Frost heave and thawing settlement of frozen soils around concrete piles: a laboratory model test

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ABSTRACT
The frost heave and thawing settlement of soil around piles can affect the pile stability. Using the soil profiles collected from a permafrost soil site in western China, laboratory tests were carried out to investigate the frost heave and thawing settlement of frozen soil around bridge piles. During the thawing process, the ambient temperature was adjusted such that the thawing occurred from top to bottom of the soil surrounding the pile, and measurements were taken as thawing reached different moments. The similar procedure was applied to the following freezing process. The temperature, the unfrozen water content and displacement of soils around 8 piles were measured during the freezing-thawing process, along with the analyses of the accompanying frost heave and thawing settlement of soil around pile. Results showed that when the thawing process was completed, the unfrozen water content of soil located at a distance equal to the pile's diameter measured from its face, was larger than that of the soil located at a distance equal to triple pile diameters. At the end of freezing, the unfrozen water content of the soil located at a distance equal to the pile's diameter (from the pile's face) was smaller than that of the soil located farther (at a distance equal to triple pile diameters from its face). It was also shown that, for the soil region between 1 and 2 times of pile diameters from its face, the amount of thawing settlement and frost heave increases, while the magnitude of soil thawing settlement and frost heave decreases from 2 to 3 times of pile diameters (from the pile's face).Analysis showed that the formation of the difference in frost heave and thawing settlement is related to the difference of the performance of heat transfer between the pile and soil during freezing process, therefore, a transverse temperature gradient exists in pile-soil system, leading to unfrozen water moving to the pile-soil interface and freezing.

Le gonflement et le tassement du sol dû au gel-dégel autour des piles peuvent affecter leur stabilité. En utilisant des profils de sols extraits d'un pergélisol d'un site situé en Chine occidentale, des tests en laboratoire ont été conduits afin d'étudier le gonflement et le tassement des sols dû au gel-dégel autour des piles de pont. Pendant le processus de dégel, la température ambiante fut ajustée de telle sorte que le dégel se produise de la partie supérieure à la partie inférieure du sol entourant les piles, et les mesures furent prises à différents instants du dégel. Un protocole similaire fut appliqué pendant le processus de gel qui s'en suivait. La température, la proportion d'eau non-gelée dans le sol et le déplacement des sols autour de 8 piles furent mesurés pendant le processus de gel-dégel. Les résultats ont montré qu'au terme du processus de dégel, la proportion d'eau non-gelée dans le sol situé à une distance égale au diamètre des piles, mesurée depuis leur front, était supérieure à celle du sol situé à une distance égale au triple du diamètre des piles. A la fin du processus de congélation, la proportion d'eau non-gelée dans le sol situé à une distance égale au diamètre des piles (mesurée depuis leur front) était inférieure à celle du sol situé au-delà (à une distance égale au triple du diamètre des piles mesurée depuis leur front). Il a également été montré que pour la région du sol située de 1 à 2 fois le diamètre des piles en partant de leur front, le volume de tassement et de gonflement dû au gel-dégel augmente, alors que le volume de tassement et de gonflement dû au gel-dégel diminue dans la région située de 2 à 3 fois le diamètre des piles (en partant depuis leur front).

1 INTRODUCTION

Since pile foundations are considered having better thermal stability than shallow foundations, piles have been widely used in sensitive permafrost environment along the Qinghai-Tibet Engineering Corridor (QTEC) from Golmud City to Lhasa City of western China. The Golmud-Lhasa section of the Qinghai-Tibet Railway was built upon 675 pile-supported bridges above dry permafrost. The piles are usually made of cast-in-place reinforced concrete. The frost heave and thawing settlement of the frozen soil around concrete piles can seriously affect the serviceability of the piles and then the safety of the railway tracks.

Most of the previous studies of frost heave and thawing settlement characteristics of soils during freeze-thaw (f-t) cycles focused on the following aspects: 1) Frost heave characteristics of different types of soils (Tester and Gaskin 1996; Guthrie et al. 2007; Hendry and Onwude 2016; Sun et al. 2016; She et al. 2018); 2) Frost heave characteristics of frozen soil under different temperatures conditions (Zhou and Zhou 2012; Zhao et al. 2014); 3) Frost heave characteristics of frozen soil under different moisture conditions (Bing and He 2009; Wang et al. 2014; Li et al.

2017; Zhang et al. 2017; Zhang et al. 2018); and 4) The theory of frost heave (Konrad and Morgenstern 1982). In recent years, there are several studies on the thawing settlement of frozen soils. Klinova et al. (2010) evaluated the relationship between thawing settlement and moisture content, dry density, and void ratio. Zheng et al. (2015) studied the changes of soil structures under f-t cycles.

Research was also dedicated to the piles heave and settlement during soil f-t cycles. Weaver et al. (1981) developed procedures for predicting the settlement of piles in ice-poor soils. Lyazgin et al. (2003) developed the techniques to stabilize pile foundations against frost heave. Lyazgin et al. (2004) introduced a system for on-line control of the temperature conditions of soils and pile foundations of transmission towers and substation equipment. Song et al. (2014) proposed some antifreeze measures for several types of frost damage. Churkin et al. (2016) investigated the frost heave of buildings in the frozen soil of Arkhangelsk City of Russia and found that the deformation of buildings supported by piles was caused by the frost heave of the mud. Lu et al. (2017) established a model to predict the frost heave effect of a single pile embedded in frozen soil. You et al. (2017) assessed the permafrost degradation around several pile foundations in the Tanggula Mountain area along the Qinghai-Tibet Railway of China and their results showed that the occurrence of sub-permafrost aquifer which was induced by permafrost degradation is the primary cause of pile settlements. The frost heave and thawing settlement characteristics of frozen soils on temperature, moisture content, external load and history of freezing and thawing have been conducted by previous studies.

Nonetheless, there are few studies on the characteristics of frost heave and thawing settlement of the soil around piles, which is considered as one of the causes of pile damage in permafrost regions. In addition, the existence of piles will cause the temperature field and moisture field of the soil around piles to be different from the cases without pile; therefore the research results of single frozen soil cannot reflect the characteristics of the soil around pile directly. It is thus necessary to study the frost heave and thawing settlement characteristics of the soil around a pile, in combination with the temperature field and moisture field of soil around piles.

In the present research, laboratory freeze-thaw tests of small-scale model pile foundations were carried out. The objective is to investigate the characteristics of frost heave and thawing settlement of soils around reinforced-concrete piles during the f-t processes. The temperature distribution, unfrozen water content and displacement of the soil around piles were monitored during the testing.

2 EXPERIMENTAL DESIGN

2.1 Design of laboratory model tests

As shown in Fig. 1, the model test box of soil-pile system in frozen environment is mainly composed of temperature-controlled system, acquisition system, freeze-thaw system and the the controller of refrigeration units (22HP / COPELADN). The temperature in the test chamber is controlled by a temperature controller. The range of air temperature in the cabinet is -40 °C to +85 °C. There are two test grooves in the test box, with the size of 4.5 m × 1.1 m × 1.8 m.

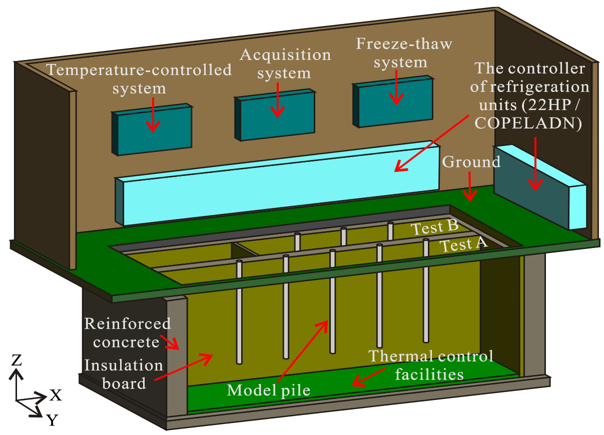


Figure 1. Laboratory test model of soil-pile system in frozen environment

The model piles was scaled from a prototype RC piles used for Chalaping Bridge in Tibet, China. The prototype cast-in-place RC piles is 1.4 m in diameter and 28 m in length. According to the principle of similarity and due to the size constraint of the chamber, the geometrical similarity ratio of this experiment was determined as mL = 1/20. It can then be obtained that the model pile has a diameter d of 7 cm and a pile length of 140 cm. Five piles were installed in Test A and three piles were in Test B (Figure 1).

The physical parameters of the soil layers from the top to the bottom are detailed in Table 1 and the grain size distribution curves of each soil layer is shown in Figure 2. The process of soil-pile model construction is described as follows. Firstly, the soil layer of 10 cm thickness was laid and compacted, and the water was sprayed uniformly to the surface of the soil according to the design moisture content. In order to achieve uniform moisture content of the soil layer, the surface of the soil was covered with plastic sheets for 12 hours before the upper layer was placed. Then, the temperature control device of the model chamber was activated, and the soil with uniform moisture content began to freeze, and followed the above process until the height reached 0.5 m. In the meanwhile, piles were laid at the designated locations. Finally, followed the above process circularly until the filling height reached to 1.8 m.

Table 1. Parameters of tested soil layers

Thickness (cm)	Moisture content (%)	Model soil	Prototype soil
10	30	Fill (ML with Sand)	Fill
20	40	Xi'an loess (ML)	Silty clay
40	20	Silt (ML)	Silt
110	10	Reconsititued Clay (CH)	Weathered mudstone

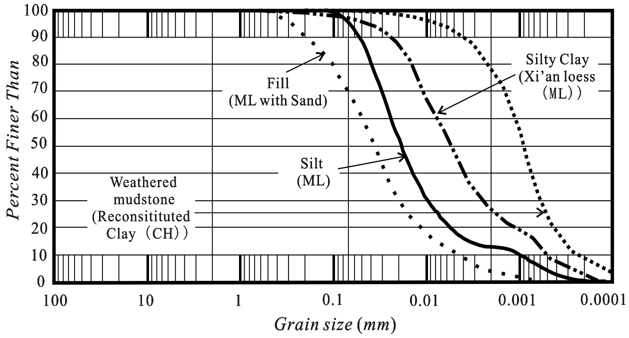


Figure 2. Grain size distribution curves of soil layers

In order to analyze the displacement of soil in different positions around the pile, 24 points of interest (POI) in terms of displacement were set on the soil surface at distances equal to one, double and triple of pile diameter (from pile shaft face). These monitoring points were used to record the displacement of soil around piles. The layout of POI and piles is shown in Figure 3. During the test, a three-dimensional laser scan of the soil in the test grooves was performed using the Leika Nova MS60 total station scanner to collect the displacement data of POI in displacement.

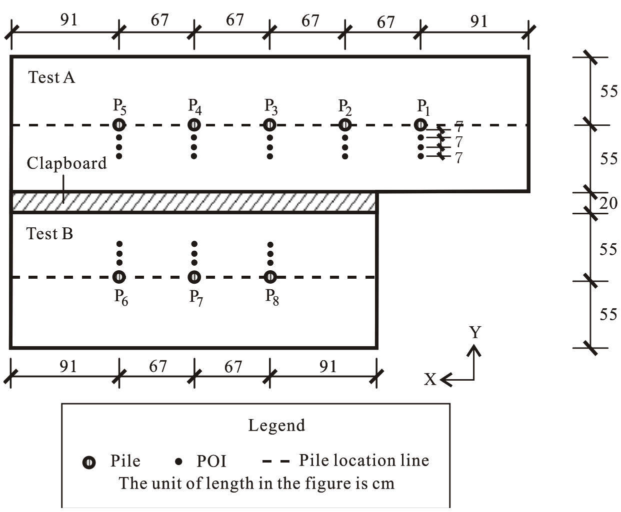


Figure 3. Plan layout of piles and POI of displacement

Temperature sensors and moisture meters were used to monitor the temperature and unfrozen water content of the soil around pile. The layout of temperature and moisture monitoring points shown in Figure 4. A total of 24 moisture meters are installed below the 3 POI around Pile 2 (see Fig. 3 for the location) and a total of 20 temperature sensors are arranged on both sides of Pile 2.

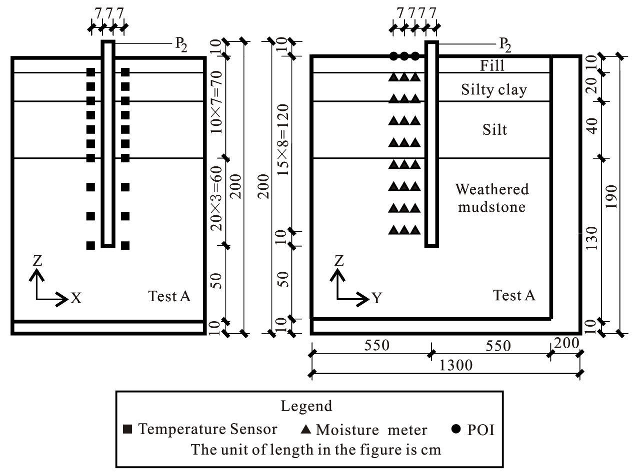


Figure 4. Vertical view of model showing the temperature and moisture monitoring points

2.2 Experiment procedure

Once the soil-pile model construction was completed, the temperature inside the box was controlled by the temperature control device to perform the thawing-freezing processes. The indoor temperature in the thawing period was maintained at 15°C for 15 days, and the indoor temperature in the freezing period was maintained at −12°C for 15 days. Before the start of the test, a three-dimensional laser scan of the soil in the pit was performed using a Leika Nova MS60 Total Station Scanner to obtain the elevation data of the soil in the grooves before the start of the test. At the 5th, 10th, 15th, 20th, 25th, and 30th days of the test, three-dimensional laser scanning was performed on the surface of soil in the test box by using the Leika Nova MS60 total station scanner to obtain the elevation data of the soil in the test box at these 6 moments. The software Geomagic Qualify was used to obtain the displacement cloud charts of the soil at each moment compared the elevation data of these six moments with the elevation data before the start of the test respectively. At the same time, the data of the temperature sensors and moisture meters at the six moments were recorded separately.

3 EXPERIMENTAL RESULTS

The data of unfrozen water content of soil at a distance equal to triple pile diameters from the pile's face at the depth of 60 cm were missing, and the data of unfrozen water content at depth of 75 cm and below were missing.

3.1 Temperature field changes of soil around pile during thawing and freezing processes

The variations of the temperature of soil around Pile 2 at different depths during the f-t processes are shown in Figure 5.

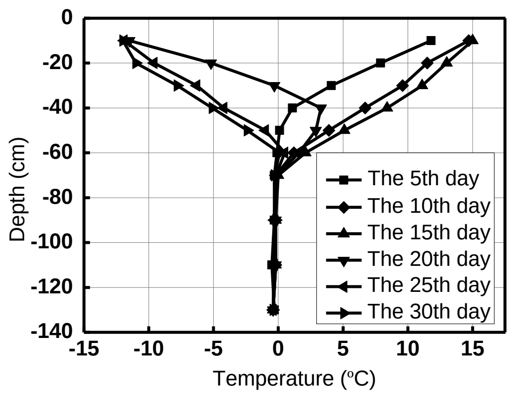
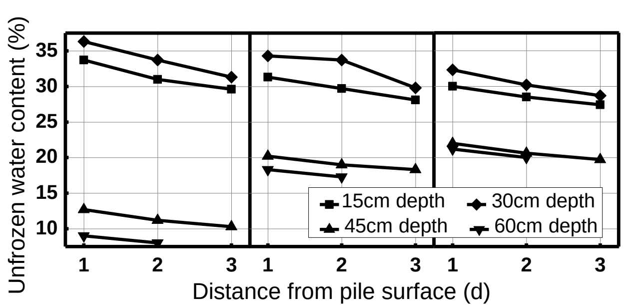


Figure 5. Temperature profiles at 6 instants

During the f-t processes, it is generally seen from Fig. 5 that the temperature at depth 70 cm and above changes while the temperature below remains close to 0 °C. As the thawing starts, at the 5th day of the test, the temperature of the upper layers of soil (> 50 cm) is positive, which indicates that the depth of thawing reaches about 50 cm. At the 10th and 15th days, the temperature of the upper layers of soil (> 60 cm) is positive, which indicates that the depth of thawing reaches about 60 cm. During the subsequent freezing process, at the 20th day of the experiment, the soil temperature becomes negative above 30cm, while the soil temperature below 30cm is still positive, indicating the freezing depth of 30 cm at this time. At the end of 25th day and the 30th day, the temperature of soils above 60 cm goes negative, indicating that the freezing depth reach 50 cm (becomes stable).

3.2 Changes of unfrozen water content of soil around pile during f-t processes

Figure 6 illustrates the changes of unfrozen water content of soils at different depths of Pile 2 during the f-t processes.



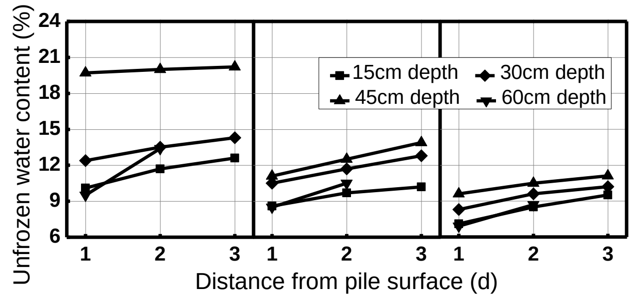


Figure 6. Unfrozen water content of soil at different distance from the pile's surface at the end of the (a) 5th day, (b) 10th day, (c) 15th day, (d) 20th day, (e) 25th day, (f) 30th day. Noted: d = pile diameter.

Figure 6 shows that at the end of 5th day, 10th day, and 15th day, the trend of unfrozen water contents of the soil at the same depth and at different horizontal positions are very close, the unfrozen water content of soil located at a distance equal to the pile's diameter measured from its face, is larger than that of the soil located at a distance equal to triple pile diameters. The difference of unfrozen water content between 1 d and 3 d varies from 3.6% to 2.3%. At the end of 20th day, 25th day, and 30th day, the trend of unfrozen water contents of the soil at the same depth and at different horizontal positions are very similar. As the measuring point is away from the surface of pile, the unfrozen water content at different positions around the pile increases, with the difference changing from 2.4% to 1.5% (between 1 d and 3 d).

The reason of difference of unfrozen water content of the soil around pile at the same depth and at different horizontal positions during f-t processes is that the existence of the pile causes the temperature field of soil to change. When the soil is filled and frozen before the start of the test, because of the performance of heat transfer of the pile larger than that of the unfrozen soil, the temperature of the pile was lower than that of the soil and a horizontal temperature gradient is produced in soil. Under the influence of temperature gradient, unfrozen water will migrate to the pile-soil interface and freeze to form ice film. Sadovskiy (1973) verified the existence of ice film through experiments. Since the water in the horizontal direction is the same when filling, the water content in the soil near the pile is larger than that in the soil far from the pile after the filling is completed. During the thawing process, the tendency of unfrozen water content is due to the migration to the pile-soil interface during the freezing process of the fill and thawing during thawing process of unfrozen water. During the freezing process, the tendency of unfrozen water content is due to the temperature of the soil near the pile is lower and the amount of frozen water is larger, so the content of unfrozen water is smaller.

3.3 Frost Heave and Thawing Settlement of Soil around Pile during f-t processes

Displacement data of POI located near Pile 2 are plotted in Figure 7.

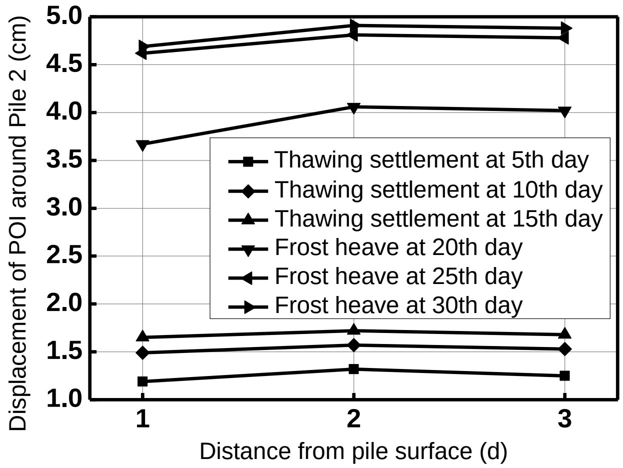


Figure 7. Displacement of POI at different distance from surface of Pile 2 at several instants.

It is generally seen from Figure 7 that during the f-t processes, the amount of thawing settlement and frost heave increase from 1 d to 2 d, and decrease from 2 d to 3 d. During the thawing process, the difference of thawing settlement between 2 d and 1 d at the 5th day, 10th day and 15th day of the test are respectively 0.13 cm, 0.08 cm, and 0.07 cm, and the differences of thawing settlement between 2 d and 3 d at the 5th day, 10th day and 15th day of the test are respectively 0.07 cm, 0.04 cm, and 0.04 cm; During the freezing process, the difference of frost heave between 2 d and 1 d at the 20th day, 25th day and 30th day of the test are respectively 0.39 cm, 0.19 cm, and 0.22 cm, and the differences of frost heave between 2 d and 3 d at the 20th day, 25th day and 30th day of the test are respectively 0.04 cm, 0.03 cm, and 0.03 cm.

The unfrozen water in the soil around pile migrated and froze when the pile is buried, and thus the amount of ice near the pile is larger, result in the greater thawing settlement of the soil near the pile. The thawing settlement of the soil around Pile 2 is 1 d > 2 d > 3 d. The thawing settlement around the pile is the difference between the free-thawing settlement and the constraint of pile on the soil, and the constraint of the pile is 1 d > 2 d > 3 d. According to the tendency of final thawing settlement in Figure 7, the constraint effect of pile at 1 d - 2 d is greater than the free-thawing settlement of soils, and the final thawing settlement is showed as 2 d >1 d; the constraint effect of pile at 2 d - 3 d is smaller than the free-thawing settlement of soils, and the final thawing settlement is showed as 2 d > 3 d.

During the freezing process, unfrozen water migrates and freezes at the interface of the pile and form the ice film. The suction force on the water in the unfrozen area by ice causing the unfrozen water to migrate to the ice film and freeze, resulting in ice crystal gather in the soil around pile. The frost heave of soil is divided into in-situ frost heaving and segregation heave. Since the amount of segregation heave is larger than that of in-situ frost heaving, the amount of segregation heave of the soil near the pile is larger than that of the soil away from the pile, result to the free frost heave of the soil around Pile 2 is 1 d>2 d>3 d. The amount of frost heave around the pile is the difference between the free-frost heave and the constraint of pile on the soil, and the constraint effect of the pile is 1 d > 2 d > 3 d. According to the tendency of final frost heave in Figure 7, the constraint effect of pile at 1 d - 2 d is greater than the free-frost heave of soil, and the final frost heave is showed as 2 d > 1 d; the constraint effect of pile at 2 d-3 d is smaller than the free-frost heave of soils, and the final frost heave is showed as 2 d > 3 d.

4 CONCLUSIONS

In this paper, a laboratory model test was carried out to study the characteristics and formation mechanism of frost heave and thawing settlement of soil around pile.

During freezing and thawing processes, depth of thawing reach 60 cm at the end of the thawing process and depth of frost reach a depth of 50 cm at the end of the freezing process, the soil with a depth of 70 cm or below is not affected by the freezing-thawing processes.

When the thawing process was completed, the unfrozen water content of soil located at a distance equal to the pile's diameter from the pile's face, was larger than that of the soil located at a distance equal to triple pile diameters from the pile's face. When the freezing process was completed, the unfrozen water content of the soil located at a distance equal to the pile's diameter from the pile's face, was smaller than that of the soil located at a distance equal to triple pile diameters from the pile's face.

The frost heave and thawing settlement characteristics of the soil around pile show that, from 1 to 2 times of pile diameters from the pile's face, the amount of soil thawing settlement and frost heave increases, from 2 to 3 times of pile diameters from the pile's face, the amount of soil thawing settlement and frost heave decreased.

The formation mechanism of frost heave and thawing settlement of soil around pile during freezing and thawing processes: There are difference of the thermal conductivity between the pile and soil during freezing process, therefore, a transverse temperature gradient exists in pile-soil system, leading to unfrozen water moving to the pile-soil interface and freezing and result to the free-thawing settlement and free-frost heave of soil near the pile larger than that away from pile. The final thawing settlement and frost heave characteristics is the combination of the restraint of pile and the free-thawing settlement and the free-frost heave.

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REFERENCES

Bing, H and He, P. 2009. Frost heave and dry density changes during cyclic freeze- thaw of a silty clay, *Permafrost and periglacial Processes*, 20(1): 65-70.

Churkin, S.V., Nikitin, A.V., Aksenov, S.E., Zaruchevnih, A.V. and Nevzorov, A.L. 2016. Deformation of building on pile foundation due to frost heave, *Japanese Geotechnical Society Special Publication*, 2(39): 1420-1423.

Guthrie, W.S., Lay, R.D. and Birdsall, A.J. 2007. Effect of reduced cement contents on frost heave of silty soil: laboratory testing and numerical modeling, *Transportation Research Board*.

Hendry, M.T. and Onwude, L.U. and Sego, D. C. 2016. A laboratory investigation of the frost heave susceptibility of fine-grained soil generated from the abrasion of a diorite aggregate, *Cold Regions Science and Technology*, 123: 91-98.

Klinova, G.I., Aksenov, V.I. and Dzhakhangirova, N.I. 2010. Thaw-induced deformation properties of frozen soils, *Soil Mechanics and Foundation Engineering*, 47(3): 102-107.

Konrad, J.M. and Morgenstern, N.R. 1982. Prediction of frost heave in the laboratory during transient freezing, *Canadian Geotechnical Journal*, 19(3): 250-259.

Li, A., Niu, F., Zheng, H., Akagawa, S., Lin, Z. and Luo, J. 2017. Experimental measurement and numerical simulation of frost heave in saturated coarse-grained soil, *Cold Regions Science & Technology*, 137: 68-74.

Lu, J.F., Yin, J. and Shuai, J. 2018. A model for predicting the frost-heave effect of a pile embedded in the frozen soil, *Cold Regions Science and Technology*, 146: 214-222.

Lyazgin, A.L., Bayasan, R.M., Chisnik, S.A., Cheverev, V.G. and Pustovoit, G.P. 2003. Stabilization of pile foundations subjected to frost heave and in thawing permafrost, *Proc. of 8th Intern. Conf. on Permafrost, Zurich, Switzerland*, 2: 707-711.

Lyazgin, A.L., Lyashenko, V.S., Ostroborodov, S.V., Ol'shanskii, V.G., Bayasan, R.M., Shevtsov, K.P. and Pustovoit, G.P. 2004. Experience in the prevention of frost heave of pile foundations of transmission towers under northern conditions, *Power Technology and Engineering*, 38(2): 124-126.

Sadovskiy, A.V. 1973. Adfreeze between ground and foundation materials, *Proceedings of 2th International Permafrost Conference. Yakutsk:[sn]*, 650-653.

She, W., Cao, X., Zhao, G., Cai, D., Jiang, J. and Hu, X. 2018. Experimental and numerical investigation of the effect of soil type and fineness on soil frost heave behavior, *Cold Regions Science and Technology*, 148: 148-158.

Song, J.Q. 2014. Pile Foundation Antifreezing Measures Research in Seasonal Frozen Soil Region, *Applied Mechanics and Materials*, Trans Tech Publications, 578: 767-771.

Sun, D., Wang, W., Wang, Q., Chen, J., Niu, C. and Cao, C. 2016. Characteristics and Prediction of Frost Heave of Saline Soil in Western Jilin Province, *International Journal of Heat and Technology*, 34(4): 709-714.

Tester, R.E. and Gaskin, P.N. 1996. Effect of fines content on frost heave, *Canadian Geotechnical Journal*, 33(4): 678-680.

Wang, T.L., Yue, Z.R., Ma, C. and Wu, Z. 2014. An experimental study on the frost heave properties of coarse grained soils, *Transportation Geotechnics*, 1(3): 137-144.

Weaver, J.S. and Morgenstern N.R. 1981. Pile design in permafrost, *Canadian Geotechnical Journal*, 18(3): 357-370.

You, Y., Wang, J., Wu, Q., Yu, Q., Pan, X., Wang, X. and Guo, L. 2017. Causes of pile foundation failure in permafrost regions: The case study of a dry bridge of the Qinghai-Tibet Railway, *Engineering Geology*, 230: 95-103.

Zhang, M., Zhang, X., Li, S., Lu, J. and Pei, W. 2017. Effect of Temperature Gradients on the Frost Heave of a Saturated Silty Clay with a Water Supply, *Journal of Cold Regions Engineering*, 31(4): 04017011.

Zhang, X., Zhang, M., Pei, W. and Lu, J. 2018. Experimental study of hydro-thermal characteristics and frost heave behavior of a saturated silt within a closed freezing system, *Applied Thermal Engineering*, 129: 1447-1454.

Zhao, H.X., Zhong, J. and Wang, Z.J. 2014. Experimental study on the influence of different cooling rate to frost heave of silty clay, *Advanced Materials Research*, 912: 136-140.

Zheng, Y., Ma, W., Mu, Y. and Bing, H. 2015. Analysis of Soil Structures and the Mechanisms under the Action of Freezing and Thawing Cycles, *Cold Regions Engineering*, 25-33.

Zhou, Y. and Zhou, G. 2012. Intermittent freezing mode to reduce frost heave in freezing soils — experiments and mechanism analysis, *Canadian Geotechnical Journal*, 49(6): 686-693.