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Experimental Study of the Mechanical Behavior of Frozen Soils - A Case Study of Tabriz Subway

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TECHNICAL NOTES

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Abstract
The mechanical properties of frozen ground are key parameters in design and implementation of artificial ground freezing (AGF) in underground projects. Soil samples were obtained from the urban underground railway project site in Tabriz, Iran. The specimens were classified as SP and CL according to the USCS. The specimens were remolded in accordance with the site conditions. Over 120 triaxial compression tests were conducted on the frozen samples at different temperatures, confining pressures and strain rates. The results show that the frozen SP and CL soils exhibit strain-softening and strain-hardening behaviour, respectively. In all cases, Young's modulus increases with decreasing temperature and increasing strain rate and confining pressure. Also, the shear strength increases with decreasing temperature and increasing strain rate. In all tests, the Young's modulus and shear strength of the SP soil are greater than the CL soil. Based on the results of this research, the application of artificial ground freezing was recommended for coarse-grained and non-cohesive soils like SP in the Tabriz underground railway project.

Keywords
artificial ground freezing, frozen soil, mechanical behaviour, Tabriz Subway

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1 Introduction

There has been a significant increase in demand for underground urban railway (subway) with rapid growth of population in Tabriz metropolis. Because of the limited space for underground construction, excavation is often difficult, especially in homogeneous loose soils. Various methods of soil stabilization have been used in underground space. Artificial ground freezing (AGF) is one of these methods [1] in which in situ soil is temporarily frozen with artificial exhaustion of heat with the aim of improving the soil properties. AGF leads to decrease in settlement and permeability and increase in shear strength of soil. AGF offers a number of technical advantages over other methods of soil stabilization. Especially, when other methods of soil improvement are considered infeasible, AGF could be the only way if it is analysed and designed properly. Furthermore, AGF is an environmentally friendly method that has no lasting negative effects on soil and groundwater considering its reversibility [2–13].

Freezing of water in soil pores changes its mechanical properties. In practice, freezing tubes are used to freeze in-situ soils [14]. Freezing tubes used in the AGF method consist of two concentric pipes [15]. The end of the outer pipe is closed while the end of the inner pipe is open. The coolant enters into the freeze pipe and after reaching the deepest point of the inner pipe it returns and passes through the gap between the two pipes (Figure 1). During the movement of the coolant in the gap, the refrigerant extracts heat from the surrounding ground [16].

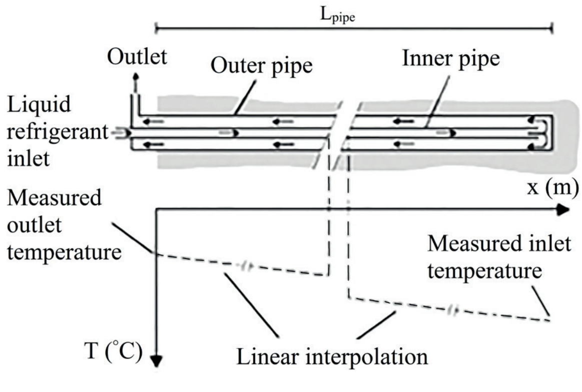

Fig. 1 General layout of a freeze pipe (after Pimentel et al.) [16]

Understanding the mechanical behavior of the frozen soil is essential in the application of AGF and the construction project that follows. Initial comprehensive studies on frozen soils [17–19] (Sayles 1968, Sayles and Haines 1974, Ting 1981) mainly focused on the creep behavior of frozen soils such as sand, silt and clay. However, in the last few decades, almost all aspects of frozen soils have been considered.

Many researchers have studied AGF and its effects on soil properties and mechanical behavior of frozen soils [20-29]. However, compared with unfrozen soils a greater effort is required to study frozen soils [30–33]. A mine shaft project near Swansea in South Wales is the first recorded application of AGF in 1862 [7]. Although AGF has been used for more than a century, there are limited publications concerning physical properties and mechanical behavior of frozen soils in practical projects and case studies. It should be noted that, the research works on the effects of freeze-thaw on the behavior of various materials should not be mistaken with AGF method [34]. The use of AGF as a soil supporting system is gradually increasing in underground engineering applications. However, there are still many unknowns, especially in frozen marl soil [35].

Freezing of soil has a considerable effect on improving its mechanical properties due to the formation of a rigid ice-soil matrix. Experimental results reported by Anagnostopoulos and Grammatikopoulos indicated that this improvement depends directly on water content and it is inversely proportional to the increase in consolidation pressure and sand content. A higher water content would lead to desirable mechanical properties after freezing [36].

Yugui conducted a series of triaxial compression tests on frozen silt at –8°C. The results showed nonlinear stress-strain curves for both axial and volumetric strains prior to failure. In the early stages of loading, the slope of the deviator stress–axial strain curve linearly increased due to closure of pre-exiting cracks. Then, the slopes of both deviator stress-axial strain and deviator stress-lateral strain curves decreased gradually with the increase in axial strain [37]. Xue-lei et al. studied the effects of freezing on Lanzhou silty clay. The results showed that, at a constant temperature, the shear strength of soil increases with increase in confining pressure. Also at constant confining pressure, shear strength of frozen soil increases with decrease in temperature [38]. Yang et al presented results from an experimental study to investigate the mechanical properties of frozen soil. More than sixty tailing samples were frozen at temperature of −16 °C and then tested under uniaxial compression. Based on the results, three failure patterns were observed in the samples: inclined plane shear failure, lateral tensile failure, and composite failure involving both. Uniaxial compressive strength of tailing was related logarithmically, exponentially, linearly and parabolically to average particle size, dry density, moisture content and strain rate, respectively [39]. Xu et al. showed that natural frozen saline silty sand exhibits flexible failure and strain-hardening behavior, whereas the desalted silty sand with the same water content exhibits brittle failure and a clear strain-softening behavior. They concluded that, the soil brittleness is reduced by the presence of salt. The strength of both the natural frozen saline silty sand and the desalted frozen silty sand increased with increasing the confining pressure and with decreasing temperature. Furthermore, the strength of the natural soil was lower than that of the desalted soil in all tests which indicates that the strength of the frozen silty sand is reduced by the presence of salt [40].

Some researchers have developed simulation models to study the behavior of frozen soils. Casini et al. presented a fully coupled thermo-hydro-mechanical model that was extended to low temperature problems. The model was validated for a freeze and thaw process against experimental results from triaxial compression tests at different temperatures and confinement pressures. The mechanical behavior of the frozen soil was simulated by an elastoplastic constitutive law based on the BBM (Barcelona Basic Model). The performance of the model was verified during all stages of the test, including drained compression, freezing, equalization, axial loading in frozen conditions, and thawing [41].

From the mechanical characteristics of frozen loess, Gibbs free energy function and dissipation function can be established by applying the hyper-plasticity theory [42]. An incremental elastoplastic constitutive model for frozen loess was derived from the two thermodynamic functions and a method was presented to determine the corresponding parameters. The simulation results showed that the constitutive model proposed by Lai et al. can describe well the deformation behavior of frozen loess under different stress levels and stress paths [43].

Yang et al. studied the mechanical properties of naturally frozen silty soil at a relatively high strain rate. The results showed that, the ultimate compressive strength of naturally frozen specimens is lower than that found in previous studies for remolded frozen silty soils [44]. Li et al. presented empirical equations to describe the accumulated shear strain, accumulated direction ratio and elastic modulus of frozen soils [45]. Li et al. developed a constitutive model by combining the empirical equations and the classical elastoplastic theory [46]. The model was successfully verified with aid of triaxial test results.

The experimental investigations presented the current paper aim to examine the mechanical properties of the specimens obtained from Line 2 of Tabriz Urban Railway in order to assess the feasibility of application of AGF in tunneling and underground excavation in this project.

2 Experimental procedure

This section presents the description of the equipment and instrumentation used to conduct the triaxial compression tests on frozen specimens and the experimental procedure.

2.1 Testing apparatus and instrumentation

Due to its limited and specific applications, triaxial compression apparatus for frozen soils is not readily available on the market. In this study, a strain controlled triaxial compression apparatus was designed and manufactured in the Geotechnical Laboratory of the University of Tabriz. Figure 2 shows the manufactured triaxial apparatus for frozen soils and its components. The components include refrigeration system and thermal transducer (Figure 2). The manufacturing steps were as follows:

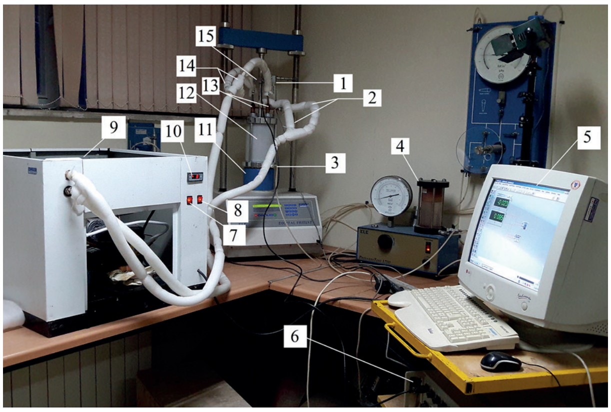

Fig. 2 Triaxial compression apparatus for frozen soils: (1) LVDT, (2) coolant output, (3) confining pressure valve, (4) confining pressure system, (5) computer system, (6) data acquisition, (7) pump power, (8) cooling power, (9) cooling machine, (10) thermostat-thermometer, (11) deviator stress system, (12) triaxial chamber, (13) thermal transducer, (14) coolant input, (15) load cell.General layout of a freeze pipe

- Lathing of triaxial chamber, connecting of transducers, sealing and examining for high pressure tests.
- Connecting the load cell and LVDT to data logger and data acquisition system.

This triaxial system was registered as a patent in the Intellectual Property and Industrial Research Organization of Iran. The development and manufacturing of the triaxial apparatus for testing of frozen soils has facilitated a wide ranges of studies including determination of mechanical and geotechnical parameters of frozen soils, constitutive modelling of frozen soils and also simulation of artificial ground freezing in underground construction projects.

2.2 Soil samples

Figure 3 shows the general layout of the Tabriz urban underground railway system. The geological profile of the subway Line 2 is shown in Figure 4. The samples for this experimental program were taken from L2T5 and L2T3 boreholes (Figure 4). The samples were identified as marl (from L2T5) and noncohesive soil (from L2T3).

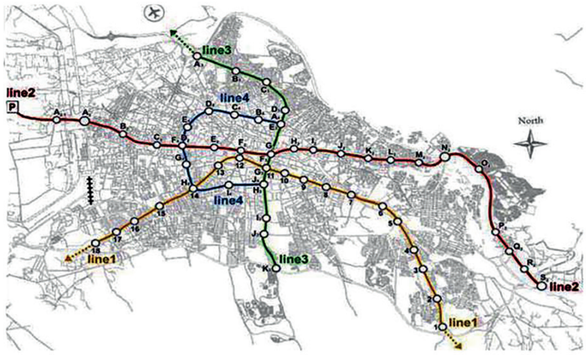

Fig. 3 A general layout of Tabriz urban railway

The marl and granular soil samples were classified as CL and SP according to the Unified Soil Classification System (USCS) with ASTM D2487 [47]. Based on the particle size distribution curves (Figure 5) and Atterberg limits tests, the physical properties of the 2 soils are summarized in Tables 1 and 2. These samples are the most frequent soil types along the subway line 2. According to the site investigation results, in the central part of the route, the CL and SP soils are mainly below the groundwater table. The soil samples were used in this study to assess the feasibility of application of AGF in excavations and underground construction along the subway line 2.

Cylindrical specimens, 50 mm in diameter and 100 mm in height, were prepared for the triaxial tests. Based on the phase relationships, in accordance with the borehole conditions on the site, all soil specimens were remolded with the same void ratio, density and water content. To ensure repeatability and comparability of the test results, this was done carefully in the laboratory. A vacuum pump was used to saturate the soil samples.

Considering the rigidity of the curing molds of frozen soils (and hence the prevention of radial expansion), the expansion due to freezing could only occur in the longitudinal direction from top and bottom. These freezing heaves were levelled off in order to cap the samples. Special molds were designed to freeze the soil at the desired subzero temperatures. These sleeve molds were made of aluminum, due to its high thermal conductivity; which were surrounded from top and bottom by insulated panels.

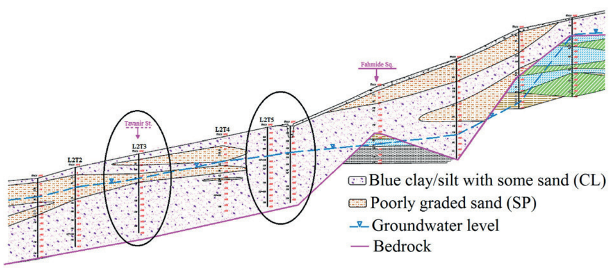

Fig. 4 Geological profile of Tabriz Subway line 2 in the study area

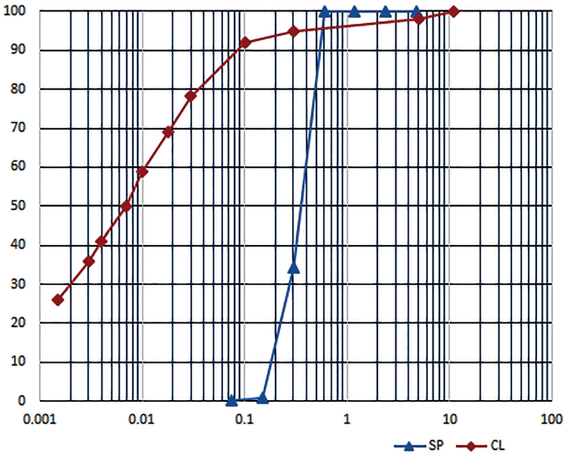

Fig. 5 Grain size distribution of soil

Table 1 Physical properties of SP soil

Soil classification	SP
γ_{sat}	1.98
ϕ	33
G_s	2.635
G(%)	0
S(%)	98.8
C and M (%)	1.2
C_u	2.17
C_c	1.04

In this work it is aimed to propagate the freezing front in the radial (rather than vertical) direction, since the in situ soil is frozen radially due to the freezing pipes. On the other hand, rapid freezing in radial direction may lead to absence of ice lenses. Figure 6 shows one of the sleeve curing molds that was used in this research.

2.3 Test program

Application of AGF in different projects is affected by various factors such as type of soil, subzero temperature (and freezing duration), ice saturation, confining pressure, rate of loading, used machine capacity and coolant. In this study, two types of soil, SP and CL, were investigated under different temperatures, strain rates and confining pressures. More than 120 unconsolidated undrained (UU) triaxial compression tests were conducted on frozen CL and SP soils obtained from boreholes to evaluate the improvement of soil strength and mechanical behavior of frozen soil, according to the ASTM D4083 [48].

Table 2 Physical properties of CL soil

Soil classification	CL
γ_{sat}	2.11
G_s	2.7
G(%)	2
S(%)	14
C and M (%)	84
LL(%)	49
PL(%)	24
PI(%)	25

Fig. 6 Aluminium sleeve curing mold

UU test was selected as it better represents the in-situ conditions for this case study. Axial load was applied under strain-controlled condition with strain rates of 0.1, 0.2, 0.5, 1 and 2 mm/min, under the confining pressures of 0, 50, 100, 200, 400 and 800 kPa, at temperatures between –1°C to –11°C to define the shear strength parameters. All the tests were performed in an insulated room where the temperature was monitored and controlled at the range of . Control tests were performed to confirm the validity of the experiments and the accuracy of the tests implementation.

3 Experimental results and analysis

Soil is a heterogeneous material, generally consisting of solids, water and air. Therefore, unforeseen stress-strain behavior is likely to occur in the above mentioned phases. Since this research is a case study investigating the feasibility of application of AGF in tunneling and underground excavation in line 2 of Tabriz urban railway, the main variable parameters are the soil type in the case study area, temperature, strain rate and confining pressure. The other parameters such as ice saturation, soil particle content and void ratio were kept constant. In this study, all the observed failures were non-brittle so that both frozen marl and frozen sand showed a flexible deformation due to sagging in the sample. Detailed discussion of the research results is presented in the following sections.

3.1 Effect of temperature on the frozen soils

To investigate the effect of freezing and subzero temperatures on the mechanical behavior of frozen soils, the soil specimens should be tested with the same confining pressure, strain rate, void ratio and ice saturation in accordance with the site conditions. Figures 7 and 8 show the stress-strain behavior of the frozen CL and SP soils at different temperatures under constant strain rate of 1 mm/min and confining pressure of 200 kPa. The effect of temperature on modulus of elasticity and shear strength of the frozen soils is summarized in Table 3.

Table 3 Effect of temperature on the mechanical properties of the frozen CL and SP soils at confining pressure of 200 kPa and strain rate of 1 mm/min.

Temperature (°C)	E (kPa)		Peak Shear strength (kPa)	
	CL	SP	CL	SP
-1	19033	128831	221	3212
-2	27686	135828	299	3531
-3	33855	144230	498	3808
-4	41041	149834	735	4072
-5	52129	154122	873	4496
-6	67676	160190	1085	4792
-7	77232	171457	1353	5096
-8	83166	180916	1549	5363
-9	92064	189993	1840	5639
-10	97352	194446	2088	5920
-11	102928	201442	2183	6179

The results show that the frozen SP soil exhibits strain-softening behavior while the frozen CL soil shows strain-hardening behavior. In the frozen SP soil, a peak is observed on the stress-strain curve and the peak stress increases and shifts to the right (occurs at higher axial strain) as the temperature decreases.

In the frozen CL soil, shear strength increases until ultimate strain and no peak is observed. In the frozen CL soil, the stress-strain behavior exhibits more strain-hardening as the temperature decreases; at lower temperatures (i.e. –1°C and –2°C) the behavior of the frozen marl is nearly elastic-perfectly plastic. For both frozen CL and SP soils, the shear strength and Young's modulus increase with decreasing temperature. Under similar conditions, the Young's modulus and shear strength of the frozen SP soil is considerably higher than the frozen CL soil but the rate of increase of these parameters with temperature is much higher for the CL soil.

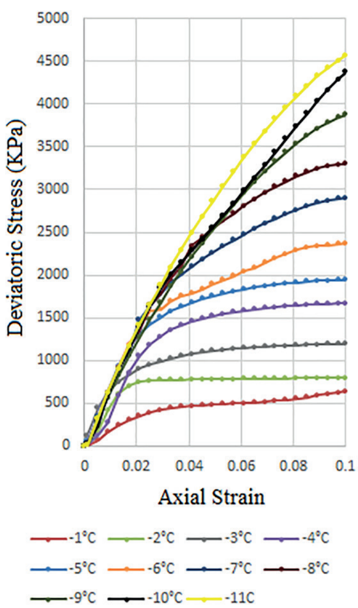

Fig. 7 Stress-strain behavior of frozen CL soil at different temperatures at confining pressure of 200 kPa and strain rate of 1 mm/min.

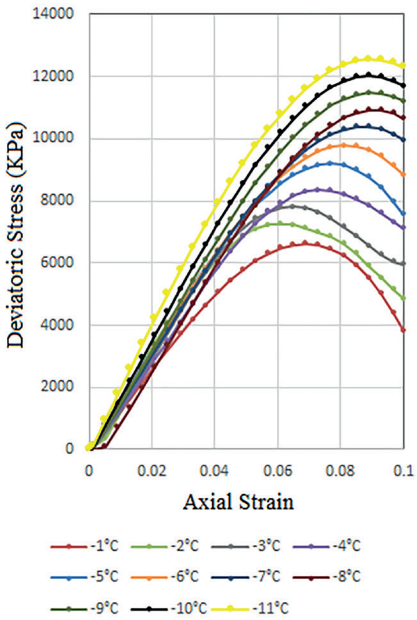

Fig. 8 Stress-strain behavior of frozen SP soil at different temperatures at confining pressure of 200 kPa and strain rate of 1 mm/min.

3.2 Effect of strain rate on the mechanical behavior of the frozen soils

To study the effect of strain rate on the mechanical behavior of frozen soils, the confining pressure, temperature, ice saturation and void ratio were kept constant. Figures 9 and 10 show the stress-strain behavior of the frozen CL and SP soils at different strain rates under constant temperature (–3°C) and confining pressure (200 kPa). The effect of strain rate on the Young's modulus and shear strength of the two soils is summarized in Table 4. The results show that, at different strain rates, the frozen SP and CP soils exhibit strain-softening and strain-hardening behavior respectively. Again, a peak stress is observed in the stress-strain curves of the SP soil while the deviator stress of the CL soil increases until ultimate strain. It appears that, by increasing the strain rate, the peak stress of the frozen SP soil slightly shifts to the right (occurs at higher strains). At all strain rates, the frozen marl shows a slight hardening behavior. The results in Table 4 and Figures 9 and 10 show that the Young's modulus and shear strength of both soils increase with increasing the strain rate. Despite the effect of temperature on the mechanical properties of frozen specimens as mentioned above, increasing strain rate leads to equal and proportional growth in the rate of increase in shear strength of both frozen CL and SP soils. Under similar conditions, the amount of increase in Young's modulus is greater for the CL soil than the SP soil.

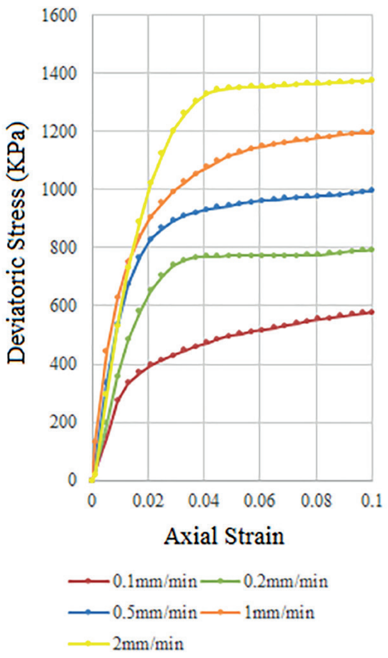

Fig. 9 Effect of strain rate on stress-strain behavior of the frozen CL soil at confining pressure 200 kPa and temperature –3°C .

Table 4 Effect of strain rate on mechanical properties of the frozen CL and SP soils at confining pressure of 200kPa and temperature of -3°C

Strain rate (mm/min)	Peak Shear Strength (kPa)		E (kPa)	
	CL	SP	CL	SP
0.1	189	1611	18840	106899
0.2	297	2262	22184	118587
0.5	398	2776	27056	133995
1	498	3808	33855	144230
2	587	4464	41922	157718

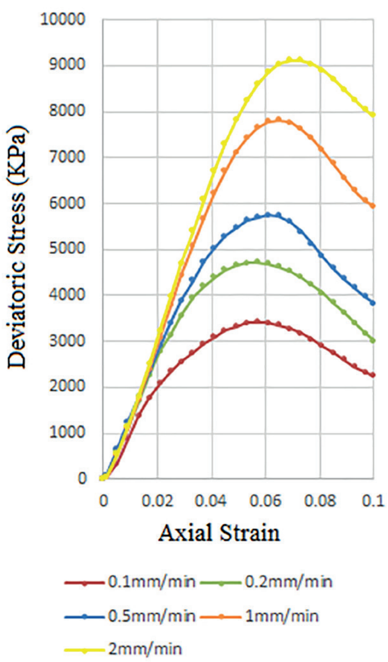

Fig. 10 Effect of strain rate on stress-strain behavior of the frozen SP soil at confining pressure 200 kPa and temperature -3°C.

3.3 Effect of confining pressure on the mechanical behavior of the frozen soils

To study the effect of confining pressure on the mechanical behavior of the frozen soils, tests were conducted at 6 different confining pressures of 0, 50, 100, 200, 400, 800 kPa under constant strain rate (1 mm/min) and constant temperature (–3°C). The effect of confining pressure on the Young's modulus and shear strength of the two soils is summarized in Table 5. Figures 11 and 12 show the stress-strain behavior of the frozen CL and SP soils at the mentioned confining pressures. As in previous tests, strain-softening and strain-hardening behaviors were observed for the frozen SP and CL soils respectively. The shear strength increases with increasing the confining pressure but the amount of increase is more for the CL soil than the SP soil. Increasing of confining pressure leads to increase in Young's modulus of the frozen CL and SP soils. Under similar conditions, the rate of increase in Young's modulus is greater for the CL soil than the SP soil.

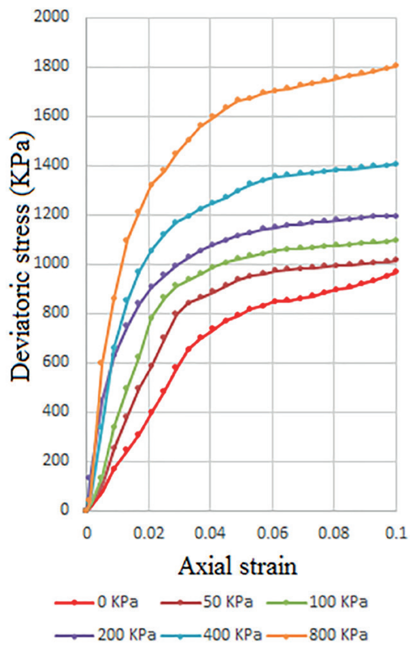

Fig. 11 Effect of confining pressure on stress-strain behavior of the frozen CL soil at temperature –3°C and strain rate 1 mm/min.

Table 5 Effect of confining pressure on geotechnical characteristics of the frozen CL and SP soils at strain rate 1 mm/min and temperature –3°C

Confining Pressure (kPa)	Peak Shear Strength (kPa)		E (kPa)	
	CL	SP	CL	SP
0	483	3799	22034	131233
50	482	3801	26850	136644
100	498	3811	30743	141161
200	498	3807	33855	144230
400	503	3811	35743	151948
800	50.2	3821	38333	155101

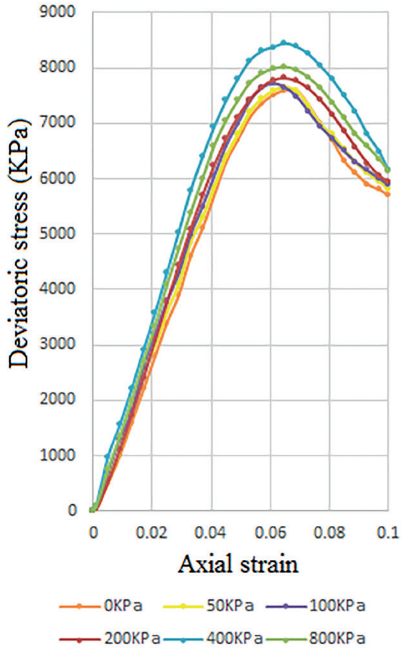

Fig. 12 Effect of confining pressure on stress-strain behavior of the frozen SP soil at temperature –3°C and strain rate 1 mm/min.

4 Conclusions

In this study, the effects of temperature, confining pressure and strain rate on the stress-strain behavior and mechanical parameters of frozen soil were examined. The study was carried out to assess the feasibility of using artificial ground freezing (AGF) for Line 2 of the Tabriz urban railway project. A program of experiments was designed and conducted on two soils obtained from the site that are the major dominant soils in the subway line 2. The specimens were remolded in accordance with the in situ soil conditions. To ensure repeatability and comparability of the tests results, ice saturation, soil particle content and void ratio were kept constant according to the in situ conditions. A special type of mold was designed and fabricated for curing the frozen samples. A triaxial compression apparatus for testing of frozen soils was designed and manufactured in the Geotechnical Laboratory of the University of Tabriz. More than 120 triaxial compression tests were conducted on the frozen specimens. It was concluded from the results that, the frozen SP and CL soils exhibit strain-softening and strain-hardening behaviors, respectively. A clear peak shear strength is observed in stress-strain curves of the SP soil, while in the case of the CL soil, the shear stress increases gradually until ultimate strain in all the tests conditions.

For both soils, the shear strength increases with decreasing temperature and increasing strain rate. However, the rate of increase is greater for the CL soil. Shear strength increases with confining pressure for the CL soil but the amount of increase in shear strength is less for the SP soil than the CL soil. Decrease in temperature results in shifting of the peak state to the right in the stress-strain curves of the frozen SP soil. At low temperatures, behavior of the CL soil is nearly elastic-perfectly plastic.

In all cases, Young's modulus increases with decreasing temperature and with increasing strain rate and confining pressure. However, the rate of increase is much greater for the CL soil. It was shown that the Young's modulus and shear strength of the frozen SP soil are much larger than the frozen CL soil in all test conditions. Based on the results, the application of the AGF method was recommended for coarse-grain and non-cohesive soils like SP in the Tabriz Subway project.

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References

[1] Ou, C.-Y., Kao, C.-C., and Chen, C.-I. "Performance and analysis of artificial ground freezing in the shield tunneling". *Journal of GeoEngineering,* 4(1), pp. 29–40. 2009. http://yo-1.ct.ntust.edu.tw/jge/files/articlefiles/v4i120090708822365976.pdf

[2] Braun, B., Shuster, J., and Burnham, E. "Ground freezing for support of open excavations". *Engineering Geology,* 13(1–4), pp. 429–453. 1979. https://doi.org/10.1016/0013-7952(79)90048-6

[3] Stoss, K. and Valk, J. "Uses and limitations of ground freezing with liquid nitrogen". *Engineering Geology,* 13(1–4), pp. 485–494. 1979. https://doi.org/10.1016/0013-7952(79)90051-6

[4] Rupprecht, E. "Application of the ground-freezing method to penetrate a sequence of water-bearing and dry formations—three construction cases". *Engineering Geology,* 13(1–4), pp. 541–546. 1979. https://doi.org/10.1016/0013-7952(79)90056-5

[5] Chamberlain, E. J. "Overconsolidation effects of ground freezing". *Engineering Geology,* 18(1–4), pp. 97–110. 1981. https://doi.org/10.1016/0013-7952(81)90050-8

[6] Da Re, G., Germaine, J. T., and Ladd, C. C. "Triaxial testing of frozen sand: Equipment and example results". *Journal of cold regions engineering,* 17(3), pp. 90–118. 2003. https://doi.org/10.1061/(ASCE)0887-381X(2003)17:3(90)

[7] Andersland, O. B. and Ladanyi, B., *Frozen ground engineering*: John Wiley & Sons, 2004.

[8] Yang, Y., Lai, Y., and Chang, X. "Laboratory and theoretical investigations on the deformation and strength behaviors of artificial frozen soil". *Cold Regions Science and Technology,* 64(1), pp. 39–45. 2010. https://doi.org/10.1016/j.coldregions.2010.07.003

[9] Xu, X., Lai, Y., Dong, Y., and Qi, J. "Laboratory investigation on strength and deformation characteristics of ice-saturated frozen sandy soil". *Cold Regions Science and Technology,* 69(1), pp. 98–104. 2011. https://doi.org/10.1016/j.coldregions.2011.07.005

[10] Zhang, S., Sun, Z., Xu, X., and Du, H. "Volumetric calculation method and temperature characteristics of frozen soil in mechanical testing". *Cold Regions Science and Technology,* 85, pp. 225–231. 2013. https://doi.org/10.1016/j.coldregions.2012.09.008

[11] Liu, J., Lv, P., Cui, Y., and Liu, J. "Experimental study on direct shear behavior of frozen soil–concrete interface". *Cold Regions Science and Technolog,* 104–105, pp. 1–6. 2014. https://doi.org/10.1016/j.coldregions.2014.04.007

[12] Zhang, Z., Zhou, H., Feng, W., Zhang, Z., and Xiao, D. "A spherical template indenter for a frozen soil long-term shear strength test". *Cold Regions Science and Technology,* 131, pp. 10–15. 2016. https://doi.org/10.1016/j.coldregions.2016.07.011

[13] Yugui, Y., Feng, G., Hongmei, C., and Peng, H. "Energy dissipation and failure criterion of artificial frozen soil". *Cold Regions Science and Technology,* 129, pp. 137–144. 2016. https://doi.org/10.1016/j.coldregions.2016.07.003

[14] Lackner, R., Amon, A., and Lagger, H. "Artificial ground freezing of fully saturated soil: thermal problem". *Journal of Engineering Mechanics,* 131(2), pp. 211–220. 2005. https://doi.org/10.1061/(ASCE)0733-9399(2005)131:2(211)

[15] Harris, J. S., *Ground freezing in practice*: Thomas Telford, 1995.

[16] Pimentel, E., Papakonstantinou, S., and Anagnostou, G. "Numerical interpretation of temperature distributions from three ground freezing applications in urban tunnelling". *Tunnelling and Underground Space Technology,* 28, pp. 57–69. 2012. https://doi.org/10.1016/j.tust.2011.09.005

[17] Sayles, F. H., "Creep of frozen sands," DTIC Document 1968.

[18] Sayles, F. H. and Haines, D., "Creep of Frozen Silt and Clay," DTIC Document. 1974.

[19] Ting, J. M., "The Creep of Frozen Sands: Qualitative and Quantitative Models," DTIC Document. 1981.

[20] Swan, C. W., "Physical mechanisms controlling the strength and deformation behavior of unfrozen and frozen Manchester fine sand," Massachusetts Institute of Technology, 1994.

[21] Da Re, G., Germaine, J. T., and Ladd, C. C., "Physical mechanisms controlling the pre-failure stress-strain behavior of frozen sand," DTIC Document. 2001.

[22] Pimentel, E., Sres, A., and Anagnostou, G., "Modelling of ground freezing in tunnelling," In: *Underground Space–The 4th Dimension of Metropolises, ITA and World Tunnel Congress 2007 and 33rd ITA/AITES Annual General Assembly.* Prague, May, 2007, pp. 331–336.

[23] Zhang, S., Lai, Y., Sun, Z., and Gao, Z. "Volumetric strain and strength behavior of frozen soils under confinement". *Cold regions science and technology,* 47(3), pp. 263–270. 2007. https://doi.org/10.1016/j.coldregions.2006.10.001

[24] Pimentel, E., Anagnostou, G., and Sres, A., "Large-scale physical model for simulation of artificial ground freezing with seepage flow". in *The 7th International Conference on Physical Modelling in Geotechnics(ICPMG 2010),* 28th June–1st July, Zurich, Switzerland, CRC Press, Zurich, 2010, pp. 379–382. https://doi.org/10.1201/b10554-59

[25] Johansson, M., "Ground freezing of weathered rock in the Mölleback zone at the Hallandsås project: Calculations for optimal freezing design," M.Sc. Master thesis, Luleå University of Technology, 2012.

[26] Zhao, X.-d., Zhou, G.-q., and Chen, G.-z. "Triaxial compression strength for artificial frozen clay with thermal gradient". *Journal of Central South University,* 20(1), pp. 218–225. 2013. https://doi.org/10.1007/s11771-013-1479-x

[27] Zhao, X., Zhou, G., and Wang, J. "Deformation and strength behaviors of frozen clay with thermal gradient under uniaxial compression". *Tunnelling and Underground Space Technology,* 38, pp. 550–558. 2013. https://doi.org/10.1016/j.tust.2013.09.003

[28] Yugui, Y., Feng, G., Yuanming, L., and Xiangxiang, Z. "Triaxial Creep Characteristic and Fractional Order Constitutive Model of Frozen Silt". *Electronic Journal of Geotechnical Engineering,* 19, pp. 3757–3768. 2014. http://www.ejge.com/2014/Ppr2014.357ma.pdf

[29] Evirgen, B., Onur, M. I., Tuncan, M., and Tuncan, A. "Determination of the Freezing Effect on Unconfined Compression Strength and Permeability of Saturated Granular Soils". *International journal of GEOMATE: geotechnique, construction materials and environment,* 8(2), pp. 1283–1287. 2015. https://doi.org/10.21660/2015.16.4369

[30] Nikookar, M., Arabani, M., Mirmoa'zen, S. M., and Pashaki, M. K. "Experimental Evaluation of the Strength of Peat Stabilized with Hydrated Lime". *Periodica Polytechnica Civil Engineering,* 60(4), pp. 491–502. 2016. https://doi.org/10.3311/PPci.8159

[31] Deák, F., Ván, P., and Vásárhelyi, B. "Hundred years after the first triaxial test". *Periodica Polytechnica. Civil Engineering,* 56(1), p. 115. 2012. https://doi.org/10.3311/pp.ci.2012-1.13

[32] Cabalar, A. F. and Clayton, C. "Effect of Temperature on Triaxial Behavior of a Sand with Disaccharide". *Periodica Polytechnica Civil Engineering,* 60(4), pp. 603–609. 2016. https://doi.org/10.3311/PPci.8631

[33] Józsa, V. "Estimation and Separation of Preconsolidation Stress Using Triaxial,-and Oedometer Test in Kiscelli Clay". *Periodica Polytechnica Civil Engineerig,* 60(2), pp. 297–304. 2016. https://doi.org/10.3311/PPci.9068

[34] Zhang, Y., Zhang, T., and Yang, P. "Investigation of Frost-Heaving Characteristics of Horizontal-Cup-Shape Frozen Ground Surface for Reinforced End Soil Mass in Shield Tunnel Construction". *Periodica Polytechnica Civil Engineering,* OnlineFirst, 2017. https://doi.org/10.3311/PPci.10169

[35] Jung, C., Jung, S., Bobet, A., and Siddiki, N. Z. "Classification of Marl Soils". 2009.

[36] Anagnostopoulos, C. A. and Grammatikopoulos, I. "The Effect of Freezing on the Strength of Silty-Clay-Sand Mixtures". *Electronic Journal of Geotechnical Engineering,* 10, 2005. http://www.ejge.com/2005/Ppr0608/Ppr0608.htm

[37] Yugui, Y. "Experimental and Theoretical Investigations on the Deformation Characteristic of Frozen Silt in Underground Engineering". *Electronic Journal of Geotechnical Engineering,* 19(1), pp. 1883–94. 2014. http://www.ejge.com/2014/Ppr2014.181ma.pdf

[38] Xue-lei, C., Shun-qun, L., and Shi-juan, S. "Application of Principal Component Analysis in the Microstructure of Frozen Soil". *Electronic Journal of Geotechnical Engineering,* 18(1), 2013. http://www.ejge.com/2013/Ppr2013.158alr.pdf

[39] Yang, Y., Wei, Z., Yin, G., Wang, J., Wang, W., and Chen, Y. "Uniaxial compression test of frozen tailings". *Cold Regions Science and Technology,* 129, pp. 60–68. 2016. https://doi.org/10.1016/j.coldregions.2016.06.007

[40] Xu, X., Wang, Y., Bai, R., Fan, C., and Hua, S. "Comparative studies on mechanical behavior of frozen natural saline silty sand and frozen desalted silty sand". *Cold Regions Science and Technology,* 132, pp. 81–88. 2016. https://doi.org/10.1016/j.coldregions.2016.09.015

[41] Casini, F., Gens, A., Olivella, S., and Viggiani, G., "Triaxial tests on frozen ground: formulation and modelling," in *Computational Plasticity XII: Fundamentals and Applications-Proceedings of the 12th International Conference on Computational Plasticity*, 2013, pp. 534–541.

[42] Collins, I. and Houlsby, G., "Application of thermomechanical principles to the modelling of geotechnical materials," in *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*. 453(1964), pp. 1975–2001. 1997. https://doi.org/10.1098/rspa.1997.0107

[43] Lai, Y., Xu, X., Yu, W., and Qi, J. "An experimental investigation of the mechanical behavior and a hyperplastic constitutive model of frozen loess". *International Journal of Engineering Science,* 84, pp. 29–53. 2014. https://doi.org/10.1016/j.ijengsci.2014.06.011

[44] Yang, Z. J., Still, B., and Ge, X. "Mechanical properties of seasonally frozen and permafrost soils at high strain rate". *Cold Regions Science and Technology,* 113, pp. 12–19. 2015. https://doi.org/10.1016/j.coldregions.2015.02.008

[45] Li, Q., Ling, X., and Sheng, D. "Elasto-plastic behaviour of frozen soil subjected to long-term low-level repeated loading, Part I: Experimental investigation". *Cold Regions Science and Technology,* 125, pp. 138–151. 2016. http://dx.doi.org/10.1016/j.coldregions.2015.11.015

[46] Li, Q., Ling, X., and Sheng, D. "Elasto-plastic behaviour of frozen soil subjected to long-term low-level repeated loading, Part II: Constitutive modelling". *Cold Regions Science and Technology,* 122, pp. 58–70. 2016. https://doi.org/10.1016/j.coldregions.2015.11.009

[47] ASTM International. "*D2487 (2011) Standard practice for classification of soils for engineering purposes (Unified Soil Classification System)*". In: *Standard, ASTM*, ed, 2011.

[48] ASTM International. "*D4083-89 (2016) Standard Practice for Description of Frozen Soils (Visual-Manual Procedure)*". In: *Standard, ASTM*, ed, 2016.