MATERIAL COMPOSITION AND STRENGTH CHARACTERISTICS OF SALINE FROZEN SOILS

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Abstract

The physical and mechanical properties of frozen ground depend mostly on its phase components (unfrozen water vs. ice content) which vary with temperature, salinity, salt composition and moisture.

Equations to calculate the temperature at the start of freezing and the phase components are presented in this paper. The former depend on the salinity, moisture and average molecular weight of dissolved particles. The phase components are calculated for different soil moistures and phase change temperatures. The unfrozen water content of clay is plotted versus temperature and salinity. Approaches to the determination of a boundary between plastic-frozen and hard-frozen states of saline soils are analyzed. The relationship between the mechanical properties of saline frozen ground and phase components is considered.

Introduction

To design structural foundations in permafrost regions, it is necessary to know the mechanical and thermal characteristics of soils at construction sites. These properties are determined during engineering-geological survey.

The mechanical properties of frozen ground depend on their mineral composition, structure and cryogenic temperature. Soil salinity and the composition of a pore solution make it possible to judge the phase composition of a pore fluid at a specific temperature $T$.

Experimental results on the phase composition of frozen soils

A compensation calorimeter was used in order to determine the phase composition of pore moisture and the temperature at the start of freezing for saline frozen ground, which is widespread on the Yamal Peninsula. Experimental data obtained with the calorimeter over the past decade have allowed us to derive formulae to calculate the temperature at the start of freezing $T_{bf}$ and the phase components $W_w$ and $W_i$.

At a specific temperature $T$, the total moisture of frozen ground ($W_{tot}$) is composed of unfrozen water ($W_w$) and pore ice ($W_i$).

$$W_w + W_i = W_{tot} \quad [1]$$

In this case, fixed water ($W_o$) not participating in phase transitions is included in the unfrozen water content. The content of fixed water is approximated as:

$$W_o = W_p / 4 \quad [2]$$

where $W_p$ is the Atterberg plastic limit, and the coefficient depends on the mineral composition of particles and the composition of dissolved salts.

Parameter $D_s$ of saline frozen ground is the ratio of the mass ($m_s$) of readily soluble salts in a unit soil volume to a dry density ($\rho_d$):

$$D_s = m_s / \rho_d \quad [3]$$

The concentration $C_p$ of a pore fluid is proportional to $D_s$:

$$C_p = D_s / (W_{tot} - W_o) \quad [4]$$

Parameters $D_s$ and $C_p$ (in %) characterize thawed soils. Concentration $C_p$ cannot be higher than the concentration of a saturated solution at a specific temperature, because excess salt precipitates from solution.

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The temperature at the start of freezing, $T_{bf}$, is an important characteristic of frozen ground. It is the warmest temperature of ice nucleation in a soil upon cooling. For sands without salts, $T_{bf} = 0^\circ$C. For non-saline clays, $T_{bf}$ is about $-0.2^\circ$C due to a high specific surface area of particles interacting with a pore water. Temperature $T_c$ of saline soils depends on the composition and concentration of salts in a pore fluid and can be determined from the following equation:

$$T_c = \frac{-1860D_s}{(W_{tot} - W_w)A}$$

where $A = M/n$ is the averaged molecular weight of particles and dissolved salt ions (in atomic mass units, amu); $M$ is the molecular weight of anhydrous salt, amu; and $n$ is the coefficient of salt dissociation in solution.

If a pore fluid contains “$k$” ion types, then

$$A = \frac{\ell_1m_1 + \ell_2m_2 + \ldots + \ell_km_k}{m_1 + m_2 + \ldots + m_k}$$

where $\ell_i$ is the atomic weight of an $i$-th ion, and $m_i$ is the concentration of an $i$-th ion in the pore fluid (mg-equiv).

The averaged ion composition of the World Ocean water is characterized by $A = 31.3$ amu and $C_p = 3.5\%$. $T_{bf}$ of sea water is $-2.0^\circ$C, and NaCl accounts for about 84\% of dissolved salts. Therefore, similar salinization is called “marine” in contrast to sulphate or carbonate types of salinization.

At temperatures colder than $T_{bf}$ ice is formed in a pore fluid due to unfrozen water freezing. In this case, dissolved salt ions are forced out of the ice segregation front, increasing the salinity of an unfrozen fluid. After that, ice can be formed only at temperatures colder than the $T_{bf}$ in a fluid with increasing salinity. If the temperature at the start of freezing and the salinity of a cooled saline sand is equal to $T_{bf}$ and $C_p$, respectively, the salinity will increase to $2C_p$ after freezing of half the pore fluid volume, corresponding to the equilibrium temperature of subsequent ice formation ($T = 2T_{bf}$). This indicates that the contents of ice, salts and unfrozen water are in a dynamic equilibrium with the soil temperature, according to the well-known Tsytovich principle (Anderson et al., 1973; Tsytovich, 1973).

The relationship between $W_i$ and $W_w$ is determined during soil calorimetry by a number of points within the temperature range under consideration.
(Nersesova, 1953). The content of unfrozen water \( (W_u) \) or ice \( (W_i) \) is plotted versus temperature using the data obtained. Figure 1 displays a set of unfrozen water content curves for frozen clays with different salinities \( D_s \) at \( W_{tot} = 48\% \).

The results of the determinations of the phase components of various saline frozen soils on the Yamal Peninsula makes it possible to propose the following calculation equations:

\[
W_i = (W_{tot} - W_o)(1 - T_{bf} / T) \quad [7]
\]
\[
W_w = W_o + (W_{tot} - W_o)T_{bf} / T \quad [8]
\]

Here, \( T_{bf} \) is calculated from Equation (5).

These formulae hold true for unsaturated pore fluids in soils with moisture equal to the Atterberg liquid limit and for temperatures warmer than the eutectic point.

Relationship between mechanical properties and phase characteristics of frozen soils

In addition to the determination of \( T_{bf} \) and \( W_u \), we tested the saline frozen sands and clays for uniaxial compression at temperatures and salinities varying from -1 to -8°C and from 0 to 1.5%, respectively. The total moisture and density of sands and clays were 0.26 and 1.85 g/cm³, or 0.48 and 1.68 g/cm³, respectively.

These experimental data have made it possible to obtain the relationship between the long-term unconfined strength \( (\sigma) \) and temperature and salinity. We calculated parameter \( R \) by the equation:

\[
R = 2.85\sigma + \rho_f d_1 \quad [9]
\]

where \( \sigma \) a long-term unconfined strength, \( \rho_f \) is a calculated soil density (g/cm³), and \( d_1 \) is the depth of foundation (m).

![Figure 2. The strength (R) of saline frozen sand vs the unfrozen water content.](image)

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The experimental data on the mechanical properties of saline frozen soils make it possible to state that the long-term strength $R$ and the coefficient of compressibility $\alpha$ depend on the phase composition of the pore fluid. The phase composition predetermines the degree of cementation of soil particles by ice and is influenced by temperature $T$, moisture $W_{\text{tot}}$, salinity $D_s$, and the salt composition of a pore fluid as described above.

Saline frozen soils differ from non-saline ones by lower temperatures for the start of freezing and a wider range of negative temperatures for active phase transitions. These differences become more perceptible with increases in soil salinity. The transient zone between the plastic-frozen and hard-frozen sections of a frozen ground also depends on its phase composition.

We have attempted to superimpose the unfrozen water content in sands and clays with different salinity on the strength-temperature relationships of these soils for different salinities in order to determine the criteria for the plastic-frozen state of the soils. The relationship between the unfrozen water content of saline soils and temperature is clearly described by the logarithmic curves. For clay soils (Figure 1), the strength varies over a narrow range of $W_w$ values (inflection points are not observed), following the strength-temperature relationships for different salinities. For various sands, the relationships between the soil strength and the content of unfrozen water (Figure 2) include virtually coincident inflection points, indicating that the sands have close strength $R$. Moreover, the inflection points correspond to the state of saline soils with 25 to 30% unfrozen water (including fixed water). This allows us to suppose that the amount of ice-cement has decreased, and the soil has gone to another state, which can characterize the boundary between its plastic-frozen and hard-frozen states.

Previously, we proposed that the change in a soil state could be assessed differently. We suggested that a saline soil will be hard-frozen when its temperature becomes five times lower than the temperature at the start of freezing. In contrast, at negative temperatures above $1.3 T_{bf}$, the mechanical properties of frozen ground are close to those of cooled unfrozen soils.

Conclusions

The temperature at the start of freezing and the unfrozen water content are the most important characteristics of saline frozen soils. Salinity substantially affects the values of these characteristics. Empirical equations to calculate values of $T_{bf}$ and $W_w$ of saline frozen soils are proposed in the paper.

The superimposition of temperature-strength relationships of saline frozen soils (obtained during unconfined compression tests) on curves of unfrozen water content at different temperatures (in logarithmic coordinates) has made it possible to outline the boundary between the plastic-frozen and hard-frozen states of frozen soils. In the case of plasticly-frozen ground, the stability of foundations should be calculated from data on the second ultimate state, i.e., on deformations.

References

