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The Fundamentals of Frozen Ground Mechanics (New Investigations)

Les Principes Fondamentaux des Sols Gelés

by N. A. Tsytovich, Professor, Corresponding Member of the Academy of Sciences of the U.S.S.R., Frozen Ground Research (Merzlotovedenya) Institute, Moscow, U.S.S.R.

Summary

The experimental investigations allow the formulation of the following fundamental statements on frozen soil mechanics: (1) principle of the equilibrium of water and ice in frozen soil; (2) conditions of moisture migration in freezing and frozen soil; (3) dependence of frozen soil strength not only on its composition and temperature but also on its structure; (4) influence of stress relaxation on frozen soil strength; (5) conditions of frozen soil consolidation and of the beginning of their plastic flow; (6) dependence of frozen thawing soil settlement on external pressure; and (7) change of structural bonds in soil subjected to freezing–thawing cycles.

In this paper the author gives data and considerations supporting the above statements and establishes their practical importance.

Sommaire

Des recherches expérimentales ont permis de dégager les principes fondamentaux de la mécanique des sols gelés. Ces principes concernent: (1) l'équilibre glace-eau dans les sols gelés; (2) les conditions de la migration de l'humidité dans les sols complètement ou partiellement gelés; (3) la dépendance de la résistance de sols gelés de leur structure; (4) l'influence de la durée d'application des contraintes sur la résistance des sols gelés; (5) les conditions de la consolidation des sols gelés et de l'apparition de la plasticité; (6) l'influence de l'intensité des charges appliquées sur le tassement; (7) les changements structuraux du course des cycles de gel et de dégel.

Dans cette communication, l'auteur fait état de résultats d'expériences et de considérations théoriques qui confirment les principes énoncés, puis il met en évidence leur intérêt pratique.

The study of the mechanics of frozen soils arose in the U.S.S.R. from the practical needs of construction and development in northern and eastern regions of the country. The present paper gives the fundamental principles of this new branch of soil science.

The difference between frozen and unfrozen soils lies in the fact that the former are cemented with ice and every variation of temperature below freezing point changes essentially their physical conditions and mechanical properties. The experiments carried out by Bouyoucos, Young and the author with his collaborators proved that a part of the water in frozen soils remains unfrozen and influences their properties (Tsytovich, 1945, 1947; and Tsytovich and Sumgin, 1937). The incomplete freezing of water in the pores is caused by its interaction with the active surface of mineral particles. Due to this interaction some of the water molecules are bound to the active surface and layers of ions are formed around the particles; this latter fact is of importance only at relatively high temperature (about — 0·5° C. and higher).

At a given negative temperature every soil is characterized by a definite content of unfrozen water W_{nf}, which is illustrated by the data obtained by Nersessova (1951) (Fig. 1).

The author's investigations (1945, 1947, 1953–56) have shown that the quantity of unfrozen water in frozen soils is not constant but changes with the variations of external influences, and remains in dynamic balance with the latter.

This principle is applied in many important practical cases. It is known, for instance, that frozen soils increase their strength when their negative temperature sinks; their elasticity modulus decreases with increase in the external pressure, and the strength of frozen sand is much greater than that of frozen clay (Tsytovich and Sumgin, 1937). These facts cannot be explained adequately if the dependence of the phase composition of water in frozen soils on the magnitude of the external influences is not taken into account. Thus, when the negative temperature sinks the ice content and the strength of the soil increases because the mobility of the hydrogen atoms in the ice lattice decreases: when the negative temperature rises the ice content decreases, since, as was shown by the author and Nersessova (1951), some of the ice in the pores thaws with any rise of negative temperature, and correspondingly the strength decreases and the plasticity of the frozen soil increases.

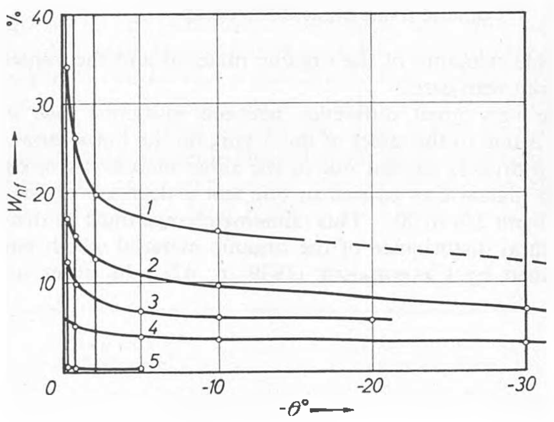

Fig. 1 Unfrozen water content of frozen soils with changes of temperature: 1, clay; 2, surface clay; 3, clayey soil; 4, sandy clay; 5, sand

Teneur en eau liquide des sols gelés en fonction de la température: 1, argile; 2, argile superficielle; 3, sol argileux; 4, argile sableuse, 5, sable

Due to the above principle the problem of freezing and thawing of soils must be set out in a different way, namely by considering the release of the crystallization heat in the whole volume of freezing soil and therefore a new differential equation for this problem must be formulated (Kolesnikov, 1952; Tsytovich, 1953–56).

A migration of moisture takes place during the freezing of soils, as was established for the first time by Tutunov's and the author's experiments (1947, 1953–56).

Those investigations showed that the migration of water in finely dispersed freezing and frozen soils is a direct function of the gradients of temperature and water content. This statement may be considered as the second principle of frozen soil mechanics. The experiments carried out by the author's collaborators, A. Bozhenova and F. G. Bakulin, support the statement that the film-crystallization (after A. Lebediev and S. Taber) mechanism of moisture movement plays the main role in the migration of water to the freezing front, the latter depending on the relation between the velocity of freezing and the velocity of water movement. It is possible to determine the limiting value of the permeability at which the migration of water to the freezing front is replaced by the squeezing of the latter out from the freezing layer (Tsytovich, 1955; Khakimov, 1955). This latter process takes place only in sufficiently permeable sands with a permeability above 0·1 m per day.

The migration of water accompanied by its freezing produces the heaving of soils (h), the total value of which consists of the volume increase on freezing of the existing local water and the volume increase of water sucked up in the process.

$$h = 0{\cdot}09w.\gamma_s.\xi.i_0 + 1{\cdot}09Q_t \qquad \ldots . \; (1)$$

where w is water content, γ_s = volume dry density, ξ = depth of freezing, i_0 = relative ice content in soil, equal to the ratio of ice weight to that of total water content, $Q_t = \int v.\mathrm{d}t$ = quantity of water sucked up in the process of water migration (v = the velocity of migration, t = time). Water volume weight = 1.

The migration and freezing of water in soils produce peculiar ice structures which have been studied in the laboratory of the Academy of Sciences by A. M. Pchelintsev. Experiments have shown that the structure of frozen soils determines in many respects their mechanical properties.

Three chief types of frozen soil structure are distinguished by P. A. Shumsky: massive, cellular and laminated (Tsytovich, 1953–56). The first type of structure is formed in the case of quick freezing, the third in the case of slow freezing with the upward migration of water from deeper layers of soil, while the second type is an intermediate one.

The author's experimental investigations carried out in collaboration with N. K. Pekarskaya and S. S. Vialov (Tsytovich, 1953–56) lead to the following statement: the more ice inclusions are present in frozen soil the greater is its instantaneous and the smaller its continuous shearing strength.

This is illustrated by the following examples. It was found that the instantaneous shearing strength of frozen clay of solid structure without layers of ice with water content 32 per cent, temperature −2° C. and external pressure 4 kg/cm^2 was equal to 8·2 kg/cm^2. The same clay with a cellular structure of segregated layers of ice and with the same total water content had an instantaneous shearing strength of 13·7 kg/cm^2. The continuous shearing strength of the same clay with a solid structure was 1·8 kg/cm^2 and with a cellular one 1·1 kg/cm^2. A change in the total ice content of frozen soils has a similar effect. Thus with an increase of total water–ice content in frozen clay from 23 to 60 per cent the momentary shearing strength rose from 9·9 to 14·5 kg/cm^2.

Under continuous load the ice layers in frozen soil undergo essential alterations due to recrystallization of the ice, partial thawing at contact points and new orientation of crystals. This is illustrated by the results of optical studies of ice inclusions made before and after loading (in collaboration with O. S. Konnova and A. G. Brodskaya (Fig. 2)).

All these and previously published data obtained by the author and other investigators (M. N. Goldstein, V. G. Berezantsev and S. S. Vialov) concerning the study of the mechanical properties of frozen soil permit the following important statement to be made: the strength of frozen soil is a function of both its composition and temperature and on account of the relaxation of stresses the strength depends also on the interval of time during which the load is applied. The latter influences especially the mechanical properties of frozen soils; therefore it is necessary to investigate their continuous resistance. For instance, while the instantaneous strength of frozen sand at − 1° C. is 62 kg/cm^2, the continuous application of load decreases its strength to 9 kg/cm^2.

The considerable decrease in the strength of frozen soil with time may be explained by the following causes: (a) viscous flow of films of unfrozen water which is particularly intense in the interval of considerable phase alterations (Tsytovich, 1953–56); and (b) plastic properties of ice which depend on the mobility of hydrogen atoms in its lattice and are represented in recrystallization of ice inclusions—therefore the limit of the continuous strength of ice approaches zero.

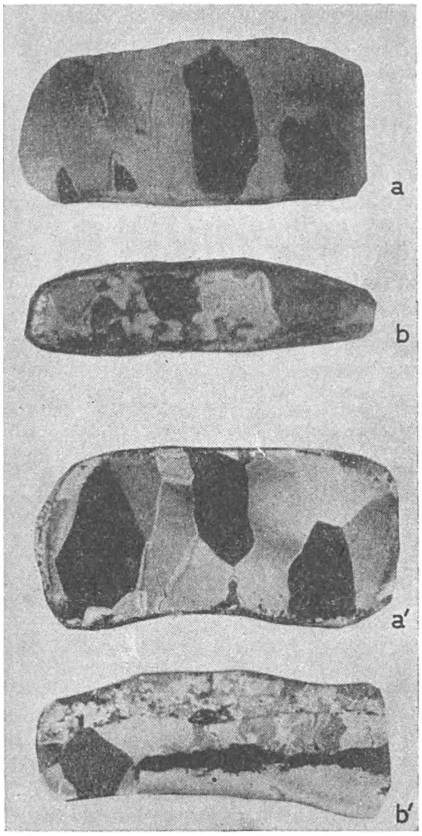

Fig. 2 Ice structure of frozen soil: (a) and (a′) before deformation, (b) after consolidation and (b′) after continuous shearing

Structure de la glace des sols gelés: (a) et (a′) avant la déformation (b) après consolidation (b′) après cisaillement lent

Besides, as the author has shown (Tsytovich and Sumgin, 1937), an external load produces great pressures at the contacts between hard particles, causing partial thawing of ice in interstices and squeezing out of the film water into lower stressed zones (Vialov, 1955).

All the above statements are supported both by direct determinations of frozen soil strength and its dependence on the duration of loading and by the data reported above obtained from the study of ice structures in frozen soils (Fig. 2).

The determination of continuous frozen soil strength is based on measurements of its shear strength, which enables the bearing capacity of frozen soils to be calculated from the known theoretical solutions.

The results of measurements of the shear strength of frozen clay (Tsytovich, 1953–56) are represented in Fig. 3a and the curve of cohesion relaxation in the same soil in Fig. 3b. These data show that the continuous shear strength, both the total one (τ) and its component (C) which is independent of the external pressure, is sometimes 5 to 10 times smaller than the instantaneous strength. It is particularly noteworthy that the cohesion (c) of frozen soils is the main characteristic of their continuous strength.

To determine the cohesion of frozen and unfrozen elastoplastic clays the author suggested the use of the ball indentation test (Fig. 3c) for which the theoretical solution is well established. It is known (Tsytovich, 1956) that the cohesion (c) of intact bodies is proportional to the hardness of material, i.e.

$$c = K\frac{P}{\pi . D . s} \qquad \dots . \ (2)$$

where K is the coefficient of proportionality, which for ideally plastic materials is equal to 0·18 according to Ishlinsky. Berezantsev (1955) has reported that in soils with an angle of friction $\phi \geqslant 7°$ the value of K will be less than 0·18, the coefficient of decrease (M) being equal to 0·61 at $\phi = 10°$; $M = 0{\cdot}28$ at $\phi = 20°$; $M = 0{\cdot}12$ at $\phi = 30°$. However, it has been shown (Vialov and Tsytovich, 1956) that this correction is not necessary for the determination of the bearing capacity in the case of frozen and hard-plastic soils, since the resistance value determined by means of the ball test represents a complex characteristic taking into account both cohesion and friction.

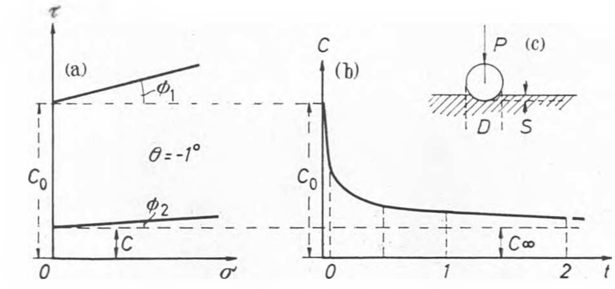

Fig. 3. Shear tests on frozen soil: (a) shearing diagram (1 quick shearing, 2 continuous shearing); (b) relaxation of cohesion; (c) diagram of ball test.

Essais de cisaillement d'un sol gelé: (a) courbe de cisaillement (1 cisaillement rapide, 2 cisaillement lent); (b) relaxation de la cohésion; (c) schéma de l'essai de la bille

If the ball sinks at a steady rate the value of cohesion obtained will be the continuous value. This practical, convenient method of continuous cohesion determination allows other important characteristics of frozen soils to be calculated. Thus, in the case of plastic frozen soils and the plane problem (after Prandtl) the bearing capacity (q) is given by (Tsytovich and Sumgin, 1937)

$$q = (\pi + 2)C_{\infty} + \gamma h$$

and in the case of the space problem for a plate of square area Ishlinsky–Berezantsev (Berezantsev, 1955) give:

$$q = 5{\cdot}71 C_{\infty} + \gamma h$$

where γh is the weight of soil above the base of the plate.

In other cases it is possible to use the known formulae of Skempton (1951), Shield and other authors.

When the loading is less than the ultimate bearing capacity soils decrease in volume. Up to the present time the volume compression of frozen soil has usually been neglected: experiments show that the compressibility of frozen clay at temperatures between 0° C. and − 0·5° C. is very considerable; it may lead to foundation settlements of inadmissible magnitude even at negative temperature. Thus the compressibility coefficient of frozen sandy clay with water content about 30 per cent and temperature − 0·3° C. proved to be equal $\mathrm{d}e/(\mathrm{d}p(1 + e))$ $= 0{\cdot}014$ cm^2/kg. At the same time frozen sands and all soils at very low temperatures have an insignificant compressibility coefficient (about one ten thousandth part of 1 cm^2/kg).

The cause of the compressibility of frozen clay lies apparently in a denser packing of the mineral particles under load, connected with the thawing of the ice in the pores and in the compression of closed air bubbles.

The investigations have shown that the volume compressibility of frozen soil is not in general a linear function of the value of the external pressure (Vialov, 1956), but in the case of coarsely grained soils and all soils at very low temperatures it is within certain limits directly proportional to the external pressure.

However a load greater than the ultimate bearing capacity produces a continuous plastic deformation of frozen soil.

According to S. S. Vialov the velocity of plastic flow is well described by the exponential function, but in the case of small values of pressure of about 1 to 4 kg/cm^2 the Bingham–Schwedoff law

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \frac{1}{\eta}(\sigma - \sigma_{\infty}) \qquad \dots . \ (3)$$

may be assumed, where η is the coefficient of viscosity and $(\sigma - \sigma_{\infty})$ the excess stress.

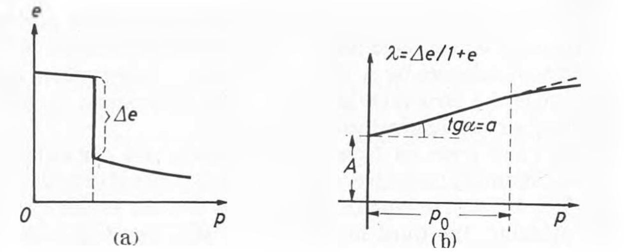

Fig. 4 Tests of thawing soil settlement: (a) change of void ratio during consolidation and thawing; (b) dependence of relative consolidation at thawing on the value of the external pressure

Essais sur le tassement des sols au cours du dégel: (a) variation de l'incide des vides pendant la consolidation et le dégel (b) variation relative de l'indice des vides au dégel en fonction de la pression de consolidation

Thus in the deformation of frozen soil steady plastic flow arises only beyond a certain state of stress, the velocity of plastic flow within certain limits, being proportional to the excess of stress.

The consolidation of frozen soil increases many times when it thaws and local quick settlements occur accompanied by severe changes in soil texture.

The author's investigations (1941) have shown that the thawing of frozen soil is indicated by a break in its void ratio–pressure curve (Fig. 4a), showing a sharp decrease in its voids.

According to the author's experimental data the change in void ratio on thawing $\lambda = \Delta e/(1 + e)$ in the case of pressures up to 7 kg/cm^2 is well expressed by the equation:

$$\lambda = A + [ap - bp^m] \qquad \dots . \ (4)$$

where A is the coefficient of thawing, the value of which varies from 0 to 1, but in some cases, according to Bakulin's and Zhukov's experiments, may be negative (Tsytovich, 1953–56): a = coefficient of volume decrease at thawing; b = coefficient of soil strengthening at thawing; p = external pressure; m = an exponent (less than 1).

The values of the coefficients, which are constant for a given soil, are determined by means of corresponding tests (TSYTOVICH, 1953–56).

Thus the consolidation of thawing soils in general consists of two parts, the first one depending on the value of external pressure and the other representing a linear function of normal pressure.

A statistical analysis of experimental data carried out by E. P. Shusherina (TSYTOVICH, 1953–56) showed that the curve of Fig. 4 b may be practically replaced by the straight line, $\lambda = A + ap$ up to the loading 3–5 kg/cm², as was assumed earlier (TSYTOVICH, 1941). Therefore the settlement of thawing soil is expressed in general by the equation

$$s = A\xi + a[F_\gamma + F_p] \qquad \ldots . (5)$$

where ξ is the depth of thawing; F_γ = the area of the pressure distribution curve due to the weight of the soil itself and integrated from the level of thawing to depth ξ, F_p = the area under the external pressure distribution curve (to the depth of thawing) (TSYTOVICH, 1941).

Calculations supported by observations in natural conditions show that the thawing of frozen clays and silty clays is accompanied by a considerable settlement which is approximately equal to the thickness of ice inclusions: construction on such soils becomes impossible unless special measures are taken. On other soils excessive settlements do not arise, but the settlement must be taken into account when the foundations are constructed.

SHUSHERINA's investigations (1955) showed that an alteration of the structural bonds takes place both in thawing soils and in all soils which undergo freezing–thawing cycles.

It has been established that the strength of thawed soils depends on their structure in the frozen state, decreasing, as a rule, in the case of cellular and laminated ice structures by several times compared to the strength of unfrozen soils, which have never been frozen. Thus, the shearing resistance of clays with excessive ice segregation decreased five times after freezing and thawing. Soils with solid or massive ice structure showed on thawing a certain increase of textural bonds as compared with their state before freezing (SHUSHERINA, 1955).

Generally, thawed soils become less dense and reconsolidate to a certain degree under the effect of external pressure if the value of the external pressure is less than the ultimate bearing capacity.

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