decrease of liquid water content in the normal embankment.

Based on the above research results, it could be concluded that the antifrost heave measure, consisted of permeable geotextile, waterproof geomembrane, and the crushed-rock interlayer, has a good effect of drainage infiltration from upper soils and preventing migration from the underlying soils, which is very beneficial to reduce the embankment frost heave.

3.3. Analysis of Displacements. During the freezing process, segregation frost is caused by transformation of in-situ and migrating water into ice. So water is the main factor to frost heave, and the rainfall may be a major source of water required for the frost heave of subgrade. Four displacement sensors were installed on the surfaces of the centers and shoulders of two embankments to monitor the deformation process of embankments during freeze-thaw cycles (Figure 6).

The deformation process of two embankments during the freeze-thaw cycles are shown in Figure 16. The deformations detected of the embankments varied periodically with the air temperature, and there are obvious differences between the two embankments during freeze-thaw cycles.

In the initial cooling stage, as the surface temperatures of two embankments dropped below the freezing point, the freezing fronts penetrated into the embankment progressively by one-sided freezing mode. Phase change of pore water occurs in the frozen fringe, leading to the volumetric expansion of soil. The maximum deformations of two embankments are different in the initial freezing stage. The maximum vertical displacements of the normal and composite embankments are 4.14 mm and 1.21 mm, respectively. The difference is 2.93 mm. During the freeze-thaw cycle stage, on the basis of the accumulative displacement in the initial cooling stage, the vertical displacements of the two embankments has changed by frost heave and thaw settlement under periodic air temperature. The experimental process should be divided into two stages, non-rainfall and rainfall stage. At the non-rainfall stage, with periodic air temperature changing, the amount of frost heave of the normal embankment increases slowly and the difference
between the center and the shoulder of the embankment increases gradually, reaching to 0.56 mm finally. The amount of frost heave of the composite embankment has been stable, and the deformations at the embankment center and the shoulder almost kept coincidence. At the rainfall stage, the artificial rainfall was imposed on embankments when the air temperature rises to the highest in the latter three cycles. The amount of frost heave of the embankment surface in the center of the normal embankment increases continuously, while the deformation in the shoulder has stabilized, so the difference between these two positions further increases, reaching to 1.12 mm and increasing by about 100%. On the contrary, the amount of frost heave of the composite embankment increases slowly. Compared with normal embankment, the frost heave is still relatively small, and the difference between the center and the shoulder of the composite embankment is only 0.49 mm. That means the composite embankment could prevent the inhomogeneous deformation and longitudinal cracks of the embankment. Consequently, on the whole, the composite embankment is proved well to prevent frost heave and settlement of the embankment.

4. Conclusions

Using the similarity theory, a composite embankment structure, consisting of permeable geotextile, crushed-rock interlayer, and waterproof geomembrane, was constructed in the test to study the water-heat behavior and freeze-thaw deformation research of the railway embankment considering rainfall in seasonally frozen regions, and a normal embankment was conducted as a control. Based on the experimental results, the conclusions are given as follows:

(1) The inner temperature of embankments varied periodically with the air temperature. Due to the insulation effect of crushed-rock interlayer, the frozen depth of the composite embankment was smaller than that of the normal embankment.

(2) In the non-rainfall period, the water content decrease gradually with the soil temperature, and in the rainfall period, the moisture content of the composite embankment was lower than that of the normal embankment, and the precipitation mainly influences the water content of the soil layer upon the crushed-rock interlayer. The composite embankment has a good drainage and a waterproof-effect.

(3) Compared with the normal embankment, the composite embankment could mitigate the frost heave and prevent the inhomogeneous deformation and longitudinal cracks of the embankment.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interests.

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