Influence of soil salinity on the bearing capacity of the frozen wall

Mikhail Semin, Lev Levin, Sergey Bublik
Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russia
seminma@inbox.ru https://orcid.org/0000-0001-5200-7931
aerolog_lev@mail.ru https://orcid.org/0000-0003-0767-9207
serega-bublik@mail.ru https://orcid.org/0000-0002-2084-0002

Andrey Brovka, Ivan Dedyulya
Institute of Natural Resources Management of the National Academy of Sciences, Minsk, Belarus
andrew_brovka@rambler.ru, dedyulyaivan@yandex.by

Frattura ed Integrità Strutturale – Fracture and Structural Integrity

Visual Abstract

Influence of soil salinity on the bearing capacity of the frozen wall

Mikhail Semin, Lev Levin, Sergey Bublik
Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russia
Andrey Brovka, Ivan Dedyulya
Institute of Natural Resources Management of the National Academy of Sciences, Minsk, Belarus

Citation: Semin, M., Levin, L., Bublik, S., Brovka, A., Dedyulya, I., Influence of soil salinity on the bearing capacity of the frozen wall, Frattura ed Integrità Strutturale, 69 (2024) 106-114.

Received: 11.03.2024
Accepted: 25.04.2024
Published: 26.04.2024
Issue: 07.2024

KEYWORDS. Artificial ground freezing, Frozen wall, Dissolved salt, Ultimate long-term strength, Unfrozen water content, Mine shaft.

INTRODUCTION

The construction of underground structures in unstable and water-saturated soils is carried out using special methods [1, 2]. When sinking vertical shafts in potash mines, the most common special method is artificial ground freezing (AGF) [1]. The primary reason for this is that the productive formations of potassium-magnesium salts are soluble in water, making it especially important to prevent the penetration of groundwater through the water-protective layer to reach the productive strata [3].

An additional challenge in constructing potash mine shafts is the presence of salt in the groundwater of supra-salt strata near the contact with the water-protective strata. This situation occurs, for example, at the Verkhnekamsk deposit of potassium and magnesium salts. According to [1], during the excavation of shaft No. 2 of the First Solikamsk potash mine, an unfrozen brine was encountered with a complex composition of dissolved salts (NaCl, KCl, $MgCl_2$, $CaCl_2$, and $CaSO_4$) with a total mineralization of more than 335 g/l and a freezing point of about -41 °C.

The presence of dissolved salt in frozen soils slows down the phase transition of pore water into ice. By shifting the phase transition to lower temperatures in the presence of dissolved salt, saline soils will cool slightly faster compared to situations without salt. Moreover, according to data from [4], the amount of unfrozen water will increase more rapidly with an increase in the initial amount of dissolved salt in the pore space. Considering that the unfrozen water content in soils significantly affects its strength properties [5], an increase in the salinity of frozen soils will lead to a decrease in the bearing capacity of the frozen wall (FW).

In this situation, the question arises of how to correctly determine the boundaries of the FW. In [4], an attempt was made to calculate the FW thickness in saline soils, considering the 'floating' isotherm of the FW boundaries. This isotherm was determined based on the actual freezing point of the pore water with a variable salt amount, determined by solving heat and mass transfer equations in the frozen soil mass. However, this approach did not account for another important circumstance: an increase in the salt amount in the pore water leads not only to a shift in the freezing point of pore water but also to a flatter appearance of the soil freezing characteristic curve, as will be shown in the present study. This results in an additional decrease in the strength of frozen soils and the bearing capacity of the frozen wall as a whole.

A comprehensive assessment of the actual bearing capacity of the FW in the presence of dissolved salts can only be made through thermomechanical analysis of the freezing of saline soils. To achieve this, it is necessary, first and foremost, to conduct laboratory experiments to determine the strength properties of frozen soils at different amounts of dissolved salt in the pore water. Additionally, it is essential to analyze the experimental dependencies of the strength properties of various types of soils on the salt amount in their pore space. The present study is dedicated to addressing this issue.

In general, the determination of mechanical and strength properties of frozen soils containing dissolved salt has been addressed in numerous studies within the field of permafrost science [6-17]. Previous studies have explored the influence of temperature and unfrozen water content on soil strength properties [6], investigated the time dynamics of frozen soil strength properties [7], and examined changes in mechanical and strength properties under high-cycle temperature loading conditions [8, 9].

A number of studies on the impact of dissolved salt on the strength criterion of frozen soil are presented in the literature [13]. The most common criteria for soils are the Matsuoka-Nakai and the Lade-Duncan criteria [14]. Much attention is given to modifying these criteria to account for the nonlinearity of the critical state line. Liao et al. [15] proposed a strength criterion for frozen saline soils, considering the influence of salt content, using the generalized nonlinear strength theory. Zhao et al. [16] developed a constitutive model for frozen saline soil, considering plastic deformation caused by the increase in principal stress amplitude and the plastic deformation caused by the rotation of principal stress axes separately. Simultaneously, Zhao et al. [17] showed that a significant deviation from the nonlinear profile of the critical state line for saline silty clay occurs only at a confining pressure of more than 6 MPa. Zhang et al. [18] and Yang et al. [19] proposed modifications to the criteria for the strength of frozen soils, where the nonlinear nature of the critical state line also appears for the first time at high confining pressures of more than 6 MPa.

It is rarely necessary to deal with such high confining pressures in geomechanical calculations of frozen wall (FW) parameters for mine shafts under construction. During the construction of the mine shafts of the Petrikovsky potash mine, the maximum pressure on the outer boundary of FW was 2.3 MPa (the depth of the freezing interval is 275 m). During the construction of the mine shafts of the Darasinsky potash mine, the maximum pressure on the outer boundary of FW was 2.1 MPa (the depth of the freezing interval is 185 m). Additionally, existing complex nonlinear criteria have many unknown empirical parameters, which require mechanical tests on samples under a wide range of loads to determine [20]. However, in engineering practice of shaft sinking, metro tunnel construction, etc., it is often impractical to conduct a large number of experimental research and determine the entire range of model parameters. Therefore, preference is given to simpler models that use strength criteria based on a small number of parameters: structural cohesion, angle of internal friction, and strength for uniaxial compression.

At the same time, the impact of soil salinity on the structural integrity of frozen soils under low confining pressures within the Mohr-Coulomb criterion framework is inadequately explored in the literature. Kutergin et al. [10] determined cohesion and the angle of internal friction for eight different concentrations of dissolved salt in frozen samples of clays and loams from Upper Pleistocene and Middle Pleistocene marine sediments of the Salekhard Formation. Ogata et al. [11] investigated the effects of salt concentration on the strength and creep behavior of artificially frozen sands and clays, exploring the dependence of compressive strength on unfrozen water content in soils. However, the analysis of this dependence only considers one type of salt (sodium chloride) and two salt concentrations. Existing works have predominantly focused on a single type of salt and typical soils such as clay, sand, and loam, excluding chalk, which is frequently encountered in the freezing depth interval during the construction of potash mine shafts [21].

Concerning frozen walls (FW), the impact of dissolved salt on the strength properties of frozen soils has been noted only qualitatively in a study [5]. In another study [22], the freezing of saline soil was considered using a complex thermo-hydro-mechanical model, but the mechanical part of the model only considered elastic deformation, neglecting a crucial aspect: the strength of frozen soils. The bearing capacity of artificially frozen soils during the excavation of mine shafts is determined based on the strength properties of the soils, as well as their creep properties.

The facts noted above indicate the significance of studying the strength characteristics of frozen soils containing dissolved salt. This issue is the subject of our study, aimed at elucidating the effect of dissolved salt on the uniaxial long-term strength of two types of soils. These findings are further used to evaluate the load-bearing capacity of the frozen wall during the construction of mine shafts.

MATERIALS AND METHODS

The impact of salt concentration in the pore water of soils on long-term strength was investigated using soil samples previously selected for excavation of mine shaft No. 1 of the Darasinsky potash mine:

1. Chalk (white light gray, highly plastic) from a depth of 128 ÷ 130 m of the Cenomanian-Turonian terrigenous-carbonate layer (K2s2-t).
2. Clay (dark gray, dense, tightly plastic) from a depth of 136 ÷ 140 m of the Polesie weakly water-bearing terrigenous complex (D2pl).

Chalk and clay were crushed using a laboratory mill and sifted through a 5 mm mesh sieve to eliminate foreign inclusions from the selected soils. Salt, in powder form, was added and thoroughly mixed with the solid soil particles. Three types of salts were studied ($NaCl$, KCl, and $CaCl_2$), corresponding to the parameters of GOST 4234-77, GOST 4233-77, and TU 6-094711-81. The calculated amounts of salt required to lower the freezing point of the sample by a given value are presented in Tab. 1.

Salt	The amount of salt (per 100 g of water) to reduce the freezing point by Δt	
	Δt=3 °C	Δt=6 °C
$NaCl$	5.15	10.3
KCl	6.8	–
$CaCl_2$	–	10.1

Table 1: Calculated salt amounts to ensure a decrease in the freezing point by a given amount.

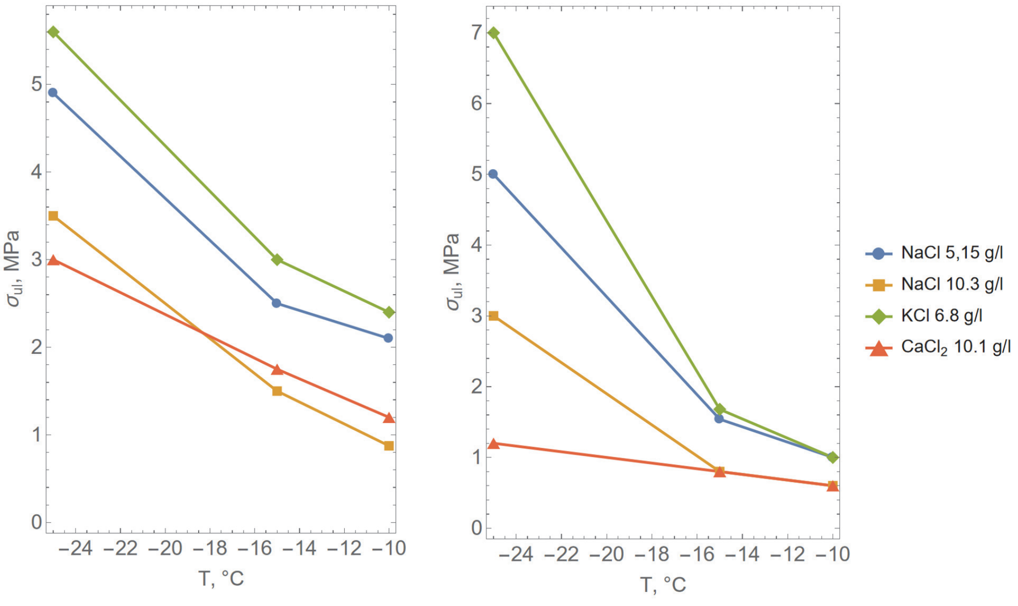
Subsequently, each processed soil mass was thoroughly mixed, filled with a pre-calculated amount of distilled water, placed in an airtight container, and kept for seven days. Preliminary experiments indicated that this time is sufficient for the uniform distribution of water throughout the entire pore volume of the sample. Following this period, the water content of the materials was determined and considered as the initial water content.

For chalk, the water content was set at 0.23 kg/kg, while for clay, it was set to 0.27 kg/kg. The density of frozen chalk ranged from 1940 to 2010 kg/m³, and for clay, it ranged from 1900 to 1930 kg/m³. It is important to note that the freezing point of the studied soil samples in the absence of salt was -0.1 °C for chalk and -1.4 °C for clay.

To analyze the unfrozen water content, a calorimetric installation was employed, developed based on the principle of creating adiabatic conditions or conditions of controlled heat exchange around the calorimetric beaker with the test sample [23, 24]. The accuracy of temperature measurement is 0.01 °C, and the relative error in determining the heat of phase transition is 1%.

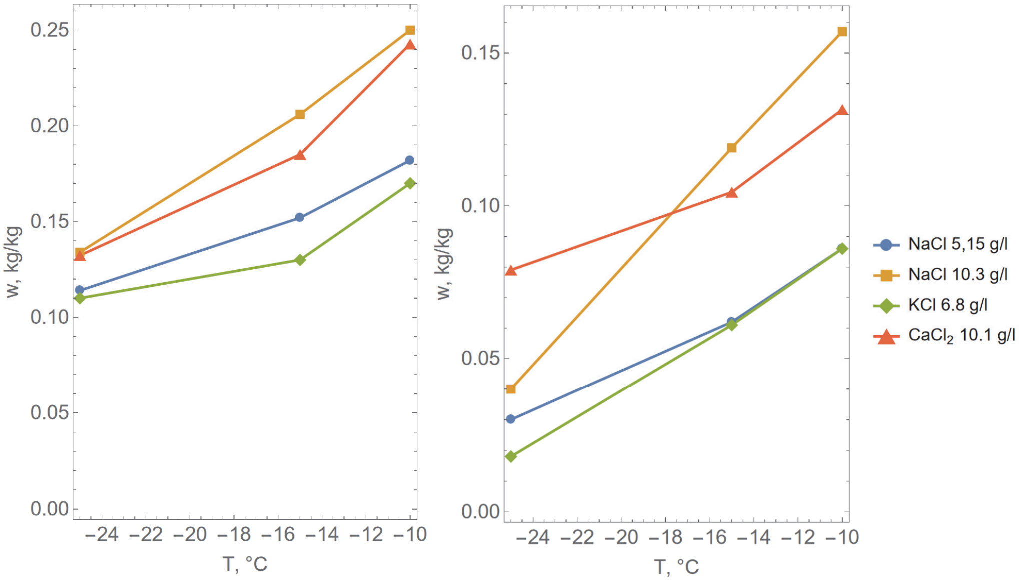
To investigate the strength characteristics of the two considered soil types, laboratory tests were conducted for ultimate long-term strength under uniaxial compression in the temperature range from -10 °C to -25 °C. The testing complex of instruments "ASIS" from LLC NPP "Geotek" was utilized, allowing for the periodic increase of the vertical load on a cylindrical sample at a given time interval in steps (4 hours), while recording vertical deformation over time. Loading steps for frozen soil samples varied in the range from 100 to 1000 kPa, depending on preliminary experimental measurements of the instantaneous strength of the soil samples. The higher the instantaneous strength was, the higher the corresponding step was when calculating the ultimate long-term strength. All experiments were performed at the Institute of Environmental Management of the National Academy of Sciences in Minsk.

Prepared samples were placed in a rubber shell and positioned on the ASIS work table. The experiment commenced with the compression of the sample: for thirty minutes, the sample sustained a load equal to half the planned load of the first stage of the research. Following this procedure, the load for the first stage was established and maintained for four hours. Subsequently, the load for the second stage was automatically set, and so forth. The experiment concluded either upon the destruction of the sample (in which case, the load dropped abruptly) or upon reaching a relative linear deformation of 20%. Upon completion of the experiment, the moisture content of the studied material was determined.



(a) (b)

Figure 1: Temperature dependences of the ultimate long-term uniaxial compressive strength for clay (a) and chalk (b).



(a) (b)

Figure 2: Temperature dependences of the unfrozen water content for clay (a) and chalk (b).

RESULTS AND DISCUSSION

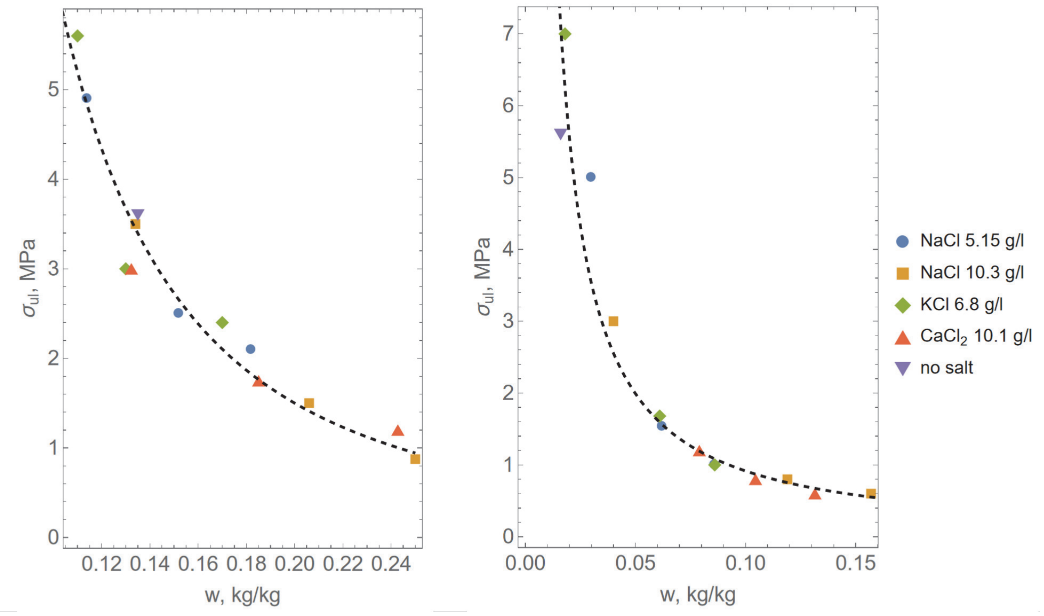
The experimentally determined ultimate long-term strengths of saline clay and chalk samples under uniaxial compression at various temperatures are presented in Fig. 1. Fig. 2 shows the temperature dependencies of the unfrozen water content for the same clay and chalk samples. In general, the figures illustrate that the strength and unfrozen water content of soils are influenced by both the type of salt and its content. The soil that freezes most quickly is the one containing KCl salt in an amount of 6.8 g/l and NaCl salt in an amount of 5.15 g/l. The freezing points of pore water were -3.3 °C for chalk and -4.9 °C for clay.

Soils containing $CaCl_2$ salt in an amount of 10.1 g/l and NaCl salt in an amount of 10.3 g/l freeze comparatively more slowly. The actual freezing point of pore moisture for $CaCl_2$ was -6.55 °C for chalk and -8.05 °C for clay. The actual freezing point for the NaCl solution (10.1 g/l) was -6.75 °C for chalk and -8.6 °C for clay.

In general, the dependences $\sigma_{ul}(T)$ and $w(T)$ exhibit a good inverse correlation. This is evident from the range of values of the Pearson correlation coefficient [25], calculated for each pair of curves in Figs. 1-2 (see Tab. 2). Given this observation, it is of interest to analyze the dependence of the ultimate strength of the considered soil samples not on temperature, but on the unfrozen water content. To achieve this, the dependences $\sigma_{ul}(T)$ and $w(T)$ were transformed into the dependence $\sigma_{ul}(w)$, which is presented in Fig. 3.

Soil	NaCl (5.15 g/l)	NaCl (10.3 g/l)	KCl	$CaCl_2$
Chalk	-0.95	-0.97	-0.96	-0.98
Clay	-0.95	-0.99	-0.86	-0.97

Table 2: Calculated salt amounts to ensure a decrease in the freezing point by a given amount.



(a) (b)

Figure 3: Dependence of the ultimate long-term uniaxial compressive strength on the unfrozen water content of soils: clay (a) and chalk (b).

Individual experimental points are approximated using power functions of the form aw^b, as shown by the dotted black lines in Fig. 3. The coefficients a and b were selected by minimizing the standard deviations of the approximating curve from the experimental points. The resulting dependencies for chalk and clay take the form:

$$\sigma_{ul}^{clay} = 0.053w^{-2.08} \tag{1}$$

$$\sigma_{ul}^{chalk} = 0.069w^{-1.12} \tag{2}$$

Upon analyzing Fig. 3, a crucial conclusion emerges that the ultimate long-term strength of frozen soils is primarily determined by their unfrozen water content. The dependence of the ultimate long-term strength on the amount and type of dissolved salt is realized mainly indirectly through the dependence of the unfrozen water content on the salt parameters. Dependencies (1)-(2) enable the approximate estimation of the decrease in the bearing capacity of the FW in the presence of dissolved salt in frozen soil layers. If we assess the load-bearing capacity of an FW in terms of the maximum load *P* on the side wall of the FW [26], then the limiting state of the FW can be expressed by a criterion dependence of the form:

$$\frac{P}{\sigma_{ul}} = f\left(\frac{E}{a}, \frac{b}{a}, \ldots\right) \tag{3}$$

where E is the thickness of the FW, m; *b* is the outer boundary of the FW, m; *a* is the internal boundary of the FW, m. Instead of σ_{ul} in (3), structural cohesion *C* [27] or nonlinear deformation modulus *A* [28] can be used, depending on the bearing capacity loss criterion used. However, all these characteristics most often change in proportion to each other. The parameter *P* in criterion dependencies (3) is usually understood as the total rock and hydrostatic pressure acting on the outer wall of the FW. Based on the known value *P*, the thickness *E* is calculated. However, if we do the opposite, and use the actual thickness of the FW $E=b-a$ and its boundaries *a* and *b* to determine the value *P*, the result will be the maximum external load that the actual FW can withstand. The actual values of the geometric parameters can be estimated, for example, based on data from continuous temperature monitoring of the FW state [22, 29].

From (3) it follows that when the σ_{ul} value changes, the maximum external load will change proportionally:

$$\frac{P}{P_0} = \frac{\sigma_{ul}}{\sigma_{ul0}} \tag{4}$$

where the index “0” denotes values in a certain initial state, by which we will mean the state of frozen soil that do not contain dissolved salt.

An assessment of the decrease in the average ultimate long-term strength of the frozen soil volume that forms the FW was conducted using data from numerical simulation of heat and mass transfer processes. The mathematical model utilized in this study was described earlier in [4]. The model accounts for the formation of the FW in a horizontal layer of saline soils, resulting from gradual heat removal through the contour of vertical freeze pipes. Fig. 4 illustrates the radial distributions of unfrozen water content in the frozen layers of clay and chalk, calculated using the model.

The initial model water content (w_0) of chalk is 0.25 kg/kg, and the initial model water content of clay is 0.26 kg/kg. The thermophysical properties of the frozen media used in the simulation were determined through laboratory tests on chalk and clay samples taken from the same depth interval during the excavation of mine shaft No. 1 of the Darasinsky potash mine. For other parameters of the model and numerical method, please refer to [4].

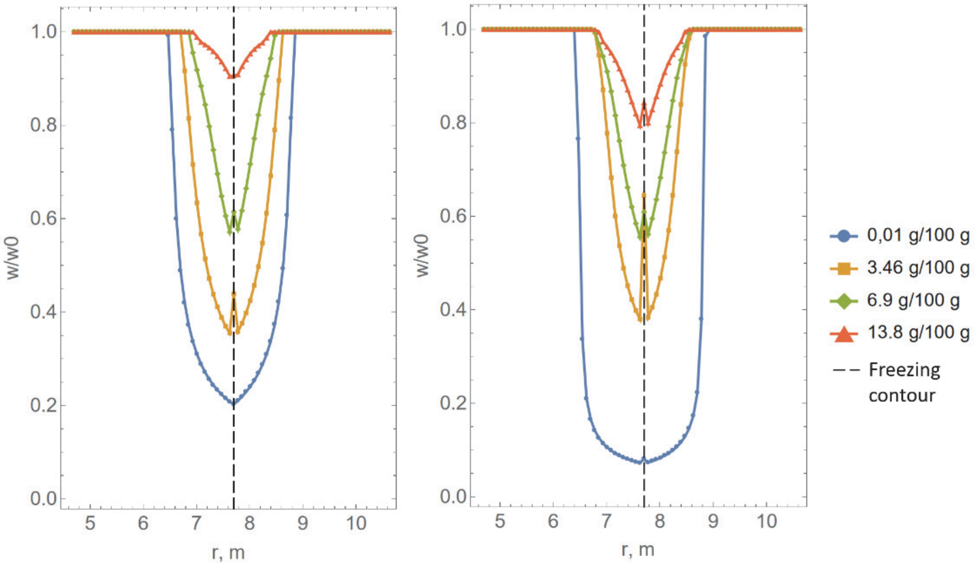
The calculated distributions of unfrozen water content were used to recalculate the average ultimate long-term strength, $\langle \sigma_{ul} \rangle$, using the formula:

$$\langle \sigma_{ul} \rangle = \frac{2\pi}{S_\Omega} \int_\Omega \sigma_{ul}(w) r dr \tag{5}$$

where *r* is the radial coordinate, m; *Ω* is the FW region, where $w < w_0$ (i.e. the temperature is below the freezing point); S_Ω – area of region *Ω* in a horizontal section of the soil mass, m^2.

Tab. 3 shows the calculated average ultimate long-term strengths at different salt amounts in the chalk and clay layers. This table also presents the values of the maximum load-bearing capacity of the FW, calculated using formula (4) taking into account the values of P_0 for chalk (1.64 MPa) and clay (2.12 MPa) [30]. The pressure acting normal to the outer wall of the

FW was determined for each soil layer based on its depth according to field studies as part of the project for AGF at the shafts of the Darasinsky mine under construction in the Republic of Belarus.



(a) (b)

Figure 4: Calculated radial distributions of unfrozen water content in frozen layers of clay (a) and chalk (b).

Soil	NaCl salt amount			
	0.01 g/ 100 g	3.46 g/ 100 g	6.9 g/ 100 g	13.8 g/ 100 g
	Ultimate long-term strength, MPa			
Chalk	3.85	0.62	0.45	0.37
Clay	11.6	4.01	1.56	0.95
	Ultimate bearing capacity, MPa			
Chalk	1.64	0.26	0.19	0.16
Clay	2.12	0.73	0.28	0.17

Table 3: Calculated values of the average ultimate long-term strength and ultimate bearing capacity of frozen wall in layers of chalk and clay at different salt amounts.

It is evident from Tab. 3 that an increase in salt amount in the soil significantly reduces the maximum bearing capacity of the soil. The most substantial reduction occurs when the salt amount increases from 0.01 g to 3.46 g per 100 g of water. For chalk, the ultimate load-bearing capacity decreases by 83.9%, and for clay, it decreases by 84.1%. Subsequent increases in salt amount result in a less significant decrease in the ultimate bearing capacity.

An increase in salt amount from 0.01 g to 3.46 g per 100 g of water also leads to a reduction in the frozen wall (FW) thickness, calculated from the freezing point isotherm. However, this decrease is not as pronounced, amounting to 25.8% for chalk and 23.3% for clay. This quantitative assessment was conducted by calculating the width of the zone ($w < w_0$) on the curves in Fig. 4. While the reduction in thickness contributes to the overall decrease in the ultimate bearing capacity of the FW, a more significant factor is the decrease in the strength of the soils due to a higher unfrozen water content in the pore space of the soils composing the FW. This finding suggests that when designing AGF, the effect of dissolved salt should be considered not only in the expression for the onset of freezing point used to determine the boundaries of the FW but also in geomechanical assessments of the load-bearing capacity of the FW.

CONCLUSIONS

Experimental studies were conducted on the thermophysical and strength properties of frozen chalk and clay samples containing dissolved salt. The temperature range considered was from −10 to −25 °C, with three types of salt (NaCl, KCl, and $CaCl_2$) under investigation. Various amounts of NaCl in the pore solution were studied. The findings revealed that the ultimate long-term strength of the studied soils is primarily determined by the unfrozen water content. The influence of the amount and type of dissolved salt on soil strength is realized indirectly through the unfrozen water content. The soil freezing characteristic curve significantly depends on both the type of dissolved salt and its quantity. A theoretical analysis of the maximum load-bearing capacity of a frozen wall formed by a circular contour of freeze pipes in clay and chalk layers was conducted. It was demonstrated that the ultimate bearing capacity of the frozen wall decreases significantly when dissolved salt is present in the pore space of soils. Two factors contributing to the decrease in ultimate bearing capacity were identified: 1) a reduction in the thickness of the frozen wall and 2) a decrease in the strength of the frozen soils due to an increase in the unfrozen water content of the soils forming the frozen wall. The second factor was found to be more significant.

The obtained results serve as the foundation for further studies on coupled thermo-hydro-mechanical processes occurring in frozen soils containing dissolved salt.

ACKNOWLEDGEMENTS

The research was carried out with the financial support of the Russian Ministry of Education and Science within the framework of project No. 122030100425-6 and the Ministry of Education and Science of the Perm Territory within the framework of project C/26-563.

REFERENCES

[1] Olkhovikov, Yu. P. (1984). Support of capital workings of potassium and salt mines, Moscow, Nedra, 238 p.

[2] Nikolaev, P., Jivkov, A., Margetts, L. and Sedighi, M. (2024). Modeling artificial ground freezing subject to high velocity seepage. International Journal of Heat and Mass Transfer, 221, 125084. DOI: 10.1016/j.ijheatmasstransfer.2023.125084.

[3] Semin, M. A. and Bublik, S. A. (2023). Phase Transitions in Saline Pore Water in Artificial Ground Freezing. Journal of Mining Science, 59 (4), pp. 611-620. DOI: 10.1134/S1062739123040117.

[4] Bublik, S., Semin, M., Levin, L., Brovka, A. and Dedyulya, I. (2023). Experimental and Theoretical Study of the Influence of Saline Soils on Frozen Wall Formation. Applied Sciences, 13 (18), 10016. DOI: 10.3390/app131810016.

[5] Hu, X. D., Zhao, F. and Yu, R. Z. (2010). Safety Problem of Freezing Projects in Saline Soils. Ground Improvement and Geosynthetics, pp. 255-262. DOI: 10.1061/41108(381)33.

[6] Li, K., Li, Q. and Liu, C. (2022). Impacts of Water Content and Temperature on the Unconfined Compressive Strength and Pore Characteristics of Frozen Saline Soils. KSCE Journal of Civil Engineering, 26 (4), pp. 1652-1661. DOI: 10.1007/s12205-022-1037-x

[7] Kotov, P. I. and Stanilovskaya, J. (2022). Predicting changes in the mechanical properties of frozen saline soils. European Journal of Environmental and Civil Engineering 2022, 26 (12), pp. 5716-5728. DOI: 10.1080/19648189.2021.1916604.

[8] Ding, Q., Hu, Z., Huang, S., Chen, K., Liu, Y. and Ding, L. (2022). An Investigation of Non-Linear Strength Characteristics of Solidified Saline Soils in Cold Regions. Materials, 15(21), 7594. DOI: 10.3390/ma15217594.

[9] Han, Y., Wang, Q., Wang, N., Wang, J., Zhang, X., Cheng, S. and Kong, Y. (2018). Effect of freeze-thaw cycles on shear strength of saline soil. Cold Regions Science and Technology, 154, pp. 42-53.

[10] Kutergin, V. N., Kal'bergenov, R. G., Karpenko, F. S., Leonov, A. R. and Merzlyakov, V. P. (2012). Influence of salinity on rheologic and strength properties of frozen soils in Yamal. Soil Mechanics and Foundation Engineering, 49, pp. 105-110.

[11] Ogata, N., Yasuda, M. and Kataoka, T. (1983). Effects of salt concentration on strength and creep behavior of artificially frozen soils. Cold Regions Science and Technology, 8(2), pp. 139-153.

[12] Xu, X., Wang, Y., Bai, R., Zhang, H. and Hu, K. (2016). Effects of sodium sulfate content on mechanical behavior of frozen silty sand considering concentration of saline solution. Results in physics, 6, pp. 1000-1007.

[13] Roman, L. T. (1994). Effect of chemical composition of soils on the strength and deformability of frozen saline soils. Soil Mechanics and Foundation Engineering, 31(6), pp. 205-210. DOI: 10.1007/BF02335068

[14] Zhao, Y., Lai, Y., Zhang, J. and Wang, C. (2018). A nonlinear strength criterion for frozen sulfate saline silty clay with different salt contents. Advances in Materials Science and Engineering, pp. 1-8.

[15] Liao, M., Lai, Y. and Wang, C. (2016). A strength criterion for frozen sodium sulfate saline soil. Canadian Geotechnical Journal, 53(7), pp. 1176-1185.

[16] Zhao, Y., Lai, Y., Zhang, J. and Bai, R. (2020). A bounding surface model for frozen sulfate saline silty clay considering rotation of principal stress axes. International Journal of Mechanical Science, 177, 105570.

[17] Zhao, Y., Lai, Y., Zhang, J. and Wang, C. (2018). A nonlinear strength criterion for frozen sulfate saline silty clay with different salt contents. Advances in Materials Science and Engineering, 2018, pp. 1-8.

[18] Zhang, D., Liu, E., Liu, X., Zhang, G. and Song, B. (2017). A. new strength criterion for frozen soils considering the influence of temperature and coarse-grained contents. Cold Regions Science and Technology, 143, pp. 1-12.

[19] Yang, Y., Gao, F. and Lai, Y. (2013). Modified Hoek–Brown criterion for nonlinear strength of frozen soil. Cold Regions Science and Technology, 86, pp. 98-103.

[20] Lai, Y., Yo, Z. and Zhang, J. (2021). Constitutive models and salt migration mechanisms of saline frozen soil and the-state-of-the-practice countermeasures in cold regions. Sciences in Cold and Arid Regions, 13(1), pp. 1-17.

[21] Semin, M., Golovatyi, I., Levin, L. and Pugin, A. (2024). Enhancing efficiency in the control of artificial ground freezing for shaft construction: A case study of the Darasinsky potash mine. Cleaner Engineering and Technology, 18, 100710.

[22] Tounsi, H., Rouabhi, A. and Jahangir, E. (2020). Thermo-hydro-mechanical modeling of artificial ground freezing taking into account the salinity of the saturating fluid. Computers and Geotechnics, 119, 103382.

[23] Brovka, A. G. and Romanenko, I.I. (2009). Instruments and methods for studying the thermophysical characteristics and phase composition of rock water at negative temperatures. Mining mechanics, 1, pp. 71-79.

[24] Brovka, G. P. (2012). Methods of laboratory research and computer modeling of the processes of transfer of heat, moisture, water-soluble compounds and the formation of a stress-strain state in natural dispersed media. Nature Management, 22, pp. 231-246.

[25] Devlin, S. J., Gnanadesikan, R. and Kettenring, J. R. (1975). Robust estimation and outlier detection with correlation coefficients. Biometrika, 62(3), pp. 531-545.

[26] Levin, L., Semin, M. and Golovatyi, I. (2023). Analysis of the structural integrity of a frozen wall during a mine shaft excavation using temperature monitoring data. Frattura ed Integrità Strutturale, 17 (63), pp. 1-12.

[27] Zhang, B., Yang, W. and Wang, B. (2018). Plastic Design Theory of Frozen Wall Thickness in an Ultradeep Soil Layer Considering Large Deformation Characteristics. Mathematical Problems in Engineering, 8513413.

[28] Vyalov, S.S. (1962). Strength and creep of frozen soils, and calculations of ice-soil barriers. Moscow, Publishing House of the USSR Academy of Sciences, 253 p.

[29] Manassero, V. (2019). Monitoring artificial ground freezing and relevant fundamental observations. Tunnels and Underground Cities. Engineering and Innovation Meet Archaeology, Architecture and Art CRC Press, pp. 1389-1398.

[30] Semin, M. A., Brovka, G. P., Pugin, A. V., Bublik, S. A. and Zhelnin, M. S. (2021). Effects of temperature field nonuniformity on strength of frozen wall in mine shafts. Mining Information and Analytical Bulletin (scientific and technical journal), 2021(9), pp. 79-93.