Experimental investigation on frost heave property of gravel mixed soil

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Abstract. Gravel mixed soil, a certain amount of gravel mixed into the clay, is often used as core material of earth-rockfill dams to improve the stress-deformation behavior of the core wall. In this paper, a series of unidirectional freezing tests were conducted to study effects of coarse grains content on the freezing process and reveal frost characteristics of gravel mixed soil. Experimental results show that the variation of coarse grains content can cause changes in the pore structure, hydraulic and thermal property of mixed soil, and then affect the temperature distribution, water intake and frost heave. It is also found that temperature gradient is the dominant factor affecting freezing front location in comparison with coarse grains content, whereas coarse grains content is the dominant factor affecting water intake in freezing process of gravel mixed soil.

Keywords. Core material; Gravel mixed soils; Coarse grains content; Frost heave

1. Introduction

Earth-rockfill dams have accounted for a large proportion of high dams in western China in recent years. Mixture of earth and rock materials is widely distributed in nature and gravel mixed soil is often used as the core material of these dams to improve the stress-deformation behavior of the core wall. As the core wall bears extremely complicated changes during the processes of construction and impounding, especially when the dams undergo sub-zero temperature and frost heaving, it is of great importance in investigating cryogenic engineering characteristics of core material.

Mechanical experiments and seepage-consolidation analyses of unfrozen mixed soil have been conducted in previous studies [1-4]. When dams undergo sub-zero temperature, cryogenic mechanical property of the core material becomes one critical issue. Thus many mechanical experiments of frozen core material have been carried out [5-7]. However, few literatures can be found referring to frost characteristics of the core material and its freezing process.
Frost heave mechanism in soils has been widely investigated in the past decades. Generally speaking, frost heave is not caused by the expansion of water freezing in situ, but by the migration of water instead. Theory on water migration varies with soil type. Capillary and capillary-film theories in fine-grained soils have been put forward and widely discussed by many researchers, and have been used in most frost heave models [8-12]. For coarse-grained soils, these theories are not suitable. More and more field tests and laboratory experiments in recent years have revealed that vapor transfer can be the primary mechanism of moisture migration and frost heave in coarse-grained soils [13-15]. Though many frost heave theories in both fine- and coarse-grained soils, they were established on homogeneous soil. A few experimental and theoretical investigations have been carried on mixed soils but most of them focused on coarse grains dominated mixture such as subgrade fillings [16-18]. Studies on frost characteristics of fine grains dominated mixture like the core material have not been conducted.

In this paper, mixture of silty clay and coarse grains was used to simulate core material and a series of unidirectional freezing experiments were conducted to reveal its frost characteristics. Effects of coarse grains content on soil initial water content, temperature profile, frost heave amount, freezing front location and water intake were analyzed in detail based on the experimental results.

2. Experimental description

2.1. Material and specimen preparation
Gravel mixed soil used in the experiments comprised of silty clay sieved by 2 mm and quartz with 2-4 mm size. The silty clay was collected from Yongdeng town of Lanzhou city, northwest of China, with plastic limit of 14.2%, liquid limit of 28% and natural moisture content of 1.6%. Mixed soil was compacted into the cylinder specimen with diameter of 100 mm and height of 100 mm, according to a certain mass ratio between silty clay and quartz. Each specimen had the same dry density of 1.7 g/cm³. Then specimen was fully saturated by vacuum pump.

![Figure 1. Specimen preparation and test apparatus.](image)

In this process, a cylindrical organic glass tube with two plates on both ends was specifically designed for restricting specimen’s deformation, which is shown in Figure 1(a).

2.2. Test apparatus
Unidirectional freezing experiments were conducted in the freezing and thawing test chamber at State Key Laboratory of Frozen Soil Engineering of China. Temperature can be controlled by temperature control system including two temperature plates on specimen’s both ends and one test chamber. Water supply can be provided by a Mariotte flask connected with the bottom plate via a plastic tube and calculated by the differences among water levels. The data of temperature and displacement can be
collected by thermistors (one installed on top plate and ten inserted along the specimen’s height with 1 cm interval) and displacement sensor (one placed on top plate to measure vertical frost heave). These details can be seen in Figure 1(b) and (c). More descriptions of test apparatus can be found in the literature [14].

2.3. Experimental design
Specimen’s initial temperature was applied by the temperature control system aforementioned. Once temperatures in the specimen at different heights achieved the uniform value, which usually took several hours, the temperature at the top plate dropped sub-zero while the temperature at bottom kept unchanged and freezing began. During freezing, the lateral of test tube kept wrapped and thus the specimen was thermally insulated in lateral. Two cold-end temperatures and four mass ratios were set to investigate the frost characteristics of gravel mixed soil and the importance of coarse grains content in freezing process. The freezing process lasted 90 hours and experimental conditions are all given in Table 1.

| Specimen No. | Mass ratio (Silty clay versus quartz) | Top plate temperature (°C) | Bottom plate temperature (°C) | Initial temperature (°C) | Initial water content (%) |
|--------------|--------------------------------------|-----------------------------|-----------------------------|-------------------------|--------------------------|
| I            | 100:0                                | -4.5                        | +3                          | +3                      | 21.8                     |
| II           | 100:20                               | -4.5                        | +3                          | +3                      | 20.2                     |
| III          | 100:40                               | -4.5                        | +3                          | +3                      | 18.3                     |
| IV           | 100:60                               | -4.5                        | +3                          | +3                      | 17.8                     |
| V            | 100:20                               | -3                          | +3                          | +3                      | 20.6                     |

3. Experimental results and analyses
It should be noted that the majority of composition in gravel mixed soil was silty clay, thus capillary-film theory in fine-grained soils used here for further analysis.

3.1. Effects of coarse grains content in freezing process
The variation of coarse grains content can cause changes in soil structure directly. Initial water content of specimens I-IV (fully saturated) are listed in Table 1. It can be seen that the initial water content decreases with coarse grains content increasing. During the sample’s preparation, quartz is incompressible and has larger size in comparison with silty clay, leading to smaller voids in specimen with higher coarse grains content. Correspondingly, the less water maintains when the specimen is fully saturated.
The variation of coarse grains content also influences temperature distribution during freezing. Temperature profiles of specimens I-IV at different heights are shown in Figure 2. For each specimen, closer to the cold end, temperature drops more rapidly. All curves can be divided into two stages: cooling stage (CS) and steady stage (SS). It can be observed that the duration of cooling stage becomes slightly shorter in specimen with higher coarse grains content. That is due to the discrepancy of thermal property between quartz and silty clay. Quartz has higher thermal conductivity, which means the specimen whose coarse grains content is higher can transfer heat faster and the temperature in specimen reaches steady more quickly. At the same height, the specimen with higher coarse grains content maintains higher temperature (temperature distributions at the height of 5.5 cm were colored for the observation). With the same cold end temperature applied, this discrepancy is caused by latent heat release in specimen. At the cooling stage of freezing, temperature descends so quickly that there is little water migrating into soil and the latent heat mainly comes from phase change in free water. The specimen with higher coarse grains content has more free water content due to lower capillary suction, thus finally causing larger amount of latent heat release and exhibiting higher temperature in the same height.

Figure 2. Temperature distributions at different heights for (a) Specimen I; (b) Specimen II; (c) Specimen III; (d) Specimen IV.
Effect of coarse grains content on frost heaving is analyzed based on freezing curves, which are shown in Figure 3. As coarse grains content increases, frost heave amount decreases and freezing front lies shallower. Frost heave amount is determined by water migration amount. The more water migrates, the larger frost heave amount generates. The specimen with a higher content of coarse grains exhibits weaker capillary action leading to less migration of water and, therefore, smaller frost heave. At the same time, the specimen with higher coarse grains content is of lower hydraulic conductivity because most voids in specimen are occupied by coarse grains. Water flow channels provided by these voids and water film are restricted, thus affecting the frost heave development eventually. When the temperature variation tends to be stable, there are continuous water migrating from unfrozen zone to frozen zone. The separating force generated by water-ice phase change at the freezing front would compress the unfrozen zone, causing the freezing front moving downwards. Thus a shallower location of freezing front can be seen in specimen with a higher content of coarse grains.

3.2. Frost characteristics of gravel mixed soil

Results among specimens with different coarse grains contents and cold temperatures can show some frost characteristics of gravel mixed soil.

Specimens II and IV differ from the content of coarse grains and specimens II and V differ from cold temperatures. Freezing curves of these specimens are depicted in Figure 4. Both coarse grains content and cold temperature can influence the frost heave amount. Specimen with higher coarse grains content and higher cold temperature generates smaller frost heave amount. The colder the temperature at cold end is, the larger the temperature gradient in specimen forms, leading to duration of cooling stage becoming shorter and freezing front invading much deeper. Obvious discrepancy in freezing front curves can be observed between Specimen II and Specimen V, which reveals that temperature gradient is the dominant factor affecting the freezing front location rather than coarse grains content.
Figure 5. Water intake during freezing for (a) Specimen II; (b) Specimen IV; (c) Specimen V.

As aforementioned, freezing process can be divided into cooling stage and steady stage, and frost heave amount is determined by water migration into specimen. Figure 5 shows water intake during freezing process. It can be seen that the water intake amount during cooling stage only makes up a small proportion in total water supply. The water intake amount of Specimen V is smaller than Specimen II and that is because Specimen V has a shallower freezing front leading to smaller temperature gradient in unfrozen zone, therefore, driving less water migrating. The water intake amount of Specimen IV is least among three specimens. The reason is that Specimen IV with highest coarse grains content has the poorest capacity driving water migrating into soil due to weakest capillary action. And it can be referred that coarse grains content is the dominant factor affecting water intake amount in comparison to temperature gradient.

4. Conclusions

A series of unidirectional freezing experiments were conducted to study effects of coarse grains content on freezing process and reveal frost characteristics of gravel mixed soil. The following conclusions are reached based on experimental results and analyses:

- The variation of coarse grains content can cause changes in pore structure, hydraulic and thermal property of mixed soil, and then affect the freezing process. The specimen with a higher content of coarse grains has lower initial water content. During freezing, it maintains higher temperature
at the same height and duration of cooling stage becomes slightly shorter. Overall, as coarse grains content increases, frost heave amount of mixed soil decreases and freezing front lies shallower.

- Temperature gradient is the dominant factor affecting freezing front location in comparison with coarse grains content. Under larger gradient, duration of cooling stage of gravel mixed soil becomes shorter and freezing front invades much deeper.

- Water intake amount during cooling stage only makes up a small proportion in total water supply. Coarse grains content is the dominant factor affecting water intake amount in comparison with temperature gradient during freezing process of gravel mixed soil.

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