ON THE CORRELATION OF ELASTIC AND STRENGTH PROPERTIES FOR SALINE FROZEN SOILS

Oksana P. Chervinskaya\textsuperscript{1}, Anatoly D. Frolov\textsuperscript{2}, Yury D. Zykov\textsuperscript{3}

1. Research Institute of Engineering Prospecting for Construction
2. Consolidated Scientific Council on Earth Cryology RAS, Fersmann Street 11, Moscow 117289, Russia
e-mail ipquis@redline.ru
3. Geological Faculty, Moscow State University, Vorobjovy Gory, Moscow 119899, Russia

Abstract

The elastic and strength properties of frozen soils are controlled by their spatial cryogenic crystalline-coagulant structure (SCCS). The main features of saline sandy-clayey soils SCCS which begin to take shape at certain critical initial concentration ($C_{ps}$) of saturating pore solution are considered in this paper. Experimental data on dynamic elastic and strength characteristics of frozen saline soils with a wide range of pore solution concentration and composition are presented and discussed. Correlations are established between elastic and strength parameters and show that the strength can be estimated using acoustical studies of saline frozen soils. The results obtained are in a good agreement with the measured values $C_{cr}$ for soils with a variety of plasticity indices.

Introduction

From the basic concepts of physical-chemical mechanics, as laid out in works of Rebinder, Shchukin and their school (Rebinder, 1979), the elasticity, strength and other properties of frozen soils related to their deformability are chiefly controlled by their spatial cryogenic crystalline-coagulant structure (SCCS) (Frolov, 1976; Frolov and Seguin, 1993).

Saline frozen soils differ from nonsaline ones in having lower temperatures for phase transition of the pore solution and therefore, at higher liquid phase contents, the latter is found in the soil as semi-discrete or discrete accumulations at inter-grain zones. At the same time, an energy state of the pore liquid undergoes changes. The ice matrix in saline frozen soils also appears essentially different; it comprises fine-crystalline saline ice consisted of doped crystals and inclusions of liquid phase (brine). These special features depend on the chemical composition of dissolved salts, their contents, grain mineralogy (which controls their adsorptivity), as well as on the range of particle dimensions in the soil skeleton (on which the active surface area depends). All those features are ultimately reflected in changes of strength and elasticity characteristics of the medium under consideration.

Two different cases may occur if SCCS is formed in frozen soils with different initial concentrations of the pore solution ($C_{ps}$). In the first case (under low $C_{ps}$) the mineral matrix is of dominant importance. This variant may be considered typical of nonsaline soils. In the second case, all the properties of soil are greatly influenced by a much higher content of liquid phase (which depends on ionic composition and $C_{ps}$ and the presence of saline ice. As a result, the soil properties, including response to applied load, change considerably. Such soils should be considered saline. It is reasonable to assume that there must be some critical concentration ($C_{cr}$) which corresponds to a line of demarcation between the two cases. It is reflected to a certain extent in the Russian “Construction Standards and Regulations”.

The initial critical concentration of pore solution which accounts for soil division into saline and nonsaline (each group with its own properties and freezing process kinetics) is not a constant. It depends, first of all, on the soil lithology. Thus, even slight increase in $C_{ps}$ of sands leads to a conspicuous changes in their properties, while in case of clays, the processes of ion exchange at grain solution interfaces largely compensate for the impact of solution concentration increase. Naturally, the critical concentration value depends on

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nature of the ion: Na\(^+\), Ca\(^{++}\), Cl\(^-\), SO\(_4\)\(^-\) etc. (Zykov et al., 1996). That is the reason why the mechanical properties of saline frozen sands and clays require special investigation.

Difficulties in testing the mechanical properties of frozen soils and the relative ease of acoustic measurements of elastic wave propagation velocity values compelled us to give preference to the latter when appraising specific features of SCCS formation in soils with different skeleton lithology, temperature, ionic composition and concentration of pore solutions, and consequently when estimating strength characteristics of the soils.

Certain interrelations have been found to exist between the elasticity and strength characteristics of nonsaline frozen soils (Frolov, 1976; Zykov and Chervinskaya, 1995), that makes possible use of acoustic methods for estimating their strength properties. Bearing this in mind, we carried out a series of laboratory tests to find similar relationships for saline frozen soils. This paper discusses some of the results obtained, including special features of dynamic elasticity characteristics and their interrelations with strength properties over a wide range of initial concentrations and compositions of pore solution saturating the samples.

Results and discussion

Some of the results of tests of artificially prepared samples of frozen sandy-clayey soils typical of the Yamal region and distinguished by massive cryogenic texture are given below. The soils with fixed composition parameters (such as plasticity index, moisture content, type of salinity, and concentration of saturating pore solution) were tested at a range of temperatures from -20°C to 0°C. Using widely known procedures (Frolov, 1976; Zykov and Chervinskaya, 1989) of ultrasonic sounding or profiling, we measured velocities of longitudinal, shear, and Rayleigh waves. The measured values together with data on the sample density were used in calculation of dynamic moduli: Young’s modulus \(E_d\), shear modulus \(G\), bulk modulus \(K\), and Poisson’s ratio \(\nu\). The same samples were tested by pressing of a ball stamp (Aksenov and Bruskov, 1993), and the value of equivalent cohesion \(C_{eq}\) was evaluated as one of characteristics of soil strength.

**Principal Characteristics**

Analysis of data obtained by studying saline frozen soils of different lithologies containing sodium and potassium chlorides permitted an estimate to be made of the critical initial concentration values for dispersive soils (Chervinskaya et al., 1997). It has been ascertained that \(C_{cr}\) rises monotonically with increase in the soil plasticity index, as shown in Figure 1.

The study of mechanical properties of saline frozen soils shows that the critical concentration appears most pronounced if we consider Poisson’s ratio as a function of \(C_{ps}\). In frozen sands, \(\nu\) increases drastically from 0.2 at \(C_{ps} \leq 0.3\) g/l (that is about \(5 \times 10^{-3}\) mole/l) to 0.33 - 0.35 at \(C_{ps} \approx 1\) g/l. Further increase in the initial concentration of pore solution causes slow growth of Poisson’s ratio up to 0.37 - 0.39 at \(C_{ps}\) equal to 80 - 100 g/l (which corresponds approximately to \(\nu\) values in unfrozen water-saturated sands).

Similar relationships for clays show different characteristic points. Poisson’s ratio begins to grow only after \(C_{ps}\) is equal to or exceeds 10 g/l (about \(1.5 \times 10^{-1}\) mole/l). In the case of higher pore solution concentrations, \(\nu\) values for frozen state also tend to values corresponding to those typical for unfrozen clays (that is 0.44 - 0.45).

Within ~ 1 to 10 g/l interval, \(\nu\) values are practically unchanging. For frozen sand and clay they are close to each other, though sands are saline within this interval while clays do not differ practically from nonsaline soils. The \(C_{ps}\) value which marks the beginning of the rapid increase in Poisson’s ratio in both cases should be considered as critical value, which agrees with data shown in Figure 1.

The results of the experiments suggest that an increase in the initial concentration of pore solutions in every type of soil leads unambiguously to a decrease in elastic wave velocity and a lower value of the Young’s modulus (Figure 2). There are nevertheless essential differences in manifestations of this regularity which may be easily explained in the context described above. Firstly, the noted decrease in \(E_d\) begins at various
values corresponding to weakly saline soils. Thus, for sands at $t = -5^\circ C$ it amounts to approximately 15 GPa, and for clays to $\sim 10$ GPa. In sands $E_d$ declines rapidly. When $C_{ps}$ changes from $\sim 0.5$ to 20 g/l, $E_d$ in sands is lowered almost by factor of 4 and in clays only by factor of 1.5. The slower decrease is at $C_{ps} = 30$ g/l in sands and only at $C_{ps} > 60-80$ g/l in clays.

Consequently, the $E_d$ ($C_{ps}$) curves intersect for soils that differ in lithology at $T = -5^\circ C$, for example, at the point corresponding to $C_{ps} \sim 15$ g/l (Figure 2). Therefore, for pore solutions at a given temperature and chemical composition, there exists such a concentration at which soils of any lithology would feature practically the same value of the dynamic Young’s modulus. The dependence of Young’s modulus on the plasticity index in saline frozen soils varies with concentration of pore solution. At low $C_{ps}$ values, the dependence takes the form of a descending curve. With an increase in concentration, the curve becomes less steep, and at $C_{ps} = 15$ g/l it becomes almost horizontal. On further increase of the pore solution concentration, Young’s modulus rises with an increase in the plasticity index of soils.

**Correlations with Strength**

It has been ascertained that under both quasi-static (mechanical tests) and dynamic (acoustic) actions, changes in mechanical properties in response to the external deforming effects are controlled by the same physical-chemical factors. Taking this into consideration there are good grounds to suggest close correlation between them. Actually, an increase in initial concentration of pore solution results in both cases in a pronounced decrease in elasticity and strength of saline frozen soils. To find the interrelation between these properties, the following parameters were chosen for comparison as technically the easiest to determine: (1) longitudinal wave propagation velocity ($V_p$) and (2) equivalent cohesion ($C_{eq}$).

It was found that in the case of chloride pore solution, the $C_{ps}$ increase, for instance in sandy loam, from $\sim 0.5$ to 18 g/l leads to decrease in longitudinal wave velocity ($V_p$) from 3300 to 2200 m/s, and lowering of the equivalent cohesion ($C_{eq}$) from 240 to 100 KPa (at $t = -3^\circ C$) (Figure 3). In this case the concentration dependence of both $V_p$ and $C_{eq}$ are described with similar empirical equations of the type $y = e^{a \cdot C_{ps}^b}$ where “$a$” and “$b$” coefficients may vary depending on the various composition of the soil mineral matrix. Therefore it appeared to be possible to find direct correlation between $V_p$ and $C_{eq}$ as follows (Figure 3b):

$$V_p = e^{2.97 \cdot C_{ps}^{-0.06}}$$

$$r = 0.74$$

$$C_{eq} = e^{4.59 \cdot C_{ps}^{-0.163 \cdot 10^x}}$$

$$r = 0.67$$

$$C_{eq} = (V_p^{-10^3 - 1.08}) \cdot 10^2$$

$$r = 0.78$$
\[ C_{\text{eq}} = 0.10 \nu_p - 108.3; r = 0.78 \ (\nu_p \text{ m/s; } C_{\text{eq}} \text{ kPa}) \]

It appears that if the data obtained in experiments for all soils (from sands to clays) tested at different fixed temperatures are brought together to a plane \( \nu_p - C_{\text{eq}} \), the experimental points form a dense enough cluster which may be approximated by a single regression equation (Zykov and Chervinskaya, 1995):

\[ C_{\text{eq}} = 1.8 \cdot 10^{-4} \nu_p^{1.75}; r = 0.81 \ (\nu_p \text{ m/s; } C_{\text{eq}} \text{ kPa}) \]

The values of the correlation coefficient, as well as a wide range of characteristics of the tested soil suggest that the relationship obtained is universal and also allow data from acoustical tests on \( C_{\text{eq}} \) of frozen saline sandy - clayey soils to be assessed.

**IONIC COMPOSITION IMPACT**

To estimate the influence of the salt composition in pore solution, samples of the same loam were tested under conditions of saturation with solutions of equal concentration \((C_{\text{ps}} = 30 \text{ g/l})\) containing chlorides (marine type of salinity), carbonates and sulphates (continental type) and their mixtures. Sodium and magnesium were taken as cations. In addition, in some experiments, solution of marine salt of the same concentration were used.

The temperature-dependencies of \( \nu_p \) obtained resemble in all cases the well-known ones for nonsaline soils (Frolov, 1976; Zykov and Chervinskaya, 1989): elastic wave velocities increase with a decrease in temperature. The beginning of freezing is marked by a conspicuous rise of velocities at a corresponding temperature \( t_{\text{bf}} \) which is related to ionic composition and saturating solution concentration with functional dependence well known in chemistry (Nekrassov, 1973). All the relationships obtained may be subdivided into two groups that differ on the basis of the temperature at which the freezing begins (according to ionic composition of the pore solutions): 1 - chlorides, and 2 - carbonates and sulphates. For chloride salinity \( t_{\text{bf}} \) values are considerably lower. Another distinguishing feature is a noticeable difference in \( \nu_p \) absolute values. Over the whole experimental range of temperatures, the carbonate-sulphate group features higher \( \nu_p \) values approaching those typical for nonsaline soils. This can be understood in the context of phase transition kinetics and formation of the solid matrix of SCCS. In the case of sulphate and hydrocarbonate salinity (eutectic temperature is -1.2 and -2.1°C respectively), virtually the complete precipitation of crystalline hydrates takes place within the temperature interval to -5°C. The pore solution then becomes desalinated, and elastic wave propagation velocities approach those obtained in corresponding nonsaline soils. In the case of chloride salinity, the eutectic temperature was not reached in our experiments. Phase transitions proceed more slowly in this group at the first stage (at temperature above -5°C) and more rapidly at lower temperatures. All this discussion is presented in the graph of \( \frac{d\nu_p}{dt} \) plotted against temperature (Figure 4).

In the case of saturation with solutions of salts of the 1st and 2nd groups mixed in various proportions, it appeared that the velocity of elastic wave propagation at soil temperatures below -5°C increases linearly from values corresponding to the chloride type of salinity towards the values typical of sulphate and hydrocarbonate composition of pore solutions. It is quite natural that the rate of increase at lower temperatures is less. Within the area of higher temperatures, the \( \nu_p \) growth becomes nonlinear in character. In thawed soil, the elastic wave velocities and other mechanical properties of soils are little affected by the composition of saturating solutions. The impact of pore solution ionic composition on the elastic wave propagation velocity in saline frozen soils refer equally to the strength parameters, though no direct measurements of the latter have been conducted in our experiments.

**Concluding remarks**

We conclude that saline frozen soils constitute media that are essentially different from nonsaline ones in terms of deformability and therefore in elasticity and strength, factors which are determined by the special conditions of their formation and the evolution of their spatial crystalline-coagulant structure. In studies of the latter, a number of physical methods may be used and a
leading role should be assigned to the acoustic studies which permit the frozen soil strength to be estimated with a reasonable degree of reliability. The correlations obtained suggest the possibility to use this approach for saline frozen soils. It seems necessary, however, to continue systematic experiments using acoustic and other methods, including tests of compressive and tensile strength applied to samples characterized by a wide range of mineral matrix composition and saturating pore solutions.

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References


