Calculation of Foundation Settlements on Thawing Soils

Calcul du tassement des fondations sur les terrains en voie de dégèlement

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SUMMARY

This paper reports a quicker method of determining the final settlement of foundations on thawing permanently frozen soils (permafrost), as a development of the progressive method of calculation according to ultimate states. The general laws of the compressibility of soils thawing under pressure are shown in the form of simple and convenient formulae. To determine the quantitative values of the relative compression and the total possible settlement of a thawing soil stratum, the physical characteristics of the soil are employed without carrying out field and laboratory tests of soil thawing under load. A brief description is given of the recommended type of core sampling tube for taking frozen soil cores, with instructions on drilling methods, selection of the monolithic pieces from the core, and determination in a laboratory of the physical characteristics of the frozen soil.

SOMMAIRE

Cet article décrit une méthode plus rapide pour la détermination du tassement final des fondations sur les terrains de type "permagel" en voie de dégèlement. Elle découle de la methode progressive qui s'appuie sur les états définitifs. Les lois générales de la compressibilité des terrains dégelant sous l'effet d'une pression, sont exprimées par des formules simples et pratiques. Pour déterminer les valeurs quantitatives de la compression relative et du tassement total d'un terrain qui dégèle, on utilise les caractéristiques physiques du sol sans faire sur le chantier ou en laboratoire les essais relatifs au dégel des terrains sous l'effet d'une charge. On donne une brève description du carottier recommandé pour le prélèvement des carottes dans les terrains gelés ainsi que les méthodes de sondage, le prélèvement de monolithes dans la carrotte et la détermination en laboratoire des caractéristiques physiques du terrain gelé.

IN PERMAFROST REGIONS and in regions where the soil freezes to a considerable depth in winter the provision of stable bases and foundations for residential buildings and industrial structures is a very complicated problem. The guaranteeing of strength, stability, long life, and fitness in operation of buildings and structures on permanently frozen soil is many times more complicated than under ordinary soil conditions, because permanently frozen soil contains a large quantity of ice (Fig. 1). The transformation of the ice into water leads to a sharp change in the physical condition of the soil, and this, in turn, leads to a special kind of settlement of base soil and to deformation of buildings and structures.

The best possible selection of the method of employing permanently frozen soil as a base when designing buildings and structures should be in a direct relation to the physical condition of the permanently frozen soil after thawing, and to the values of the final settlement of the thawing soil under pressure.

The designing of bases and foundations on permanently frozen soil according to the ultimate conditions is possible only when there is at hand a sufficient quantity of reliable data on the physical properties of the soils to be used in the bases (taking account of the climatic, engineering, geologic, and permanently frozen soil conditions at the construction site) and on the design of the buildings and structures, their temperature conditions, sensibility to uneven settlement, the technological requirements which the structures must meet, and the thermal resistance of the enclosing structure members.

For designing bases and foundations according to the ultimate conditions it is necessary to know the values of relative compression when the frozen soil thaws under a given pressure, the densities of sandy and coarsely fragmented frozen soil, the amount of settlement in the thawing soil, and the relative subsidence of the frozen soil stratum. These values are determined according to the changes in the physical characteristics of frozen soil obtained from monolithic pieces of the natural formation.

In engineering and geological surveys of permanently frozen soil for determining the possibility of erecting foundations, it is necessary to obtain from the trial pit monolithic samples that retain their natural formation and density. The difficulties encountered in excavating trial pits to the entire depth to which thawing of the soil is expected limit the possibility of detailed investigation of permanently frozen soil over the whole construction site. Lately, therefore, attempts are being made to employ various rotary drilling techniques for the extraction of a solid frozen core which can be used to determine the physical characteristics of the soil with its structure intact.

A variety of core sampling devices for both manual and mechanical drilling has been invented in various countries. For example, the Pchelintsev drill in the U.S.S.R. (1951), a mechanical drilling installation with a toothed cutter in Canada (*Civil Engineering and Works Rev.*, 1958). These devices are not used to any considerable extent in engineering and geological surveying in permafrost regions, however. The requirements for taking cores of frozen soil with its physical state and natural formation retained intact are best met by the mechanical drilling rig (Nyzovkin, 1963) with a rotary core sampling tube of the Kulbitski system. The advantage of this tube is that no liquid or compressed air is

FIG 1. Structure of frozen soil layer. *Top*, seasonally frozen layer of soil, with single intermediate layers of ice; *Bottom*, permanently frozen layer of soil. (Photograph by A. M. Pchelintsev.)

used for removing drilling cuttings from the head of the borehole.

COMPRESSIBILITY OF THAWING SOIL

A stratum of permanently frozen soil that is thawing under foundations is characterized by the magnitude of the conditional subsidence S. According to the values of S, the method of using the soil is chosen and the types of foundations for buildings are determined (*Construction Ratings*, 1962). The conditional subsidence is an approximate value of the settlement of subsiding, permanently frozen, soils upon thawing, and is determined from the formula (Kiselev, 1957):

$$S = \sum_{1}^{n} \delta_i H_i + \sum_{1}^{x} K_0 m_i \qquad (1)$$

where S = conditional subsidence; n = number of subsiding layers. δ_i = relative compression of frozen soil of i^{th} layer upon thawing; H_i = thickness of the i^{th} layer in cm; x = number of intermediate layers of ice; m_i = thickness of one intermediate layer of ice (over 1 mm) in cm; K_0 = factor taking into account the incomplete closing up of the macropores, which is taken equal to 0.4 with m_i from 0 to 3 cm, 0.6 with m_i from 3 to 10 cm, and 0.8 for greater thicknesses.

The quantity showing the compressibility of thawing soils under pressure in Equation 1 is the magnitude of the relative compression δ_i. The magnitude of the conditional subsidence S and the accuracy of its determination by means of Equation 1 depend solely upon the accuracy and reliability of the values of the relative compression of the separate permanently frozen soil layers; therefore no approximate or average values of the physical characteristics should be employed in determining δ_i.

Up to the present, the compressibility of soils under pressure in building foundation practice has been determined by means of experimental methods of testing the soils in field conditions under test loads with thawing of the soil by means of hot settlement plates, and in laboratory conditions in a compression apparatus. These methods are not used to any great extent, however, because of the technical difficulties and high costs involved.

To obtain the data necessary for calculation, new methods of determining the relative compression of soils according to their physical characteristics have been developed and are already being used (*Technical Requirements*, 1960).

The relative compression is measured by the magnitude of the ratio of the change in the volume of the soil to its initial volume, and is equal to the quotient obtained by dividing the difference between the bulk density of the consolidated soil skeleton (γ_{dd}) and the bulk density of the natural soil skeleton (γ_d) by the bulk density of the consolidated soil skeleton, viz.

$$\delta = (\gamma_{dd} - \gamma_d)/\gamma_{dd}. \qquad (2)$$

This basic relationship between the compressibility of soil and the changes in its physical characteristics, illustrated by Equation 2, has been proved by the results of compression tests involving the thawing of soils under pressure (Kiselev, 1957).

In a particular case for frozen sandy and clayey soils, which flow upon thawing, as well as for saturated thawed soils, the values of relative compression depend upon the difference between the initial volume of the sample and the final one after thawing and compaction, related to the initial volume, and are determined (*Technical Requirements*, 1960): (*a*) for sandy soil under condition of its maximum consolidation

$$\delta = (\gamma_{ds} - \gamma_d)/\gamma_{ds}; \qquad (3)$$

(*b*) for permanently frozen clayey soil with partial filling of all the pores with ice and unfrozen water

$$\delta = 1 - \gamma_d[1/\gamma_s + 1/\gamma_w(w_p + KI_P)]; \qquad (4)$$

(*c*) for permanently frozen clayey soil with all the pores completely filled with ice and unfrozen water

$$\delta = (1.09w_i + w_{in} - w_P - KI_P) : (1/\gamma_s + 1.09w_i + w_{in}); \qquad (5)$$

(*d*) for unfrozen or thawed soil saturated with water

$$\delta = (w - w_P - KI_P) : (1/\gamma_s + w); \qquad (6)$$

where δ = relative compression of the soil; γ_{dd} = bulk density of soil skeleton after thawing and consolidation in grams/cu.cm.; γ_d = bulk density of frozen soil skeleton in grams/cu.cm.; γ_{ds} = bulk density of sandy soil skeleton under conditions of maximum density in grams/cu.cm.; w = natural moisture content of soil expressed as a fraction of the weight of the oven-dry soil; w_i = ice content of the soil expressed as a fraction of the weight of the oven-dry soil; w_{in} = unfrozen water in soil expressed as a fraction of the weight of the oven-dry soil (the quantity of moisture that does not transform into ice when the soil freezes); w_P = plastic limit expressed as a fraction; I_P plasticity index expressed as a fraction; γ_w = specific gravity of water in grams/cu.cm., taken equal to unity; γ_s = specific gravity of soil in grams/cu.cm.; K = the compressibility factor of clay soil.

The ice content w_i of permanently frozen soil and the unfrozen water content w_{in} (Tsytovich, 1947) are determined from the following formulae (Davidochkin, 1957):

$$w_i = w - w_{in} \qquad (7)$$

$$w_{in} = C \cdot w_P \qquad (8)$$

where C = factor depending upon the kind of soil and the temperature below freezing point (below 0 C) and determined from Table I.

TABLE I. VALUES OF FACTOR C

Item No.	Kind of soil	Plasticity index	Temperature of soil in °C. −0.3	−0.5	−1.0	−2.0	−4.0	−10.0
1	Sandy loam	2 to 7	0.9	0.8	0.7	0.6	0.5	0.4
2	Loam	7 to 13	1.0	0.9	0.8	0.7	0.6	0.5
3	Loam	13 to 17	–	1.2	1.0	0.9	0.8	0.6
4	Clay	more than 17	–	1.4	1.1	1.0	0.9	0.7

According to the results of 348 experiments of the thawing of clayey soils under pressure in a compression apparatus, the values of the compressibility factors for pressures from 0.5 to 6 kg/sq.cm. have been calculated from the formula

$$K = \frac{\gamma_s \cdot \gamma_w(1 - \delta_0) - \gamma_d(\gamma_w + \gamma_s \cdot w_P)}{\gamma_s \cdot \gamma_d \cdot I_P} \qquad (9)$$

where δ_0 = experimental value of the relative compression of clayey soils. Equation 9 has been obtained by reducing Equation 4.

Regular relationships between the values of the compressibility factor and the consolidating pressure and plasticity number are illustrated in Fig. 2. For using the chart the plasticity index I_P is reduced to a fraction by dividing it by 100.

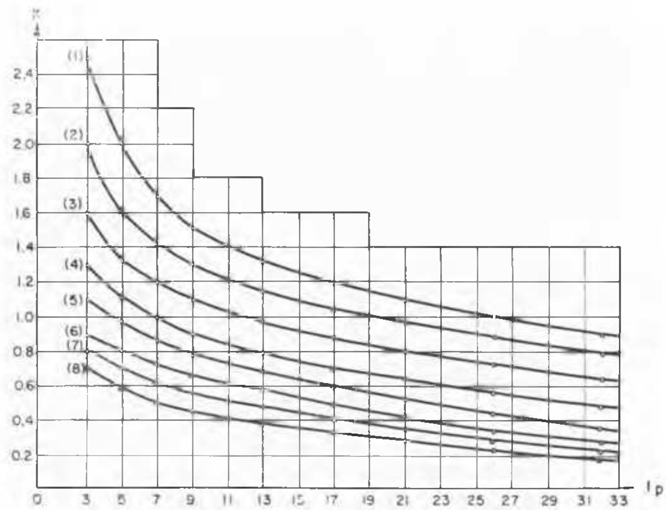

FIG. 2. Relationship between compressibility factor K and plasticity index I_P and consolidating pressures: (1) pressure of 0.5 kg/sq.cm., (2) pressure of 0.75 kg/sq.cm., (3) pressure of 1.00 kg/sq.cm., (4) pressure of 2.00 kg/sq.cm., (5) pressure of 3.00 kg/sq.cm., (6) pressure of 4.00 kg/sq.cm., (7) pressure of 5.00 kg/sq.cm., (8) pressure of 6.00 kg/sq.cm.

As can be seen from a comparison of the curves in Fig. 2 the variation of the compressibility factor values reduces with an increase in the pressure. Thus, for example, with a pressure of 0.5 kg/sq.cm. the compressibility factor ranges within maximum limits from 2.5 to 0.9, while for a pressure of 6 kg/sq.cm. this factor ranges within minimum limits, from 0.7 to 0.15. The values of the compressibility factors taken from Fig. 2 permit, within known limits, determination of the quantitative values of the relative compression of clayey soils according to Equations 4, 5, and 6.

The principal physical characteristic in calculations for determining the compressibility of thawing soils is the bulk density of the frozen soil skeleton γ_d, which is determined from the results of laboratory investigations of frozen soil cores.

TAKING AND INVESTIGATION OF FROZEN SOIL CORES

The numerical values of the physical properties of frozen soils are determined for construction purposes by investigating cores of these soils in field and in permanent laboratories.

Frozen soil cores are true cylindrical columns with a diameter of 40 mm, on the surface of which the finest details of the frozen structure can readily be seen. The cores are cut out of the solid mass of frozen soil to be investigated, without using any washing fluid, by means of a core sampling tube of the Kulbitski system (Fig. 3) which is connected to the spindle of a portable rotary drilling rig (Nyzovkin, 1963).

The core sampling tube consists of a thin-walled tube (1), 1,200 mm long, provided with screw (2). The upper end of the tube is connected by means of a transition piece (3) and a bayonet-type joint to the spindle of a drilling rig. To the lower end of the thin-walled tube, also by means of a bayonet-type joint, a boring crown (4) with hard alloy plates is connected. The diameter of the intake opening of the crown is 6 mm less than the internal diameter of the thin-walled tube.

With a slight axial pressure on the core-sampling tube, and

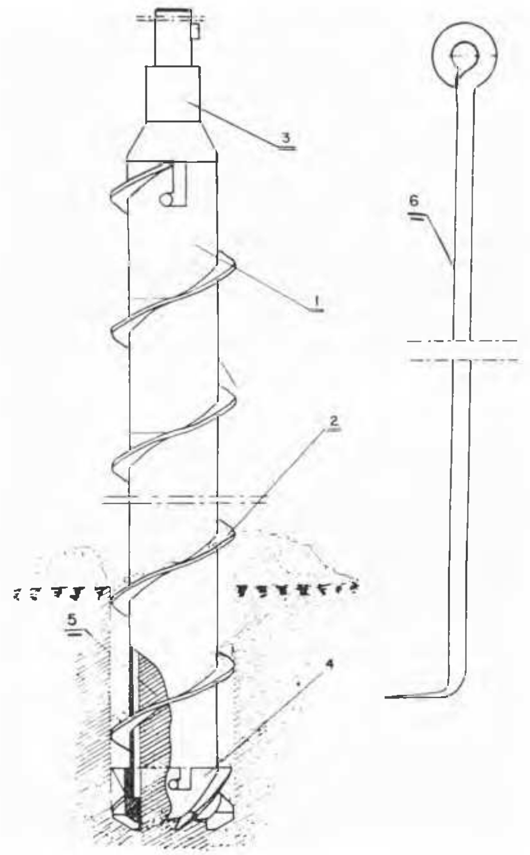

FIG. 3. Diagram of core sampling tube for taking frozen soil cores. 1, thin-walled tube; 2, screw; 3, transition piece; 4, boring crown; 5, core of frozen soil; 6, core cutter.

FIG. 4. Extraction of frozen soil core from borehole.

rotation at a speed of 250 to 300 rpm, the lower edges of the hard alloy plates will cut an annular gap around the core (5), while the inner sides of the plates will polish the side surface of the core. The slight heating of the frozen soil that takes place during this process is insufficient to cause thawing. Therefore the sludge of bored frozen soil, in the form of fine and loose frozen powder, is thrown out of the borehole by the tube screw (2).

As the annular gap is drilled, the core of frozen soil enters the boring crown and then the thin-walled tube. Since the diameter of the core is 6 mm smaller than the internal diameter of the thin-walled tube, the core does not touch its walls and as a result does not undergo any changes.

After the annular gap has been drilled to a depth of 1,200 mm the sampling tube is extracted from the borehole. The core remains, however, as the boring crown has no built-in core extractor. Experience has shown that a core extractor scratches the side surface of the core making it difficult to investigate its frozen structure and violating the technology of core investigation. To extract the core from the borehole, it is first cut at the bottom. For this, the core cutter (6) is lowered into the annular gap. This cutter consists of a long steel rod with a sickle-shaped blade on the end. By turning the blade the core is cut off at the bottom and by means of the same tool the core is extracted from the borehole (Fig. 4). When drilling is continued to a depth of 15 m the core sampling tube is elongated by adding snakes at the top, which throw the sludge out to the surface. The annular gap is drilled each time to a depth of 1,200 mm. For deep holes a longer cutter is used for cutting off the core and bringing it to the surface.

For drilling frozen sandy soil, three-stage boring crowns that cut and break off the frozen soil are used, and in frozen clayey soils one-stage crowns are employed that only cut the frozen soil. A core (1,200-mm) of frozen sandy soil can be recovered by means of the core sampling tube in less than 15 minutes; a similar core of frozen clayey soil can be recovered in less than 10 minutes. The drilling time depends upon the temperature of the frozen soil, as with a reduction of the temperature the strength of the soil increases greatly.

The frozen soil cores extracted from the boreholes are cut in a special device into pieces exactly 7.96 cm long. These samples have a volume of 100.0 cu.cm. For this reason the weight of each sample divided by 100 will be equal to the bulk density of the frozen soil (γ). If the sample contains lines of contact between soils having different properties, for example in respect to the nature of the ice inclusions or to the granulometric composition, it is cut up in the same device along these lines of contact and the bulk density of each new sample is determined. The bulk density of the frozen soil skeleton can be determined by means of the formula

$$\gamma_d = 100\gamma \;/\; 100 + (w_{in} + 1.09\, w_i). \qquad (10)$$

After finding the bulk density of the frozen soil, the ice inclusions of the samples are determined. All the samples are placed on special trays having serial numbers that correspond to the sequence of the samples in the geological section of the borehole from the surface downward. A stream of air is blown over the samples at a temperature of about 0 C by means of a fan until the ice inclusions on the side surface of the core evaporate to a depth of 3 to 4 mm. After this, the samples are photographed using a high contrast film and longer exposures than normal, with oblique lighting of the sample in the direction of its axis. The prints should be made on high contrast paper to ensure obtaining black ice inclusions on a white background, which makes it easy to determine x and m for calculation by means of Equation 1.

Example of Calculating Settlement

Given a circular foundation with a diameter of 1.5 m, a depth of 1 m, a load on the soil caused by the weight of the structure of $\sigma = 2$ kg/sq.cm., and data on the soils (Table II). The relative compression of the sand from Equation 3

TABLE II. PHYSICAL CHARACTERISTICS OF SOILS FOR CALCULATING SETTLEMENT

No. of layer	Kind of frozen soil below bottom of foundations	H (cm)	γ (grams per cu.cm.)	γ_d (grams per cu.cm.)	γ_{dd} (grams per cu.cm.)	γ_s (grams per cu.cm.)	w_P	I_P	K*	m (cm)
1	Fine-grained sand	200	1.80	1.502	1.565	—	—	—	—	—
2	Loam	300	2.0	1.56	—	2.73	0.156	0.09	0.935	—
3	Clay	400	1.90	1.43	—	2.77	0.196	0.175	0.725	2.6

*The value of K is determined from Fig. 2 in accordance with the consolidating pressure: for the loam layer – 1.66 kg/sq. cm., for the clay layer – 1.50 kg/sq. cm.

is $\delta_1 = (1.565 - 1.502)/1.565 = 0.04$. The relative compression from Equation 4 for loam is $\delta_2 = 1 - 1.56\ [1/2.73 + 1/1(0.156 + 0.935 \times 0.09)] = 0.054$; and for clay is $\delta_3 = 1 - 1.43\ [1/2.77 + 1/1\ (0.196 + 0.725 \times 0.175)] = 0.023$. The total settlement expected, using Equation 1, will be $S = 200 \times 0.04 + 300 \times 0.054 + 400 \times 0.023 + 2.6 \times 0.04 = 36.44$ cm.

CONCLUSIONS

The design of bases and foundations on permanently frozen soil according to the ultimate states is the most progressive method. The design solutions according to this method can be based on data showing the magnitude of the possible final subsidence of the thawing soil under the foundations of buildings and structures.

The method proposed in this report permits rapid and more complete determination of the final settlement resulting from thawing permanently frozen soil according to its basic physical characteristics.

The tasks of further investigations in this direction consist in broadening the possibility of using the method of determining the relative consolidation of soil, in perfecting the methods of taking frozen soil cores, and in standardizing the ways of determining the bulk density of frozen soil skeletons.

REFERENCES

DAVIDOCHKIN, A. N. (1957). Field estimation of ice content and subsidence of frozen soils. *Proc. Conference on Engineering and Geological Properties of Rock and the Methods of Their Investigation*, Vol. 2. U.S.S.R. Academy of Sciences Publishing House.

KISELEV, M. F. (1957). To the calculation of foundation settlement on thawing soil beds. Moscow, Gosstroiizdat Publishing House.

NYZOVKIN, G. (1963). Mechanization of Engineering—geological survey of the deformed bases of roads. *Proc. Second Asian Regional Conference on Soil Mechanics and Foundation Engineering* (Japan), Vol. 1, pp. 353–8.

PCHELINTSEV, A. M. (1951). New drill for taking samples of frozen soil with structure intact. *Pochvovedeniye*, No. 1.

TSYTOVICH, N. A. (1947). On unfreezing water in loose rock. *Bulletin (Izvestiya) of the U.S.S.R. Academy of Sciences* (Geological Series), No. 3.

——— (1962). *Construction ratings and rules*, part II, Section A, Chapter 10. Structure members and beds. Principal prescriptions for designing. Moscow, Gosstroiizdat Publishing House.

——— (1958). *Soil sampling in permafrost areas. Civil Engineering and Works Rev.* Vol. 53, No. 628, p. 1147.

——— (1960). Technical requirements for designing beds and foundations on permanently frozen soils (CH 91–60). Moscow, Gosstroiizdat Publishing House.