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Experimental and Modeling of Residual Deformation of Soil–Rock Mixture under Freeze–Thaw Cycles

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Abstract: Projects in seasonal frozen soil areas are often faced with frost heaving and thawing subsidence failure, and the foundation fill of most projects is a mixture of soil and rock. Therefore, taking soil–rock mixture with different rock contents as research objects, the residual deformation of soil–rock mixture under multiple freezing–thawing cycles is studied. In addition, the deep learning method based on the artificial neural network was pioneered combined with the freezing–thawing test of the soil–rock mixture, and the Long short-term memory (LSTM) model was established to predict the results of the freezing–thawing test. The LSTM model has been verified to be feasible in the exploration of the freeze–thaw cycle law of a soil–rock mixture, which can not only greatly reduce the period of the freeze–thaw test, but also maintain a high prediction accuracy to a certain extent. The study found that the soil–rock mixture will repeatedly produce frost heave and thaw subsidence under the action of freeze–thaw cycles, and the initial frost heave and thaw subsidence changes hugely. With the increase of the number of freeze–thaw cycles, the residual deformation decreases and then becomes steady. Under the condition that the content of block rock in the soil–rock mixture is not more than 80%, with the increase of block rock content, the residual deformation caused by the freeze–thaw cycle will gradually decrease due to the skeleton function of block rock, while the block rock content's further increase will increase the residual deformation. Furthermore, the LSTM model based on an artificial neural network can effectively predict the freezing and thawing changes of soil–rock mixture in the short term, which can greatly shorten the time required for the freezing and thawing test and improve the efficiency of the freezing and thawing test to a certain extent.

Keywords: soil–rock mixture; freeze–thaw cycle; residual deformation; rock content; long short-term memory network

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1. Introduction

In recent years, for the sake of adapting to the transition of our country's economic development model from fast to stable, construction of the transportation system, especially the high-speed railway, is increasing. However, the complex geographical conditions also bring more challenges to the project's construction. In particular, projects in seasonal permafrost areas also need to take into account the freezing and thawing deformation of foundation fill composed of soil–rock mixture. Therefore, it is necessary to fully explore the change law of the volume and strength of soil–rock mixture under the action of freeze–thaw cycles, and to grasp the influence of rock content on the residual deformation of the soil–rock mixture, so as to ensure the engineering quality and operation safety to the greatest extent.

Many scholars at home and abroad have done plenty of research on the freeze–thaw cycle mechanism and theoretical model, and they usually focus on the basic theory of the soil frost heave effect. There is still no systematic reference model for the research on the freeze–thaw cycle mechanism of soil–rock mixture. Foreign research on the mechanism of the freeze–thaw cycle roughly started in the 1960s. Corte [1,2] observed that the rocks in the soil were exposed to the surface due to repeated freezing and thawing in the cold winter area. After research, it was found that under the action of repeated freezing and thawing, when the soil contains enough water, the non-uniform soil particles will undergo vertical sorting of particle sizes. Further laboratory experiments determined the basic conditions for vertical sorting to occur, that is, the effects of the freezing rate range, water content on the frozen surface, and particle size on soil particle migration. Inglis and Corte [3] proposed another explanation for this phenomenon, which was, assuming that the soil particles are spherical and are of sufficient mass, embedded in a cold mud composed of fine particles frozen from top to bottom, then the direction of the particles' movement is decided by the orientation of freezing and thawing, which is not determined by the direction of gravity. Jackson and Uhlmann [4] believe that, in addition to the freezing expansion of soil water, the frost heave effect of soil water on soil during the freezing process should also be taken into consideration. Due to the repulsion between ice and particles and the tension created by unfrozen water, larger particles tend to be sorted to the surface layer, while smaller particles are migrated deep into the soil. Vliet-Lanoë [5] expounded the frost heave theory from a geological point of view. That is to say, the separation of ice occurs during the frost heave process of soil. Different forms of separated ice such as ice layers and ice wedges will cause the soil to bulge with the continuous growth. With the seasonal freezing and thawing, the soil particles are sorted and the rocks in the soil are migrated. The study by Viklander [6] pointed out the soil conditions necessary for the uplift of the rock under the action of freeze–thaw cycles. The test results show that the void ratio of the soil is the key parameter that determines the upward or downward movement of the rock. In addition, the soil must contain enough water for ice to form and to cause frost heave. During the freeze–thaw cycle, vertical cracks are induced in the fine-grained soil, and the water in the soil continuously replenishes the water for the formation of ice lenses. This process causes the rock and coarse particles to continuously move towards the cold end, that is, generally towards the surface. An artificial neural network model was proposed and validated by Ren et al. [7], who tested the modulus of elasticity of pavement subgrade soils in seasonal permafrost zones. Thus, the elastic modulus of the soil can be estimated under freeze–thaw cycling conditions by combining the initial moisture content of the specimen and the soil type. The introduction of the artificial neural network model provides a new idea for the investigation of the freeze–thaw cycle mechanism.

The research on the freeze–thaw cycle mechanism of the soil–rock mixture by domestic scholars started a little later, but it has developed rapidly due to the increase in the demand for engineering construction in seasonally frozen land areas. Xu et al. [8–10] defined a soil–rock mixture as an extremely inhomogeneous and loose geotechnical material composed of pore space, soil particles, and rocks with large strength and a certain engineering scale. To explore the freeze–thaw cycle mechanism of soil–rock mixture, it is necessary to figure out the freeze–thaw cycle mechanism of soil first. Xu et al. [11], Peng et al. [12], Yan et al. [13], Zhao et al. [14], Wang et al. [15], Ma et al. [16], and Fang et al. [17] researched the freeze–thaw characteristics of loess by indoor freeze–thaw tests and obtained the relationships between freezing rate, freeze–thaw volume, freezing temperature, recharge conditions and water content. Secondly, it is essential to find out the moisture condition in the soil. Li et al. [18] believed that repeated freezing and thawing would increase the moisture content of soil samples and cause water to accumulate in the upper part. The research of Wang et al. [19] proposed that the moisture content of the samples after multiple freeze–thaw cycles under the condition of replenishment will be much greater than the initial moisture content, and the replenishment amount during the freezing process is much greater than that during the thawing process. Yu et al. [20] proposed the conditions that ice lens formation must meet during the frost heave process of soil, which is stress failure and the necessary water field. The sufficient water supply will cause partial condensation and frost heave, but if the partial condensation temperature is too low, the migration of unfrozen water will be interrupted, so it needs to be controlled within a certain temperature range. Ming et al. [21] supplemented the ice lens judgment criteria. The formation position of the ice lens is significantly affected by the temperature boundary, while the generation of segregated ice is restricted by the amount of water migration. However, as the load increases, it will show an exponential decay. At the same time, according to the research of Zhang et al. [22], freeze–thaw cycles will destroy the original structure between soil particles, resulting in an increase in soil permeability and a decrease in the plasticity index. It can even increase the large pores in the loess-like soil without collapsibility and produce collapsibility. Zhao et al. [23] believed that under the repeated freezing and thawing of the slope soil in the seasonal frozen soil area, the soil compactness decreased and the pores increased, and proposed the relationship between the frost heave amount and the freezing depth, and the residual deformation amount and the freezing depth. The residual deformation of soil in freeze–thaw cycles is formed by the superposition of frost heave and thaw subsidence. Qi et al. [24] believes that the research on soil frost heave is more in-depth, and the research on thaw settlement is mostly based on empirical methods, and the influence of soil mechanical properties is not paid enough attention. The laboratory test and actual monitoring should be combined to build a model. Liang et al. [25] proposed the thawing characteristics of different soils during repeated freezing and thawing under different moisture content, compactness, and load conditions, and believed that the increase in load would inhibit the frost heave deformation, but at the same time, increase the thawing deformation. Qiu et al. [26] proposed the influence of soil compaction and saturation on the law of freeze–thaw deformation characteristics. That is to say, under the condition of water replenishment, the frost-heave rate, thaw coefficient, and volume change rate of the sample are proportional to the saturation, but the volume change rate tends to be the same with the increase in the number of freeze–thaw cycles. Saturation only affects the number of freeze–thaw cycles at which the volume variability reaches a stable value, and the degree of compaction also affects the size of the stable value. With the in–depth investigation of the mechanism of freeze–thaw cycles, the tests on soil–rock mixture have been carried out gradually.Li et al. [27], Zhou et al. [28], Yao et al. [29], Zhao et al. [30], Gao et al. [31], Zhang et al. [32], Hu et al. [33], Shen et al. [34], Li et al. [35], Hu et al. [36] conducted uniaxial compression strength testing and other indoor tests on the soil–rock mixture under freeze–thaw cycles, and obtained its mechanical properties and damage mechanisms, which can provide valuable references for the engineering in cold regions.

In summary, the research and practice of the freeze–thaw cycle mechanism of soil–rock mixtures have their strengths. Studies by foreign scholars focus on the formation of ice lenses and the movement of soil particles during the freeze–thaw process, and are dominated by indoor experiments. Although domestic scholars' research on this topic started relatively late, it was gradually carried out due to the support of a large number of engineering construction data. In the research direction, not only the stress, water, and other conditions of soil freezing and thawing are discussed, but also factors such as changes in the physical properties of soil through freezing and thawing cycles are considered. Nevertheless, a relatively systematic theoretical model has not been formed for the frost heave, thaw settlement, and residual deformation during the freeze–thaw cycle. Therefore, the test takes the residual deformation of the soil–rock mixture after freeze–thaw cycles as the research object and analyzes the frost heave and thaw settlement after the freeze–thaw cycles. It can fit the actual engineering conditions in the frozen soil area to a certain extent so that the exploration of the freezing–thawing cycle mechanism of the soil–rock mixture has certain practical significance.

2. Materials and Methods

2.1. The Basic Physical Index of the Test Sample

The test sample is a saturated remodeled soil–rock mixture, of which the soil sample is taken from Lvliang, Shanxi Province, and belongs to Q3 Malan loess. According to the

"Standards for Geotechnical Test Methods" (GB/T50123-2019), the soil mechanics basic test was carried out on the soil samples. The particle size distribution curve of the soil samples is shown in the Figure 1.

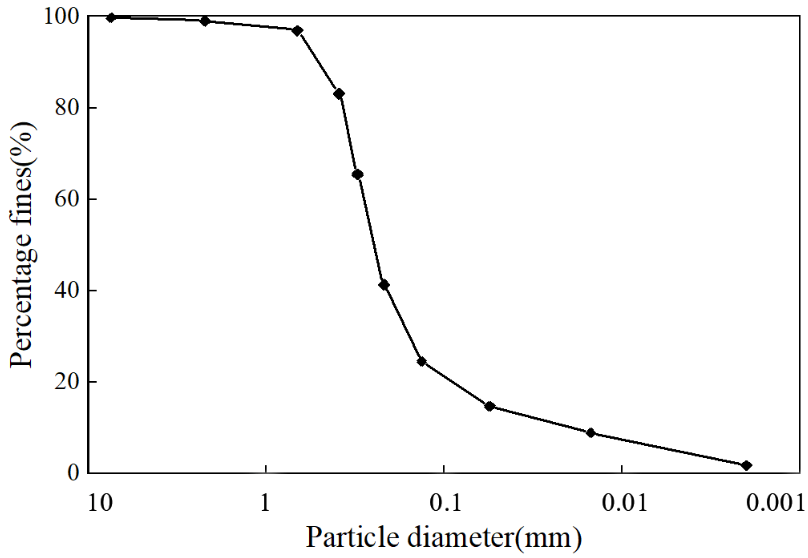

Figure 1. Particle size distribution curve of soil.

After calculation, the uniformity coefficient is 20.500 and the coefficient of curvature is 5.378, so the test soil sample has poor gradation and is not easy to be compacted. In addition, the results obtained by testing and calculating the basic physical properties of the soil samples are shown in Table 1.

Table 1. Basic physical parameters of soil.

Material	Density (g/cm^3)	Dry Density (g/cm^3)	Water Content (%)	Grain Specific Gravity
Soil	1.65	1.44	14.20	2.72

The block stone is gray-white marble with rough surface, as shown in Figure 2. The sample diameter is 60 mm and the height is 100 mm. According to the "Geotechnical Test Method Standard" (GB/T50123-2019), it can be seen that the maximum particle size of the block stone in the soil–rock mixture does not exceed the diameter of the sample, 1/8 of the height, or 1/4 of the height, so the particle size of the stone selected for this test was 10 mm.

Figure 2. The main constituent materials of soil–rock mixture.

2.2. Specimen Preparation and Test Protocol

2.2.1. Preparation of Soil–Rock Mixture Samples

The size of the soil–rock mixture sample was 60 mm in diameter and 100 mm in height. The undisturbed loess soil sample was air-dried, crushed, and passed through a 2 mm sieve, then dried, mixed with distilled water, configured into a saturated state, and sealed for 12 h to make the water uniform. After that, the block stone particles were rinsed with distilled water to remove surface impurities, saturated in distilled water by vacuum saturation method, and then fully mixed with soil samples with rock contents of 60%, 70%, 80%, and 90%, stirred, and put into Layered static compaction in the mold. Since the thickness of each layer needed to be greater than 1.5 times the maximum particle size of the rock, the design thickness of the layered compaction in this test was 20 mm. After compaction, the samples were sealed at an ambient temperature of 0 °C for 36 h.

2.2.2. Equipment and Programs for the Test

The test used the precision triaxial frost heave tester of the State Key Laboratory of Frozen Soil Engineering to carry out the freeze–thaw cycle test. The main instruments used in the freeze–thaw cycle system are shown in Figure 3 and the schematic diagram is shown in Figure 4. In the test, EYELA's NCB–3100 precision low-temperature constant temperature water tank was connected to the top plate to provide a ±20 °C circulating cold bath for one-way freezing test, freezing for 6 h, thawing for 6 h, and circulating for 20 times, and the Martens bottle was used for free water replenishment. The top of the sample was equipped with an infrared displacement sensor, which could monitor the deformation of the sample in the vertical direction. The temperature and relative displacement changes were collected by Keysight's 34972A data acquisition instrument. The acquisition accuracy was 0.01 mm, and the acquisition interval was 5 min. The effects of different boulder contents on the residual deformation of saturated soil under the action of freeze–thaw cycles were systematically studied through the data system of frost heave, thaw settlement, and residual deformation of samples after freeze–thaw cycles.

Figure 3. The main instrument used in the experiment: (**a**) Precision frost heave triaxial instrument; (**b**) Constant temperature water tank; (**c**) Data collector.

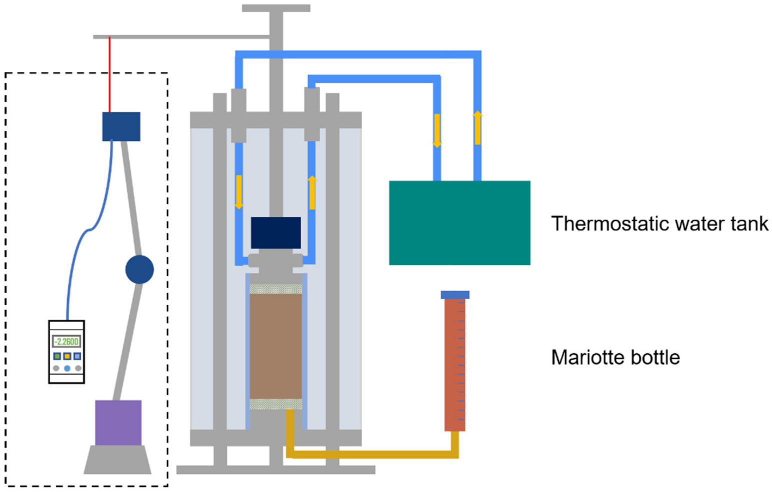

Figure 4. Freeze–thaw cycle device schematic diagram.

3. Experimental Results

3.1. Freeze–Thaw Deformation Analysis

According to the available experimental data, the skeletal effect of the blocks will gradually increase when the rock content in the soil–rock mixture is greater than 40%. Generally speaking, the amount of soil freezing and swelling is positively correlated with the water content, so four sets of tests were conducted with specimens saturated and under open recharge conditions at 60%, 70%, 80%, and 90% rock contents to obtain the freeze–thaw changes of soil–rock mixture with different rock contents. The freeze–thaw cycle process of the soil–rock mixture is shown in Figure 5 (taking group S1 as an example).

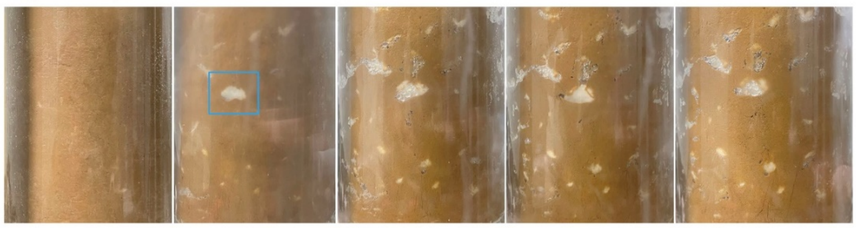

Figure 5. Freeze–thaw cycle process of soil–rock mixture samples.

The temperature of the top plate of each group of specimens varied cyclically within ±20 °C during the freeze–thaw cycle, and the data recorded by the temperature sensors at the top and bottom of the specimens were observed to vary regularly within the predetermined range (as shown in Figure 6). It was found that the soil–rock mixture specimens showed more obvious and different degrees of freezing and thawing changes in each group during the freeze–thaw cycle. In the S1 group specimens with a higher rock content, as the number of freeze–thawing cycles increases, it can be observed that the blocks become closer to the inner wall of the transparent container. That is, the specimens are subject to significant radial displacement by freeze–swelling during the freeze–thawing cycle.

According to the change of frost heave of each group of samples, the soil rock mixture samples have different degrees of frost heave during the freeze–thaw cycles (as shown in Figure 7). With the increase in the freeze–thaw cycles, the frost heave of the sample gradually decreases and tends to be stable. However, with the increase of the content of block rock in the sample, the number of freeze–thaw cycles required for the frost heave of the sample to reach a stable state also increases correspondingly. With the increase of the rock content, the frost heave of the sample first decreases at 60–80% and increases at

80–90%. The S2 group sample with the rock content of 80% at the extreme value even has the phenomenon of frost shrinkage.

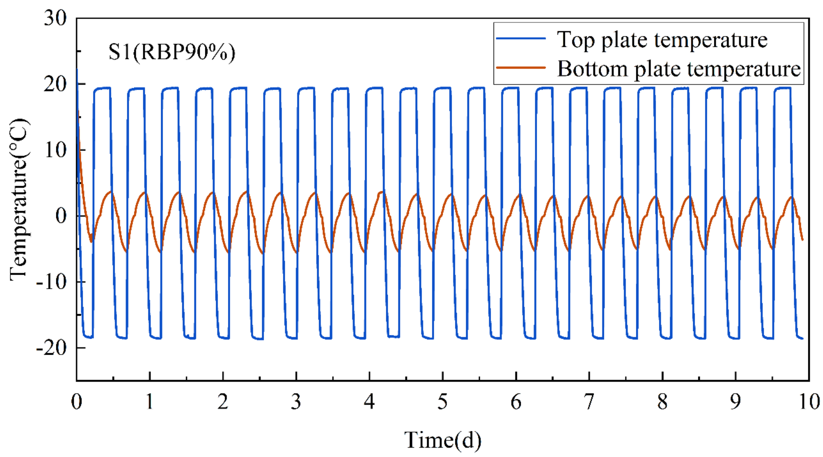

Figure 6. Freeze–thaw cycle temperature of samples in group S1.

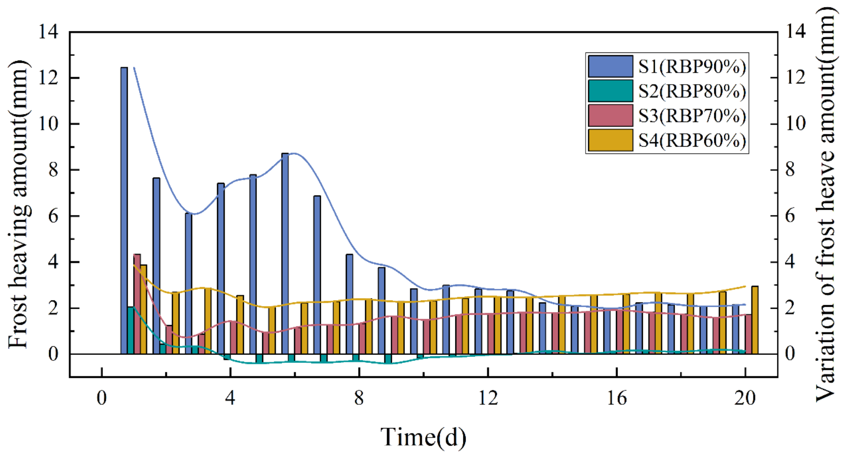

Figure 7. Frost heave amount of each group of samples.

3.2. Residual Deformation Analysis

The soil–rock mixture specimens will alternately produce freezing expansion and thawing settlement during the freeze–thaw cycle, and the superposition of the two is the residual deformation of the specimens. The residual deformation of each group of specimens is shown in the Figure 8.

As can be seen from the Figure 8, almost all of the soil–rock mixture specimens produced thawing and sinking after the freeze–thaw cycles. The initial residual deformation of the specimens is larger than the later residual deformation, but with the increase of the number of freeze–thaw cycles, the residual deformation gradually stabilizes. The residual deformation decreases and then increases with the increase in the rock content in the specimens, and reaches the minimum residual deformation in the S2 group specimen with 80% rock content.

According to the freeze–thaw change curves of the soil–rock mixture specimens as shown in the Figure 9, the residual deformation of each specimen is shown as settlement deformation. When the rock content of the specimens is between 70% and 80%, the freeze-swelling and thawing changes of the specimens in the S2 and S3 groups are smaller than those in the S1 group with 90% rock content and the S4 group with 60% rock content, or the blocks in the specimens in this rock content range can provide the best skeletal support. The freeze-swelling and thawing changes of the specimens in the other two groups are larger, with a maximum deformation of about 12%, and thus eventually also produce larger residual changes.

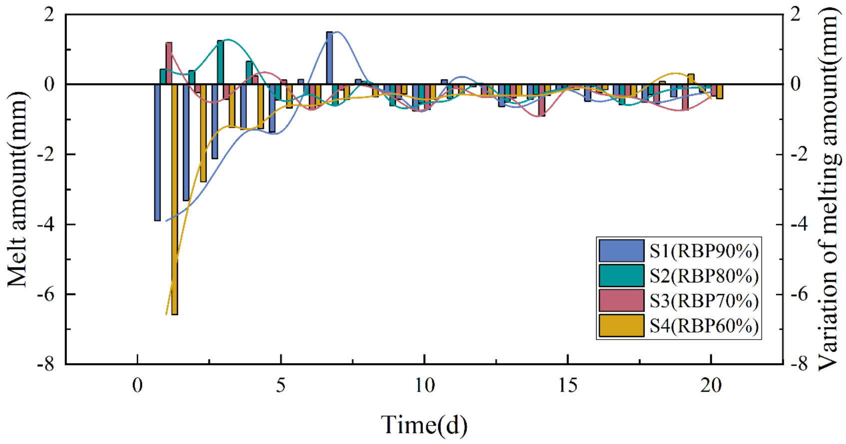

Figure 8. The residual deformation of each group of samples.

The final residual deformation produced by each specimen is shown in Table 2. When the rock content of the soil–rock mixture specimen is 60~80%, the residual deformation is all settlement deformation. With the increase of the lumpy rock content in the specimens, the settlement amount gradually decreased and reached the minimum settlement amount of 2.54 mm in the specimens of group S2 with 80% rock content, which was only 48.29% and 25.81% of the settlement amount in the specimens of groups S3 and S4, while the specimens of group S1 produced the maximum settlement amount, which was almost six times of the settlement amount in group S2.

Table 2. The final residual deformation of each sample.

Number	S1	S2	S3	S4
Residual Deformation (mm)	−14.62	−2.54	−5.26	−9.84

It can be inferred that there is an optimal rock content in the range of 80% to 90%, and until this content is reached, the increase of the boulder content can make the skeleton effect of the boulders in the soil–rock mixture specimens more and more obvious, so that they can resist the deformation caused by the freeze–thaw cycles. However, the S1 group specimens with the highest rock content showed the largest settlement, either because the boulder content was too high or the soil could not completely fill the pores between them, thus producing a larger amount of melting and settlement under the freeze–thaw cycles.

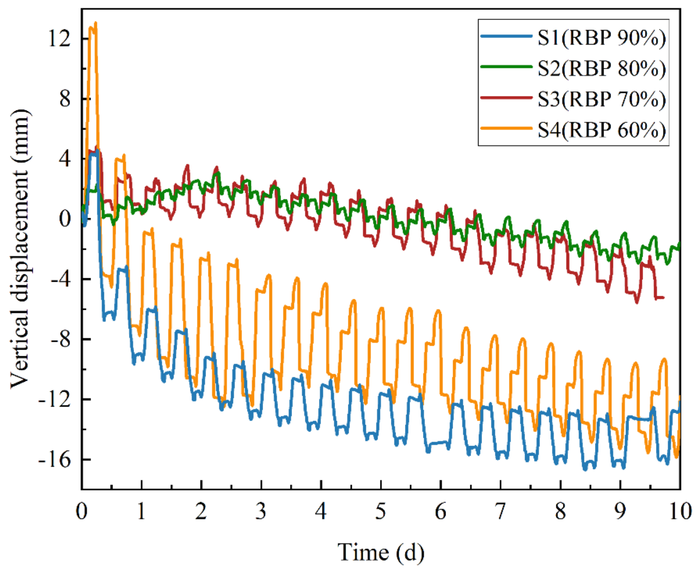

Figure 9. The distribution of freezing and thawing.

4. Model Building and Prediction

The deep learning method based on an artificial neural network can quickly extract effective data features, according to a large number of existing experimental data, and analyze the evolution law of experimental data. In this experiment, the applicability of the freeze–thaw test data prediction of frost heave and thaw deposition was studied by establishing the LSTM model, and the actual test data and the results of the model output were compared, thus confirming the feasibility of the model prediction.

The LSTM model is a neural network model proposed by Hochreiter in the 1990s, and its model structure is shown in the Figure 10. LSTM models contain a special unit, a memory block in the recursive hidden layer. The memory block consists of a cell state and three gating mechanisms (input gate, forget gate, and output gate) to control the flow of information. The gating mechanism is implemented by the Sigmoid function. After the data flow in, they first enters the forget gate. After discarding some redundant information to obtain key feature data, they enter the input gate to control the update of data. Finally, they go through the output gate for output.

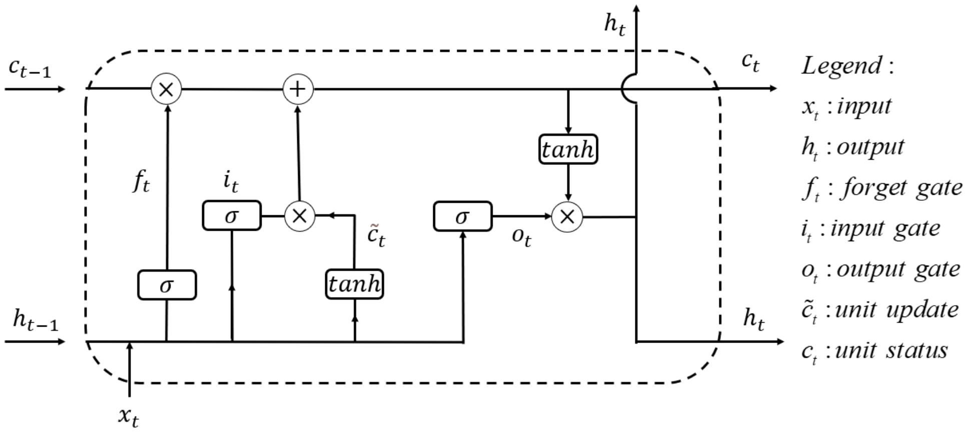

Figure 10. Schematic diagram of LSTM unit structure.

Each LSTM unit updates six parameters (see the legend of the Figure 10) in each time step. The LSTM unit extracts the mapping between input sequence x_t and output sequence h_t, and the update of the LSTM unit can be represented by the following formula:

$$i_t = \sigma(W_i \times [h_{t-1}, x_t] + b_i)$$

$$f_t = \sigma\left(W_f \times [h_{t-1}, x_t] + b_f\right)$$

$$o_t = \sigma(W_o \times [h_{t-1}, x_t] + b_o)$$

$$\widetilde{c}_t = tanh \cdot (W_c \times [h_{t-1}, x_t] + b_c)$$

$$c_t = f_t * c_{t-1} + i_t * \widetilde{c}_t$$

$$h_t = o_t * tanh(c_t)$$

where W is the matrix of input weights, b is a vector of bias, and σ represents a logistic sigmoid function. The four groups of soil–rock mixture samples were all frozen and thawed 20 times, and each group of experiments lasted 10 days. The LSTM model took the data of the first 7 days of each group of experiments as the training set, and the last 3 days of experiments as the test set. The deep learning method of the neural network predicted the effect in the freeze–thaw cycle test of the soil–rock mixture.

It can be seen from the Figure 11 that the results of the learning and prediction of the LSTM model have achieved good expected results, which are highly consistent with the data obtained from the actual test. Therefore, the long and short-term memory network model in deep learning can effectively and accurately predict the soil–rock mixture. The development law of body freezing and thawing can greatly reduce the time span of the soil–rock mixture freezing and thawing test.

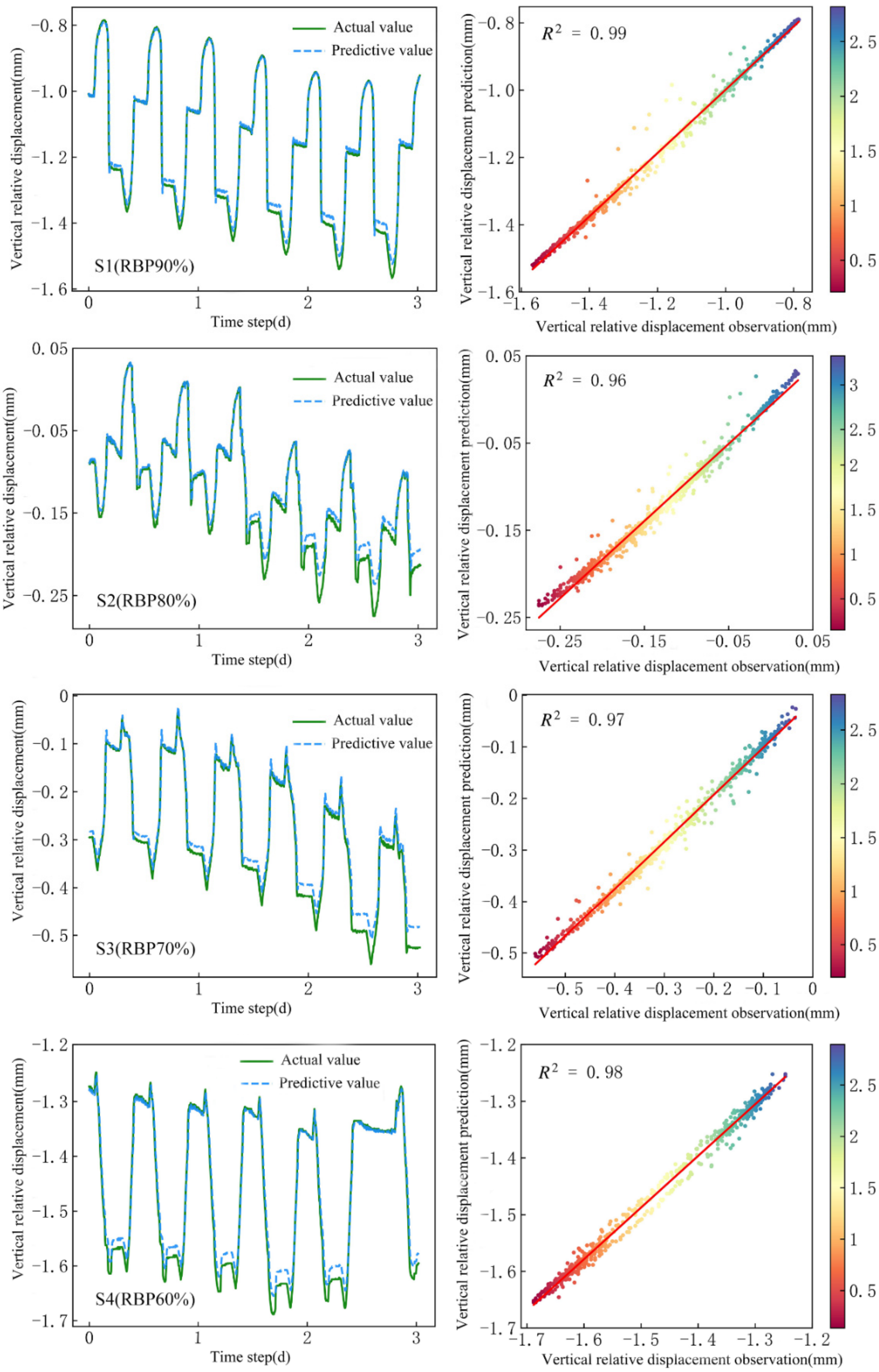

Figure 11. LSTM model predictions.

5. Discussion

In this study, we investigated the residual deformation of soil–rock mixture under the action of freeze–thaw cycles with the rock content as a variable. It was found that the boulders in the soil–rock mixture assumed the main skeletal role. With the increase in the rock content, the residual deformation after the freeze–thaw cycle gradually decreased, and a smaller amount of residual deformation was produced when the rock content was about 80%. This conclusion is similar to the results of Jin et al. [37]. However, when the rock content of the soil–rock mixture reached 90%, a larger residual deformation was produced again. This phenomenon may be related to the "lubricating" effect of the soil filling between the boulders and destroying the skeletal structure, as mentioned in Liao et al. [38]. In addition, the residual deformation of all groups of specimens was settling. According to Zeinali et al. [39], the water migrates upward when the soil thaws, and thus the excess pore space generated leads to the redistribution of fine particles in the soil and the appearance of softening of the soil, which fits with the experimental results. We also tried to build an LSTM model using deep learning methods. The model was validated based on the results of freeze–thaw cycling tests on soil–rock mixture, and the numerical simulation results were relatively small in error with the actual test results, which proved the feasibility of the LSTM model in simulating freeze–thaw tests.

However, there are still some limitations in this study on the freeze–thaw cycle mechanism of soil–rock mixture. First, due to the test equipment, the changes inside the soil–rock mixture during the freeze–thaw process cannot be clearly and directly observed. Secondly, the deep learning method has been little involved in the study of the freeze–thaw cycle mechanism, and the constructed LSTM model is not mature yet. Given the above problems, it is hoped that future research can be combined with high-precision CT scanning equipment to visualize and monitor the stages of freeze–thaw of the soil–rock mixtures so that more specific experimental data can be obtained. It can also provide more references for deep learning models.

6. Conclusions

Through the experimental exploration of the residual deformation of soil–rock mixtures with different rock contents under the action of freeze–thaw cycles, and the simulation prediction and verification of the LSTM model, the following conclusions can be drawn:

(1) Under the action of freeze–thaw cycles, the soil–rock mixture will repeatedly produce frost heave and thaw subsidence, and the initial frost heave and thaw subsidence change greatly and become steady.
(2) Under the condition that the content of boulders in the soil–rock mixture is not more than 80%, as the content of boulders increases, the residual deformation caused by the freeze–thaw cycle will gradually decrease due to the skeleton effect of boulders, while the increase in the content of the boulders will increase the residual deformation.
(3) The LSTM model based on the artificial neural network can effectively predict the freezing and thawing change law of the soil–rock mixture in the short term, thereby reducing the period of the freezing and thawing test and improving the fault tolerance rate.

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