Research Article

Volume Changes and Mechanical Properties of Expansive Mudstone below Canals under Wet-Dry/Wet-Dry-Freeze-Thaw Cycles

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The complex environment in northern China is the main reason for degradation of expansive mudstone below the canals, which resulted in instability and damage of canal slopes. In this study, a serial of laboratory tests was conducted to explore the volume changes and mechanical behaviors of expansive mudstone below the canals in Xinjiang. The experimental program includes wet-dry (WD) and wet-dry-freeze-thaw (WDFT) tests, volume measurement, and unconfined compression tests. The test results show that during the WD cycles, the volume changes of expansive mudstones with a higher dry range would be more significant. The freeze-thaw process in the WDFT cycles resulted in a decrease of volume change ranges when the expansive mudstones had a relatively smaller dry range and a slight increase of volume change ranges when the expansive mudstones had a relatively larger dry range. In the meantime, the stress-strain relationships of expansive mudstones with different dry ranges all presented strain softening under the cycles of WD or WDFT. The first cycle resulted in a significant decrease of failure strength. After seven WD/WDFT cycles, the failure strength of expansive mudstones with different dry ranges decreased by 37.2%~59.1%. In addition, the freeze-thaw process in the WDFT cycles promoted the softening of the stress-strain relationships and aggravated the failure strength attenuation of expansive mudstones. Through this study, we expect to provide a preliminary basis for the construction and maintenance of expansive mudstone canals in Xinjiang.

1. Introduction

Long-distance water transfer projects are a major strategy to realize the optimal allocation of water resources, and water transfer canals are the main methods used in water transfer projects. China has approximately 4.5 million km of various water transfer canals, but the utilization coefficient of canal water is relatively low [1]. Canals in northern China are particularly susceptible to damage by the harsh natural environment, resulting in hidden dangers to the stable operation of the canals [2, 3], as shown in Figure 1.

Wet-dry cycles and freeze-thaw cycles are two typical boundaries simplified from natural environment of on-site canals. On this basis, a large number of experimental studies have been conducted on volume changes and mechanical

degradation of foundation soils below the canals under wet-dry and freeze-thaw cycles [4–8]. Lu et al. [9, 10] investigated the freeze-thaw performance of the expansive soil taken from South-to-North Water Transfer Project by UCS and SEM tests. It is found that the internal porosity of expansive soil increased and became more uniform after several freeze-thaw cycles, which is more significant among the soils with a higher moisture content. Wang et al. [11, 12] studied the mechanical characteristics of saline soil under different moisture contents, salt contents, and freeze-thaw cycles, which provide a basic reference for canal construction in Jilin. Li et al. [13–15] investigated the frost damage mechanism of foundation soil in cold regions, which is helpful to theoretical and numerical studies. Recently, some innovative instruments, such as NMR, CT, and TDR, have been used in

FIGURE 1: Typical damages of canals in northern China [2, 3].

frozen soil studies [16–18], which greatly perfect the quantitative analysis of unfrozen water content and microstructure development [19–22]. Additionally, Zhu et al. [23] investigated the relationships between surface cracks and mechanical properties of expansive soil and then analyzed the damage characteristics of canal slopes under wet-dry cycles by centrifugal model tests [24, 25].

The above studies play an important role in the mechanism investigation of foundation soil below the canals under cyclic actions of wet-dry or freeze-thaw [26–28]. However, studies related to a typical canal in Xinjiang showed that the expansive mudstone below the canals experienced a wet-dry-freeze-thaw process throughout the year [29–31], as shown in Figure 2. The volume changes and mechanical properties of expansive mudstone below the canals in Xinjiang are very scarce in the literature. Consequently, current studies cannot provide a well reference for these canals.

Accordingly, the objective of this study is to investigate the volume changes and mechanical properties of expansive mudstone below the canals in Xinjiang. Specially, a series of wet-dry (WD)/wet-dry-freeze-thaw (WDFT) tests and unconfined compressive strength tests were performed, and then, performances of deformation and strength upon the dry ranges and cycle numbers of WD/WDFT were analyzed. Through this study, we expect to provide a preliminary basis for the construction and maintenance of expansive mudstone canals in Xinjiang.

2. Materials

The samples tested in this study were prepared with a natural expansive mudstone material, which was taken from the field of a typical canal in Xinjiang [29, 30], as shown in Figure 3. Some fundamental properties of the mudstone were measured following procedures described in the specifications [32–34], as given in Table 1. In the meantime, the grain size distribution was analyzed using sieving analysis [35] and the hydrometer method in the laboratory [36], as shown in Figure 4. It is found that the percent passing #200 sieve is as high as approximately 69%.

3. Experimental Program

3.1. Sample Preparation. Before preparation, the original soil material was air-dried for about two weeks. Then, it was grinded and sieved through a 2.0 mm sieve. The sieved soil

was stored in buckets. According to the test scheme, the soil was added with water in measured quantities and mixed completely until initial moisture content reached 18.4%, which is the optimum moisture content. The mixed soil was sealed in plastic bags for approximately 24 hours for a homogeneous soil moisture distribution. Next, the soil was compacted using a stratified sample preparation device and prepared samples with 39.1 mm in diameter and 80 mm in height, as shown in Figure 5. Six samples for each condition were prepared. Among them, three samples were for the measurement of volume changes and three samples were for unconfined compression tests, which significantly reduced the disturbance of the samples for mechanical tests [9, 10, 37]. All the samples were compacted to the same dry density of 1.60 mg/m^3 , which is on the basis of the field test results [23–25]. After compaction, the samples were extracted from the mold for the WD and WDFT tests.

3.2. WD and WDFT Tests. After sample preparation, all the samples were divided into two series: half of the samples experienced the repeated WD processes while the other part underwent the WDFT cycles. Both of the WD cycles and the WDFT cycles were 0, 1, 3, and 7 cycles, which was decided because the soil properties tended towards stability after 3 WD cycles [38, 39]. The wet, dry, freeze, and thaw processes were as follows:

(1) Wet process

The wet process corresponds to the operation period of the typical canal. During this period, the foundation soil below the canals was saturated due to the water infiltration. Consequently, the wet process of the samples was simulated by the vacuum saturation method.

(2) Dry process

The drying process corresponds to the nonoperation period of the typical canal. During this period, there is no water inside the canal, resulting in that the foundation soil below the canals was air-dried continuously. Thus, the samples were air-dried in the test room with a temperature of $20 \pm 1^\circ\text{C}$ and a relative humidity of $55 \pm 5\%$. The saturation variations of samples were monitored by weight, and the dry process would be terminated until it came to the target saturation (S_p).

FIGURE 2: Temperature observed by a weather station along the canal in Xinjiang [29–31].

FIGURE 3: Location of the sampling area in Xinjiang, China.

(3) Freeze process

The freeze process corresponds to the time when the field temperature was lower than 0°C. Therefore, the freeze process of the samples was simulated by the low-temperature environment test chamber in Nanjing Hydraulic Research Institute, as shown in Figure 6. The samples were wrapped with plastic film first, which was effective to avoid moisture loss in the freeze process and thaw process in the previous studies [9, 10]. Then, the wrapped samples were exposed to three-dimensional closed environment with a consistent temperature of -20°C for 12 hours.

(4) Thaw process

The thaw process corresponds to the time when the field temperature was higher than 0°C. Thus, the thaw process of the samples was simulated by thawing at the room temperature of 20°C for 12 hours.

It is noted that the -20°C in the freeze process and 20°C in the thaw process were derived from the average temperature in the field during winter and the average temperature in the field during summer, respectively. The time of the freeze process and thaw process was decided because 12 hours proved that it

TABLE 1: Fundamental properties of mudstone material.

Properties	Value
Specific gravity	2.67
Potential expansion	71.0
CHCS classification	CH
Consistency limit	
Liquid limit	52.6%
Plastic limit	18.4%
Plasticity index	34.2
Compaction study	
Optimum moisture content	18.4%
Maximum dry density	1.70 mg/m ³
Mineral components	
Montmorillonite	61.5%
Quartz	31.9%
Feldspar	6.1%
Calcite and albite	0.5%

FIGURE 4: Grain size distribution.

is an adequate period after which the volume changes would become constant [9, 10]. Additionally, the target saturation (S_t) of samples was a variable in the dry process, resulting in that the sample saturation changed during the cyclic WD processes and WDFT processes, which are given in Table 2.

3.3. Measurement of Volume Changes and Unconfined Compression Strength Tests. In order to obtain the volume changes of samples exposed to WD cycles and WDFT cycles, the diameter (D) and height (H) of samples were measured after each period of wet, dry, freeze, and thaw, since the sample deformation was basically homogeneous along the sample height. The measurement of sample dimensions using an electronic vernier caliper has a precision of 0.01 mm, as shown in Figure 7. Additionally, the measured dimensions of samples were derived from the three values along cross-section and two values along the longitudinal section. Consequently, the average values of sample volume were calculated on the basis of the above measured values of diameter and height during the cyclic WD and WDFT processes.

The strength of samples was measured by an YSH-2 unconfined compression device in Nanjing Hydraulic Research Institute (Figure 8), which can obtain a great quantity of data to describe the mechanical behaviors of samples. The maximum load capacity and maximum strain rate of this device are 5 kN and 1 mm/min, respectively. The samples were deformed under a compression load until the axial strain of samples reached 16%. During this process, the strain rate was kept at 0.8 mm/min, which is equal to 1%/min. Consequently, the stress-strain response, resilient modulus, and failure strength of samples subjected to WD cycles and WDFT cycles can be obtained. Figure 9 shows the typical failure characteristics of samples with different dry ranges.

4. Test Results

4.1. Volume Changes. In order to characterize the volume changes of samples better, a dimensionless parameter, named volumetric strain (ε_v), was proposed to indicate relative volume change of samples during the cyclic WD and WDFT processes. The volumetric strain can be calculated as

$$\varepsilon_v = \frac{\Delta V}{V_0}, \quad (1)$$

$$= \frac{(V_N - V_0)}{V_0},$$

where V_N is the sample volume after N cycles of WD or WDFT, and V_0 is the initial volume of samples after preparation. Consequently, the positive values of volumetric strain indicated volume expansion, while the negative ones represented volume contraction. Figure 10 shows the curves of volume changes variation with WD and WDFT cycles. Among the horizontal axis, 0 represents the initial state of samples, and 1, 2, 3, 4, 5, 6, and 7 refer to the completion of corresponding cycles of WD or WDFT.

As shown in Figure 10(a), the samples presented the typical characteristics of volume expansion in the wet process and volume contraction in the dry process, and the sample volumes changed alternately with the increasing WD cycles. Specifically, the volume variation trend of samples with dry range I during each WD cycle is relatively constant, especially after four WD cycles. Additionally, the volumetric strain of samples with dry range II during each WD cycle showed the similar variation characteristics to the ones with dry range I. However, the volumetric strain of samples with dry range II decreased gradually, resulting in a downward trend of sample volumes after each WD cycle. Different from the above samples with dry range I and dry range II, the volumetric strain of samples with dry range III during the wet process and dry process decreased significantly with the increasing WD cycles. Compared with the volumetric strain in the first WD cycle, the volumetric strain of samples with dry range III in the seventh cycle decreased by 65.8%. In the meantime, it is also found from Figure 10(a) that the samples with dry range I showed the largest volumetric strain in a single WD cycle, indicating that the volume changes of

FIGURE 5: Stratified sample preparation device.

FIGURE 6: Low-temperature environment test chamber.

FIGURE 7: Schematic diagram of sample dimension measurement.

TABLE 2: Saturation variations of sample during the WD/WDFT processes.

Processes	Wet S_t	Dry S_t	Freeze S_t	Thaw S_t
Sample		30% (dry range I)	30%	30%
Saturation	100%	70% (dry range II) 90% (dry range III)	70% 90%	70% 90%
Remarks	In the dry process, different S_t means different dry ranges. Among them, dry range I represents that S_t is 30%; dry range II represents that S_t is 70%; dry range III represents that S_t is 90%.			

samples with a larger dry range would be more significant, which is consistent with that reported in the literature [40].

Figure 10(b) shows the volume changes of samples exposed to WDFT cycles. It is found that the volumetric strain of samples with different dry ranges all present the variation characteristics of fluctuation during the cyclic WDFT processes. Among them, the volumetric strain of samples with dry range I after each WDFT cycle is relatively stable and basically remains constant after three WDFT cycles, while the volumetric strain of samples with dry range

FIGURE 8: Device for unconfined compression.

FIGURE 9: Typical failure characteristics of samples subjected to WDFT cycles.

FIGURE 10: Curves of volume changes with cycles under different dry ranges. (a) Samples exposed to WD cycles. (b) Samples exposed to WDFT cycles.

II and dry range III after each WDFT cycle presented a downward trend with the increasing WDFT cycles. In addition, the samples with dry range I showed a significant wet-dry effect on the volume changes, which is reflected in a higher volume changes in the wet-dry process during the WDFT cycles than that in the freeze-thaw process during the WDFT cycles. Conversely, the samples with dry range III showed the freeze-thaw effect on the volume changes, which means that the volumes of samples with dry range III changed significantly in the freeze-thaw process during the WDFT cycles than that in the wet-dry process during the WDFT cycles. As previously mentioned, the volume changes

of samples with dry range III presented a downward trend, indicating that the freeze-thaw effect weakened gradually with the increasing WDFT cycles, which is consistent with the volume change characteristics of expansive soils under freeze-thaw cycles reported in the literature [41]. The samples with dry range II, which is between dry range I and dry range III, presented a different volume change variation under WDFT cycles. At the beginning of WDFT cycles, the samples with dry range II had larger variation ranges of volumetric strain in the wet-dry process during the WDFT cycles, indicating a more significant wet-dry effect on the volume changes in the cyclic WDFT processes. With the

FIGURE 11: Comparison curves of volume changes under WD and WDFT cycles. (a) Dry range I. (b) Dry range II. (c) Dry range III.

increase of WDFT cycles, the volumes of samples with dry range II changed more significantly in the freeze-thaw process during the WDFT cycles, indicating that the freeze-thaw effect gradually dominated the volume changes of samples during the cyclic WDFT processes. This phenomenon indicated that there may be a coupled effect between the wet-dry process and freeze-thaw process when the samples with a medium dry range were exposed to WDFT cycles, which was never reported in the previous studies.

It was noted that the volumetric strain of samples with dry range I and dry range II showed a downward trend in the freeze process and a rising trend in the thaw process. The main reason for this phenomenon is as follows: the saturation of samples with dry range I and dry range II is relatively low after the dry process. During the freezing process, a large number of air in the pores and the water in the sample turned into ice, leading to an increase of sample volumes. In the meantime, the expansive mudstone particles lost water and shrink, and the shrinkage would be large due to the

sufficient shrinkage space, which offset the frost heave. Consequently, the macrovolume of samples decreased in the freeze process. In the thaw process, the ice in the pores thawed into water. Concurrently, the expansive mudstone particles expanded with water, and the expansion was greater than the shrinkage. Therefore, the macrovolume of samples would increase in the thaw process [9, 10].

For the purpose of quantitatively analyzing the difference of volume changes with WD cycles and WDFT cycles, the relationships between the difference of the maximum volumetric strain and the minimum volumetric strain during each cycle and the number of cycles are plotted, as shown in Figure 11. It is found that with the increasing cycles, the volume changes of samples with dry range I under WD cycles were more significant than that under WDFT cycles, while the samples with dry range II and dry range III showed the opposite phenomenon. It indicated that the freeze-thaw process in the WDFT cycles resulted in a decrease of volume change ranges when the samples had a

FIGURE 12: Curves of stress-strain relationships. (a) Dry range I. (b) Dry range II. (c) Dry range III.

FIGURE 13: Curves of failure strength variation with cycles. (a) Dry range I. (b) Dry range II. (c) Dry range III.

relatively smaller dry range and a slight increase of volume change ranges when the samples had a relatively larger dry range. This is also consistent with the volume change characteristics of shallow foundation soils below the canal with a large dry range in Xinjiang [29, 30].

4.2. Mechanical Behaviors

4.2.1. Stress-Strain Behaviors. Unconfined strength tests were conducted on samples exposed to WD cycles and WDFT cycles. To compare the characteristics of stress-strain behaviors, the stress-strain relationships of samples subjected to 0, 1, 3, and 7 cycles of WD and WDFT are plotted as shown in Figure 12. It is found that under WD and WDFT cycles, the stress-strain relationships of samples with different dry ranges all presented strain softening. According to the previous studies [42], the stress-strain relationships of soils had six types. Consequently, the stress-strain relationships of samples in this study could be divided into strong softening type, general softening type, and weak softening type, respectively, which depended on the dry ranges of samples. Specifically, the stress-strain relationships of samples with dry range II and dry range III were general softening type and weak softening type, respectively, while the stress-strain relationships of samples with dry range I was strong softening type, indicating that the samples maintained high strength within a small strain. Additionally, compared with the stress-strain relationships under WD cycles, the stress-strain relationships of samples subjected to WDFT cycles entered the softening stage earlier, which indicated that the freeze-thaw process in the WDFT cycles promoted the softening of the stress-strain relationships.

4.2.2. Failure Strength. As previously described, all the stress-strain relationships of samples showed strain softening. Consequently, the failure strength of samples was estimated according to the peak values shown in Figure 12. Figure 13 shows the curves of failure strength variation with cycles. It is found that under the WD and WDFT cycles, the failure strength of samples with the same dry range has a similar variation trend, that is, decreased at the beginning of cycles and then tended to be stable. Among them, the first cycle resulted in a significant decrease of soil strength, which was consistent with that reported in the literature. After seven WD cycles and WDFT cycles, the failure strength of samples with dry range I decreased by 37.2% and 46.9%, while the failure strength of samples with dry range II and dry range III decreased by 53.2%, 55.7% and 48.2%, 59.1%, respectively. In addition, compared with the failure strength of samples subjected to WD cycles, the failure strength attenuation of samples subjected to WDFT cycles was more significant. It indicated that the freeze-thaw process in the WDFT cycles aggravated the failure strength attenuation of samples.

According to the previous studies [23–25], it is found that the average dry range of shallow foundation soil below the canals in the field was close to dry range II. For the purpose of accurately predicting the variation trend of the

failure strength of foundation soils below the canal with WDFT cycles, the failure strength of samples (dry range II) with WDFT cycles shown in Figure 13(b) was fitted with a COD (R^2) of 0.99. The formula was as follows:

$$f_{\text{WDFT}} = 27.1 + 30.9 \cdot e^{-1.44 \cdot N_{\text{WDFT}}}. \quad (2)$$

5. Conclusions

On the basis of the above studies, the following conclusions are drawn:

- (1) During the WD cycles, the volume changes of expansive mudstone with a higher dry range would be more significant. The freeze-thaw process in the WDFT cycles resulted in a decrease of volume change ranges when the expansive mudstone had a relatively smaller dry range and a slightly increase of volume change ranges when the expansive mudstone had a relatively larger dry range.
- (2) Under the cycles of WD or WDFT, the stress-strain relationships of samples with different dry ranges all presented strain softening. In the meantime, the freeze-thaw process in the WDFT cycles promoted the softening of the stress-strain relationships.
- (3) During the WD/WDFT cycles, the first cycle resulted in a significant decrease of failure strength. After seven WD/WDFT cycles, the failure strength of expansive mudstones with different dry ranges decreased by 37.2%~59.1%. Additionally, the freeze-thaw process in the WDFT cycles aggravated the failure strength attenuation of expansive mudstones.
- (4) Further study is encouraged on the investigation of phase change materials used to treat expansive mudstone under freeze-thaw/wet-dry-freeze-thaw cycles

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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