Effect of Freezing on Stress–Strain Characteristics of Granular and Cohesive Soils

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Abstract:

To investigate the stress–strain behavior of frozen soils, a program of triaxial compression tests was designed and carried out on samples of unfrozen and frozen cohesive (CL) and granular (SP) soils and pure ice. The experiments involved study of the influence of freezing, temperature reduction, and loading rate on the stress–strain characteristics of the frozen ground. The aim of this study is to assess the possibility of using the Artificial Ground Freezing (AGF) technique in the excavation and tunneling in Line 2 of the Tabriz Subway project. The results show that freezing of the CL soil has no significant effect on the type of soil behavior (strain hardening), whereas freezing of the SP soil changes its strain-hardening behavior to strain softening. The effect of freezing on the increase in shear strength of the saturated SP soil is much greater than that of the saturated CL soil; however, the rate of increase in the shear strength due to freezing and temperature reduction is much greater for the CL soil. Freezing and reduction in temperature cause an increase in the elastic modulus of all the materials tested in the present study. Also, the shear strength and elastic modulus of these materials increase with loading rate.

Keywords: Frozen ground; Stress–strain characteristics; Triaxial compression test; Strain hardening; Strain softening.

Introduction

The improvement of soil behavior by Artificial Ground Freezing (AGF) has been utilized by engineers in many construction projects. The technique involves excursion of a refrigerated coolant through subsurface freezing tubes in order to reduce the soil temperature below freezing point (Andersland and Ladanyi, 2004). The freezing process is conducted using two concentric pipes. A smaller diameter tube within each freezing tube permits the downward circulation of the coolant; the refrigerant fluid arrives into the double sleeve freeze tube and after reaching the lowest point of the inner tube, it returns through the annulus between the inner and outer tubes (Fig. 1) (Harris, 1995; Esmaeili-Falak et al., 2018). The pore water within the soil is then frozen and the soil becomes stronger and watertight. The frozen soil can be used as a sealing and soil support system in underground construction (Chamberlain, 1981; Lackner et al., 2005; Yang et al., 2015; Zhou et al., 2015; Esmaeili-Falak, 2017; Fei and Yang, 2018). Compared with other soil treatment techniques, AGF is an effective and stable method for controlling groundwater and improving soil strength (Braun et al., 1979). It is an efficient and green technique which poses no short-term or long-term threat to the environment (Frivik, 1981). AGF consists of two phases (Stoss and Valk, 1979). The first (active) phase involves cooling the ground until its temperature drops below the freezing point of the groundwater. The second (passive) phase involves maintaining the frozen body by circulating the coolant until the end of construction operations.

The first use of AGF was reported on a mineshaft construction in UK (Li et al., 2006). Studies have shown that, under loading, frozen soils can experience plastic volumetric and shear strains. The concept of elasto-plastic deformation has been used to describe the behavior of frozen ground as well as other geotechnical materials (Youssef, 1988; Puswewala and Rajapakse, 1990; Wijeweera and Joshi, 1992; Nassr et al., 2018; Esmaeili-Falak et al. 2019). AGF has been shown to be effective in loose and homogeneous soils that contain some pore water. AGF is particularly useful where the application of other conventional techniques is deemed unfeasible (Rupprecht, 1979). Changes in geological strata and layer permeability have some effect on freezing, while these factors can significantly influence the success of other soil improvement techniques (Jones and Brown, 1979).

Early investigations of AGF primarily focused on the creep behavior of frozen soils (Sayles, 1968; Sayles and Haines, 1974). However, in the recent years, with the developments in the laboratory equipment and techniques, the experimental investigation of various aspects of behavior of frozen ground has received greater attention. The influence of AGF on physical and mechanical characteristics of the frozen ground has been studied by many researchers (e.g., Andersen, 1991; Soo and Muvdi, 1992; Da Re, 2000; Zhao et al., 2013; Li et al., 2018; Torok et al., 2019). It has been shown that AGF could significantly improve the physical and mechanical properties of soils due to the formation of a rigid ice-soil matrix (Wang et al., 2006).

AGF is known as a cost-effective, environmentally friendly and practical method for soil stabilization for construction in cold regions (Ladanyi, 1972; Jones & Brown, 1979; Parameswaran & Jones, 1981; Spaans & Baker, 1995). In this study, a program of triaxial compression tests has been designed and carried out to investigate the influence of freezing, temperature reduction and loading rate (strain rate) on the mechanical behavior of frozen soils. These are the most important parameters that affect the ground behavior in underground construction projects involving AGF. For the experiments, the soil samples were taken from the site of the second Line of the Tabriz Subway project. The present study also aims to verify the possibility of using the AGF technique in tunneling and underground construction of the subway station in the above case study.

Materials and Methods

Unfrozen water can still be found in soil even at temperatures far below the freezing point of pure water (Ziegler et al., 2009). The amount of unfrozen water for various soils at different temperatures is shown in Fig. 2. Experimental results are required for calibration and validation of numerical models for AGF. In this study, an extensive program of experimental research was designed and conducted to study the mechanical behavior of frozen soils subject to different conditions. The experimental program is described in the following sections.

Testing equipment and instrumentation

The test equipment used in this investigation is a triaxial apparatus for frozen soil, which was designed and manufactured at the University of Tabriz. The designed apparatus was registered as a patent in the Iranian Research Organization for Science and Technology with ref. No. 9705036 (Fig. 3). This apparatus facilitated the study of constitutive modeling and determination of the stress–strain behavior of frozen ground and simulation of AGF techniques in real projects. All of the tests were conducted in a cold and insulated room in the Advanced Soil Mechanics laboratory of the University of Tabriz where the temperature was constantly monitored.

Test specimens

The required samples for the study were taken from the site of the site of the second line of the Tabriz Subway project (Fig. 4). The specimens tested included a cohesive soil (marl) obtained from L2T5 borehole and a coarse grained soil obtained from L2T3 borehole (see Fig. 4). This marl soil with green-blue color, is from a carbonate deposit which is located mainly below the alluvial deposits. According to the United soil Classification System (USCS), these soils are classified as clay, silty clay and silt with low to high plasticity index. The constituents of the marl include ilite, calcite and albite. Moreover, the non-cohesive soil is a limestone sand. The physical properties of the above samples are shown in Tables 1 and 2, respectively. The cohesive and coarse grained soil specimens were classified as CL and SP according to the USCS (ASTM D2487, 2007). The soils gradation curves are shown in Fig. 5. According to Fig. 4, both SP and CL soils are located principally under the water table. Accordingly, both CL and SP specimens were tested at a water content (ω) corresponding to their degree of saturation. In other words, ω and Sr are the constant parameters of the present study.

Pervious researchers have shown that, the length-to-diameter ratio of test specimens has a considerable effect on the stress distribution and mechanical behavior of triaxial test specimens. ASTM D2850 (2007) recommends length-to-diameter ratios between 2 and 2.5 for triaxial testing specimens. In the present study, cylindrical specimens with length-to-diameter ratio of 2 (height = 100 mm and diameter = 50 mm) were used. Since, obtaining undisturbed samples under the groundwater level was not possible, especially for the sandy soil, all of the soil samples were prepared by remolding in accordance with the unit weight, porosity and water content of the in-situ soils.

The sleeve molds of the frozen soils were radially rigid and hence, prevented the radial expansion of the samples. The sleeve cylindrical mold was made of aluminum in two parts which were fixed by four bolts. It was confined by rigid polyurethane plates at the top and bottom. So, freezing-induced heaving only occurred in the vertical direction from the top and bottom of the specimens which were then flattened by a spiral grinding machine at the end of the freezing process. It is worth mentioning that heat transfer could occur in the radial direction because of the insulation from the top and bottom. This process was adopted for accurate simulation of the frozen soil conditions around the freeze pipes in the AGF technique. Fig. 6 shows a schematic layout of the cylindrical sleeve curing mold for frozen soil which was used in this research.

Testing program

To accelerate the process of the experiments, the specimens were frozen in a refrigerator up to the desired temperature (outside the triaxial chamber). The frozen samples were then transferred into the triaxial chamber. The tests started after reaching to the desired equilibrium temperature in the triaxial chamber. The mechanical tests were conducted under axisymmetric condition according to the ASTM D4083 (2016). The stress condition of the frozen soil in the triaxial compression apparatus is shown in Fig. 7.

Various factors affect the mechanical behavior of frozen soils. Also, the type of unfrozen soil affects the mechanical behavior of the soil after freezing. One of the main goals of this study is to investigate the influence of freezing and reduction in temperature on the stress–strain behavior of soils. The effects of loading (strain rate) on the frozen and unfrozen specimens are also investigated. After preparation, the specimens were placed in the triaxial chamber and a series of triaxial shear tests were performed.

Results and discussion

The variable parameters were temperature and loading (strain) rate of the soil. Based on the laboratory observations, all the frozen SP and CL specimens exhibited ductile behavior during shearing. This was not observed in the ice specimens which showed a brittle behavior. In what follows, the effect of each variable on the behavior of the tested materials is presented and discussed.

Effect of freezing on stress–strain behavior of saturated cohesive soils

Triaxial experiments were carried out on identical samples of SP and CL soils under the same cell pressure and loading velocity but at different temperatures. Fig. 8 shows the effect of freezing and reduction in temperature on the saturated CL soil under cell pressure of 200 kPa and loading with displacement rate of 1 mm/min. It is seen that the behavior of the unfrozen CL soil is almost linear elastic up to the yield point after which the soil experiences elastoplastic behavior. The yield stress increases with decreasing the temperature. The general trend of behavior is nearly the same as that of the frozen CL soil in freezing temperatures close to 0°C. Decreasing the freezing temperature to -1°C, -4°C, -7°C and -11°C increases the shear strength of the CL soil by 591%, 1696%, 3027% and 4817% with respect to unfrozen CL soil and the soil behavior gradually changes to strain hardening. Fig. 9 shows the influence of freezing and decrease in temperature on the unfrozen CL soil, frozen CL soil and pure ice at cell pressure of 200 kPa and loading with displacement rate of 1 mm/min. The results show that, under the same conditions (cell pressure of 200 kPa and displacement rate of 1 mm/min), pure ice exhibits a strain-softening behavior and this softening increases with decrease in temperature. Following the softening after peak state, the pure ice reaches nearly the same residual state in all temperatures. The shear strength of frozen CL soil at temperatures -1°C, -3°C and -5°C is less than that of the pure ice at the same temperatures. However, at lower temperatures (-7°C and lower), the shear strength of the frozen CL soil is larger than the pure ice. The effect of freezing and temperature reduction on elastic modulus of the CL soil is presented in Table 3. The results show that freezing leads to a significant increase in the elastic modulus of the soils; by freezing, elastic modulus of the SP and CL soils shows increase of 1351% and 159% (with respect to the unfrozen state) respectively. This increase due to freezing is much greater for the SP soil. Also reduction of temperature from -1°C to -11°C causes to further increase in elastic modulus of 47% and 38% for the frozen SP and CL soils, with respect to the unfrozen state. This increase is slightly greater for the SP soil

Effect of freezing on mechanical behavior of saturated granular soil

The influence of freezing and reduction in temperature on the performance of the saturated SP soil under cell pressure of 200 kPa and displacement rate of 1 mm/min is shown in Fig. 10. The results show that the behavior of the unfrozen SP soil is strain-hardening while the frozen SP soil reveals a strain-softening behavior. A peak state is realized in the behavior of the frozen SP soil which occurs at higher strains by decreasing temperature. Decreasing the freezing temperature to -1°C, -4°C, -7°C and -11°C increases the shear strength of the SP soil by 390%, 810%, 1174% and 1472%, with respect to the unfrozen state.

Fig. 11 shows the influence of freezing and decrease in temperature on the behavior of the unfrozen and frozen SP soil and pure ice at same cell pressure and loading (displacement) rate (200 kPa and 1 mm/min, respectively). The results show that the pure ice and the frozen SP soil exhibit strain-softening behavior. In contrast to the frozen SP soil, decreasing temperature leads to a peak state in the stress–strain behavior of pure ice occurring at lower strains. Under the same conditions (of temperature, cell pressure and loading rate) the shear strength of the frozen SP soil is much greater than that of pure ice. The effect of freezing and temperature reduction on modulus of elasticity of the SP soil is presented in Table 3. It is seen that freezing results in a significant increase in modulus of elasticity for both CL and SP specimens. Also, decrease in temperature leads to a significant increase in the elastic (Young's) modulus of pure ice.

The results show that the shear strength of the frozen SP soil is significantly greater than that of the frozen CL soil, especially at low temperatures. However, the influence of freezing on the increase in shear strength of the CL soil is much greater than the SP soil.

Effect of loading velocity

To examine the effect of loading (loading velocity) on the behavior of the frozen ground, a set of triaxial experiments were conducted on the specimens of the unfrozen and frozen CL and SP soils and pure ice at constant cell pressure, temperature and ice saturation (according to the site conditions). Fig. 12 shows the influence of loading rate on the unfrozen and frozen CL soil and pure ice under cell pressure of 200 kPa at -3°C. For the loading, displacement rates of 0.2, 0.5 and 1 mm/min were selected for this study. The results show that the shear strengths of the unfrozen CL soil, frozen CL soil and pure ice increase with increasing the loading velocity. The increase in loading velocity from 0.2 to 0.5 mm/min and from 0.5 to 1 mm/min leads to 37.1% and 280.3% increase in shear strength of the unfrozen CL, respectively. The increase in loading velocity from 0.2 to 0.5 mm/min and from 0.5 to 1 mm/min leads to 25.6% and 20% increase in shear strength of the frozen CL, respectively. The increase in loading velocity from 0.2 to 0.5 mm/min and from 0.5 to 1 mm/min leads to 11.5% and 11.4% increase in shear strength of the pure ice, respectively. It is noted that the rate of increase in shear strength due to increase in loading (strain) rate, is larger for the unfrozen CL soil than the frozen CL soil and for the frozen CL soil than the pure ice. However, the magnitude of shear strength for pure ice is greater than the frozen CL soil and for the frozen CL soil is greater than the unfrozen CL soil. It is noted that the variation of loading velocity has no effect on the type of behavior of the studied materials; so that, the frozen and unfrozen CL soils still show strain-hardening behavior and pure ice exhibits strain-softening behavior. Table 4 presents the effect of loading velocity on the elastic modulus of the materials tested under cell pressure 200 kPa at -3°C. It is shown that the modulus of elasticity of these materials generally increases with increasing loading velocity.

Fig. 13 illustrates the effect of loading rate on the behavior of the unfrozen and frozen SP soil and the pure ice under cell pressure of 200 kPa at -3°C. The results show that increase in loading (displacement) rate from 0.2 to 0.5 mm/min and from 0.5 to 1 mm/min leads to 27.4% and 15.8% rise in shear strength of the unfrozen SP soil, respectively. These values for the frozen SP soil are 21.7% and 36%, respectively. The increase in shear strength due to the increase in the loading velocity is greater for the frozen SP soil at lower loading velocities and for the unfrozen SP soil at higher loading velocities. This increase in strength for pure ice is less than both the frozen and unfrozen SP soils. However, the shear strength of the frozen SP soil is greater than the pure ice and that of pure ice is greater than the unfrozen SP soil. The variation of loading velocity has no effect on the type of behavior (strain-hardening or strain-softening) of the unfrozen and frozen SP soil. The observed influence of loading velocity on shear strength of the unfrozen SP and CL soils shows a good agreement with the results reported by Svoboda (2013).

The results show that, overall, the AGF technique can be recommended for the CL and SP soils in Line 2 of Tabriz Subway, as freezing greatly improves the shear strength of both soils.

Conclusion

This paper presented the results from a comprehensive program of experimental investigation to study the effect of freezing on the stress–strain behavior of the ground in Line 2 of the Tabriz Subway. This was done for assessing the potential of using the AGF technique for excavation and tunneling projects in Tabriz Subway. Strain-controlled triaxial compression tests were carried out on unfrozen and frozen specimens of CL and SP soils, and pure ice. The influence of freezing, temperature reduction and loading velocity on the mechanical behavior of these materials was investigated. All the soils exhibited ductile behavior but the pure ice showed brittle failure. The unfrozen CL and SP soils and the frozen CL soil showed strain-hardening behavior while the frozen SP soil and pure ice exhibited strain-softening behavior. Under the same test conditions, the shear strength of the frozen SP soil is greater than the frozen CL soil. However, the rate of increase in shear strength due to freezing and reduction in temperature is much greater for the frozen CL soil. In all cases, the shear strength of the frozen SP soil is greater than pure ice. At temperatures between -1°C to -5°C, the shear strength of pure ice is greater than the frozen CL soil; but, at lower temperatures, the strength of the frozen CL soil is greater. The modulus of elasticity of the materials tested increase due to freezing and temperature reduction. Generally, the Young's modulus and strength of the frozen SP and CL soils increase with increasing the loading velocity. The occurrence of such a significant increase is likely to be due to reinforcing of the soil with the ice matrix in frozen soil system. Finally, based on the obtained results, the utilization of the AGF technique is endorsed for the CL and SP soils just in a specific site of Line 2 of Tabriz Subway, as freezing greatly improves the shear strength and shear behavior of both soils. It should be mentioned that, these results cannot be generalized to all soils.

Acknowledgments

The authors gratefully acknowledge the financial support from the Ministry of Science of Iran.

Notation

The following symbols are used in this paper:

CL: Clay with Low plasticity

SP: Poorly graded Sand

AGF: Artificial Ground Freezing

γ_{sat} : Saturated unit weight

Φ: Internal friction coefficient

G_s: Specific Gravity

G: Gravel

S: Sand

M: Silt

C: Clay

C_u: uniformity coefficient

C_c: curvature coefficient

ω: water content

Sr: Saturation degree

PL: Plastic Limit

LL: Liquid Limit

PI: Plasticity Index

References

Andersen, G. R. (1991). *Physical mechanisms controlling the strength and deformation behavior of frozen sand* (Doctoral dissertation, Massachusetts Institute of Technology).

Andersland, O. B., & Ladanyi, B. (2004). *Frozen ground engineering*. John Wiley & Sons.

ASTM Standard, D2487 (2007) Standard practice for classification of soils for engineering purposes (unified soil classification system). West Conshohocken (PA): ASTM International.

ASTM Standard, D2850-03a (2007) Standard test method for unconsolidated undrained triaxial compression test on cohesive soils. West Conshohocken (PA): ASTM International.

ASTM Standard, D4083-89 (2016) Standard Practice for Description of Frozen Soils (Visual-Manual Procedure). West Conshohocken (PA): ASTM International.
Spaans, E. J., & Baker, J. M. (1995). Examining the use of time domain reflectometry for measuring liquid water content in frozen soil. *Water Resources Research*, *31*(12), 2917-2925.
Braun, B., Shuster, J., & Burnham, E. (1979). Ground freezing for support of open excavations. *Engineering Geology*, *13*(1-4), 429-453.
Chamberlain, E. J. (1981). Overconsolidation effects of ground freezing. *Engineering geology*, *18*(1-4), 97-110.
Da Re, G. (2000). *Physical mechanisms controlling the pre-failure stress-strain behavior of frozen sand* (Doctoral dissertation, Massachusetts Institute of Technology).
Esmaeili-Falak, M. (2017). Experimental investigation of stress and strain characteristics of frozen sandy soils-A case study of Tabriz subway. *Modares Civil Engineering journal*, *17*(5), 13-24.
Esmaeili-Falak, M. (2017). Effect of System's Geometry on the Stability of Frozen Wall in Excavation of Saturated Granular Soils. *Doctoral dissertation, University of Tabriz*.
Esmaeili-Falak, M., Katebi, H., & Javadi, A. (2018). Experimental Study of the Mechanical Behavior of Frozen Soils-A Case Study of Tabriz Subway. *Periodica Polytechnica Civil Engineering*, *62*(1), 117-125.
Esmaeili-Falak, M., Katebi, H., Vadiati, M., & Adamowski, J. (2019). Predicting Triaxial Compressive Strength and Young's Modulus of Frozen Sand Using Artificial Intelligence Methods. *Journal of Cold Regions Engineering*, *33*(3), 04019007.
Fei, W., & Yang, Z. J. (2018). Modeling unconfined compression behavior of frozen Fairbanks silt considering effects of temperature, strain rate and dry density. *Cold Regions Science and Technology*.
Frivik, P. E. (1981). State-of-the-art report. Ground freezing: thermal properties, modelling of processes and thermal design. *Engineering Geology*, *18*(1-4), 115-133.
Harris, J. S. (1995). *Ground freezing in practice*. Thomas Telford.
Jones, J. S., & Brown, R. E. (1979). Design of tunnel support systems using ground freezing. *Engineering Geology*, *13*(1-4), 375-395.
Lackner, R., Amon, A., & Lagger, H. (2005). Artificial ground freezing of fully saturated soil: thermal problem. *Journal of Engineering Mechanics*, *131*(2), 211-220.
Ladanyi, B. (1972). An engineering theory of creep of frozen soils. *Canadian Geotechnical Journal*, *9*(1), 63-80.
Li, H., Yang, Z. J., & Wang, J. (2018). Unfrozen water content of permafrost during thawing by the capacitance technique. *Cold Regions Science and Technology*, *152*, 15-22.
Li, S., Lai, Y., Zhang, M., & Zhang, S. (2006). Minimum ground pre-freezing time before excavation of Guangzhou subway tunnel. *Cold regions science and technology*, *46*(3), 181-191.
Nassr, A., Esmaeili-Falak, M., Katebi, H., & Javadi, A. (2018). A new approach to modeling the behavior of frozen soils. *Engineering Geology*, *246*, 82-90.
Parameswaran, V. R., & Jones, S. J. (1981). Triaxial testing of frozen sand. *Journal of Glaciology*, *27*(95), 147-155.
Puswewala, U. G. A., & Rajapakse, R. K. N. D. (1990). Numerical modeling of structure-frozen soil/ice interaction. *Journal of Cold Regions Engineering*, *4*(3), 133-151.
Rupprecht, E. (1979). Application of the ground-freezing method to penetrate a sequence of water-bearing and dry formations—three construction cases. *Engineering Geology*, *13*(1-4), 541-546.
Sayles, F. H. (1968). *Creep of frozen sands* (No. CRREL-TR-190). COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH.
Sayles, F. H., & Haines, D. (1974). *Creep of Frozen Silt and Clay* (No. CRREL-TR-252). COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH.
Soo, S., & Muvdi, B. B. (1992). Design method for frozen-soil retaining wall. *Journal of cold regions engineering*, *6*(2), 73-89.
Stoss, K., & Valk, J. (1979). Uses and limitations of ground freezing with liquid nitrogen. *Engineering Geology*, *13*(1-4), 485-494.

Svoboda, J. (2013). *Impact of strain rate on the shear strength and pore water pressure generation of clays and sands* (Doctoral dissertation, University of Colorado at Boulder).
Török, Á., Ficsor, A., Davarpanah, M., & Vásárhelyi, B. (2019). Comparison of Mechanical Properties of Dry, Saturated and Frozen Porous Rocks. In *IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018—Volume 6* (pp. 113-118). Springer, Cham.
Wang, D. Y., Zhu, Y. L., Ma, W., & Niu, Y. H. (2006). Application of ultrasonic technology for physical–mechanical properties of frozen soils. *Cold Regions Science and Technology*, *44*(1), 12-19.
Wijeweera, H., & Joshi, R. C. (1992). Temperature-independent relationships for frozen soils. *Journal of cold regions engineering*, *6*(1), 1-21.
Yang, Z. J., Still, B., & Ge, X. (2015). Mechanical properties of seasonally frozen and permafrost soils at high strain rate. *Cold regions science and technology*, *113*, 12-19.
Youssef, H. (1988). Volume change behavior of frozen sands. *Journal of cold regions engineering*, *2*(2), 49-64.
Zhao, X., Zhou, G., & Wang, J. (2013). Deformation and strength behaviors of frozen clay with thermal gradient under uniaxial compression. *Tunnelling and Underground Space Technology*, *38*, 550-558.
Zhou, G., Hu, K., Zhao, X., Wang, J., Liang, H., & Lu, G. (2015). Laboratory investigation on tensile strength characteristics of warm frozen soils. *Cold Regions Science and Technology*, *113*, 81-90.
Zhou, M. M. (2013). Computational simulation of soil freezing: multiphase modeling and strength upscaling. *Ruhr University Bochum*.
Ziegler, M., Baier, C., & Aulbach, B. (2009). Simplified phase change model for artificially frozen ground subject to water seepage. In *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering: The Academia and Practice of Geotechnical Engineering, Alexandria, Egypt, 5-9 October 2009, Volume 1* (pp. 562-565). IOS Press.

Table 1 Physical properties of the SP soil

Parameter	Value
γ_{sat} (kN/m^3)	19.1
ω (%)	12.3
Φ(°)	33
G_s	2.635
G(%)	0
S(%)	98.8
C & M (%)	1.2
C_u	2.17
C_c	1.04

Table 2 Physical properties of the CL soil

Parameter	Value
γ_{sat} (kN/m^3)	21.1
ω (%)	19.8
G_s	2.7
G(%)	2
S(%)	14
C & M (%)	84
LL(%)	49
PL(%)	24
PI(%)	25

Table 3 Effect of freezing and temperature reduction on modulus of elasticity (kPa) of the SP and CL and pure ice at cell pressure 200 kPa and loading velocity 1 mm/min.

Temperature (°C)	CL (kPa)	SP (kPa)	Ice (kPa)
Unfrozen	7342	8882	-
-1	19033	128831	55483
-2	27686	135828	-
-3	33855	144230	69441
-4	41041	149834	-
-5	52129	154122	1044565
-6	67677	160191	-
-7	77233	171457	153113
-8	83165	180916	-
-9	92064	189994	-
-10	97352	194446	-
-11	102928	201442	-

Table 4 Effect of freezing and temperature reduction on modulus of elasticity (kPa) of all specimens under cell pressure 200 kPa at -3°C.

Soil type	loading velocity		
	0.2mm/min	0.5mm/min	1mm/min
Unfrozen CL	346	1297	7342
Frozen CL	31084	32814	33855
Unfrozen SP	5877	7196	8882
Frozen SP	122759	135960	144230
Pure ice	64706	72172	69440

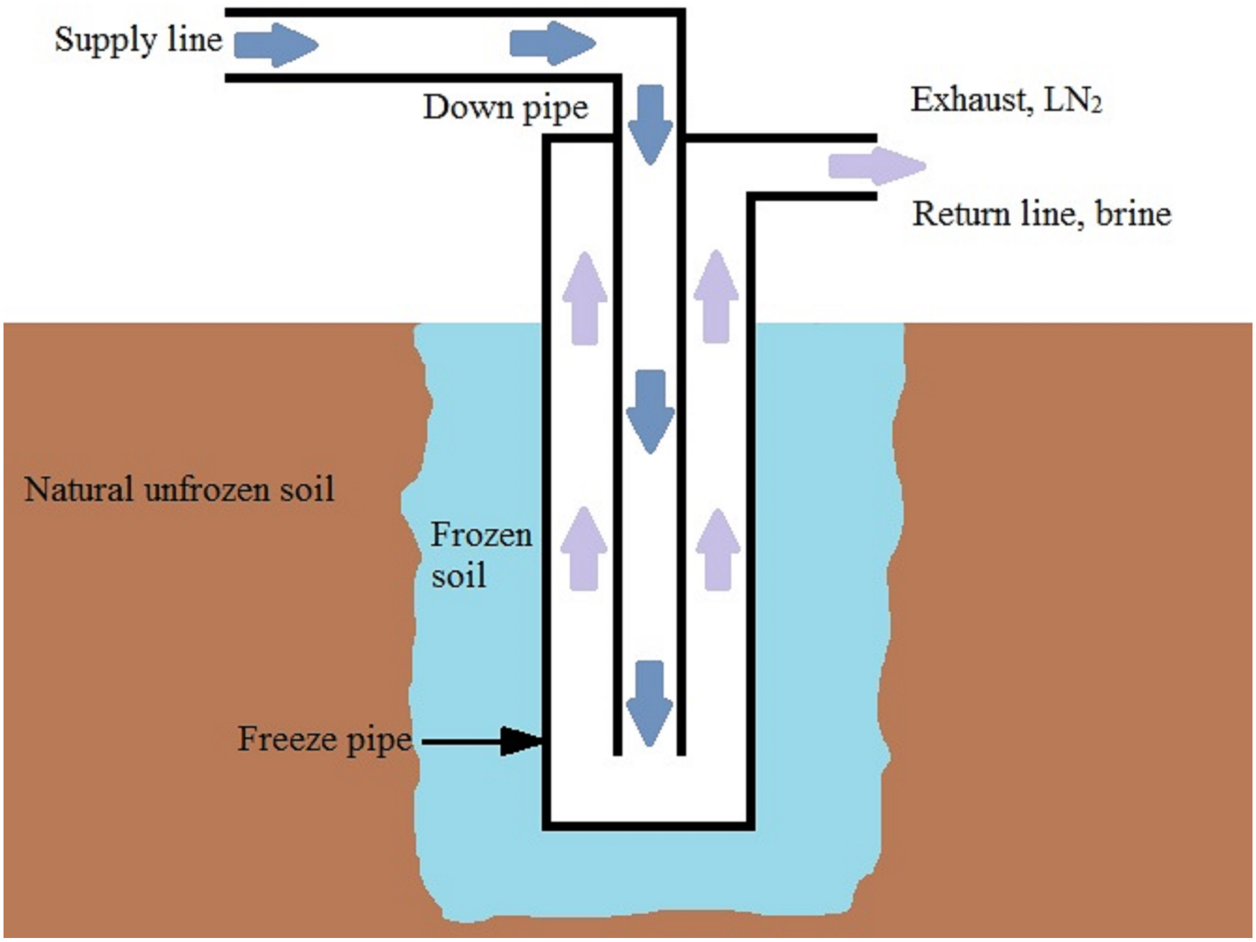

Fig. 1 Illustration of a double sleeve freezing pipe

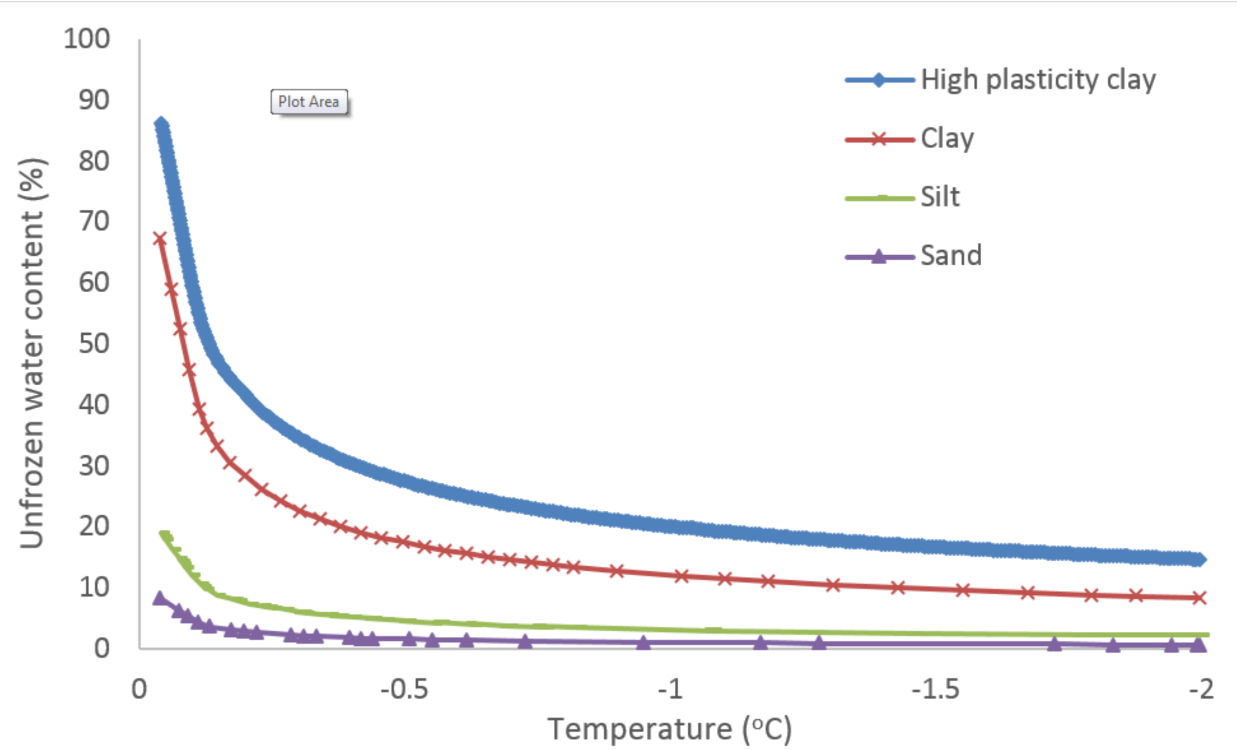

Fig. 2 Effect of temperature on the unfrozen water of various frozen soils (Ziegler et al., 2009)

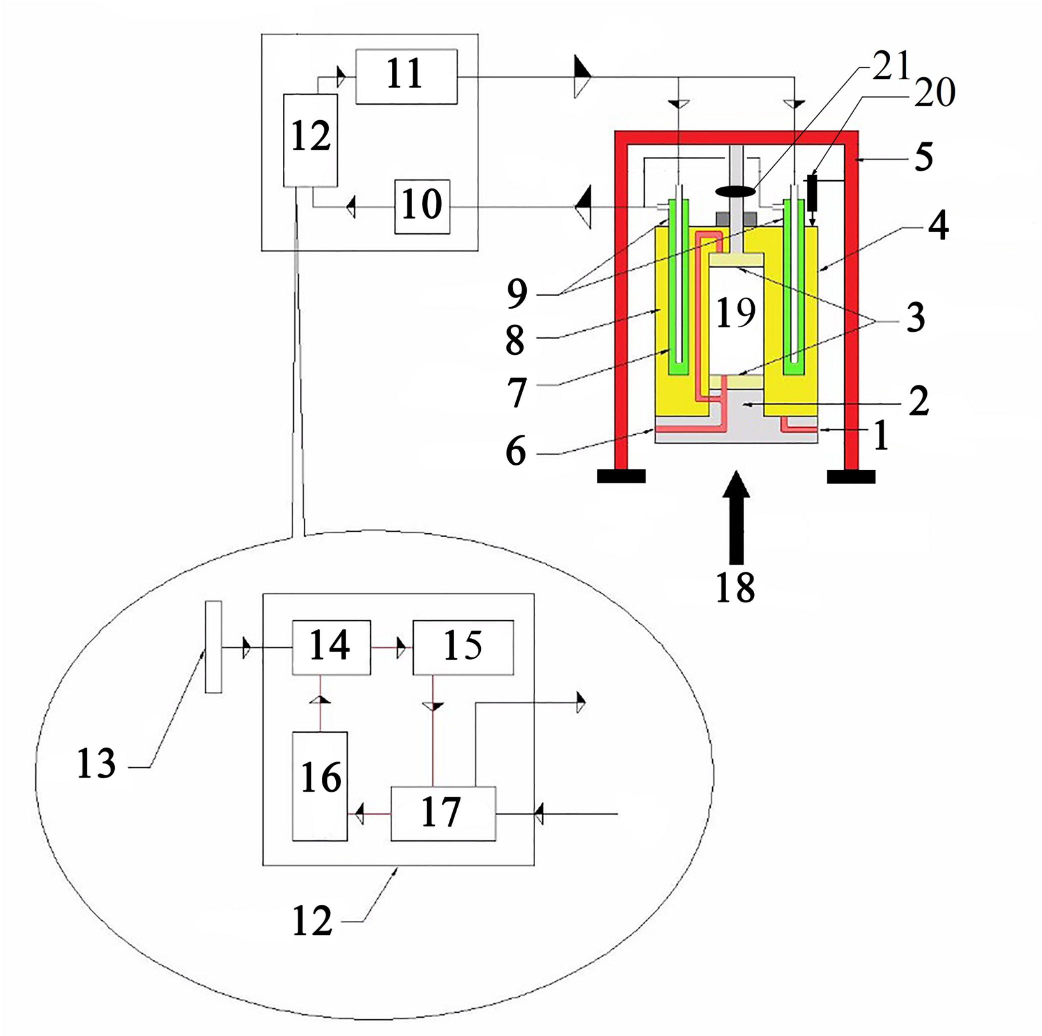

Fig. 3 Schematic layout of triaxial test apparatus for frozen soils: 1 = confining pressure valve; 2 = pedestal; 3 = thermal isolators; 4 = triaxial chamber; 5 = rigid chassis; 6 = drainage valve; 7 = circulating brine; 8 = ethanol; 9 = heat transducer; 10 = pump; 11 = thermostat-thermometer; 12 = refrigeration plant; 13 = reverse fan; 14 = cooling pump; 15 = condenser; 16 = compressor; 17 = evaporator; 18 = deviatoric stress; 19 = frozen soil specimen; 20 = LVDT; 21 = load cell.

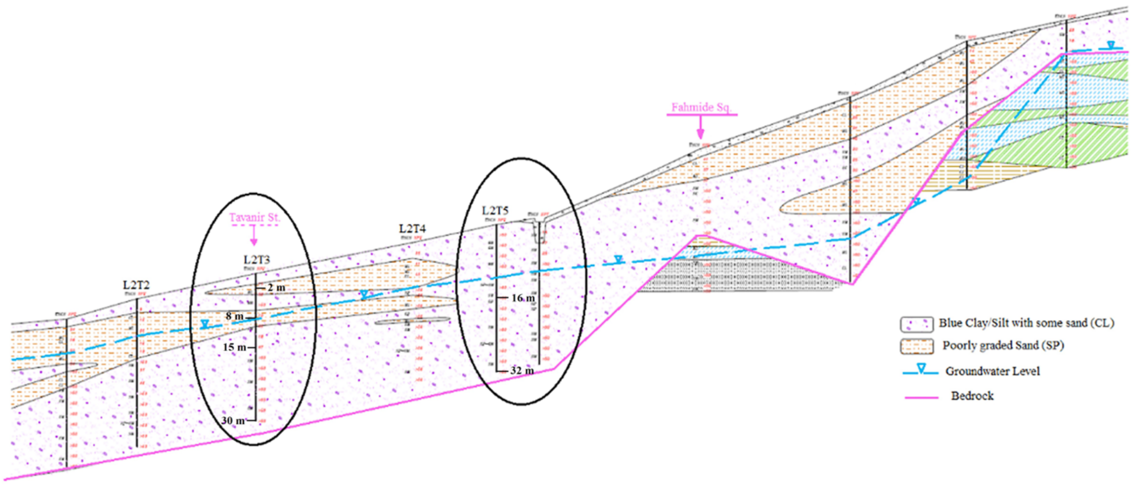

Fig. 4 Geological profile of Tabriz Subway Line 2 in the study area

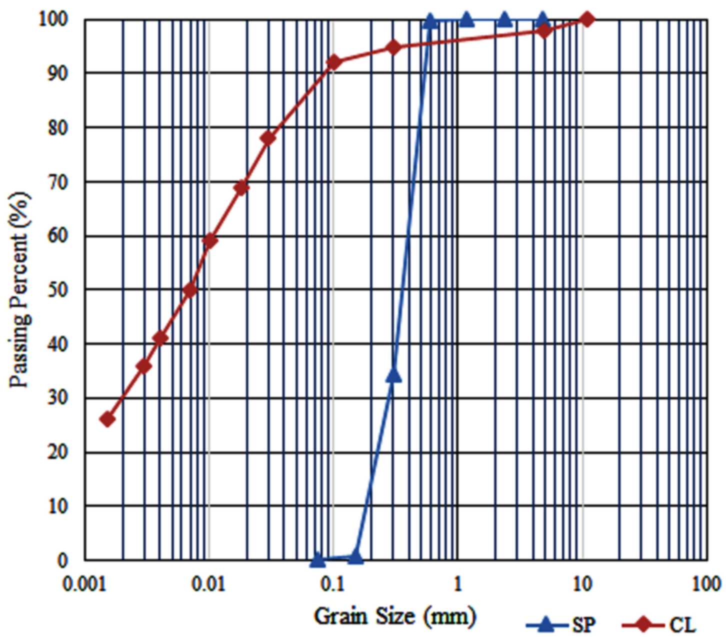

Fig. 5 Grain size distribution of the soils

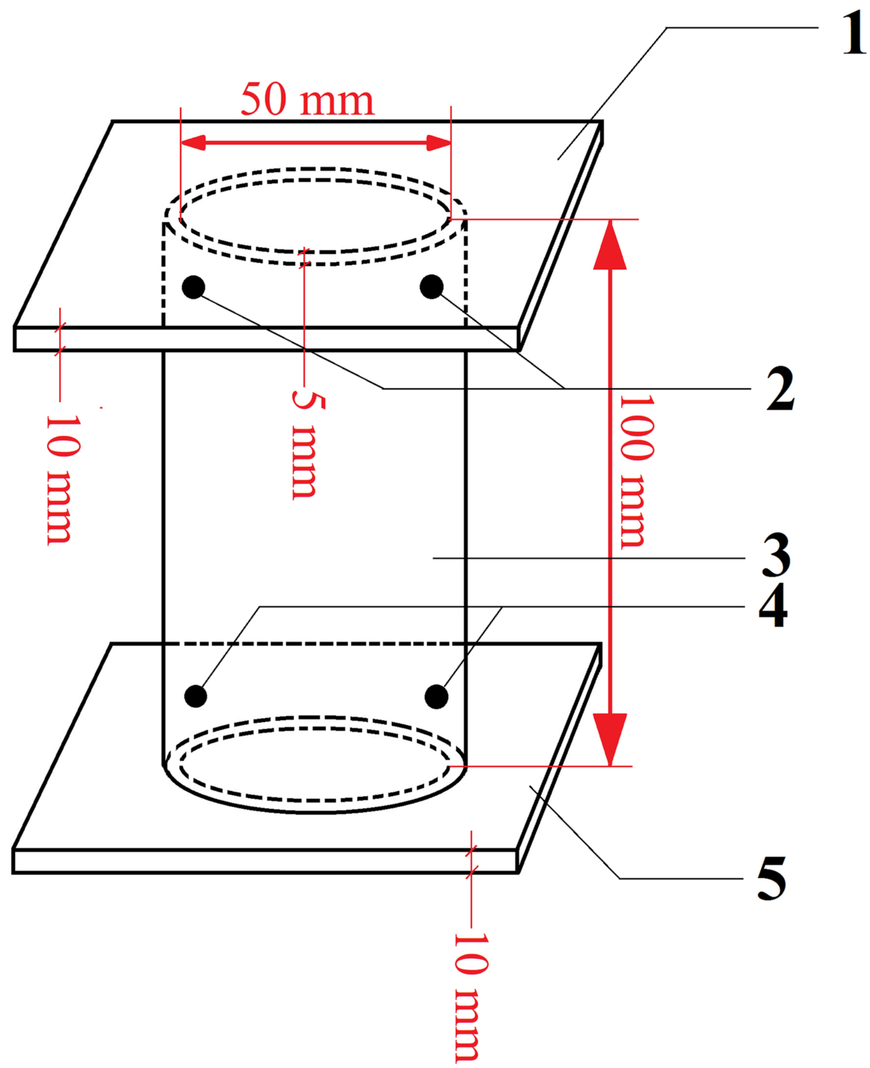

Fig. 6 Schematic layout of the cylindrical sleeve mold: 1 = upper polyurethane plate; 2 = upper bolts; 3 = Aluminum sleeve mold; 4 = lower bolts; 5 = lower polyurethane plate.

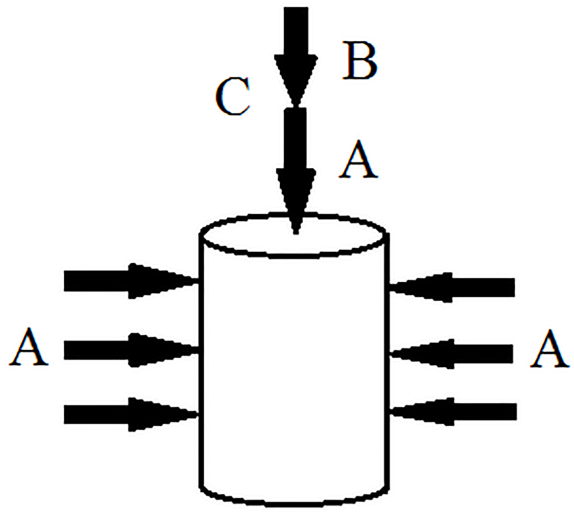

Fig. 7 Stress condition of frozen soil specimen: A = confining pressure (σ_r); B = deviatoric stress (σ_d); C = major principle stress (σ_a).

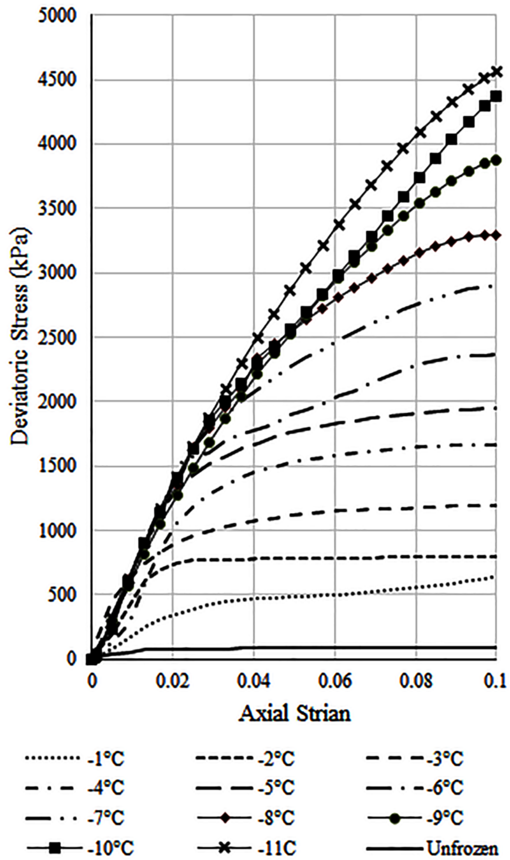

Fig. 8 Effect of freezing and temperature reduction on the CL specimens

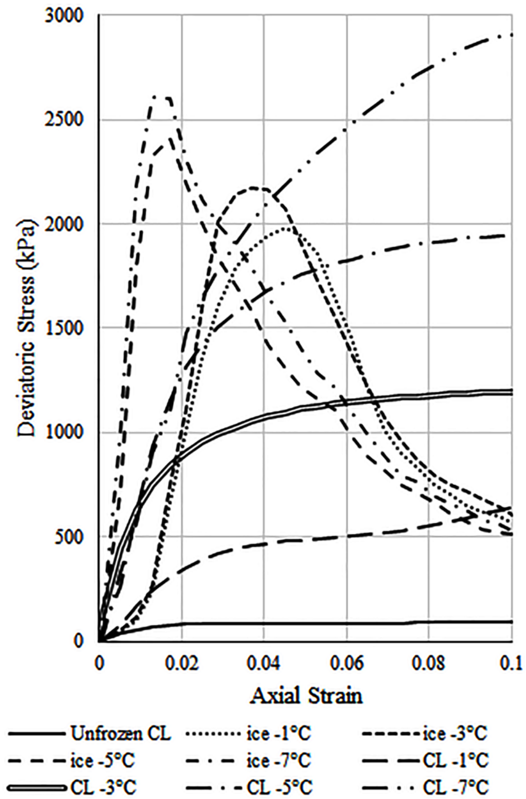

Fig. 9 Effect of freezing and temperature reduction on the behavior of the unfrozen and frozen CL soil and pure ice

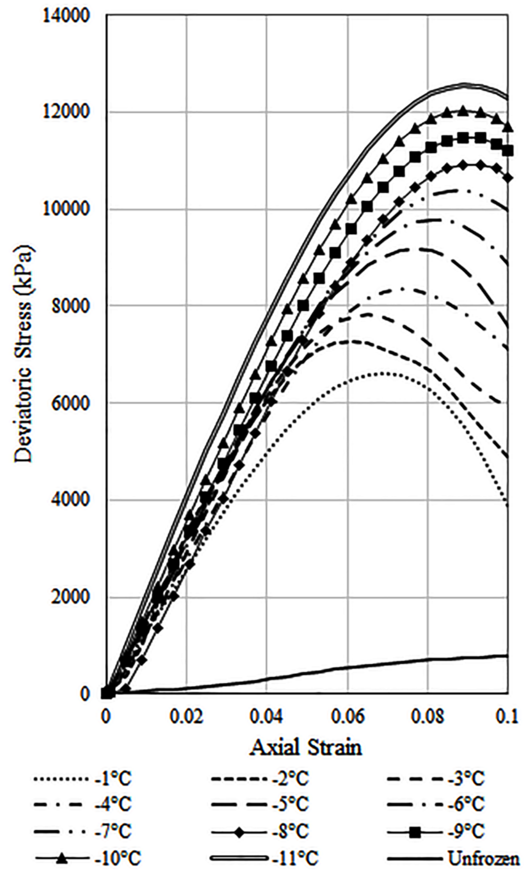

Fig. 10 Effect of freezing and temperature reduction on the behavior of the SP soil

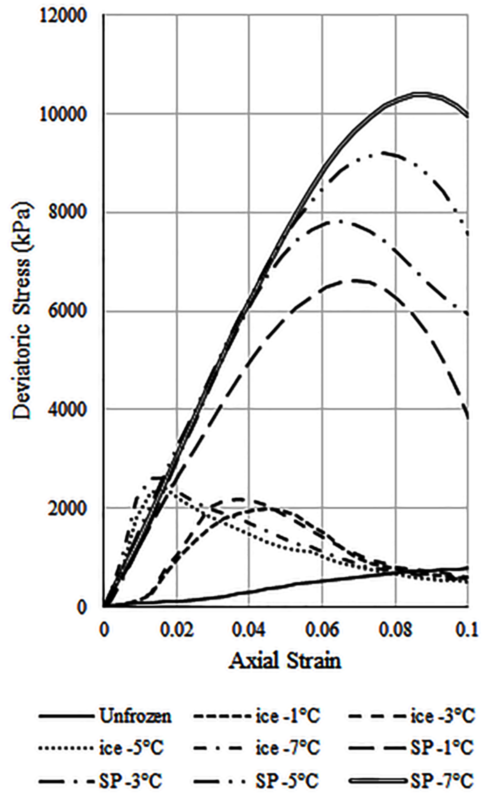

Fig. 11 Effect of freezing and temperature reduction on the behavior of the unfrozen and frozen SP soil and pure ice

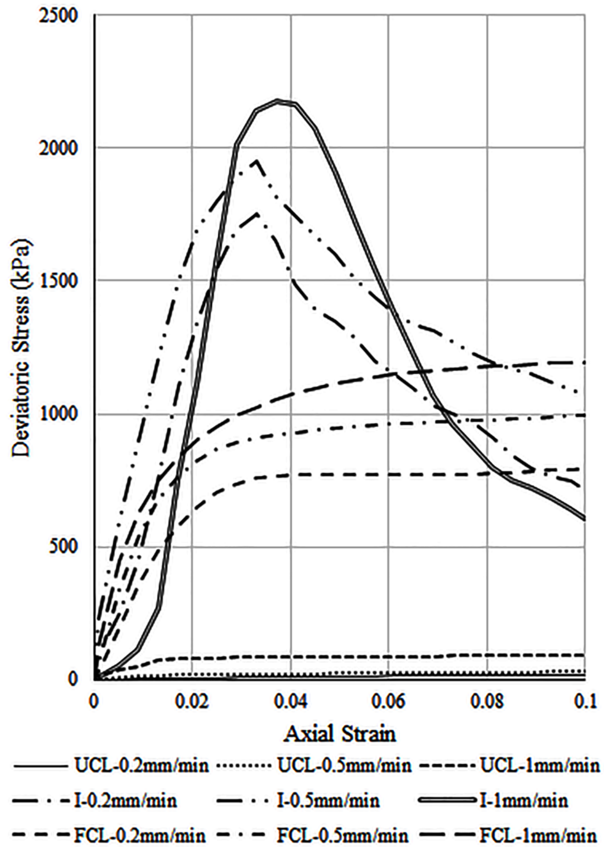

Fig. 12 Effect of loading velocity on the shear behavior of the CL soil. UCL = unfrozen CL; I = pure ice; FCL = frozen CL.

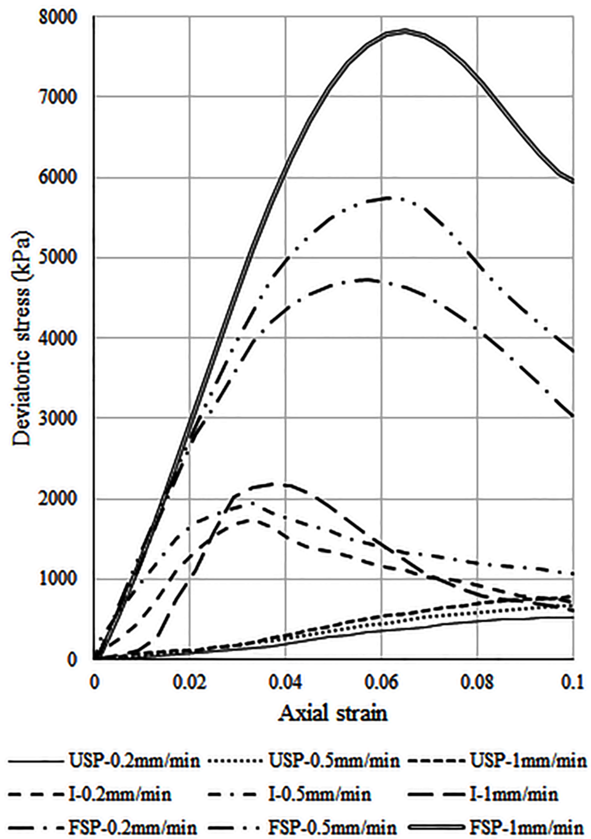

Fig. 13 Effect of loading velocity on the shear behavior of the SP soil: USP = unfrozen SP; I = pure ice; FSP = frozen SP