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Heat transfer characteristics of gravelly soils with different compactness during unidirectional freezing process

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Abstract

During the construction of clay core rockfill dam in cold regions in winter, the heat transfer characteristics of gravelly soil are important to the anti-freezing control of the core. Laboratory experiment and field test data showed that the frost depth of gravelly soil in unconsolidated state was deeper than that in compacted state at the early period of soil freezing. With the increase of the freezing time, however, the frost depth of compacted soil is deeper than that of unconsolidated soil. Further study showed that this phenomenon was main caused by the change of thermophysical parameters between unconsolidated and compacted soil. Under the same soil temperature, the thermal conductivity of compacted soil was approximately 2.6 times of that of unconsolidated soil, and the volume heat capacity and phase change latent heat of compacted soil was approximately 1.7 times of that of unconsolidated soil. The different thermophysical parameters caused the differences of the heat transfer rate, temperature distribution and heat release by cooling between compacted soil and unconsolidated soil. This study provides a theoretical guidance for freezing process of soil with different compactness and anti-freezing technology of clay core rockfill dam in cold regions.

Keywords Compactness · Unidirectional freezing · Cooling process · Heat transfer characteristics

1 Introduction

The Lianghekou Hydropower Station (LHS) is located in Yajiang County, Sichuan Province, China, with an elevation of 3000 m, which adopts a clay core rockfill dam with a height of 295 m, the third highest dam in the world. It belongs to the seasonally frozen ground region, and the extremely minimum air temperature of this region reaches − 15.9 °C. Considering on the filling progress of dam core wall, winter construction is necessary due to rainfall affecting construction from May to October, and about 30 % of construction work is planned in winter. Therefore, the filling of anti-seepage soil material is affected by freezing-thawing process during the construction of the dam. The anti-seepage soil material in the core of LHS is mainly frozen at night and melts after sunrise. According to the construction schedule, two compaction states, compacted states and unconsolidated states, may be overnight on the site, which means that the anti-seepage soil will be frozen in two compaction states.

During the construction of clay core rockfill dam in cold regions in winter, the physical and mechanical properties of soil such as strength and deformation modulus increase significantly after soil freezing [1–3]. This will make the unconsolidated soil difficult to compact [4], whereas the compacted soil will reduce its strength and increase its permeability after freeze-thaw cycles [5–7]. The freezing of soil brings hidden dangers to the quality and safety of the engineering. Soil freezing is affected by air temperature, topography, lithology, snow cover and thermophysical properties and water content of soil, which dominates frost depth and the freezing rate of soil [8–10]. Frost depth of soil is an important parameter affecting the application of anti-freezing measures in the construction process of LHS. Previous studies have shown that the frost depth of soil is related to air temperature, annual average ground temperature, total radiation and soil properties [11,

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12]. The trend between ground temperature and air temperature is basically the same [13]. The frost depth deepens with the drop range of air temperature below zero [14]. Under the conditions of the same dry bulk density and water content, the frost depth in the coarse-grain soil is larger than that in the fine-grained soil because the thermal conductivity of the coarse-grained soil is larger than that of the fine-grained soil [15]. However, there were few studies on the influence of the same soil with different compactness on frost depth. After the change of compactness, the thermophysical parameters of soil, such as thermal conductivity and volume heat capacity, will be changed. With the increase of dry density, the thermal conductivity, volume heat capacity and thermal diffusivity of soil increase [16]. The different thermophysical parameters changes the heat transfer characteristics of soil, which will affect the distribution of temperature field and frost depth [17]. It is important for anti-freezing measures to understand the heat transfer characteristics of anti-seepage soil with compacted and unconsolidated state.

Based on the field test on LHS and laboratory experiment, this paper discusses the cooling process of the anti-seepage soil with unconsolidated and compacted states. And then the change law of soil temperature and its influencing factors are analyzed. Finally, the reason why the frost depth of compacted soil in the core is less than that of unconsolidated soil is clarified from heat transfer perspective.

2 Field test and mechanism test in laboratory

During the construction of the core of LHS dam in winter, it often appears that the frost depth of gravelly soil in unconsolidated state is greater than that in compacted state. To study the freezing process of compacted and unconsolidated soil in-situ, a field test was carried out on the core of the LHS dam, and the freeze-thaw process of the test site was observed. However, the test lasted only two days due to the affection by construction work. To further analyze the heat transfer characteristics of gravelly soils with different compactness during unidirectional freezing process, a systematic unidirectional freezing experiment was carried out in laboratory.

2.1 Introduction of test site and observational system

Figure 1 shows the schematic view of the field test. The test site consisted of two square areas with a side length of 3 m, one of which was an unconsolidated soil area, and the other was a compacted soil area with a paving thickness of 30 cm. The surface roughness of compacted soil is smaller than that of unconsolidated soil. The testing soil layer was paved in the original compacted soil. The test was carried out for two days due to the influence of construction arrangements, from January 17, 2017 to January 19, 2017. Two groups of thermo-sensors with an accuracy of ± 0.05 °C were arranged in the compacted and unconsolidated soil areas, respectively. According to the field observation data, the maximum frost depth on site does not exceed 20 cm in late January. There were 9 thermo-sensors in each group, which were placed in the middle of the area respectively, with buried depth of 0 cm, 3 cm, 6 cm, 9 cm, 12 cm, 15 cm and 20 cm from the soil surface. The data was automatically collected every 10 minutes by a CR6 data logger (Campbell Scientific, Inc., U.S.).

2.2 Introduction of testing system in laboratory

Since the field test conditions are not artificially controllable, a systematic unidirectional freezing experiment was carried out in laboratory to study the heat transfer characteristics of gravelly soils with different compactness. The experimental device in laboratory mainly consists of three parts: sample cylinder, temperature control unit and temperature measurement system, as shown in Fig. 2. An iron cylinder with a diameter of 30 cm, a height of 40 cm and the wall thickness of 1 cm was used in the experiment. The cylinder was covered with 10 cm thickness thermal insulation material, whose thermal conductivity is 0.02 $W \cdot m^{-2} \cdot K^{-1}$. Temperature control unit has a two-stage temperature control mechanism. The first stage was the environmental temperature control around the sample cylinder in the cold room. The accuracy of the controlling temperature was ± 0.5 °C, which ensured a stable temperature around the sample cylinder and thus the stability of the experiment. The second stage control was comprised of an ultra-low refrigerated heating bath circulator (XT5702ULT, made in China) with an accuracy of ± 0.1 °C and cooling plate. The working medium circulates between the circulator and the cooling plate contacted with the top of the soil sample through the circulating pipe to cool the soil sample. The temperature measurement system consists of seven thermo-sensors with an accuracy of ± 0.05 °C and a CR6 data logger. The thermo-sensors arranged in the middle of the soil sample with the distance of 1 cm, 5 cm, 10 cm, 15 cm, 20 cm, 25 cm and 30 cm, respectively, from the cooling plate. The temperature data was collected every 10 minutes by the CR6 data logger. The soil used in the experiment is gravelly soil taken from the construction site of the core of the LHS dam. To simulate the compacted and unconsolidated states, the soil samples in the sample cylinder are treated by two methods: (1) directly pouring the soil into the sample cylinder, whose compactness is 60 %; (2) stratified compaction the soil samples in the sample cylinder, whose compactness is 100 %. The compactness is based on the compactness of unconsolidated and compacted soil on site. In the experiment, two kinds of cooling plate temperatures (CPT), namely − 5 °C and − 10 °C, were adopted, and the initial temperatures of soil samples (ITS) were 8 °Cand 15 °C, respectively, as shown in Table 1. Before the experiment, the soil sample was heated or cooled to the designed initial temperature by the cooling plate. When the temperature probe in the soil sample was constant to

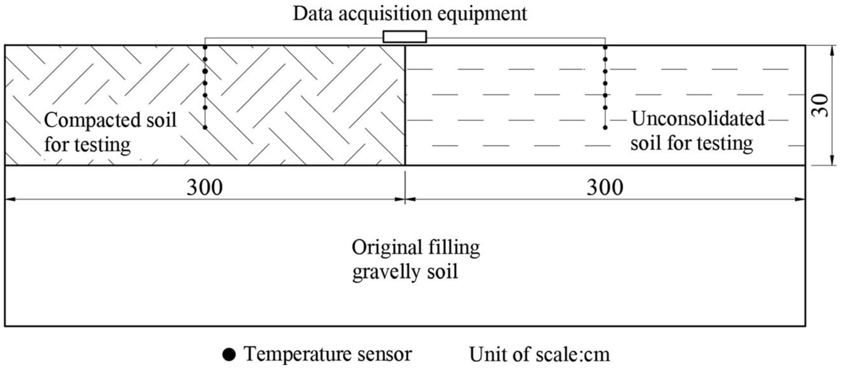


Fig. 1 The schematic view of the field test

the designed temperature, the heating or cooling was stopped. Then the cooling plate temperature was adjusted to the designed cooling plate temperature, and the experiment was started. The experiment was carried out under different experimental conditions to analyze the influence of different cooling plate temperature and initial soil temperature on the freezing characteristics of compacted and unconsolidated soil. Under the same experimental conditions, there are two kinds of compacted soil samples in each group. Therefore, four groups of experiment were carried out under different testing conditions, and each group had soil samples in both compacted and unconsolidated states.

3 Field observational results and analysis

Air temperature, the freezing-thawing law and influencing factors of the soil under different compactness on the dam were analyzed in the following.

3.1 Environmental conditions

During the test period, air temperature and total radiation, 2 m above ground surface, were observed by an automatic weather station about 30 m away from the test site, as shown in Fig. 3. During the observational period, air temperature reached the lowest at about 10 a.m. and the highest at about 16 p.m., and the air temperature in these two days was basically same. The maximum and minimum air temperatures were 17.8 °C and −2.7 °C, respectively, and the average air temperature was 6.1 °C. The cooling process of air is slower, and the heating process is faster. The ratio of positive to negative daily temperature was about 3:1, that is, the period when soil was in positive air temperature was about 3 times that of negative temperature in a day. In addition, the total radiation was nearly the same in these two days. The radiation heat up the anti-seepage soil from about 10 a.m. to 16 p.m..

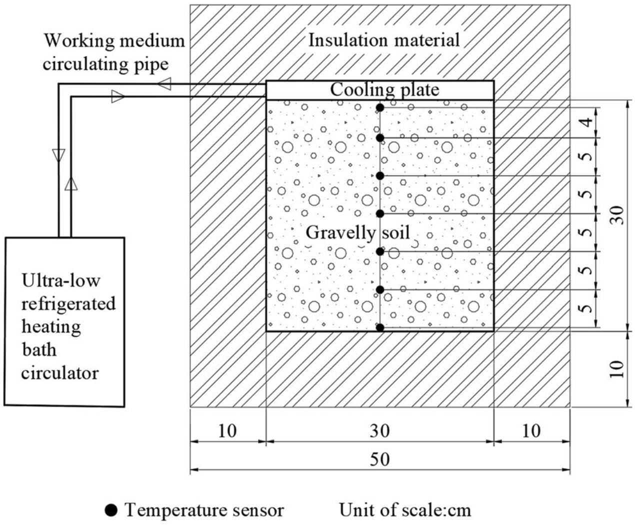


Fig. 2 Schematic diagram of test device

3.2 Comparative analysis of temperature between compacted and unconsolidated soil

Figure 4 is the observation data of soil temperature with different compactness from January 17, 2017 to January 19, 2017. The soil temperature of the two compactness has the same change process. From the daily change process of the soil temperature, the heating process takes longer, and the cooling process takes less time. The time for the temperature of the unconsolidated soil and compacted soil to reach the maximum and minimum values is the same. The surface soil temperature reached its maximum at 15 p.m., the minimum at 9 a.m.. And the soil temperature reached its maximum at 15 cm depth about 3 hours later than the surface. Compared to these two compactness states, the temperature of unconsolidated soil was higher than that of compacted soil in the daytime. At night, however, the temperature of unconsolidated soil was lower than that of compacted soil. That is, the cooling

Table 1 Temperature of the cooling plate and initial temperature of the soil samples

Number	CPT / °C	ITS / °C
1	-5	8
2	-10	8
3	-5	15
4	-10	15

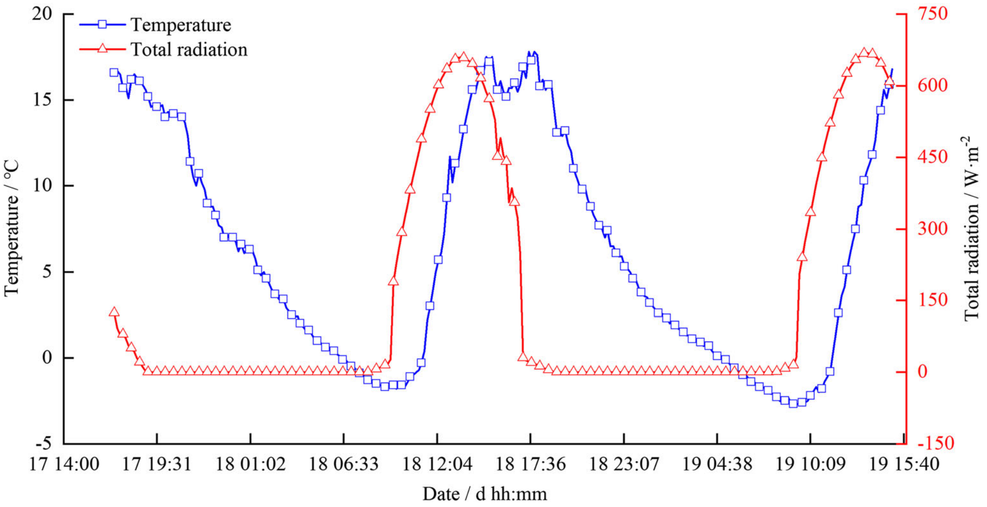


Fig. 3 The observation data of air temperature and total radiation from 17 January 2017 to 19 January 2017

rate and heating rate of unconsolidated soil was faster than that of compacted soil. Figure 5 showed the temperature variation of unconsolidated and compacted soil with depth at different times on January 18, 2017. From Fig. 5, the temperature of unconsolidated soil was lower than that of compacted soil, however, the temperature difference between the two kinds of compactness of soil tended to be smaller with depth. This is related to the volume heat capacity, thermal conductivity and other properties of the soil, which changes with the increase of compactness. The specific reasons will be explained in detail in the following section of the laboratory experimental results analysis.

4 Laboratory experimental results

4.1 The characteristics of the unidirectional freezing

Figure 6 is the experimental data of soil temperature variation with time at different depths of the soil samples under different experimental conditions. In the unidirectional freezing process, the temperature of soil samples with different compactness had the same change trend with time. According to the cooling rate, the cooling process at the soil samples top can be divided into rapid cooling and slow cooling periods that were divided by the vertical dotted lines in Fig. 6. The cooling process at the soil samples bottom can be divided into stable and slow cooling periods that were divided by the vertical solid lines in Fig. 6. The cooling periods was divided by the vertical dotted lines in Fig. 6. For the soil samples top, the soil temperature decreased quickly at the rapid cooling period, and its temperature remained basically unchanged after a certain period of freezing time. For the soil samples bottom, the soil temperature basically unchanged at the stable periods, and slowly decreased after a certain period of freezing time. Moreover, temperature drop amplitudes at the soil samples top was relatively larger than that at the soil samples bottom. By comparing the soil temperature of different compactness under the same experimental condition, however, it was found that the temperature of the two soil samples had opposite

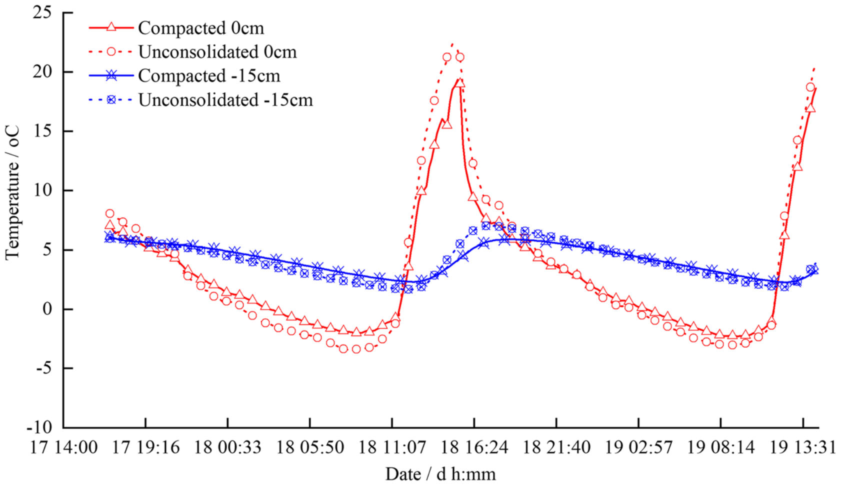


Fig. 4 The observation data of soil temperature with different compactness from January 17, 2017 to January 19, 2017

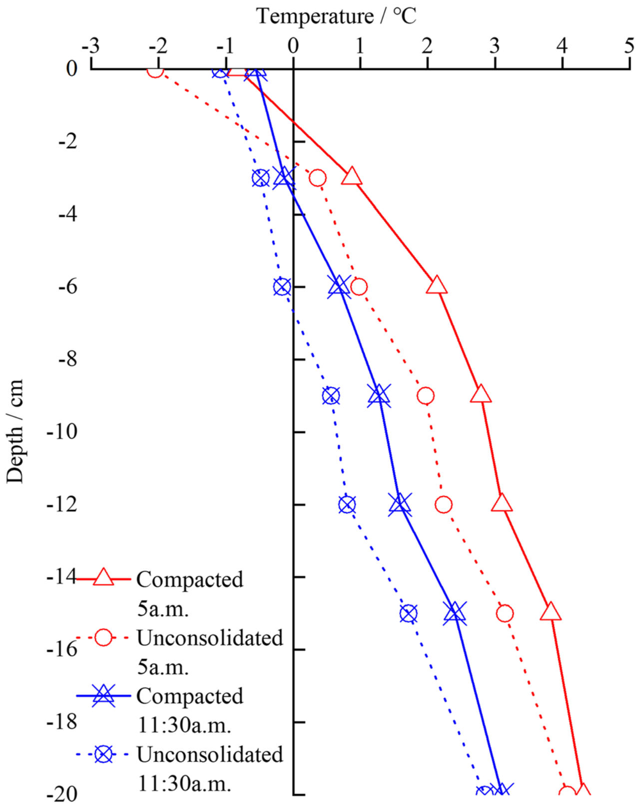


Fig. 5 The temperature variation of unconsolidated and compacted soil with depth at different times on January 18, 2017

relationship at the different depth. The temperature of unconsolidated soil at the depth of -5 cm was lower than that of compacted soil, while the temperature of unconsolidated soil at the depth of -30 cm was higher than that of compacted soil. This showed that the temperature dropping range was different under different compactness conditions with depth. To further analyze this phenomenon, using the data of experiment no.2, the changes of soil temperatures with depth were shown in Fig. 7.

From Fig. 7, at the start of freezing, the temperature of soil samples with different compactness was the same. The soil samples began to cool down from the top with the time of experiment, but the cooling rate was different between unconsolidated soil and compacted soil at the same depth. As a result, the temperature difference between unconsolidated and compacted soil at different depths was different. From the top to the bottom of the soil sample, the temperature difference between compacted soil and unconsolidated soil changed from positive value to negative value. Thus, there existed an intersection point in the temperature curves between compacted soil and unconsolidated soil along the freezing direction at the same time. The intersection point was called temperature intersection point (TIP), which moved downward with the freezing time. Soil samples were divided into upper part and lower part with the TIP. The temperature difference between the two soil samples below the TIP was larger, and reaching the largest at the depth of -15 cm. In addition, the frost depth relationship between compacted soil and unconsolidated soil can be judged by the temperature at the TIP: when the temperature is greater than 0 °C, the frost depth of unconsolidated soil samples is deeper; on the

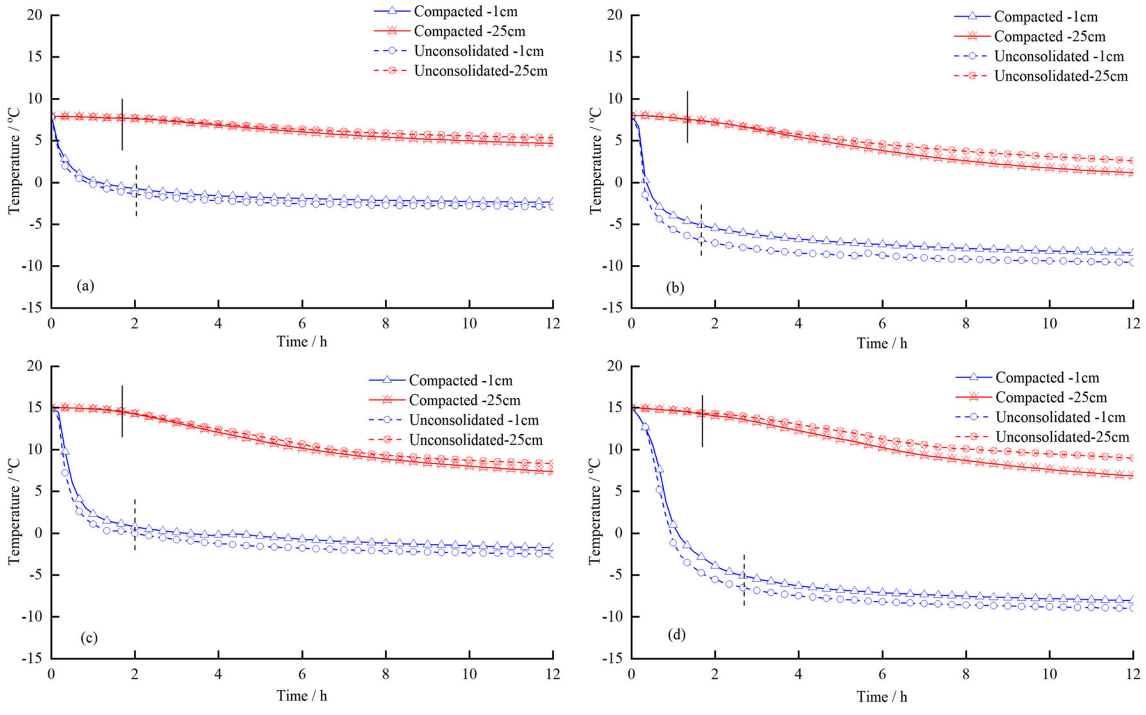


Fig. 6 Soil temperature variation at different depth with time under different testing conditions

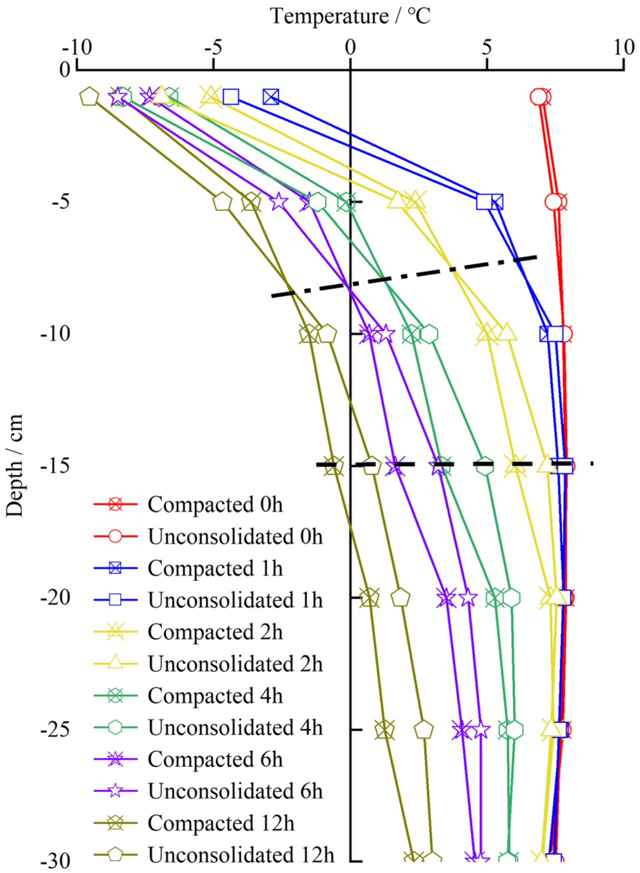


Fig. 7 Soil temperature variation at different testing time with depth

contrary, the frost depth of compacted soil samples is deeper. The presence of TIP indicated that the heat transfer rate in the two compactness is different with depth. Moreover, the temperature difference of the soil sample below the TIP increased faster with time than that above the TIP, which may be related to the influence range of the cooling plate temperature.

4.2 Influence of physical properties on the heat transfer characteristics

To further analyze the heat transfer characteristics of compacted soil and unconsolidated soil, the thermal conductivity and volume heat capacity of the soil were tested by a QuickLine TM-30 Thermal Properties Analyzer (Anter Corporation, U.S.). We tested the thermal conductivity and volume heat capacity of the compacted soil and unconsolidated soil with 10 % water content under the conditions of soil temperature at -15 °C, -10 °C, -5 °C, -1 °C, -0.5 °C, 0 °C, 0.5 °C, 1 °C, 5 °C, 10 °C, 15 °C, respectively. And six parallel samples were taken under each test condition. The test results were shown in Fig. 8. The percentage error and uncertainty were evaluated, as shown in Table 2. From Fig. 8, under the same soil temperature, the thermal conductivity of compacted soil is approximately 2.6 times of that of unconsolidated soil, and the volume heat capacity and phase change latent heat of compacted soil is approximately 1.7 times of that of unconsolidated soil. The thermal conductivity and volume heat capacity varied largely at 0 °C. However, thermal conductivity and volume heat capacity changed slightly in negative temperature and positive temperature, respectively. In this paper, the average value in the two stages of negative temperature and positive temperature was adopted to analyze the heat transfer characteristics of the soil samples in frozen and unfrozen states. And the thermal diffusivity of the soil was calculated by the average value of volume heat capacity and thermal conductivity. The formula [16] is as follows:

$$\alpha = \frac{\lambda}{C_\rho} \tag{1}$$

where α is Thermal diffusivity (m^2·s^{-1}); λ is the thermal conductivity (W·m^{-1}·K^{-1}); C_ρ is volume heat capacity (kJ·m^{-3}·K^{-1}). The average thermal conductivity, average volume heat capacity and the thermal diffusivity of the soils with the two kinds of compactness were calculated respectively, as shown in Table 3.

From Table 3, with the increase of compactness, the thermal conductivity, volume heat capacity and other physical parameters of soil changed, which changed the characteristics of temperature field in different compactness soil. Firstly, with the increase of compactness, the volume heat capacity increased. At the same time, the water content per unit volume increased, so the latent heat increased. These made the compacted soil need to release more heat to decrease the same temperature compared to unconsolidated soil. Secondly, the

Table 2 Experimental measurement result percentage error and uncertainty of volume heat capacity and thermal conductivity

	Percentage error [a] / %	Percentage uncertainty [b] / %	
		Frozen	Unfrozen
Volume heat capacity of compacted soil	1.74	0.41	0.29
Volume heat capacity of unconsolidated soil	2.74	0.58	0.61
Thermal conductivity of compacted soil	3.49	0.88	0.69
Thermal conductivity of unconsolidated soil	4.71	1.13	1.04

[a] The percentage error was the maximum value under different experimental conditions

[b] The percentage uncertainty was indirect uncertainty of the average in positive and negative temperature

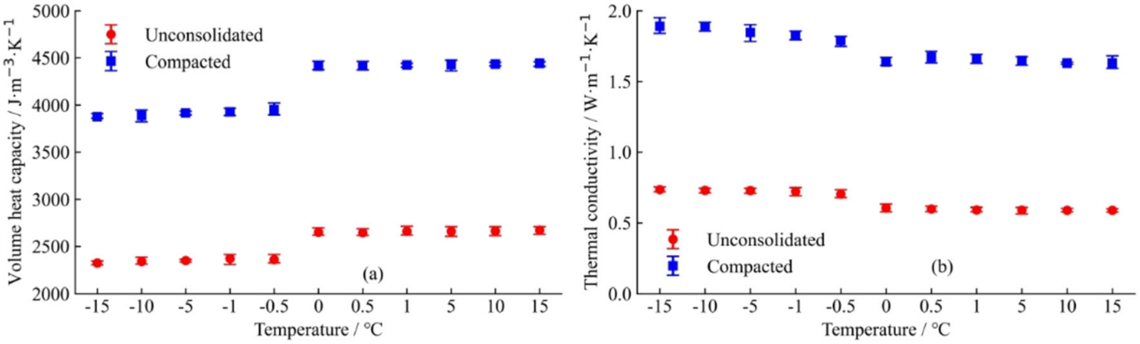


Fig. 8 Volume heat capacity (**a**) and thermal conductivity (**b**) of the soil sample at different temperatures. The upper and lower limits of the error bar represent the maximum and minimum values, respectively

thermal conductivity and thermal diffusivity of compacted soil were larger than those of unconsolidated soil in both freezing and thawing states. With the increase of thermal conductivity, more thermal energy was transferred from the lower part of soil sample to the upper part. And larger thermal diffusivity made the heat in the compacted soil sample transfer faster. Therefore, the cooling range along the depth of compacted soil was more uniform than that of unconsolidated soil. As shown in Fig. 7, the temperature different between top and bottom of compacted soil was smaller than that of unconsolidated soil at the same experiment time. In addition, the emissivity of the same material increases with its surface roughness [18]. The surface roughness of unconsolidated soil is relatively high than that of compacted soil, thus the unconsolidated soil infrared radiation emittance and absorption rate are relatively higher. The unconsolidated soil absorbed more heat at noon when the solar radiation was stronger and dissipated more radiation energy at night. Therefore, the temperature of unconsolidated soil increased greatly at noon and dropped more greatly when the ambient temperature decreased compare to compacted soil.

4.3 The process of heat release at the bottom of soil samples

The heat flux at the bottom of soil samples were calculated with the temperatures at depth of -25 cm and − 30 cm of soil samples in test no.2. From Fig. 7, the bottom of soil samples was not frozen, which means that there was no phase change in the layer and heat transfer is dominated by heat conduction. Hence, the heat flux can be calculated by the Fourier's heat conduction law:

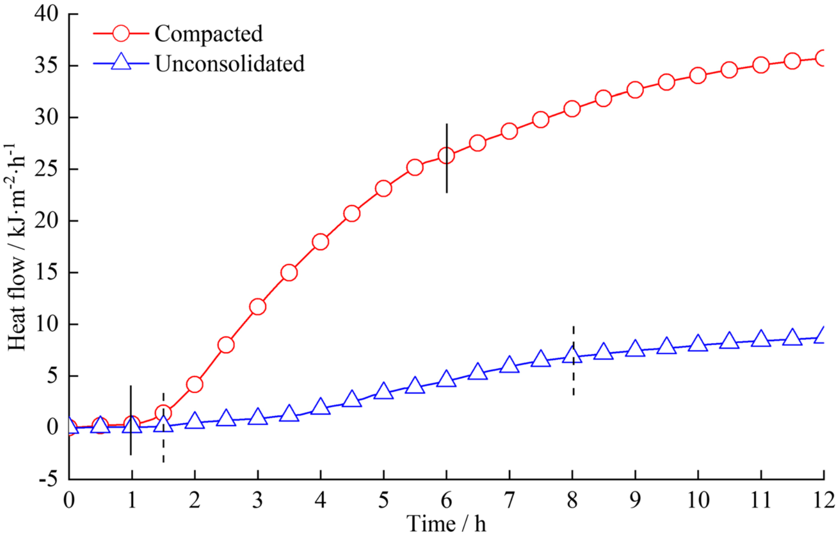
$$q \approx \lambda_u \frac{t_{-30} - t_{-20}}{\Delta z} \tag{2}$$

where λ_u is the thermal conductivity of unfrozen soil in Table 3 (W·m^{-1}·K^{-1}); t is temperature (°C); z is the thickness of the bottom soil (m). Figure 9 shows the change of heat flux with the soil layer of soil samples between − 30 cm and − 20cm, and the positive value represents the upward direction of heat flux. In Fig. 9, the period between the vertical short solid lines represents the stage of rapid increase in heat flow of compacted soil, and the period between the vertical short dotted lines represents the stage of rapid increase in heat flow of unconsolidated soil. At the beginning of the experiment, the heat flow was unchanged, because the influence range of the cooling plate had not yet reached the bottom. With the experimental time, the heat flow increased rapidly, and the heat flow of compacted soil increased faster and more greatly. After a rapid increase period, the increase rate of heat flow reduced, which because the temperature gradient decreased with the heat exchange in the soil samples. Comparing the time of rapid increase of heat flow between compacted soil and unconsolidated soil, the heat flow of compacted soil began to increase was earlier than that of unconsolidated soil, and the period of rapid increase stage of compacted soil was shorter than that of unconsolidated soil. This indicated that the heat effect of cooling plate transferred faster in compacted soil. Due to the large temperature difference and thermal conductivity, the heat flow at the compacted soil bottom was

Table 3 Physical properties of soil under two compaction conditions

	Volume heat capacity / kJ·m^{-3}·K^{-1}		Thermal conductivity / W·m^{-1}·K^{-1}		Thermal diffusivity / 10^{-3}·m^2·h^{-1}	
	Frozen	Unfrozen	Frozen	Unfrozen	Frozen	Unfrozen
Compacted	3912.03	4430.49	1.86	1.64	1.71	1.33
Unconsolidated	2348.34	2660.92	0.72	0.59	1.10	0.80

Fig. 9 The change of heat flux with the soil layer of soil samples between − 30 cm and − 20cm



larger. At the end of the test, the heat flow of compacted soil was about 4 times that of unconsolidated soil. From the heat flow perspective, the thermal energy released from the compacted soil bottom was more.

4.4 The differences of heat release in lower and upper part

To further analyze the heat dissipation of soil samples under the two kinds of compactness conditions, the total heat dissipation and percentage of latent heat at both upper part and lower part were estimated, respectively. The specific calculation includes the heat release by the temperature reduction of soil skeleton, unfrozen water and ice, and the latent heat of ice-to-water phase change. The calculation results were shown in Table 4. The total heat dissipation of compacted soil was 1.9 times than that of unconsolidated soil. And the proportion of composition of the heat dissipation was different between the upper part and lower part. The heat dissipation ratio of compacted soil to unconsolidated soil was 1.54 in the upper part and was 2.18 in the lower part. This indicated that the heat dissipation in the lower part of the compacted soil was relatively larger. Due to unidirectional heat conduction, the heat released from the lower part passed through the upper part, which made the upper soil sample absorb the heat and heating up. In addition, the heat released by soil samples can be divided into heat released by cooling and latent heat released by ice-to-water phase change. The heat used for cooling in the upper part of the compacted soil was 1.4 times that of the unconsolidated soil. However, the volume heat capacity of the compacted soil was 1.7 times that of the unconsolidated soil. Therefore, the temperature drop range of compacted soil in the upper part was smaller. On the other hand, the heat used for cooling in the lower part of the compacted soil was 1.8 times that of the unconsolidated soil. Therefore, the temperature drop range of compacted soil in the lower part was larger.

5 Discussion

Due to the different heat transfer characteristics of gravelly soil in compacted and unconsolidated state, there are intersection point in the temperature curves between along the freezing direction at the same time (Fig. 7). From the four groups of testing data, the location of TIP was calculated, as shown in Table 5. The location of TIP changed with the cooling plate temperature and the soil initial temperature. The lower the cooling plate temperature and the lower the soil initial temperature are, the higher the TIP position is.

According to the observation data of field test on LHS (Fig. 5), the minimum soil surface temperature was − 3.4 °C, and the average value of the negative soil surface temperature was approximately − 2.0 °C. The duration of negative

Table 4 Heat release from soil samples at different locations

Position	Total heat dissipation / kJ		Heat released by cooling / kJ	
	Compacted	Unconsolidated	Compacted	Unconsolidated
Upper part	615.71	400.43	252.45	182.20
Lower part	967.31	443.49	523.82	287.83

Table 5 Variable temperature point location under different test conditions

Number	CPT / °C	ITS / °C	Location of TIP / cm
1	-5	8	-8.6
2	-10	8	-7.9
3	-5	15	-9.5
4	-10	15	-8.9

temperature is approximately 9 h. And the maximum average temperature of soil along the depth is approximately 9 °C in the observation depth. By the analysis above, in the field test, the temperature curves of compacted soil and unconsolidated soil with depth should exist the TIP. Considering the short freezing time and higher soil surface temperature in the field, the TIP will appear in the deeper position. According to the decreasing trend of the temperature difference between the compacted soil and unconsolidated soil, the TIP will appear at a depth of more than 20 cm. Since the soil temperature on site is positive at a depth of 8 cm and below, the temperature of the TIP will be higher than 0 °C. Therefore, temperature of unconsolidated soil on the dam was lower, and its frost depth was deeper than that of compacted soil.

Under the same temperature conditions, the thermal energy of the same volume of compacted soil is larger than that of unconsolidated soil. However, the heat loss of compacted soil is larger than that of unconsolidated soil under the same freezing conditions. Therefore, from the perspective of heat budget, ambient conditions and storage time of anti-seepage soil should be considered to choose compacted soil or unconsolidated soil overnight. When the period of the negative temperature and storage is short, compacted soil should be chosen, otherwise unconsolidated soil should be chosen.

In this paper, we have studied the heat transfer characteristics of gravelly soil with different compactness during unidirectional freezing process, and the characteristics during the thawing process remains to be studied. Also, the characteristics of water migration of gravelly soil with different compactness during freeze-thaw process need to be studied. In addition, due to the heterogeneity of gravel soil and the random distribution of gravel, the measured thermal physical parameters are more discrete. To reduce the discrete, the thermal physical parameters testing method should be improved and larger soil samples should be used for the testing in further study.

6 Conclusions

Based on the unidirectional freezing experiment and field test, the heat transfer and temperature distribution characteristics of gravelly soils with different compactness were analyzed, some conclusions are draw as follows:

1) The frost depth of gravelly soil in unconsolidated state was larger than that in compacted state at the early period of soil freezing. With the freezing time increase, however, the frost depth of compacted soil is deeper than that of unconsolidated soil.
2) The thermophysical parameters difference between unconsolidated and compact soil is the main reason for the change of frost depth. Based on the thermophysical parameters test, under the same soil temperature, the thermal conductivity of compacted soil was approximately 2.6 times of that of unconsolidated soil, and the volume heat capacity and phase change latent heat of compacted soil was approximately 1.7 times of that of unconsolidated soil.
3) The heat transfers rate and heat release by cooling is different. The heat used for cooling in the upper part of the compacted soil was 1.4 times that of the unconsolidated soil. And the heat used for cooling in the lower part of the compacted soil was 1.8 times that of the unconsolidated soil. These caused the difference of the temperature distribution between compacted soil and unconsolidated soil.
4) An intersection point (TIP) existed in the temperature curves between compacted soil and unconsolidated soil along the freezing direction at the same time due to the different cooling rates. The experiment results showed that the lower the cooling plate temperature and the lower the soil initial temperature are, the higher the TIP position is.
5) By comparison of laboratory experiment conditions and field test condition, the TIP will appear at a depth of more than 20 cm in the field test, and the temperature of the TIP is higher than 0 °C. Therefore, the frost depth of unconsolidated soil is deeper than that of compacted soil on the testing site.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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