Research on water migration and deformation characteristics of coastal composite strata under artificial ground freezing affected by seepage

J Zhou\textsuperscript{1,2}, J J Ren\textsuperscript{1}

\textsuperscript{1} Department of Geotechnical Engineering, Tongji University, Shanghai, 200092, China.  
\textsuperscript{2} Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, 200092, China.

Abstract. When the artificial ground freezing (AGF) method is used to construct underground structures in the coastal composite strata, the differences between characteristics of soft clay and silty sand under seepage often increase the risk of freezing construction and the difficulty of deformation control. In order to find out water migration and deformation characteristics of coastal composite strata under seepage condition in freezing process, a series of unidirectional freezing tests of silty sand and soft clay in Shanghai and AGF model experiments on composite strata of soft clay and underlying silty sand were carried out under seepage condition. The results of unidirectional freezing tests of single soil type showed that the layered deformation curve of silty sand and soft clay can be divided into two types that steep mode of silty sand and gradual mode of soft clay. It also indicates that the water migration is fully developed within soft clay during freezing; but most of water inside silty sand froze quickly, thus water migration was not developed as that much in soft clay. In AGF model experiments, the seepage contributed to the development of water migration inside composite strata. However, the deformation characteristics of composite strata under seepage condition were evidently different from that of unidirectional freezing tests. The frost heave force development of the lower silt sand in the area directly affected by seepage was gradual mode, while that of the upper soft clay in the area indirectly affected by seepage was steep mode. The above results demonstrated that influence on freezing process of seepage is greater than that of soil properties in freezing process. Through research results, some optimization strategies can be made for the relevant measures to deal with the adverse effects of seepage and frost heave in the practice of the freezing method for coastal composite strata.

1. Introduction
Artificial ground freezing (AGF) plays a significant role in the construction of underground projects in coastal cities like Shanghai, Shenzhen and Tianjin, etc. Because of it is an environment-friendly method of good water resistance and strong adaptability, especially under adverse hydro-geological conditions. It is found that the strata at the depth of common underground projects are mostly composed of a combination of upper soft clay and lower silt sand by collecting and analysing the stratigraphic data of representative coastal cities. The differences between properties of silty sand and soft clay and the seepage would influence water migration and deformation characteristics of composite strata under artificial ground freezing. And the influence should be taken into consideration in design and practice of AGF in composite strata.
The effects of soil properties and seepage on migration and deformation characteristics during freezing were paid a lot of attention by researchers. Xu[1] compared the unfrozen water content of different kinds of soils under same freezing temperature. Nixon[2] stated that the specific surface area of soil was the important parameter related with deformation characteristics under freezing. Wang[3] studied the effects of soil properties on ice formation through freezing tests of five soils at the same freezing temperature. Guthrie[4] obtained the rule of frost heave deformation and water migration silty sand during freezing process through variable water head frost heave test. Cheng[5] studied the influence of moisture content and degree of compaction on the frost heave of silty sand, and proposed a mathematical model to predict frost heave. Darrow[6] proved that the content of clay was the most sensitive factor affecting frost heave deformation through several experiments. Wu[7] analysed the deformation characteristics of unsaturated clay under different saturation and density during freezing process, and focused on the influence of dry density and water content on the development of freezing front. Yan[8] discussed the impact of some critical factors on deformation characteristics of silty sand, including initial water content, dry density, load and times of freeze-thaw. Tang[9] conducted several experiments on the frost heave characteristics of Shanghai fourth layer clay, and explored the pore structure characteristics of frozen-thawed clay from fractal perspectives[10]. Chen[11] studied the effects of temperature, water content and density on the compressive strength of frozen clay in Shanghai. Yang[12] established the mathematical model of development of frozen wall affected by large groundwater flow velocity. Song[13] carried out model test and numerical situation to study the temperature field of seepage fissure rock mass.

However, most of the current researches focus on the water migration and deformation characteristics of silty sand and clay respectively and the comparative studies about two kinds of soils are few. Additionally, there are few researchers on the influence of seepage for water migration and deformation characteristics of composite strata under freezing. Therefore, to figure out the differences of water migration and deformation characteristics between soft clay and silty sand in Shanghai, unidirectional freezing tests were conducted respectively. A series of AGF model experiments were also carried out to explore the water migration and deformation characteristics in composite strata under seepage condition.

2. Materials and Method

2.1. Materials

The soil used in this research was saturated grey silty sand in the second layer and mucky soft clay in the fourth layer from Qingpu district in Shanghai. The grain gradation curves of two soil samples are shown in figure 1 and their basic physical properties are shown in table 1.

![Figure 1](image.png)

**Figure 1.** Grain-size distribution of silty sand and soft clay.

**Table 1.** Basic physical properties and mechanical strength indexes of silty sand, soft clay and remoulded soft clay.
2.2. Unidirectional freezing test

The undisturbed silty sand samples used in tests were obtained by thin-wall sampler. For soft clay, considering its inhomogeneity and memory structure, the soil samples used in test were remoulded according to “Standard for geotechnical testing method (GB/T 50123-2019)”. And the remoulded soft clay sample consolidated under practical self-weight condition. The basic physical properties and mechanical strength indexes of undisturbed soft clay and remoulded soft clay are close to each other shown by table 1, which also means the remoulding was carried out well.

The schematic diagram of test system is presented as figure 2(a). It involves the self-made unidirectional freezing instrument, freezing circulation system, and transducer measurement system. The cryostat tank cooled glycol liquid for the freezing circulation, where it pumps out from a valve through silicone hoses into the freezing pipe system inside baseboard of self-made unidirectional freezing instrument and after one-circle heat exchange the fluid returns back. The 90% glycol was employed as circulation fluid to prevent frost during testing. In order to find out the effect of freezing temperature on water migration and deformation characteristics of silty sand and soft clay, the freezing temperature was respectively controlled around -10℃, -15℃, -20℃ shown as table 2.

| Soil type          | Freezing temperature (℃) |
|--------------------|--------------------------|
| A1, A2, A3 (silty sand) | -10                      |
| B1, B2, B3 (soft clay)     | -10                      |

Temperature sensors were deployed evenly in central axis of soil sample, arranging every 2cm from the height of 1cm to 23cm from the bottom shown as figure 2(b). In this experiment, settlement signs combined with displacement transducers were applied to measure the deformation of different layers inside soil sample during freezing.

Figure 2. Schematic diagram of test system and transducer arrangement of unidirectional freezing test.
2.3. AGF model experiment

The prototype of AGF model experiment is the most common connecting channel of a subway tunnel with a buried depth of 12m and a frozen curtain of 6m in the Shanghai area. To diminish the boundary effect, the largest model container with an insider dimension of 400mm×400mm×1000mm was utilized in this experiment and the geometrical ratio between the model and the prototype is 1:30. Considering the large size of model container, both of silty sand and soft clay used in this test were remoulded according to “Standard for geotechnical testing method (GB/T 50123-2019)” and consolidated under practical self-weight condition by loading certain weight until the settlement was stable. The composite strata were consisted of upper soft clay with thickness of 46cm and lower silty sand with thickness of 34cm. To form a seepage path, porous plexiglass partitions were installed at the position of sand layer of the model container. The schematic diagram of whole test system is presented as figure 3.

Temperature sensors were deployed in arrays at depths within the model soil. Each temperature sensor array had five temperature sensors paralleling distributed at the same depth with equal spacing of 70mm shown as figure 3. The temperature sensors were arranged every 6cm from the depth of 34cm to 52cm from the top surface of soil. There are four earth pressure transducers were set evenly along the vertical direction on the central axis of box accompanied with temperature sensors. Besides, there five displacement transducers were evenly deployed on the surface of soil shown as figure 3. More specific model experimental design and procedures has been addressed in details in our previously published paper [14]. To find out the water migration and deformation characteristics of composite strata under seepage, two experiments with seepage velocity of 0.5 m/d and the absence of seepage were carried out under freezing temperature of -20°C (table 3).

| Seepage velocity (m/d) | Freezing temperature (°C) |
|------------------------|---------------------------|
| A1                     | 0.5                       | -20                      |
| A2                     | 0                         | -20                      |

Table 3. Test plan of AGF model experiment.

Figure 3. Schematic diagram of experimental system and transducer arrangement of AGF model experiment.
3. Results and discussion

3.1. Water migration of unidirectional freezing tests

The freezing cycle equipment was not shut down until the temperature inside soil sample was stable and the data acquisition was stopped when the temperature inside soil sample was stable again. When the freeze-thaw finished, soil samples near the position of temperature sensors were taken to measure the water content. To avoid the effect of initial water content, the data were normalized as change rate of water content that is equal to the ratio of change of water content after freeze-thaw to initial water content. The change rate of water content of different position inside soil sample, in some extent, illustrated the water migration during freezing. The water migration of silty sand and soft clay are shown as figure 4.

The test system is a closed system, there is no external water supply. It is evidently that the direction of water migration inside the soil sample is related to the temperature gradient, and the water moves from the high temperature area to the low temperature area with the movement of the freezing front. The water migration characteristics of silty sand and soft clay are quite different under same freezing temperature indicated by figure 4. In silty sand, the water content of upper part increased and the that of top layer decreased. However, in soft clay, the water content of upper-middle part deceased and there were steep increase and decrease of water content in middle part of soil. The degree of water migration inside soft clay was larger than that inside silty sand. The position where the abrupt change of water content happened inside silty sand was further from freezing pipes than that inside soft clay. It is considered that soft clay has larger surface area and surface energy for more fine particles. Therefore, the freezing rate was slowly inside soft clay, which means the water migration fully developed inside soft clay. However, in silty sand, the water in the area close to the freezing pipes froze quickly, and the water migration developed in small degree in the distance from the freezing pipes. Besides, there is a weak relationship between the freezing temperature and the development degree of water migration. The development degree increased slightly with the decrease of freezing temperature.

![Figure 4](image)

Figure 4. Change rate of water content of silty sand and soft clay of unidirectional freezing tests.

3.2. Layered deformation characteristics of unidirectional freezing tests

Since the difference of deformation characteristics on two kinds of soils were presented more significantly at -20°C, the layered deformation-time curves are shown as figure 5. To explore the relationship between layered deformation characteristics and water migration, the figures of change rate of water content are exhibited with layered deformation-time curves.
From figure 5, it is evident that the frost heaving and frost shrink correspond to the increase and decrease of water content inside soil sample. In silty sand, the deformation increased quickly with time, which also states that the water in the area close to the freezing pipes froze so quickly that the water migration developed slightly. But the growth rate of deformation inside soft clay was slower than that.
of silty sand. The obvious alternating heaving and shrink presented by figure 5(b) indicate that the movement of the freezing front and the existence of water migration. Overall, the layered deformation curve of silty sand and soft clay can be divided into two types that steep curve of silty sand and gradual curve of soft clay.

3.3. Water migration of freezing model experiments

Considering the existence of seepage inside lower silty soil, only the soft clay samples with different depths in the model box is taken to measure the water content after the freeze-thaw shown as figure 6.

![Figure 6](image)

**Figure 6.** Change rate of water content of silty sand and soft clay of AGF model experiments.

It can be seen from the figure 6 that whether it is in composite strata or a single stratum, the direction of water migration within the soil sample is related to the temperature gradient, and the water moves from the high temperature area to the low temperature area. Because of the existence of silty sand of composite strata (external water supply), the change rate of water content in composite strata without seepage were quite larger than that of single strata. When seepage occurred in silty sand, the changing trend of water content inside soft clay are same with that of condition under no seepage. But the increase of water content near the freezing pipe is smaller than that of condition under no seepage, and the decrease of water content in upper area is larger than of condition under no seepage. The comparison indicated that the seepage took away part of energy and water content, resulting in the increase of temperature gradient and more water migrated from the upper part to the colder area. Therefore, the development of water migration inside composite strata is fuller that inside single stratum. And the existence of seepage would contribute to the development of water migration.

3.4. Layered deformation characteristics of AGF model experiment

In AGF model experiments, the layered deformation was characterized by the change of frost heaving force at different depth. The measured data obtained by earth pressure transducers respectively subtracted the overburden pressure at different depth to acquire the frost heaving force. The layered frost heaving force-time curve of composite strata with seepage velocity of 0.5 m/d are shown as figure 7.

Transducer P1, P2 were arranged in soft clay and P3, P4 were in silty sand as shown by figure 7. The layered deformation characteristics of composite strata are totally from that of single stratum in figure 5. Compared with deformation characteristics of silty, the deformation increased more quickly with time in soft clay (P1, P2). The deformation inside silty sand gradually increased. The change of type of deformation development is due to the existence of seepage. Affected by seepage, ice formation was significantly disturbed that frost heave developed slowly. However, for soft clay, there
was no direct contact with seepage. Thus, the seepage plays more important role in deformation characteristic of composite strata than soil properties.

![Figure 7. Layered deformation of AGF model experiment at -20°C.](image)

4. Conclusions
In order to find out water migration and deformation characteristics of coastal composite strata under seepage condition in freezing process, a series of the unidirectional freezing tests of silty sand and the soft clay in Shanghai and AGF model experiments on composite strata of upper soft clay and lower silty sand were carried out under seepage condition. Several important conclusions are drawn as follows:

1. The results of unidirectional freezing tests indicated the development of water migration inside soft clay is fuller than that inside silty sand as single stratum. And layered deformation curve of silty sand and soft clay can be divided into two types that steep mode of silty sand and gradual mode of soft clay.

2. In AGF model experiments, the seepage contributed to the development of water migration inside composite strata.

3. The deformation characteristics of composite strata under seepage condition were evidently different from that of unidirectional freezing tests. The frost heave force development of the lower silt sand in the area directly affected by seepage was gradual mode, while that of the upper soft clay in the area indirectly affected by seepage was steep mode. Thus, the seepage plays more important role in deformation characteristic of composite strata than soil properties.

Overall, it is suggested that more attention should be paid on quick increase of deformation in soft clay at first stage of freezing and the scheme of freezing pipes directly affected by seepage should be refined, when applying AGF to construction at composite strata of upper soft clay and lower silty sand.

5. References
[1] Xu X, Wang J and Zhang L 2001 Permafrost Physics (Beijing: Science Press)
[2] Nixon J F D 1991 Discrete ice lens theory for frost heave in soils Can. Geotech. J. 28 843-859
[3] Wang J, Xu X, Zhang L and Deng Y 1995 Experimental study on the influence of soil types on ice formation and cold-formed fabric of frozen soil J. Glaciol. Geocryol. 16-22
[4] Guthrie W S and Hermansson A 2003 Trans. M. (Washington) pp 13-19
[5] Cheng P, Yu D and Xu Y 2011 Frost heaving test and Subgrade Frost Heaving model of silty sand in seasonal frozen area J. China & Foreign Highway. 31 20-22
[6] Darrow M M, Huang S L, Shur Y and Akagawa S 2008 Improvements in frost heave laboratory testing of fine-grained soils J. Cold. Reg. Eng. 22 65-78
[7] Wu L, Xu Q and Huang R 2011 Analysis of freezing-thawing test process of unsaturated clay Rock. Soil. Mech. 32 1025-1028
[8] Yan H, Wang T and Liu J 2013 Experimental study of repeated frost heave and thaw settlement properties of silty sand Rock. Soil. Mech. 34 3159-3165
[9] Tang Y, Hong J, Yang P, Wang J and Hu X 2009 Frost-heaving behaviors of mucky clay by artificial horizontal freezing method Chinese. J. Geotech. Eng. 31 772-776
[10] Tang Y and Yan J 2019 Fractals of pore structure characteristic of muddy clay in shanghai after artificial ground freezing J. Tongji. University. (Natural Sci). 47 627-633
[11] Chen Y, Wang M, Xu S, Chang L and Yin Z 2009 Tensile and compressive strength tests on artificial frozen soft clay in Shanghai Chinese. J. Geotech. Eng. 31 1046-1051
[12] Yang P and Pi A 2001 Study on the effects of large groundwater flow velocity on the formation of frozen wall Chinese. J. Geotech. Eng. 23 167-171
[13] Song L, Wang G, Yang C, Han L, Li H and Yang W 2019 Model test study on freezing temperature field of seepage fissure rock mass J. Mining & Safety Eng. 36 1256-1263
[14] Zhou J, Li Z, Wang P, Tang Y and Zhao W 2021 The effects of clay-sand composite strata seepage on artificial ground freezing and surrounding engineering environment Chinese. J. Geotech. Eng. 43 471-480

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